Can black soldier fly *Desmodium intortum* larvae-based diets enhance the performance of Cobb500 broiler chickens and smallholder farmers' profit in Kenya?

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ABSTRACT This study aimed to evaluate the performance of broiler chickens fed on 3 black soldier fly larvae (**BSFL**) (*Hermetia illucens*) and Greenleaf desmodium (*Desmodium intortum*)-based meals. We evaluated growth performance, carcass quality, and profitability under various commercial pathways (doorstep, retail, whole, and assorted). *Desmodium* and BSFL powders were formulated into 3 ratios: T1 25:75, T2 50:50, and T3 75:25. A commercial feed was used as a control. One hundred and twenty mixed-sex 1-day-old broiler chicks (Cobb) were reared in pens for 42 d in a completely randomized design. The chickens were weighed weekly to monitor their growth rate. After the 42-day rearing period, they were slaughtered for carcass quality evaluation and recording of the weights of internal organs. During the initial growth phase (7–21 d), significant effects of fish meal replacement were found on the chickens' average weight ($P < 0.001$), average daily body weight gain ($P < 0.001$), average daily feed intake ($P < 0.001$), and feed conversion ratio ($P < 0.001$). However, during the second phase (21–42 d), no significant effect of the replacement was detected except on average daily feed intake ($P = 0.003$). No significant differences were found in terms of the relative weights of internal organs. It was found that *Desmodium*-BSFL-based feeds were more profitable than the control feed, and the assorted and retail modes of sale generated more revenue compared to when the chickens were sold at doorstep and on whole-chicken basis. The return on investment was higher for a push-pull adopter compared to a non-adopter. The study found that a BSFL-*Desmodium* mixture can be a valuable replacement for the protein component in conventional feed and would provide a new impetus for the adoption of push-pull.

Key words: feed, insect, push-pull, smallholder-farmer

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INTRODUCTION

The poultry sector is one of the fastest growing industries in Kenya (Omiti and Okuthe, 2009) and beyond (Nkukwana, 2018). The demand and consumption of broiler chicken meat in Kenya are projected to reach 165 thousand metric tonnes by 2030, up from 55 thousand metric tonnes in 2000 (Robinson and Pozzi, 2011). This growth is a response to rapid urbanization, growth of the middle class, the rising number of quick-service restaurants, the ever-growing recent global health concerns promoting poultry products as a healthier source of protein than red meat, high turnover, and the continuing viability of current broiler chicken systems (Vernooij et al., 2018). The highest volume of both poultry meat and eggs is produced by the local backyard systems characterized by low input and low productivity. Commercial production systems through small and medium enterprises are, however, on the rise with the use of hybrid chickens, and higher input and productivity (Vernooij et al., 2018).

Chicken producers face several challenges, including access to safe, affordable feed in terms of energy, protein, mineral, and vitamin sources (Prabakaran 2003; Ravindran, 2013). Feed costs account for up to 80% of a farmer's total production costs (Van der Poel et al., 2013), leaving the resource-poor farmers with very small

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profit margins. Different birds have different nutritional requirements for optimal performance (Moges et al., 2010). Protein is the most expensive component in poultry feed, and amino acid composition remains a limiting factor for optimum performance (Mapiye et al., 2008).

In most developing countries, soybean is the most preferred source of protein for poultry feed (Chianu et al., 2009; Rusike et al., 2013). In Kenya and Uganda, the silver cyprinid fish *Rastrineobola argentea*, commonly referred to as "omena" or "mukene," is also used as a protein source for feed (Ojwang et al., 2014; Wangechi et al., 2015). However, both soybeans and fish meal (**FM**) are available in lower quantities than required and are often imported from other countries. The soybean price fluctuates with the global cost of fuel, thus becoming less accessible to most farmers. Liberalization of the feed market in Kenya has resulted in many small-scale processors infiltrating the market, supplying expensive substandard poultry feeds with limited alternatives for farmers. As such, identifying an affordable and accessible alternative diet is a necessity for the profitability and competitiveness of the feed sector (Józefiak et al., 2016; Chia et al., 2019; De Souza-Vilela et al., 2019; Frempong et al., 2019).

