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Beneficial Uses of Insects

Big opportunities for tiny bugs: rush to boost laying hen performance using black soldier fly larvae meal

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Rising feed cost challenges due to expensive conventional protein sources continue to make headlines in Africa causing drops in profit margins. We assessed the impact of insect (*Hermetia illucens* Linnaeus larvae meal, HILM) protein as a substitute for soybean meal and sunflower seed cake on layer chicken performance and profitability. Our results showed that apart from the growers, chicks (12.37 g/bird) and layer hens (2.02 g/bird) fed diets with 75% HILM inclusion levels had significantly higher average daily weight gain. The average daily feed intake (ADFI) and feed conversion ratio (FCR) varied significantly when the chicks and layer hens were provided with the HILM-based diets. For the chicks and layer hens, the lowest ADFI and FCR were observed in birds subjected to diets with 75% and 100% HILM compared to the growers fed diets with 50% HILM. Significantly higher egg production was observed for layer hens fed diets containing 75% of HILM throughout the first (87.41%) and second (83.05%) phase production cycles. Layer hens fed HILM-based diets had a 3–10% increase in egg laying percentage. There was higher profit margins when birds were fed diets containing 75% of HILM (~1.83 and 5.98 US$ per bird), which mirrored the return on investment estimated at 63.95% and 33.36% for the pullets (growers) and laying hen, respectively. Our findings demonstrate that diets with 75% HILM provided optimum growth performance, reduced feeding costs, increased weight gain and egg production as well as improved economic returns for commercial on-farm poultry production systems.

Key words: black soldier fly, insect protein, alternative poultry feed, ISA Brown chicken, profitability

Introduction

The Population Division of the United Nations projects an increase in the human population from 8.0 billion in 2022 to 8.5 billion by 2030, 9.7 billion by 2050, and 10.4 billion by 2100, with more than half of the population increase occurring in sub-Saharan Africa (United Nations [UN] 2023). This increase in world population, coupled with urbanization, increased standards of living and economic growth has implications on demand for animal proteins especially meat and eggs. The 2 plant protein sources that are most frequently used in the formulation of poultry diets in Kenya include soybean meal (SBM) and sunflower seed cake. However, in recent years, the prices of SBM as well as sunflower seed cake have increased drastically mainly due to inadequate supply and competition between human and animal nutrition (Souza et al. 2021). The local production of SBM, sunflower seed cake and cotton seed cake cannot sustain the demands for the animal feed industry and therefore has to be imported (Vernooij and Veldkamp 2019). These protein sources account for 60–70% of the total cost of production; thus, there is an urgent need for cheaper alternative sources of protein to reduce the cost of production (Van Huis et al. 2015). In laying hen production, farmers are likely to abandon their enterprises when the high cost of feed becomes unbearable and unaffordable to them (Cicek et al. 2008).

Insects are considered as excellent sources of nutrients for poultry due to their high protein content, well-balanced amino acid profile and energy (fat/oil) levels (Abd El-Hack et al. 2020). Their short life cycle allows rapid breeding and adaptation to different ecological conditions. The low cost of breeding insects, their efficient feed conversion and their high nutritional quality make them suitable for large-scale production for use as a readily available and accessible source of protein in poultry feeds (Khusro et al. 2012). Black soldier fly (*Hermetia illucens* L., HI) larvae have been shown to be very nutritious with 40–56% crude protein (CP), 25–40% fat level, and a good balance of amino acids (especially lysine and methionine) and minerals (Makkar 2014, Onsongo et al. 2018, Shumo et al. 2019). Other studies by Sebatta et al. (2018) and Okello et al. (2021) revealed that most poultry farmers (>85%) were willing to use insect-based feeds as an alternative and dependable source of protein for their chicken feed. Apart from animal feed, HI larvae also have environmental importance by recycling organic wastes into organic fertilizers for improved soil health and crop yield (Rindhe et al. 2019, Beesigamukama et al. 2021).

The organic wastes, however, may contain contaminants, such as heavy metals, which can accumulate in the larvae and pupae of HI, resulting in their accumulation in the food chain (Wang et al. 2017, Proc et al. 2020). The flow of heavy metals from the organic wastes to the larvae and their potential to pose risks to the food chain cannot be ignored (Wang et al. 2017). However, a study by Diener et al. (2015) reported a low bioaccumulation factor of cadmium, zinc, and lead in HI larvae when fed with chicken feed spiked with low, medium, and high concentrations of heavy metals that were within allowable limits. The results also indicated that heavy metal concentrations in adult flies were significantly lower than in prepupae. A similar study by Shumo et al. (2019) reported low concentration levels of cadmium and lead in HI when fed on chicken manure, brewers' spent grain, and kitchen waste. It is therefore obvious that the bioaccumulation of heavy metals by the larvae strongly depends on the type of substrate used, the insect growth stage, and highly contaminated environmental conditions (Wang et al. 2017, Proc et al. 2020). Furthermore, Proc et al. (2020) report supported previous observations that the bioaccumulation of copper, iron, mercury, magnesium, molybdenum, selenium, and zinc in different insect life stages was less than one. No evidence of bioaccumulation of aluminum, arsenic, cobalt, potassium, lead, and silicon has been documented in literature. According to Wang et al. (2017), chickens fed 15% HI larvae reared with swine manure had very low levels of chromium, arsenic, lead, and cadmium bioaccumulation factors in the meat (0.525, 0.003, 0.031, and 0.003 mg/kg, respectively) and liver (0.345, 0.02, 0.038, and 0.019 mg/kg), which met the Food and Agriculture Organization (FAO), World Health Organization (WHO), and European Union food standards. Future studies should continue to investigate the impact of various contaminants on the safety of livestock food production when subjected to feeds enriched with HI protein source.

The fifth-instar larvae meal of black soldier fly has been reportedly shown to successfully replace fish meal (FM) (fully or partially) in the diets of livestock and fish (Dabbou et al. 2018, Onsongo et al. 2018, Ruhnke et al. 2018, Chia et al. 2019, 2020, 2021, Zarantoniello et al. 2019, Chu et al. 2020, Star et al. 2020, Park et al. 2021, Sumbule et al. 2021, Tahamtani et al. 2021, Wachira et al. 2021). Previous work done on insect-based feed globally has focused on substituting FM or SBM alone. No information exists on substituting SMB and sunflower seed cake, which are the most commonly used combinations of plant-based protein sources in laying hen diets by smallholder poultry farmers in Africa. Furthermore, there is limited information on the marginal analysis of insect-based feed for poultry production, which is very important if farmers have to make an informed decision of behavioral shift to novel insect-based diets over the expensive conventional poultry feeds. Therefore, the aim of this study was to determine the effect of different inclusion levels of black soldier fly HI larvae meal (HILM) in laying hens' (ISA Brown) diets on growth, laying performance, feed use efficiency, and cost effectiveness under commercial on-farm conditions.

Materials and Methods

Study Site

The study was carried out at Buru Buru Farm located in the northern suburbs of Nairobi City, Kenya. The facility is at 1,800 m above sea level with ambient temperature range of 17–22 °C. Its coordinates are 0° 43′ 12.85″ S and 36° 25′ 42.71″ E. It receives 1,000 mm of rain on average each year.

Experimental Ethics

The permission to conduct the experiment and collect data was in accordance with the animal welfare regulations, granted by the National Commission for Science, Technology, and Innovation (NACOSTI); research permit license no: NACOSTI/P/20/6955. This research also received approval from the Institutional Animal Care and Use Committee (IACUC) of the Kenya Agricultural and Livestock Research Organization (KALRO)-Veterinary Science Research Institute (VSRI), Muguga North, upon compliance with all provisions vetted under and coded: KALRO-VSRI/IACUC028/16032022.

Experimental Birds and Housing

A total of two hundred and ten (*n* = 210) one-day ISA Brown chicks were sourced from Kenchic Ltd, Nairobi, Kenya. Chicks were randomly placed in cubicles measuring 5.5 feet (ft) length by 2.6 ft wide fitted with wood shavings litter to a depth of 5 cm, and each equipped with a feeder, drinker, and laying nest measuring 1 ft length by 1 ft wide, also fitted with soft wood shavings. The 35 brooder cages were fitted with 250-W infrared bulbs to provide heating during the 2-week adaptation phase. The house was fitted with a hygrometer, which was used to measure temperature and humidity during the experiment in accordance with the guidelines of the ISA Brown Nutrition and Management Guide (Version L7121-2). In addition, the house was adequately ventilated to ensure air circulation. Chicks were grouped into 5 treatment diets with each diet replicated 7 times and 42 birds per diet. Individual cubicles sufficiently housed 6 birds and individual chicks were weighed before being placed in the cubicles. Birds were vaccinated against Marek's disease, infectious bursal disease, Newcastle disease, infectious bronchitis, fowl typhoid, fowl pox, and fowl cholera and dewormed at 3 months of age.

Experimental Feed Ingredients and Diets

All experimental diets for the entire experimental period were formulated once using Brill software according to the nutrient requirements for the birds (NRC 1994) and ISA Brown Nutrition Management Guide (Version L7121-2, Leentfaar 2020). The diets were formulated to provide the required amounts of 18%, 16%, and 17% CP for the chicks, growers, and layer hens, respectively, as well as 2,875, 2,750, and 2,800 kcal/kg of metabolizable energy (Tables 1, 2, and 3), respectively. The slight variation observed in the CP and metabolizable energy values presented in Tables 1–3 is

Table 1. Ingredients, proximate and mineral composition (DM basis) of *Hermetia illucens* larvae meal and experimental chick's diets

		0% HILM	25% HILM	50% HILM	75%HILM	100%HILM
Corn meal	-	541.40	507.50	526.30	556.50	593.40
Maize germ	-	88.30	142.50	121.70	77.50	91.90
Wheat middling	-	50.00	50.00	50.00	50.00	70.00
Soybean meal	-	229.70	183.70	151.90	131.20	0.00
Sunflower cake	-	50.00	35.00	20.00	5.00	0.00
HILM[a]	-	0.00	50.00	100.00	150.00	200.00
Dicalcium phosphate	-	20.10	19.40	19.20	19.90	30.00
Limestone	-	8.70	0.50	0.50	0.50	0.50
Common salt	-	3.40	3.30	3.20	3.10	3.00
Chick premix[b]	-	2.50	2.50	2.50	2.50	2.50
Lysine	-	2.30	2.00	2.00	1.30	6.30
Methionine	-	2.10	2.10	2.10	1.90	1.80
Toxin binder	-	1.00	1.00	0.10	0.10	0.10
Coccidiostat	-	0.50	0.50	0.50	0.50	0.50
Analyzed values (g/kg)						
Dry matter	939.00	887.00	888.30	888.90	884.00	887.00
Crude protein	466.00	183.10	183.30	183.10	183.40	183.20
Fat	145.00	70.50	70.09	68.40	72.40	73.03
Crude fiber	46.10	49.90	50.08	50.04	49.48	48.80
Ash	139.00	66.30	65.64	66.50	66.40	66.00
Metabolizable energy (kcal/kg)	3,638.00	2,863.31	2,863.46	2,862.77	2,863.63	2,863.53
Mineral composition (g/kg)						
Calcium	38.80	12.82	13.80	13.30	12.81	13.40
Potassium	12.00	8.40	8.40	8.50	7.50	6.00
Magnesium	3.50	2.50	2.50	2.80	2.40	2.70
Phosphorous	8.30	6.10	7.60	8.70	7.30	9.80
Sulfur	3.60	2.30	2.30	2.50	2.30	2.10
Boron	0.01	0.01	0.01	0.01	0.01	0.01
Molybdenum	0.01	0.03	0.02	0.02	0.01	0.02
Cobalt	0.01	0.02	0.01	0.02	0.01	0.01
Copper	0.01	0.01	0.01	0.01	0.01	0.01
Zinc	0.24	0.05	0.05	0.07	0.06	0.08
Manganese	0.65	0.04	0.06	0.10	0.11	0.15
Sodium	1.29	0.47	0.64	0.68	0.54	0.71
Iron	0.87	0.24	0.33	0.46	0.37	0.47

[a] HILM: full-fat *Hermetia illucens* larvae meal (HILM), soybean meal (SBM), and sunflower cake (SC), 0% HILM (control) (100% SBM&SC + 0% HILM), 25% HILM (75% SBM&SC + 25% HILM), 50% HILM (50% SBM&SC + 50% HILM), 75% HILM (25% SBM&SC + 75% HILM), and 100% HILM (0% SBM&SC + 100% HILM).

[b] Chick premix contents per 2.5 kg: Vit. (Vitamin) A: 12,000,000 IU, Vit. D3: 3,000,000 IU, Vit. E: 30,000 mg, Vit. K3: 3,000 mg, Vit. B1: 3,000 mg, Vit. B2: 8,000 mg, Niacin: 50,000 mg, Pantothenic acid: 15,000 mg, Vit. B6: 4,000 mg, Folic acid: 1,500 mg, Vit. B12: 20 mg, Biotin: 100 mg, Manganese: 70,000 mg, Zinc: 70,000 mg, Iron: 30,000 mg, Copper: 14,000 mg.

a clear shortcoming, which might be attributed to the processing procedures of the locally sourced feed ingredients (Sumbule et al. 2021). The study utilized 3 feeding phases: chicks (0–8 weeks), growers (8–18 weeks), and layers (18–60 weeks). The HILM was included in the experimental diets to replace the SBM and sunflower cake (SC) partially and completely at various inclusion levels: 0% HILM (control) [100% SBM&SC + 0% HILM]; 25% HILM (75% SBM&SC + 25% HILM); 50% HILM (50% SBM&SC + 50% HILM); 75% HILM (25% SBM&SC + 75% HILM); and 100% HILM (0% SBM&SC + 100% HILM). The various individual diet treatments were composed into mash form before feeding to the birds throughout the chick, grower, and layer hen's phases.

All the feed ingredients except HI larvae meal were sourced from local commercial suppliers in Nairobi, Kenya. The HI larvae were acquired from the International Centre of Insect Physiology and Ecology (ICIPE). The insects were reared on brewers' spent grains obtained from Kenya Breweries Limited. At the fifth-instar stage, the larvae were harvested and sterilized in hot water at 84 °C for 10 min. The larvae were then washed and dried using a commercial stainless-steel hot air circulating oven drier machine (CT-C-III Series, Henan Forchen Machinery Co., Ltd., Henan, China) for 2.5 h at 120 °C, then dried and allowed to cool. Thereafter, a hammer mill was used to grind the dried larvae into larval meal then mixed with other feed ingredients using inclined auger mixers (Chia et al. 2019). The 5 diets were replicated 7 times in a complete random design and provided to the birds ad libitum throughout the experimental period.

Proximate and Nutrient Analysis

The dry matter of the formulated diets was determined by heating the samples in an electric oven at 135 °C for 2 h according to Association of Official Analytical Chemists (AOAC) (1990, Method 930.15), while the ash content was determined by heating the samples at 550 °C for 2 h in the muffle furnace (AOAC 1990, Method 942.05). Samples were sent to Crop Nutrition (CROP NUTS) Laboratory Services Ltd., Kenya (a firm providing nutrient and mineral analysis in livestock feeds), where formulated diets were subjected to wet chemistry analysis. Standard AOAC laboratory procedures were used to determine the protein content (AOAC 1990 Method 984.13), where CP was determined by weighing 1 g of the sample, which was digested using sulfuric acid for 2 h using a

Table 2. Ingredients, proximate and mineral composition (DM basis), and experimental grower's diets

Ingredients (g/kg)	0% HILM	25% HILM	50% HILM	75% HILM	100% HILM
Corn meal	369.100	368.30	360.00	350.50	358.30
Maize germ	210.00	222.70	223.00	208.40	199.40
Wheat middling	200.00	200.00	200.00	200.00	207.80
Soybean meal	135.50	89.70	63.20	57.90	0.00
Sunflower cake	50.00	35.00	20.00	5.00	0.00
HILM[a]	0.00	50.00	100.00	150.00	200.00
Dicalcium phosphate	15.80	15.70	15.40	10.00	18.00
Lime	10.50	10.00	10.00	10.00	8.00
Common salt	3.30	3.20	3.10	3.10	3.00
Grower premix[b]	2.50	2.50	2.50	2.50	2.50
Lysine	0.80	0.50	0.50	0.50	0.50
Methionine	1.00	0.90	0.80	0.60	1.00
Toxin binder	1.00	1.00	1.00	1.00	1.00
Coccidiostat	0.50	0.50	0.50	0.50	0.50
Analyzed values (g/kg)					
Dry matter	889.50	890.70	891.40	894.00	895.00
Crude protein	162.10	162.80	162.40	162.540	162.60
Fat	68.60	70.80	70.20	69.24	70.90
Crude fiber	58.80	60.00	58.10	56.40	56.20
Ash	67.70	63.90	70.50	75.30	71.20
Metabolizable (kcal/kg)	2,779.94	2,780.71	2,779.04	2,800.00	2,781.15
Mineral composition (g/kg)					
Calcium	12.80	12.90	12.00	12.30	12.90
Potassium	9.00	9.80	8.60	8.60	8.10
Magnesium	3.60	4.00	3.00	2.90	2.70
Phosphorous	7.30	8.40	5.50	7.80	8.50
Sulfur	2.10	2.20	2.40	2.00	2.10
Boron	0.01	0.01	0.01	0.01	0.00
Copper	0.03	0.02	0.01	0.02	0.01
Molybdenum	0.01	0.01	0.01	0.01	0.01
Copper	0.03	0.02	0.01	0.02	0.01
Cobalt	0.01	0.01	0.01	0.01	0.01
Iron	0.44	0.48	0.48	0.37	0.37
Zinc	0.11	0.16	0.16	0.14	0.14
Manganese	0.13	0.20	0.20	0.20	0.20
Sodium	0.53	0.93	0.93	1.03	1.03

[a] HILM: full-fat *Hermetia illucens* larvae meal (HILM), soybean meal (SBM), and sunflower cake (SC), 0% HILM (control) (100% SBM&SC + 0% HILM), 25% HILM (75% SBM&SC + 25% HILM), 50% HILM (50% SBM&SC + 50% HILM), 75% HILM (25% SBM&SC + 75% HILM), and 100% HILM (0% SBM&SC + 100% HILM).