The black soldier fly (**BSF**) *Hermetia illucens* is considered as a novel protein source for the poultry and aquaculture industries (Cullere et al., 2016; Barragan-Fonseca et al., 2017; Nyakeri et al., 2017). The BSF larvae (**BSFL**) protein has a wide range of essential amino acids required for pigs and poultry (Spranghers et al., 2017). There is a body of research that demonstrated the potential of BSFL meal as a substitute in poultry feed (Baldrighi and Zamprogna, 2017; Schiavone et al., 2019). However, the nutritional composition of BSFL depends primarily on the composition of the organic substrate (Liland et al., 2017). This suggests variability in the amino acid profile (Makkar and Ankers, 2014), which implies that the exclusive use of larvae as a protein source might be costly. Not only is the supplementation of various essential amino acids recommended (Cullere et al., 2018), but also the integration of other sources is necessary to provide a diverse and balanced nutrient composition for the chickens. In that regard, the use of plant-based proteins such as *Desmodium* is suggested as a valuable substitute for poultry feed (Abdullah, 1974; Teguia and Beynen, 2005). In East Africa, the use of *Desmodium* is being promoted as an intercrop in push-pull technology; an agroecological farming system developed by the International Centre of Insect Physiology and Ecology (**icipe**), for controlling agricultural cereal pests (Khan et al., 2018). *Desmodium* is a perennial legume commonly used in dairy farms for feeding goats and cows (Tolera and Sundstøl, 2000). It has an impressive protein content, as high as 24% (Heinritz et al., 2012). As a plant source of protein, *Desmodium* has a reasonable content of methionine-cystine and threonine (Kariuki et al., 2001) with impressive palatability. No cases of toxicity have been reported thus far (Chadd et al., 2002; Govindarajan et al., 2003; Rastogi et al., 2011). Some species of *Desmodium* are currently being used in the herbal medicine industry to treat various conditions such as rheumatism, wounds, hemoptysis, etc. (Govindarajan et al., 2003; Al Hasan et al., 2011; Tsai et al., 2011; Rahman et al., 2013). Based on these scientific virtues, it was hypothesized that the integration of *Desmodium* and BSFL into chicken feed could substitute the protein component in FM and provide functional benefits to chickens (Al Hasan et al., 2011; Ma et al., 2011). Despite the potential of *Desmodium intortum* (**DI**) to salvage the poultry feed industry, no studies have been conducted to explore its integration in poultry feeds to provide cheaper, balanced nutrient-rich diets for the chickens. Therefore, the present study is aimed at evaluating the effect of BSFL-DI-based meals on the growth and cost of production, and hence profitability of the enterprise.

MATERIALS AND METHODS

Study Site

The study was conducted at icipe, Duduville campus, Kasarani subcounty, Nairobi, Kenya (latitude: −1.23228; longitude: 36.9275). The general care and management of the animals followed accepted guidelines as described by the Federation of Animal Science Societies (FASS, 2010).

Origin of the BSF Colony

The colony of *H. illucens* was initiated at the Animal Rearing and Containment Unit of icipe in Nairobi, Kenya. The wild population of the *H. illucens* colony was established from eggs collected from the field (S 01°13′14.6″; E 036°53′44.5″, 1,612 m above sea level). The egg clusters were transferred to plastic trays containing pig manure. The manure was hydrated to approximately 70 ± 2% moisture by weight and confirmed using a moisture sensor with two 12-cm long probes (HydroSense CS620; Campbell Scientific, Inc., Logan, UT). The culture was monitored daily for larval development, and prepupal stages were kept in transparent rectangular plastic containers (Kenpoly Manufacturers Ltd., Nairobi, Kenya) containing moist sawdust as pupation substrate. An opening was made in the lid of each container and covered with fine netting material capable of retaining emerging adult flies. Conditions in the rearing room were maintained at 28 ± 1°C, 70 ± 2% RH, and a photoperiod of 12L:12D. Adults were transferred to outdoor cages where a water and sugar solution was provided ad libitum to the flies. When the adult flies in the cage were 7 d old, moist pig manure (300 g diluted in 600 mL of water) was provided in plastic containers with the surface covered with wire mesh. Plastic electrical conduits with multiple grooves were placed on top of the wire mesh, which provided the flies with sites for laying eggs. The containers were checked daily to collect egg clusters deposited by the flies. The electrical conduits with egg clusters were transferred into plastic containers and placed in climate-controlled chambers. The newly hatched larvae were fed ad libitum with pig manure until full development into prepupal stages. The pupae collected were regularly transferred into outdoor rearing cages designed specifically to hold the adult fly stock populations. The BSF colony was maintained at icipe for approximately 4 yr, and once every 6 mo, wild-caught fly populations were added to the colony to minimize inbreeding depression.

The fifth instar larval stages harvested from the stock colony were cleaned by washing in warm water (84°C) for 10 min and then oven-dried using a commercial stainless steel fruit/vegetable/meat/fish drying machine: model CT-C-III series hot air circulating drying oven (Henan Forchen Machinery Co. Ltd., Henan, China). This machine could dry 360 kg/batch of fresh insects for 2.5 h at 120°C. Dried larvae were ground into larval meal using a Münch hammer mill, model M6FFC-230 (Wuppertal, Germany) and stored for further use in the formulation of the experimental diets.

Origin of Desmodium

Greenleaf *Desmodium* biomass was harvested from a 15 m × 15 m push-pull plot located at the icipe Duduville campus. *Desmodium* plants were trimmed every month, and harvested biomass was dried under the shade until required quantities were collected from the field for the experiment. Dried biomass was ground into a powder using a Retsch milling machine, model SM 100 (Haan, Germany), before the experiment.

Diet Formulation

The analyzed nutrient and essential amino acid composition of the meals are presented in Table 1. The test diets were formulated according to the Kenya Bureau of Standards as guided by NRC specifications for broiler starter and finisher feeds. The isonitrogenous and isoenergetic diets (3,000 kcal/kg ME, 220 g CP/kg, and 3,000 kcal ME, 180 g CP/kg) were prepared by replacing the FM content in the conventional diet (control diet) with BSFL and DI. The following formulations were tested: 25% DI +75% BSFL (T1), 50% DI + 50% BSFL (T2), and 75% DI + 25% BSFL (T3).

Table 1. Analyzed nutrient composition (% dry matter basis) of BSFLM, DIM, and FM.

	BSFLM	DIM	FM
DM	95.9	86.0	92.0
CP	43.8	20.5	42.6
Ether extracts	28.3	2.40	5.40
Crude fiber	20.9	30.5	1.80
Ash	12.9	7.80	49.0
Essential amino acids of BSFLM and DIM			
Methionine	0.8	1.3	
Lysine	2.9	3.4	
Threonine	1.7	4.2	
Arginine	2.2	4.1	
Histidine	1.3	1.7	
Leucine	2.8	5.4	
Isoleucine	1.8	3.3	
Valine	2.6	4.8	
Phenylalanine	1.9	4.3	

Abbreviations: BSFLM, black soldier fly larvae meal; DIM, *Desmodium intortum* meal; FM, fish meal.

The ingredients used in the feed formulation are shown in Table 2. For the finisher diets, the different mixtures containing all the required ingredients were pelletized at a temperature of 65°C using a 50 to 80 kg/h pellet machine (Muharata Co. Ltd., Nairobi, Kenya). The pellet size was customized at 3-mm size for chickens, as indicated by the manufacturer. The dry matter, ash, CP, crude fiber, and ether extracts of the test diets FM, BSFL meal (**BSFLM**), and *Desmodium* meal were analyzed according to the Association of Official Analytical Chemists methods. Amino acid content of the BSFLM and *Desmodium* was determined following the methods of 994.12.

Growth Performance

One hundred and twenty (n) mixed-sex 1-day-old broiler chicks (Cobb500) were sourced from Kenchic Ltd. hatchery in Thika, Nairobi, Kenya and reared for 42 d (i.e., 7 d adaptation phase and 35 d feeding phase). The chicks were placed in a common brooder room of 5 × 6 feet for the first 7 d. Brooder temperatures were maintained between 33°C and 35°C using light heating bulbs of 250 W suspended at 45-cm height over the brooder to provide heat. These bulbs were supplemented with an automated thermostat heater model (WH30, 3 KW wall heater; Xpelair, Peterborough, UK). Before the commencement of the experiment, all the chicks were fed on starter mash (conventional feed) purchased from Unga Feeds Ltd. (Nairobi, Kenya), which is the largest animal feed manufacturer in East Africa. The chicks were fed at a rate of at least 125 g per day per chick. Feather-sexing was performed before the chicks were randomly distributed in 12 pens each measuring 1.5 m × 1.8 m × 1.5 m in a poultry house. Sexing was done to ensure that each pen contained 10 chicks (5 females and 5 males). The pens were separated using wooden blocks. A metallic mesh was used as the source of ventilation on the upper side of the pens. Each treatment was replicated 3 times in a completely randomized design. The whole experiment comprised 120 chickens, with 30 chickens in each treatment, including the control.