[b] Grower premix contents per 2.5 kg: Vit. (Vitamin) A: 10,000,000 IU, Vit. D3: 2,600,000 IU, Vit. E: 20,000 mg, Vit. K3: 2,600 mg, Vit. B1: 2,000 mg, Vit. B2: 5,000 mg, Niacin: 30,000 mg, Pantothenic acid: 12,000 mg, Vit. B6: 3,000 mg, Folic acid: 800 mg, Vit. B12: 15 mg, Biotin: 80 mg, Manganese: 50,000 mg, Zinc: 50,000 mg, Iron: 30,000 mg, Copper: 10,000 mg.

Kjeldhal digestion unit. The solution was then titrated and distilled in a Kjeldhal distillation and titration unit. The CP value was calculated by multiplying the *N* factor as outlined by Janssen et al. (2017).

Crude fiber, acid detergent fiber, and neutral detergent fiber content were determined by weighing 1 g of the samples and loading them in a raw fiber extractor (AOAC 1990 Method 920.29). Ether extract was determined by weighing 1 g of the samples and loading them into a solvent extraction unit (Van Soest et al. 1991). In brief, the mineral content of the feed and HILM was analyzed by inductively coupled plasma-atomic emission spectrometry. Sample preparation involved microwave-assisted acid digestion. Aliquots of ground feed samples were transferred to a glass tube in the microwave system, then, a mixture of nitric acid and hydrochloric acid was added to the sample and allowed to digest. The resulting solution was filtered into a volumetric flask and used for inductively coupled plasma optical emission spectrometry (ICP-OES) analysis to determine the following minerals: boron, molybdenum, iron, copper, zinc, cobalt, manganese, sodium, sulfur, magnesium, potassium, phosphorus, and calcium (Barałkiewicz et al. 2007, Dos Santos et al. 2012, Sreenivasulu et al. 2017, Płotka-Wasylka et al. 2018).

Performance Measurements of the Chicks, Growers, and Layer Hens

Before the experiment began, the initial body weight per bird in every cage (replicate) was recorded. Thereafter, the birds were weighed on a weekly basis by placing them on an electronic weight-weighing balance. Weekly live body weight, weight gain, feed consumption, the number of dead birds, and the number of eggs laid daily in each cubicle were also recorded. The feed conversion ratio (FCR), average daily feed intake (ADFI), and average daily weight gain (ADG) were also computed. The FCR in layer hens was expressed as a ratio of feed intake to the number of eggs produced and egg weight (egg mass).

$$FCR\ \ (chicks\ and\ growers)\,,g/g\ \ = (ADFI\ /ADG)$$

$$FCR\ \ (layer\ hens)\,,g/g\ \ = (ADFI/\,(no\ of\ \ eggs * egg\ weight\,(g))$$

Economic Evaluation

The cost-benefit ratio (CBR), return on investment (RoI), and marginal rate of return (MRR) were used to evaluate the economic

Table 3. Ingredients, proximate and mineral composition (DM basis), and experimental layer hens diet

		0%HILM	25%HILM	50%HILM	75%HILM	100%HILM
Corn meal	-	423.80	470.50	515.80	531.80	596.90
Maize germ	-	121.00	97.60	67.70	65.00	94.40
Wheat middlings	-	64.40	63.40	65.70	69.40	0.00
Soybean meal	-	223.70	175.00	131.10	79.20	0.00
Sunflower cake	-	50.00	35.00	20.00	5.00	0.00
Dicalcium phosphate	-	16.00	16.30	16.70	16.30	16.20
HILM[a]	-	0.00	50.00	100.00	150.00	200.00
Limestone	-	91.50	82.70	73.70	65.50	76.90
Common salt	-	4.10	4.10	4.10	4.10	4.00
Layer premix[b]	-	2.50	2.50	2.50	2.50	2.50
Lysine	-	0.50	0.50	0.50	9.00	7.40
Methionine	-	1.50	1.40	1.20	1.20	0.70
Toxin binder	-	1.00	1.00	1.00	1.00	1.00
Analyzed value (g/kg)						
Dry matter	939.00	895.40	900.50	900.80	898.10	898.30
Crude protein	466.00	171.8	172.00	172.30	172.50	172.30
Fat	145.00	76.70	76.40	77.20	77.28	77.40
Crude fiber	46.10	44.50	45.90	45.20	44.90	44.10
Ash	139.00	133.50	132.30	134.20	133.50	131.30
Metabolizable energy (kcal/kg)	3,638.00	2,818.21	2,818.51	2,818.43	2,817.98	2,818.51
Mineral composition (g/kg)						
Calcium	38.80	30.00	30.10	31.80	31.20	30.00
Potassium	12.00	8.60	8.90	8.60	7.70	7.40
Magnesium	3.50	7.20	6.60	8.10	6.10	5.70
Phosphorous	8.30	7.00	6.60	6.90	6.60	6.10
Sulfur	3.60	2.10	2.10	2.20	2.00	1.90
Boron	0.01	0.01	0.01	0.01	0.01	0.01
Molybdenum	0.01	0.01	0.01	0.01	0.01	0.01
Copper	0.01	0.01	0.01	0.02	0.01	0.01
Cobalt	0.01	0.01	0.03	0.02	0.02	0.01
Iron	0.24	0.58	0.53	0.57	0.56	0.46
Zinc	0.65	0.06	0.07	0.10	0.10	0.08
Manganese	1.29	0.09	0.10	0.15	0.17	0.15
Sodium	0.87	0.93	0.96	1.26	1.23	1.26

[a] HILM: full-fat *Hermetia illucens* larvae meal (HILM), soybean meal (SBM), and sunflower cake (SC), 0% HILM (control) (100% SBM & SC + 0% HILM), 25% HILM (75% SBM & SC + 25% HILM), 50% HILM (50% SBM & SC + 50% HILM), 75% HILM (25% SBM & SC + 75% HILM), and 100% HILM (0% SBM & SC + 100% HILM).

[b] Layer premix contents per 2.5 kg: Vit. (Vitamin) A: 8,0000,000 IU, Vit. D3: 3,000,000 IU, Vit. E: 15,000 mg, Vit. K3: 2,000 mg, Vit. B1: 1,500 mg, Vit. B2: 4,000 mg, Niacin: 20,000 mg, Pantothenic acid: 6,000 mg, Vit. B6: 2,750 mg, Folic acid: 500 mg, Vit. B12: 10 mg, Biotin: 75 mg, Manganese: 65,000 mg, Zinc: 55,000 mg, Iron 3: 8,000 mg, Copper: 14,000 mg.

benefits of substituting SC and SMB with full-fat HILM in the birds' diets. Total costs comprised of medication, feed costs, labor costs, housing, electricity, water, feeders, and drinkers. However, only feed costs were utilized in this study because all other costs were assumed to be same across all treatment diets. The CBR was calculated using the difference between production profits and feed costs, and values that were discovered to be more than 1 indicated that the benefits of production outweighed production costs and vice versa. Higher numerical values were regarded as a better representation of RoI, which was used to show financial gain or loss (Onsongo et al. 2018, Sumbule et al. 2021).

For each treatment diet, the total cost that varied (cost of feeding growers) was computed for the entire experimental period (18 weeks). The sales of live birds (18th week) and the sales of eggs for each treatment diet were used to determine the net benefits. It was expected that the net benefits attained would equal the current market rate the poultry farmer would receive if he or she resolved to sell them as grower pullets (ready for the laying phase) at that age. Before proceeding with the net benefit curve and calculation of marginal return rates, a dominance analysis was first performed by listing the total costs that vary from the lowest to the highest. This was done by eliminating treatments that had lower net benefits than or equal to proceeding with treatments with lower costs. In addition, a marginal rate of return was computed as a ratio of the change in net benefits (US$/bird) to the change in costs that vary (CIMMYT 1988).