Clean sawdust was obtained from a local carpentry workshop and spread on polythene papers on the floor of the cages at a height of 5 cm from the ground. After the 7 d brooding period, the chicks were weighed individually to obtain their initial weight before being introduced to starter diets of the BSFLM-DI formulations. The chickens were fed daily between 9:00 and 10:00 am. Feeding was ad libitum but to monitor the bird's daily intake, 12.5 kg of each feed treatment was measured daily using a weighing scale (model: Camry EK 5055-005, Zhongshan Camry Electronic Co. Ltd., Zhongshan, Guangdong, China). The weight of feed

Table 2. Feed composition for broiler starter and finisher diets (diets [g/kg] as fed) of experimental diets.

	Broiler starter diets				Broiler finisher diets			
	Control	T1	T2	T3	Control	T1	T2	T3
Feed ingredients								
Maize germ	528.8.0	527.0	540.0	550.2	550.0	526.0	534.0	576.5
Wheat pollard	104.0	108	97.6	98.9	201.6	200.5	198.2	165.5
Corn oil	24.60	16.3	11.4	4.0	27.2	22.1	15.2	5.4
Fish meal	325.4	0	0	0	191.0	0	0	0
Desmodium intortum	0	82.65	165.3	247.0	0	55.0	110.0	165.0
BSFL meal	0	247.95	165.3	82.7	0	165.0	110.0	55.0
Limestone	10.0	10.0	10.0	10.0	22.6	22.6	22.6	22.6
Salt	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Dicalcium phosphate	0.5	1.0	3.3	3.2	0.5	1.7	2.9	3.3
Broiler premix[1]	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Mycotoxin binder	0.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Total	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Calculated values for ME and nitrogen free extracts								
ME (kcal/kg)	2,997	3,018	3,021	3,037	3,052	3,053	3,059	3,100
Non-phytate phosphorus (%)	0.4558	0.4528	0.4572	0.4532	0.4537	0.4546	0.4597	0.4528
Nitrogen-free extracts (%)	43.9	44.1	42.0	42.1	45.2	44.6	43.5	34.0
Analyzed nutrient content (% DM basis) of experimental diets								
DM	88.9	89.7	89.3	89.8	88.4	89.2	89.5	89.7
CP	22.1	23.1	22.8	21.4	21.5	22.5	22.0	21.0
Ether extracts	6.8	7.3	7.4	8.1	8.4	7.9	8.1	9.2
Calcium	0.900	0.9389	0.9290	0.9938	0.8746	0.8715	0.8850	0.8635
Total phosphorus	0.5592	0.5563	0.5692	0.5643	0.5540	0.5620	0.5784	0.5592
Crude fiber	3.4	5.7	7.1	7.6	3.1	5.9	7.3	7.8
Ash	9.7	10.1	9.8	9.4	8.7	7.9	7.3	7.5

T1 = 25% *D. intortum* + 75% BSFL, T2 = 50% *D. intortum* + 50% BSFL, T3 = 75% *D. intortum* + 25% BSFL, and control = commercial feed.
Abbreviation: BSFL, black soldier fly larvae.

[1]Broiler premix (provided per kg of diet) = vitamin A (IU) 625,0000, vitamin D3 (IU) 100,0000, vitamin E (IU) 15,000, vitamin K3 (mg) 1,000, vitamin B1 (mg) 500, vitamin B2 (mg) 2,500, vitamin B6 (mg) 2,500, vitamin B12 (mg) 10, pantothenic acid (mg) 600, nicotinic acid (mg) 15,000, folic acid (mg) 500, biotin (mg) 35, choline chloride (mg) 15,0000, iron (mg) 2,0000, copper (mg) 2,500, zinc (mg) 25,000, manganese (mg) 15,000, iodine (mg) 600, cobalt (mg) 400, butylated hydroxytoluene (antioxidant, mg) 12,5000.