The experiment further estimated that the minimum return would be 100% since the use of HILM as a new protein in laying hens diets was a new practice for poultry farmers (CIMMYT 1988). This would require a farmer to settle for the best practice which is above the minimum return which indicates that the farmer would recover the costs used and gain more net benefits. Formulas (1), (2), and (3) below for grower i and farmer j provide a summary of all of these.

$$\textit{Net benefits (US\$ per bird)} = \sum_{ij}^{n} (P_{ij}Q_{ij} - r_{ij}X_{ij}) \tag{1}$$

$$\textit{Marginal return rate (US\$ per bird)} = \partial \textit{ net benefits} / \partial \textit{ total cost that vary} \times 100 \tag{2}$$

Table 4. Mean performance (±SE) of chicks, growers, and layer hens fed with diets containing full-fat *Hermetia illucens* larvae meal

Parameters measured	0% HILM	25% HILM	50% HILM	75% HILM	100%HILM	*df*	*F* value/ KW chi-square	*P* value
Chick stage (0–8th weeks)								
Initial weight (g)	144.26 ± 2.60a	159.57 ± 2.35a	137.45 ± 3.61a	136.80 ± 3.77a	144.51 ± 2.46a	4	6.905[a]	0.141
Final weight (g)	473.66 ± 14.74b	549.76 ± 14.46a	553.88 ± 13.78a	569.77 ± 16.67a	547.34 ± 12.17a	4,170	6.813	0.001
Weight gain (g)	329.40 ± 12.14a	390.19 ± 12.11b	416.43 ± 10.17b	432.97 ± 12.9b	402.80 ± 9.71b	4	25.711[a]	0.001
Percentage weight gain (%)	69.54 ± 0.64a	70.97 ± 0.31bc	75.14 ± 1.22bc	75.99 ± 1.21b	73.60 ± 0.43c	4	29.718[a]	0.001
Average daily weight gain (ADG) (g/day)	9.41 ± 0.61a	11.19 ± 1.04b	11.81 ± 0.53b	12.37 ± 0.96b	11.51 ± 0.36b	4	25.711	0.001
Average daily feed intake (ADFI) (g/day)	52.43 ± 1.23a	49.53 ± 1.67ab	46.45 ± 2.47abc	42.77 ± 2.23bc	40.45 ± 0.94c	4,30	7.381	0.001
Total feed intake (ADFI × 35 d)	1,835.07 ± 10.67c	1,733.45 ± 12.42bc	1,625.67 ± 15.11abc	1,497.01 ± 14.39ab	1,415.60 ± 9.31a	4	19.578[a]	0.001
Feed conversion ratio (FCR) (g/g)	5.58 ± 0.29b	4.43 ± 0.517ab	3.93 ± 0.20ab	3.46 ± 0.24a	3.51 ± 0.10a	4.30	3.34	0.022
Grower stage (8th–18th weeks)								
Initial weight (g)	473.66 ± 14.74b	549.76 ± 14.46a	553.88 ± 13.78a	569.77 ± 16.67a	547.34 ± 12.17a	4,170	6.813	0.001
Final weight (g)	1,420.29 ± 17.02a	1,465.70 ± 18.53ab	1,485.00 ± 15.56b	1,480.00 ± 17.53b	1,489.60 ± 22.80b	4	11.058[a]	0.026
Weight gain (g)	946.63 ± 11.68a	915.94 ± 15.35a	931.12 ± 15.04a	910.23 ± 13.10a	942.26 ± 19.08a	4,170	4.971	0.290
Percentage weight gain (%)	66.65 ± 0.78a	62.49 ± 0.81a	62.70 ± 0.83a	61.50 ± 0.89a	63.26 ± 0.71a	4,170	2.000	0.097
ADG (g/day)	13.52 ± 0.17a	13.08 ± 0.22a	13.30 ± 0.21a	13.00 ± 0.19a	13.46 ± 0.27a	4,170	2.227	0.068
ADFI (g/day)	90.69 ± 3.54a	81.78 ± 4.65ab	78.20 ± 2.67ab	72.14 ± 3.26b	72.45 ± 1.66b	4,30	4.603	0.005
Total feed intake (ADFI × 70 d)	6,348.62 ± 25.61b	5,724.79 ± 29.34ab	5,474.32 ± 22.24a	5,049.92 ± 24.57a	5,071.77 ± 1 7.57a	4	18.223[a]	0.001
FCR (g/g)	6.71 ± 0.31a	6.25 ± 0.48ab	5.88 ± 0.28bc	5.55 ± 0.20cd	5.38 ± 0.15d	4	21.322[a]	0.001
Total body weight gain (chick and grower)	1,276.03 ± 14.21a	1,306.13 ± 18.24b	1,347.55 ± 17.31b	1,343.20 ± 15.04b	1,345.09 ± 21.06b	4,170	11.834	0.018
Layers stage (18th–60th weeks)								
Initial weight (g)	1,420.29 ± 17.02a	1,465.70 ± 18.53ab	1,485.00 ± 15.56b	1,480.00 ± 17.53b	1,489.60 ± 22.80b	4	6.938[a]	0.026
Final weight (g)	1,825.42 ± 25.62a	1,978.77 ± 29.19b	2,044.85 ± 33.62b	2,061.14 ± 27.10b	1,991.17 ± 29.47b	4,170	10.260	0.001
Weight gain (g)	405.14 ± 25.84a	513.07 ± 35.69b	559.86 ± 35.49b	581.14 ± 28.90b	501.57 ± 31.39b	4,170	5.692	0.001
Percentage weight gain (%)	21.32 ± 2.66a	25.24 ± 3.02ab	26.91 ± 2.80b	28.49 ± 2.57b	24.79 ± 2.78ab	4,170	4.210	0.001
ADG (g/day)	1.37 ± 0.09a	1.74 ± 0.12b	1.90 ± 0.12b	2.01 ± 0.10b	1.70 ± 0.11b	4,170	5.708	0.001
ADFI (g/day)	134.78 ± 3.72bc	136.76 ± 3.77c	124.79 ± 1.67ab	119.86 ± 1.29a	117.91 ± 1.77a	4	75.485[a]	0.001
Total feed intake (ADFI × 295 d)	39,626.50 ± 1,092.70bc	40,208.83 ± 1,108.88c	36,688.73 ± 491.19ab	35,238.17 ± 379.09a	34,666.21 ± 519.46a	4	75.482[a]	0.001
Total number of eggs	189.00 ± 4a	217.00 ± 70b	205.00 ± 40ab	218.00 ± 40b	198.00 ± 20ab	4,30	4.381	0.001
Egg weight (g)	60.69 ± 0.33a	62.82 ± 0.30b	62.79 ± 0.28b	63.33 ± 0.28b	60.11 ± 0.25a	4,30	19.230	0.001
FCR (g/g)	3.08 ± 0.12c	2.56 ± 0.08ab	2.56 ± 0.06ab	2.24 ± 0.05a	2.67 ± 0.15b	4	21.631[a]	0.001
Egg laying %, phase I (18–42 weeks of age)								
Week 18	0.00	0.00	0.00	0.00	0.00	0	0	0.00
Week 42	85.51 ± 1.87a	88.50 ± 3.15a	78.64 ± 2.88a	87.41 ± 2.97a	78.50 ± 3.48a	4,30	2.72	0.048
Average (18–42)	66.08 ± 1.87a	73.76 ± 2.56ab	71.67 ± 1.18ab	75.83 ± 2.12b	70.07 ± 2.03ab	4,30	3.126	0.020
Egg laying %, phase II (43–60 weeks of age)								
Week 43	87.76 ± 1.94a	83.33 ± 3.02a	79.93 ± 2.54a	82.65 ± 2.78a	77.81 ± 4.44a	4	5.565[a]	0.444
Week 60	66.41 ± 3.27a	81.44 ± 1.33b	82.35 ± 1.83b	83.05 ± 1.66b	76.54 ± 1.80b	4	17.832[a]	0.001

Table 4. Continued

Parameters measured	0% HILM	25% HILM	50% HILM	75% HILM	100%HILM	*df*	*F* value/ KW chi-square	*P* value
Average (43–60 weeks)	76.33 ± 1.24a	85.15 ± 1.90bc	83.12 ± 1.46bc	87.93 ± 0.96c	80.30 ± 1.20ab	4,30	10.320	0.001
Percentage egg production (18th–60th weeks)	70.03 ± 1.88a	77.58 ± 2.22bc	75.68 ± 1.73abc	79.32 ± 1.89c	72.70 ± 1.85ab	4,30	6.938	0.001

Within rows, means followed by different lowercase letters differ significantly ($P < 0.05$).
[a]KW: Kruskal–Wallis chi-square. 0% HILM (control) (100% SBM&SC + 0% HILM); 25% HILM (75% SBM&SC + 25% HILM); 50% HILM (50% SBM&SC + 50% HILM); 75% HILM (25% SBM&SC + 75% HILM); and 100% HILM (0% SBM&SC + 100% HILM).

$$\textit{Marginal return rate (US\$ per bird)} = \frac{[\Sigma i{=}\ 2\ P2jQ2j\ \text{-}\ r2jX2j)]\ \text{-}\ [\Sigma i{=}\ 1(P1jQ1j\ \text{-}\ r1jX1j)]}{\Sigma i{=}\ 2\ r2jX2j\text{-}\Sigma\ i{=}\ 1r1jX1j} \quad (3)$$

(Alemu et al. 2021 and CIMMYT 1988)

Where, P_{ij} = the price of the final live body weight (grams) (18th week) of the grower or the price of one egg per layer hen *i* for respondent *j*; Q_{ij} = the final live body weight (grams) (18th week) of the grower or the number of eggs for layer hen *i* for respondent *j*; r_{ij} = the price of feed consumed by the grower or layer hen *i* for respondent *j*; X_{ij} = quantity (grams) of feed by grower or layer hen *i* for the respondent *j*, $i = 1 \ldots p$, and $j = 1 \ldots n$.

Statistical Analysis

Prior to analysis, data were tested for conformity to the requirements of normality and homogeneity of variances using the Shapiro–Wilk normality test and Bartlett's test for homogeneity of variance, respectively. Data that conformed to normality and homogeneity of variances included the final body weight of chicks and layer hens, initial body weight of growers, percentage weight gain in growers and layers, average daily gain of growers and layer hens, average daily feed intake of chicks and growers, FCR of chicks, number of eggs, laying percentage (week 42, average 18–42 and 43–60), and economic returns. These data were subjected to analysis of variance (ANOVA) and the treatment means were separated using the Tukey test at $P < 0.05$. Data on initial body weight of chicks and layer hens, body weight gain in chicks and growers, final body weight of growers, total body weight gain, percentage weight gain in chicks, average daily gain of chicks, growers, and layer hens, average daily feed intake for layer hens, total feed intake of chicks, growers, and layers, egg weight, laying percentage (weeks 43 and 60), and FCR of growers and layer hens were not normally distributed and were analyzed using the Kruskal–Wallis test and treatment means were separated using the Wilcoxon test at $P < 0.05$. All data analyses were performed using R Version 4.0.2 (R Core Team 2020).

Results

Nutrient Content of Feed Ingredients and Diets

The proximate and mineral composition of the experimental chicks, growers, and laying hens' diets and HILM is presented in Tables 1, 2, and 3, respectively. The values of the CP, crude fat, crude fiber and ash were, 466, 145, 46.1, and 139 g/kg, respectively. The CP and metabolizable energy of the formulated diets attained the minimum requirements for ISA Brown chicks, growers, and laying hens, respectively. Diet containing 100% HILM had the highest crude fat, lowest crude fiber, and lowest ash for chicks, growers, and laying hens, respectively. There was generally a good balance of minerals in HILM and experimental diets.

Performance of the Chicks, Growers, and Layer Hens

Table 4 shows the performances of the chicks (3rd–8th weeks), growers (8th–18th weeks), and layer hens (18th–60th weeks) when fed on the different experimental diets containing HILM. The average daily weight gain (ADG), body weight gain, and final live body weight of the chicks and layer hens fed with HILM were significantly higher ($P < 0.001$) compared to those fed 0% HILM. Except the final live body weight ($P = 0.026$) that was significantly different across the treatment diets, the ADG ($P = 0.068$) and body weight gain ($P = 0.290$) of the growers were not significantly different across the different diets. The highest body weight gain of the chicks and layer hens was achieved when fed diets with 75% HILM. Figure 1 shows the overall live weekly body weight gain of the chicks, growers, and layer hens throughout the experiment for 60 weeks. There was a gradual increase in weight gain for all the birds fed on the different diets. The live body weight of birds fed diets containing full-fat HILM was consistently observed to be higher compared to those fed diets with 0% HILM. The average daily feed intake and FCR were significantly lower ($P < 0.001$) for chicks, growers, and layer hens fed diets with HILM as a substitute for SBM and SC. The lowest daily feed intake and best FCR were recorded for chicks, growers, and layers fed diets with 75% and 100% inclusion levels of HILM. Table 4 presents the laying performance (%) of layer hens. There was a significantly higher ($P = 0.020$) egg production (%) for layer hens fed diet containing 75% of HILM throughout the first (weeks 18–42) (87.41%) and second ($P < 0.001$) (weeks 43–60) (83.05%) phases of the production cycle, whereas those fed 0% HILM had the lowest ($P < 0.05$) with 66.08% and 76.33% within the same periods. Weekly egg production (number of eggs) of layer hens consuming diets containing HILM was observed to be significantly higher ($P < 0.05$) throughout the experimental period compared to those fed diets with 0% HILM as shown in (Fig. 2). Laying hens fed with a diet containing 75% HILM had the highest proportion (21.97%) while those fed 0% HILM had the lowest proportion (18.24%) in the total number of eggs produced per bird (weeks 18–60). Laying hens fed HILM-based diets had a 1–4% increase in the total number of eggs produced (i.e., a 3–10% increase in laying percentage) (Table 4; Fig. 3).

Economic and Marginal Analysis

Table 5 represents the gross profit margin, RoI, CBR, and marginal rate of return (MRR) of the chicks, growers, and layers fed on the

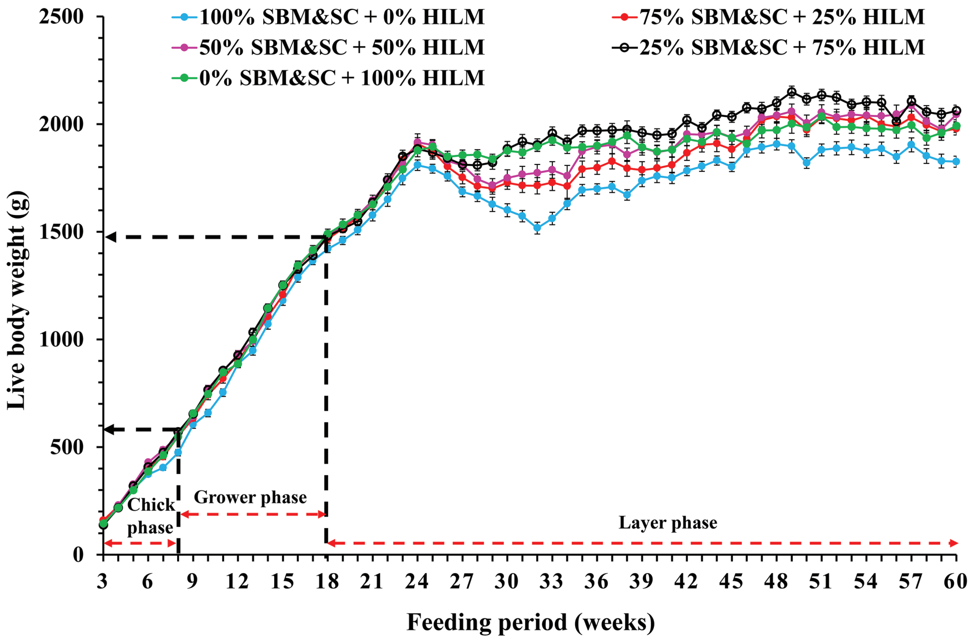

Fig. 1. Weekly live body weight (±SE) of chicks (0–8 weeks), growers (8–18 weeks), and layer hens (18–60 weeks) fed diets with increasing levels of HILM. 0% HILM (control) (100% SBM&SC + 0% HILM); 25% HILM (75% SBM&SC + 25% HILM); 50% HILM (50% SBM&SC + 50% HILM); 75% HILM (25% SBM&SC + 75% HILM); and 100% HILM (0% SBM&SC + 100%).