consumed per cage was measured by the difference (weight of feed in the bucket the following day during feeding time subtracted from the weight of feed in the bucket the previous day). Finisher diets containing BSFL and *Desmodium* were provided to the chicks after 21 d. Clean drinking water was provided ad libitum using Kenpoly plastic feeders (10 L capacity; Nairobi, Kenya) per pen until the end of the rearing period when the chickens were isolated for slaughtering. The chickens were maintained at 28 ± 1°C, RH of 65 ± 5%, and a photoperiod of 12L:12D. Waterproof Universal Serial Bus temperature/humidity data loggers were placed strategically inside the poultry house to monitor the internal conditions of the rearing facility. All the chickens were vaccinated against Newcastle disease on the 14th day. The chickens were weighed weekly by placing them in a tared plastic container using a weighing balance (Camry EK 5055-005). The body parts of the chickens were also measured weekly using a measuring tape. The following measurements were recorded, as shown in Figure 1: 1) body length: the length from the tip of the beak to the uropygial gland; 2) body width: the circumference of the body measured at the tip of the pectus; 3) thigh length: the length between the hip bone and the knee on the right limb; 4) shank length: the length between the knee and the regiotarsis on the right limb; 5) wing length: the length from the base of the shoulder to the tip of the longest primary feather; and 6) neck length. The measurements were carried out with the assistance of 2 trained technicians throughout the study period. The 2 technicians were trained on handling the chickens and accurate data recording. The measurements were conducted with minimal disturbance of the chickens to avoid stressing them in the process.

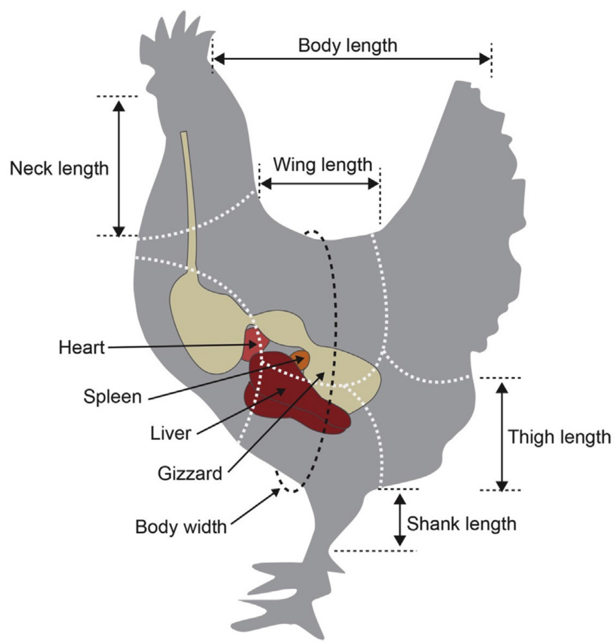

Figure 1. Diagram showing external and internal organs measured.

Slaughtering and Carcass Dissection

The performance trial lasted 42 d, after which the chickens were feed-restricted overnight. Five chickens from each replicate were randomly selected for carcass and organ weight evaluation. The chickens were weighed to capture the live weights. The birds were sacrificed humanely by a professional following procedures reviewed and approved by the Institutional Animal Care and Use Committee (**IACUC**). The birds were first stunned electrically before slaughtering. The chickens were then scalded at 75°C in a water bath for about 30 s before defeathering. The carcasses were reweighed to determine feather weight by subtraction. The dressed chickens were later eviscerated to remove the internal organs, and the wings were removed by cutting anteriorly, severing at the humeroscapular joint. The cuts were made through the rib head to the shoulder girdle, and the back was removed intact by pulling anteriorly. Internal organs such as the liver, gizzards, heart, and spleen were weighed (Figure 1). The wings, thighs, breast, and organs were dissected from each carcass and weighed separately with a sensitive weighing balance (Camry EK 5055-005) in grams. The carcasses were then packaged in Ziploc plastic bags measuring 28 cm × 40 cm and frozen at −20°C for subsequent analysis.

Profitability

The net monetary benefit was calculated using the partial budgeting procedure, which assesses the costs and benefits associated with a specific change in an individual enterprise within the business operation (Soha, 2014). Only variable input costs are used in a partial budget. The net benefit is the difference between the gross farm-gate benefit and total variable input costs. The cost-benefit analysis was carried out, taking into account the prices and practices in poultry farming in Kenya where conventional feeds are used, carcass weights are low, and production is low-input and unstable. Prices were compared of the current methods of selling in Kenya which are either doorstep or retail. A preliminary baseline survey indicated that farmers and local butchers mostly practice the doorstep method of selling, whereby chickens are sold as a whole and the price is negotiable and not dictated by the weight of the chicken. In retail, the chickens are sold either whole or in an assorted form (a combination of various parts of the chicken); the price is usually fixed and is dictated by the weight of the chicken. A comparison was also made between a push-pull adopter who had free access to *Desmodium* and a non-push-pull adopter who needed to source *Desmodium* for $5.5 per bale of 15 kg. The cost of BSFL was based on the retail price of $0.99 for 1 kg in Kenya. The price of feed varied from one treatment to another as the ingredients and quantities used varied. Among the non-push-pull adopters, the cost of the entire feed per treatment was as follows: treatment 1 = $97.87, treatment 2 = $79.55, and treatment 3 = $64.07.94. For the push-pull adopters, the price was as follows among the treatments: treatment 1 = $87.37, treatment 2 = $64.03, and treatment 3 = $38.49. The cost of the control feed amounted to $86.07. The cost of labor was defined as the cost of time spent by a worker attending to the chickens (feeding, cleaning the poultry house, immunizing, and slaughtering), calculated according to the wage in Kenya of $5 per day for the 42-day rearing period. Apart from the feed, the cost of other inputs that were involved in production, such as water, electricity, labor, sawdust, immunization, and the cost of chicks used, was calculated as a whole, as these amenities were shared by the chickens and hence remained constant across the treatments. This cost was calculated according to the current rates in Kenya and amounted to $97.06 for the entire rearing period. To determine the total revenue obtained from each treatment, the selling price of the chicken at the end of the rearing period was used. A small survey was conducted among farmers and retailers (local butchers and supermarkets around Nairobi). On average, a whole chicken retailed at around $6.50 and this was used to calculate the revenue obtained at doorstep, as the weight of the chicken was not considered. For the assorted method of selling, the chicken is usually sold in pieces (chicken breast, thigh, wing, back) with or without internal organs (usually liver and gizzard). The price is usually based on weight and, from our survey, this retailed between $9.50 and $12 per kg. To obtain the price of an assorted package of a particular treatment, we obtained the weight of the various pieces in that treatment and multiplied it by the cost per kg. On average, 1 kg of the other chicken pieces retailed as thighs = $10.42, drumsticks = $6.54, wings = $10.43, gizzard = $ 7.26, liver = $4.26, and breast = $10.57.

Profit was the difference between the accrued revenue and the production cost. The cost-benefit ratio was obtained by dividing the total revenue by the cost of production. In contrast, the return on investment was obtained by dividing the profit by the production cost and then multiplying the result by 100.

Data Analysis

To calculate the weekly growth rates of the body length, thigh length, wing length, and body width, a linear regression was fitted to the weekly data collected in each chicken.

A linear regression line with an equation of the form $Y = ax + b$ was obtained where x was the explanatory variable (week) and Y was treated as the dependent variable (weight). The slope of the line was a, while b was the intercept (the value of Y when $x = 0$). The slope or the tangent of the regression lines, which was the growth rate, was then compared among different treatments (diets). Because the body, thigh, breast, wing, intestines, heart, and spleen weights did not meet those assumptions, the Kruskal-Wallis test was used to check for the presence of any significant difference among diets. All data were checked for normality and homogeneity of variance using the Shapiro-Wilk and Bartlett tests. The

AllPairsTest in the PMCMRplus (R Core Team, 2019) package was used for all-pairs comparisons with Bonferroni corrections after a significant Kruskal-Wallis test.

Also, the weight at days 7, 21, and 42, and the ADBWG, ADFI, and FCR were analyzed with one-way ANOVA or a GLM with gamma distribution and log-link function to compare the different diets. All these analysis were carried out in R version 3.0.1 (R Core Team, 2019). The net monetary benefit was calculated using the partial budgeting procedure, which assesses the costs and benefits associated with a specific change in an individual enterprise within the business operation (Soha, 2014).

Ethical Approval

The experimental design and all procedures conducted were based on animal welfare principles recommended by the NRC to avoid any discomfort or pain (McGlone, 2001). Sound animal husbandry practices were used to provide systems of care that permitted the chickens to grow to maturity and express their species-specific behavior. Adequate veterinary care was provided to ensure proper animal health, and research assistants involved in the study were trained and motivated to achieve high-quality animal care throughout the experiment. A program was put in place for disease prevention, surveillance, diagnosis, and treatment (McGlone et al., 2001). Chickens were slowly acclimatized to handling by frequent exposure to kind and gentle handling by research personnel, starting at 1 d of age to ease handling at later stages of the study and to increase feed efficiency as well as body weight gain (Gross and Siegel, 1983). Ethical approval for the study was provided by the IACUC of the Kenya Agricultural and Livestock Research Organization—Veterinary Science Research Institute; approval code: KALRO-VSRI/IACUC019/30082019.