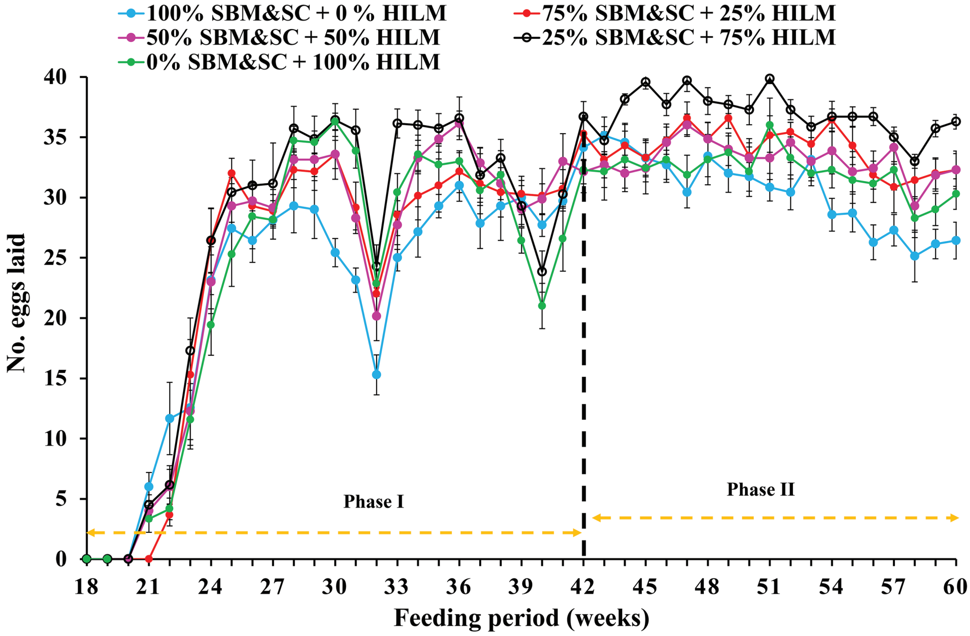

Fig. 2. Weekly egg production (number of eggs) (±SE) of layer hens (18–60 weeks) fed diets with increasing levels of HILM. 0% HILM (control) (100% SBM&SC + 0% HILM); 25% HILM (75% SBM&SC + 25% HILM); 50% HILM (50% SBM&SC + 50% HILM); 75% HILM (25% SBM&SC + 75% HILM); and 100% HILM (0% SBM&SC + 100%).

experimental diets containing HILM. The inclusion of HILM in the chicks, growers, and layer hens diets to replace the plant protein sources resulted in a more expensive formulation, with diets 75% HILM (0.48 US$/kg), 100% HILM (0.43 US$/kg), and 75% HILM (0.51 US$/kg), respectively. However, when factoring in the feed intake, the cost of feed consumed by chicks, growers, and laying hens decreased with the inclusion of full-fat HILM in the diets. No significant differences ($P = 0.096$) were observed in the total cost of feed consumed by chicks and growers. For chicks and growers, diets with 75% inclusion of HILM generated the most affordable cost of feed consumed (2.85 US$ per bird). On the other hand, for laying hens, diet with 100% HILM was the most affordable feed (16.29 US$ per layer) (Table 5). The highest ($P < 0.001$) total number of eggs (218 per bird) and sales of eggs (23.95 US$ per bird) were produced by laying hen fed on diet with 75% inclusion of HILM. But laying hens provided diet with 0% HILM had the lowest number of eggs ($P < 0.001$) produced, estimated at approximately 20.82 US$ per bird (Table 5).

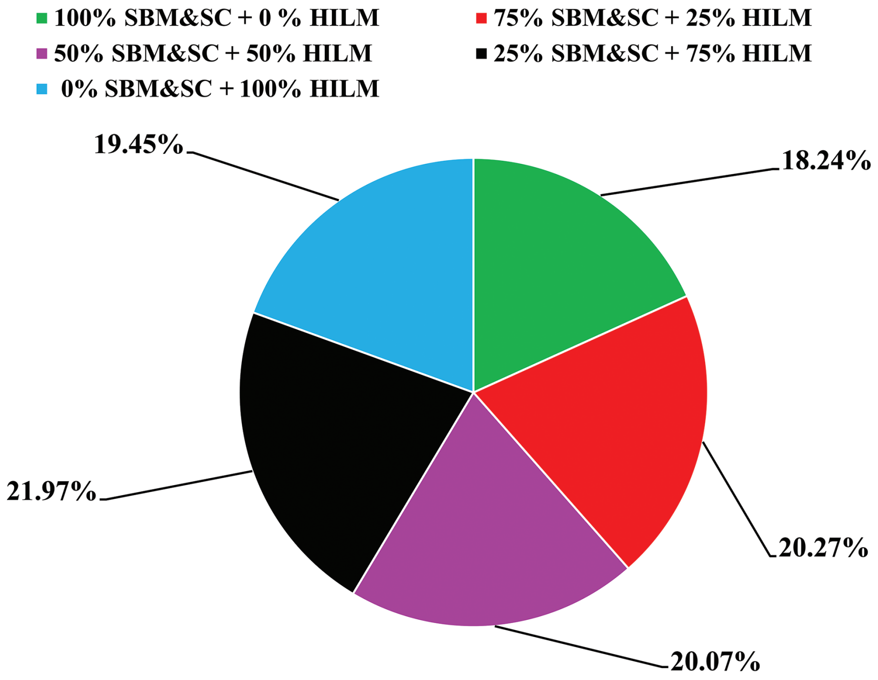

Fig. 3. Proportion of dietary treatment contribution to the total number of eggs laid by layer hens (18–60 weeks) fed diets with increasing levels of HILM. 0% HILM (control) (100% SBM&SC + 0% HILM); 25% HILM (75% SBM&SC + 25% HILM); 50% HILM (50% SBM&SC + 50% HILM); 75% HILM (25% SBM&SC + 75% HILM); and 100% HILM (0% SBM&SC + 100%).

There was no significant difference ($P = 0.096$) in gross profit margin, CBR, or RoI for chicks and growers raised on the various diets except for laying hens (Table 5). Chicks, growers (pullets), and laying hens fed diet with 75% HILM had the highest monetary gross profit margin (1.83 US$ and 5.98 US$, respectively). Birds fed on diets with 100% HILM had the highest investment of (63.95% and 33.36%), respectively. Growers and laying hens raised on diet with 0% HILM had the lowest profit margins, CBR, and RoI.

With regard to all of the diet treatments, marginal analysis of pullets at the 18th week showed no significant difference ($P = 0.096$) in terms of total cost and net benefits (US$ per bird), except for laying hens ($P < 0.001$) (Table 5). The pullets and laying hens provided diet with 0% HILM had the highest total cost that varied, except for those fed a diet with 100% HILM, which translates to the highest net benefits between the 18th and 60th weeks. The decision of the poultry farmer to shift from feeding the pullets a diet containing 75–100% inclusion levels of HILM resulted in the highest positive MRR of 100%. A change from the inclusion of 50–100% HILM in the diets as well as changes from 25% to 50% HILM led to a reduction in the MRR per bird. At the layer phase of the experiment, any decision by the poultry farmer to shift from feeding laying hens with diets with changes from 75% to 50% inclusion levels of HILM resulted in the highest positive MRR (300%). Changes for feeding layer hens with diets containing 25–75% HILM and 50–100% HILM led to a reduction in the MRR (Table 5).

Discussion

The proximate analyses of HILM revealed a CP content of 466 g/kg, which is lower than 500 g/kg reported by Khan et al. (2018) but higher than 410–436 g/kg documented by Makkar et al. (2014) (410–436 g/kg). This variation can be attributed to the substrate type used for rearing the larvae. This is supported by Shumo et al. (2019) and Mahmud et al. (2020), who demonstrated that the CP of HI larvae raised on chicken manure, kitchen food waste, and brewer's spent grain varied considerably (411, 330, and 413 g/kg, respectively). The incorporation of full-fat HILM in the diet increased the amount of crude fat content, which is consistent with previous studies of ISA Brown chicks and pullets by Sumbule et al. (2021). Similarly, feed formulated with HILM as an ingredient for female quail chicks as a substitute for FM (*Rastrineobola argentea*) exhibited a considerable increase in CP (Yusuf et al. 2020).

In this present study, chicks final body weight (FBW), average daily weight gain (ADG), and overall live body weight gain (LBW) varied significantly, with higher weight gain in birds fed on diets with 50% and 75% HILM than those fed on the other diets. This is consistent with the findings by Dugyala et al. (2018), who reported the highest weight gain for chicks fed a diet with 75% HILM inclusion levels. Moula et al. (2018) also reported a similar significant increase in weight gain among the chicks fed on HILM diets for a period of 30–50 days. This might be attributed to the higher protein and energy content of the diet with HILM. The HILM contains high levels of medium-chain fatty acids, which might be implicated in the increase in energy levels in the gut of the birds, thereby promoting growth (Chu et al. 2020). These findings are also consistent with the results by Marono et al. (2017), who demonstrated that feeding Barbary partridges diets containing 25% and 50% HILM as a substitute for SMB protein had a significant impact on the live body weight of the birds.

In addition, Dahiru et al. (2016) showed that 1-day-old Cobb (CP 747) broiler chicks fed different diets with varying inclusion levels of HILM (5%, 7.5%, and 10%) had a significant influence on the LBW and ADG. This is further supported by Chu et al. (2020), who found that Hy-line Brown an improvement over ISA Brown layer hens fed on diets containing 3%, 6%, and 9% HILM replacement levels resulted in a significant increase in ADG and FBW. Increased HILM inclusion levels in diets increase nutrient digestibility, promoting growth performance due to a decrease in non-starch polysaccharides.

Table 5. Feeding costs and a marginal analysis (±SE) of diets incorporating full-fat *Hermetia illucens* larval meal fed to layer hens

Parameters measured	0% HILM	25% HILM	50% HILM	75% HILM	100% HILM	df	*F* value/ KW chi-square	*P* value
Cost of feed per kg US$								
Chick	0.45	0.45	0.47	0.49	0.48			-
Grower	0.37	0.38	0.40	0.42	0.43			-
Layer hen	0.46	0.47	0.48	0.51	0.47			-
Cost of protein (%) US$								
Chick	36.13	36.98	39.11	41.95	32.46			-
Grower	25.99	27.02	30.96	37.23	36.48			-
Layer hen	49.37	47.13	46.85	44.20	33.99			-
Average daily feed intake (ADFI) (g per bird)								
Chick	52.43 ± 1.23a	49.53 ± 1.67ab	46.45 ± 2.47abc	42.77 ± 2.23bc	40.45 ± 0.94c	4,30	7.381	0.001
Grower	90.69 ± 3.54a	81.78 ± 4.65ab	78.20 ± 2.67ab	72.14 ± 3.26b	72.45 ± 1.66b	4,30	4.603	0.001
Layer hen	134.78 ± 3.72bc	136.76 ± 3.77c	124.79 ± 1.67ab	119.86 ± 1.29a	117.91 ± 1.77a	4	75.485*	0.001
Total feed intake (g per bird)								
Chick (ADFI × 35 days)	1,835.07 ± 10.67c	1,733.45 ± 12.42bc	1,625.67 ± 15.11abc	1,497.01 ± 14.39ab	1,415.60 ± 9.31a	4	19.578*	0.001
Growers (ADFI × 70 days)	6,348.62 ± 25.61b	5,724.79 ± 29.34ab	5,474.32 ± 22.24a	5,049.92 ± 24.57a	5,071.77 ± 1 7.57a	4	18.223*	0.001
Layer hen (ADFI × 295 days)	39,626.50 ± 1,092.70bc	40,208.83 ± 1,108.88c	36,688.73 ± 491.19ab	35,238.17 ± 379.09a	34,666.21 ± 519.46a	4	75.485*	0.001
Cost of feed consumed (US$ per bird)								
Chick	0.83 ± 0.23b	0.78 ± 0.26ab	0.76 ± 0.33ab	0.73 ± 0.31ab	0.68 ± 0.20a	4,30	3.892	0.011
Grower	2.35 ± 0.54a	2.18 ± 0.62a	2.19 ± 0.48a	2.12 ± 0.54a	2.18 ± 0.38a	4,30	1.327	0.271
Total feed cost (Cfc) (chick and growers)	3.17 ± 0.58a	2.96 ± 0.62a	2.95 ± 0.55a	2.85 ± 0.58a	2.86 ± 0.41a	4,30	2.135	0.096
Total feed cost (Cfc) (layer hen)	18.23 ± 2.33b	18.90 ± 2.39b	17.61 ± 1.47ab	17.97 ± 1.41b	16.29 ± 2.39a	4,30	4.488	0.001
Economic analysis (US$ per bird)								
Final body weight of growers (g)	1,420.29 ± 17.02a	1,465.70 ± 18.53a	1,485.00 ± 15.56a	1,480.00 ± 17.53a	1,489.60 ± 22.80a	4	11.058*	0.164
Sales of birds (Spb) (growers)	4.68	4.68	4.68	4.68	4.68	-	-	-
Gross profit margin (Pr)[a] (chick and growers)	1.51 ± 0.34a	1.72 ± 0.41a	1.73 ± 0.31a	1.83 ± 0.33a	1.82 ± 0.17a	4,30	2.135	0.096
Cost benefit ratio (CBR)[b] (chick and growers)	1.48 ± 0.37a	1.59 ± 0.39a	1.60 ± 0.39a	1.64 ± 0.30a	1.64 ± 0.26a	4,30	1.961	0.120
Return on investment % (RoI)[c] (chick and growers)	47.41 ± 3.61a	58.35 ± 4.42a	58.44 ± 3.59a	63.95 ± 3.90a	63.62 ± 2.90a	4,30	1.957	0.122
Total number of eggs	189.00 ± 3.00a	217.00 ± 4.00b	205.00 ± 4.00ab	218.00 ± 3.00b	198.00 ± 4.00ab	4,30	4.381	0.001
Cost of 1 whole egg	0.11	0.11	0.11	0.11	0.11	-	-	-
Sales of eggs (Spb)	20.82 ± 1.09a	23.85 ± 1.42b	22.51 ± 1.33ab	23.95 ± 1.12b	21.83 ± 1.25ab	4,30	4.372	0.001
Pr[a] (layer hen)	2.59 ± 1.08a	4.95 ± 1.42b	4.90 ± 1.33b	5.98 ± 1.12b	5.54 ± 1.25b	4,30	5.387	0.001
CBR[b] (layer hen)	1.15 ± 0.25a	1.26 ± 0.33b	1.31 ± 0.26b	1.33 ± 0.26b	1.37 ± 0.31b	4,30	6.629	0.001
RoI %[c] (layer hen)	14.21 ± 2.55a	26.42 ± 3.26b	27.83 ± 3.16b	33.36 ± 2.65b	34.01 ± 3.08b	4,30	6.671	0.001
Marginal analysis for pullets at 18th week								
Total cost that vary (TCV)	3.17 ± 0.58a	2.96 ± 0.62a	2.95 ± 0.55a	2.85 ± 0.58a	2.86 ± 0.41a	4,30	1.327	0.096
Marginal costs (MC)	-	0.01	0.09	0.01	-			-
Net benefits (NB)	1.51 ± 0.34a	1.72 ± 0.41a	1.73 ± 0.31a	1.83 ± 0.33a	1.82 ± 0.17a	4,30	2.135	0.096

Table 5. Continued

Parameters measured	0% HILM	25% HILM	50% HILM	75% HILM	100% HILM	df	*F* value/ KW chi-square	*P* value
Marginal net benefits (MNB)	-	−0.01	−0.10	0.01	-	-	-	-
Marginal rate of return % (MRR)	-	−100.00	−111.11	100.00	-	-	-	-
Marginal analysis for layer hens (Week 18–60)								
TCV	18.23 ± 2.33b	18.90 ± 2.39b	17.61 ± 1.47ab	17.97 ± 1.41b	16.29 ± 2.39a	4,30	4.488	0.001
MC	-	0.93	1.32	0.36	-			-
NB	2.59 ± 1.08a	4.95 ± 1.42b	4.90 ± 1.33b	5.98 ± 1.12b	5.54 ± 1.25b	4,30	5.357	0.001
MNB	-	−1.03	−0.64	1.08	-	-	-	-
MRR %	-	−110.75	−48.48	300.00	-	-	-	-

Within rows, means followed by different lowercase letters differ significantly ($P < 0.05$). *KW: Kruskal–Wallis chi-square. 1 grower (pullet) cost was 4.68 US dollars when the exchange rate was US$ = 106.57 in August 2020. 1 egg cost was 0.11 US dollars when the exchange rate was US$ = 106.57 in May 2021. (-) indicates that no calculation was done. Cost (US$/kg) of protein ingredients used in formulating the experimental diets: SBM (0.66), SC (0.24), HILM (0.80).

[a] $Profits\ (Pr) = Selling\ price\ (US\$)/bird\ (Spb) - Cost\ price\ (US\$)\ of\ feed\ consumed/bird\ (Cfc)$.

[b] $CBR = Spb/Cfc$.

[c] $RoI = Profits\ (Pr)/Cfc * 100$.

In contrast to our findings, Yusuf et al. (2020) reported that female quails fed a diet with FM and SBM substituted with varying levels of HILM up to 10% showed no significant difference in weight gain or final live body weight. This could have been attributed to the nutrient profile of the control diet (0% HILM), which significantly had a higher proportion of methionine, calcium, and protein compared to the other experimental diets.

The ADG, LBW, and FBW of the grower birds fed on the 5 experimental diets did not vary considerably. However, from weeks 9 to 14, birds fed diets containing HILM showed a consistent increase in LBW, which gradually declined toward the commencement of the egg-laying phase. The same period is also the stage when the major organs and muscles are developing. These observations are comparable to those reported by Sumbule et al. (2021), where the same trend in LBW started to decline from week 11 to week 16. According to Whitehead (2004), the slow growth rates reported between weeks 12 and 18 could probably be attributed to the formation of body tissues (medullary bone), which play a key role in the excellent supply of calcium for the formation of eggshells prior to the laying stage. Toral and Saleh (2017) observed that changes in the growth performance of pullets toward the layer phase are a good indication of how they will utilize the nutrients efficiently, which in turn will influence egg production during the laying phase. The ADG, LBW, and ADG were significantly improved when layer hens were provided with a diet of 75% HILM. The findings are in agreement with those reported by Mwaniki et al. (2020), who demonstrated that White Shaver layers fed diets with 10% and 15% HILM substitution levels from 28 to 43 weeks had a significant increase in LBW. This might be attributed to well-balanced CP, energy, amino acids, fatty acids, and other nutrients capable of increasing the energy levels in the gut and promoting growth (Chu et al. 2020). Contrarily, Marono et al. (2017) reported that layer hens fed diets with SBM had higher LBW than those fed diets containing HILM.

The average daily feed intake (ADFI) and FCR of the chicks, growers, and layer hens decreased substantially with increasing inclusion levels of full-fat HILM in the diets. These findings are consistent with those by Widjastuti et al. (2014), who observed a similar trend for quail's diet with HILM as a replacement for FM. The improved FCR observed for birds fed diets with HILM might be attributed to sufficient energy to allow the birds to lower their feed intake once they reached the point of satiation (satisfactorily full and unable to take on more) (Poorghasemi et al. 2013). Fat and protein are very essential to the growth layer hens and provide the energy and amino acids required during the early stages. There was a reduction in feed intake with increasing inclusion levels of HILM in layer hens' diets, which resulted in a decrease in the ADFI. There was a lower FCR ratio for layer hens fed diets with HILM, which is attributed to low feed intake and high egg mass (no eggs* egg weight). These findings are consistent with those presented by Ruhnke et al. (2018), who revealed that ISA Brown layers (47–62 weeks of age) fed diets with HILM experienced lower feed intake compared to those fed diets without HILM. Our findings concur with the study by Patterson et al. (2021), who reported that the inclusion of SBM and oil in the diets of layer chickens resulted in a lower FCR. Similarly, Zotte et al. (2019) also observed that increasing the quantity of HILM in the diet of laying quails led to reduced FCR over a period of 6 months. The findings are in contrast to those reported by Liu et al. (2021), who found that increasing HILM integration to replace SBM in the test diets of 45-week-old Xuefeng black-bone hens led to increased feed intake, which could be linked to better palatability.

The cost of feed consumed (US$ per bird) by the chicks, growers, and layer hens decreased following increasing inclusion levels of HILM in the diets due to decreased ADFI (Poorghasemi et al. 2013). The findings are in agreement with those reported by Onsongo et al. (2018), where HILM was used to replace FM and SBM in both the starter and finisher diets. Broiler diets with 75% HILM had the least cost (Sumbule et al. 2021), probably due to decreased feed intake (Poorghasemi et al. 2013). Similarly, Sumbule et al. (2021) reported lower feed costs for ISA Brown layer pullets fed diets containing HILM as a substitute for FM. Overall, it is clear that a lower cost of feeding would boost profitability because protein accounts for the largest portion of a layer's total feed cost (Cicek et al. 2008). This might be explained by the improved CBR, ROI, and gross profit margin observed when pullets were fed diets with HILM, which is consistent with the report by Sumbule et al. (2021).

In the present study, inclusion of HILM in the experimental diets led to a significant increase in egg production, particularly for those fed diets with 75% HILM throughout the phase I and phase II laying cycles. These results are in agreement with those of Al-Qazzaz et al. (2016), who reported that Arabic strains of layer chicken provided a diet with 5% HILM had higher weekly egg production (58.77%) compared to those fed the control diet. Furthermore, Patterson et al. (2021) findings also supported that raising the amount of HI larval oil in the diets of White Leghorn layer hens from weeks 43 to 47 significantly enhanced weekly egg production. Ruhnke et al. (2018) reported that ISA Brown layer (47–62 weeks of age) fed dry HILM laid more eggs (91.6%) than those fed a diet without HILM (82.8%). This is further supported by Liu et al. (2021) who observed a high egg production percentage for Xuefeng black-bone chickens fed a diet with HILM as a substitute for SBM for a duration of 45 weeks. On the other hand, Shaver White Leghorns (28–43 weeks) fed on a control diet (0% HILM) were observed to lay more eggs per week (96.7%) compared to those fed diets with 10% and 15% HILM (94.6% and 95.5%, respectively) (Mwaniki et al. 2020). Marono et al. (2017) also showed that Lohmann Brown hens (24–45 weeks of age) fed a diet with 100% replacement of SBM with HILM had a lower egg-laying percentage (92%), though not significantly different from those subjected to diets with 100% SBM (95%). Our findings revealed a significant correlation between body weight, age of birds (weeks), and laying performance, indicating that these factors are reliable predictors that should be considered in layer chicken production systems. This is supported by Toral and Saleh (2017), who showed that these are useful predictors of efficient nutrient resource utilization by layer chickens.

The marginal analysis performed helped rank the potential of the various diets from least expensive to most expensive, providing information on estimated marginal returns. This would inform poultry farmers of the expenditures they would recoup by switching from conventional plant-based protein feed to insect-based feed with net advantages. This will also allow the poultry farmers to make informed decisions before investing in any new agricultural practices or adjusting their current practices (CIMMYT 1988). There is limited information on the marginal analysis of insect-based feed for poultry production, particularly when insects are used as protein sources.

In growers (pullets) and laying hens, the marginal rate of return (MRR) were positive (100% and 300%) when inclusion levels of HILM was changed from 75% to 100% HILM and 75% to 50% HILM replacement levels. This indicates that, going from the lowest cost combination of HILM, a poultry farmer would recover the 1US$/ bird they invested in all diets with zero and 2 US$/ bird in net benefits, respectively. The MRR was negative 100%, 110.75%, and 48.48%, and below the required estimated minimum return of positive 100%, when the HILM substitution levels were changed from 50% to 100%, 25% to 75%, and 50% to 100% HILM, respectively. Hence, the poultry farmer would recover the 1 US$/bird invested in all diets and lose 0.10, 0.11, and 0.48 US$/bird in net benefits if they switched to the next highest cost combination, respectively. As evidenced by our present study trends in marginal analysis, increasing the inclusion levels of HILM in diets would yield significant financial benefits. This excellent economic return in MRR is attributed to high egg production, a low cost of feed consumption, and reduced daily feed intake following the increasing inclusion of HILM in laying hens' diets. These results are in line with the report by Alemu et al. (2021), who demonstrated a MRR of −74.74%, meaning farmers would receive 1 USD per kg they invested and lose 0.74 USD per kg of net benefits. Furthermore, a MRR of 319.60% (positive) implies farmers would receive 1 USD per kg they invested and receive an additional 2.96 USD per kg in net profits. In additional studies by Ndegwa et al. (2016), it was reported that a MRR of −73% would recover 1 USD per kg they invested and lose 0.73 USD per kg therefore losing out on the net benefits. However, a MRR of 587% indicated that the farmers would recover 1 US$/kg they invested and get an additional 4.87 US$ per kg of the net benefits. This variability in reports demands additional studies.

The utilization of HILM to replace plant-based proteins in laying hen diets significantly influenced poultry farmer operations and profitability. The results showed that layer chicks and growers fed HILM reached early maturation age by the standard of 18 weeks, as seen by weight gains, which are a sign of strong laying ability. The farmer's production expenses would decrease as a result of the higher FCR, high egg output, and low feed intake, resulting in increased profitability. Black soldier flies can be mass -raised easily and locally utilizing readily accessible organic waste. This would save farmers money on expensive conventional proteins as well as competition from other livestock and humans in the case of soybeans (Onsongo et al. 2018). Organic waste is turned into frass fertilizer that could be used to enhance soil health and increases crop yields (Beesigamukama et al. 2021). However, larger quantity of larvae meal would be required to attain full realization in commercial poultry production business enterprises. This can only be accomplished by establishing mass rearing semi-automated on-farm facilities for year-round production and supply of HILM to the feed industry. The application of solar driers for processing of larvae into dry forms will reduce the high cost of electricity involved in microwave, oven, and hot air drying of larvae. However, the use of a high percentage of HILM in poultry feed formulation should be studied further, which could be a particular shortcoming due to previously reported low digestibility coefficient compared to general protein sources.

We conclude that 75% HILM substitution levels of sunflower seed cake and SBM remain the most economical and profitable alternative diets for improved layer chicken production. The FCR was significantly improved for the chicks, growers, and layer hens due to high average daily gain, low average daily feed intake, and high egg mass, which is a direct reflection of decreased total feeding costs and increased revenues for smallholder farmers. Thus, HILM contains favorable nutrients and low production costs and is environmentally friendly compared to plant-based proteins with commonly reported inappropriate amino acid profiles, anti-nutritional factors, and frequent mycotoxin contamination. HILM represents a promising alternative source of protein that could be sustainably used to promote climate-smart sustainable layer chicken production.

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Data availability

All the supporting data used in this study have been submitted to a public repository (https://data.mendeley.com/datasets/pg4my5b753/1).

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