RESULTS

Effect of Different Diets on the Growth Performance of Birds

During the first feeding phase (days 7–21), there was a significant effect of the replacement of FM with BSFL and DI meals on the growth performance of broiler chickens (Table 3). There were, however, no significant differences in the parameters analyzed except for the ADFI for the second phase (days 21–42) ($P = 0.003$) and whole feeding period (days 7–42) ($P < 0.001$).

Effect of the Treatments on Weekly Growth Rates of Body Length, Thigh Length, Wing Length, and Body Width

Generally, there were significant differences in body length, thigh length, and wing length between the treatments (Table 4). Chickens fed on T2 and T3 had the highest body length. The thigh length was higher in T3 and control compared to the other treatments. The wing length was significantly higher in the control but not significantly different from T3. No significant difference was observed in body width ($P = 0.309$).

Effect of the Treatments on the Dressed Carcass and Relative Weight of Internal Organs

The replacement of FM with BSFL and DI meals had no significant effect on the dressed weight of carcasses ($P = 0.836$) as well as on the relative weight of internal organs (liver, heart, spleen, gizzard, and intestines) for all treatments (Table 4).

Profitability of BSFL-Desmodium-Fed Full Chicken Sold at Doorstep, Retail, or Assorted Prices

BSFL-*Desmodium*-based diets were observed to be more profitable for feeding Cobb500 broiler chickens than the control diets. Chickens fed with T3 feed generated more return on investment than the other treatments. Push-pull adopters achieved more economic returns (profits) than the non-adopters. Also, chickens fed with conventional FM feed (control diet) were only profitable when sold at the retail model (Table 5). Similarly, chickens sold as assorted pieces generated more revenue compared to those sold at the doorstep (per unit) (Table 5).

DISCUSSION

The current study demonstrated clearly that the mixture of BSFL (insects) and *Desmodium* (legume fodder) could act as a protein substitute for fish and soya meals in poultry feed. This study confirms previous findings on the benefits of BSFL as an excellent protein substitute in poultry feed (Onsongo et al., 2018). The use of the 2 sources of protein gave equally promising results as shown in Table 3, and analysis of the BSFLM suggests a judicious balance between BSFL and *Desmodium* to provide satisfactory chickens (Jobling, 2012). In our current study, the CP value of the BSFL was higher than what was reported by Makkar and Ankers, 2014 and Liland et al. (2017). BSFL protein content can range between 39 and 44% depending on the substrate (Tibayungwa et al., 2011; Lalander et al., 2019), and this difference in our study and that reported by others is proof of the same. The 2 most limiting amino acids in poultry diets, methionine and lysine, vary between 1.6 and 2.0, and 3.7 and 4.0, while tryptophan is exceptionally high in *Desmodium* compared to BSFL and this has been shown in this study. Threonine levels were also relatively high in *Desmodium*. This suggests that the inclusion of *Desmodium* might have a significant positive effect on animal performance, although no significant differences were observed in our current study at slaughter. Legume

Table 3. The effect of replacing fish meal with black soldier fly larvae meal and *Desmodium intortum* meal in broiler chicken diets on mean (±SE) growth performance during different growth phases.

Variables	T1	T2	T3	C	*P*-values
Starter phase (days 7–21)					
Weight at day 7 (g)	167.1 ± 0.54[a]	167.4 ± 1.2[a]	168.1 ± 1.0[a]	167.2 ± 1.4[a]	0.917
Weight at day 21 (g)	785.8 ± 11.5[a]	667.6 ± 11.8[c]	687.4 ± 10.3[bc]	719.9 ± 9.9[b]	<0.001
ADBWG (g/day)	44.2 ± 0.8[c]	36.9 ± 0.9[a]	37.7 ± 0.6[ab]	40.2 ± 0.8[b]	<0.001
ADFI (g/day)	61.6 ± 0.1[a]	59.5 ± 0.2[b]	56.1 ± 0.2[c]	60.9 ± 0.1[d]	<0.001
FCR	1.4 ± 0.0[b]	1.6 ± 0.0[a]	1.50 ± 0.0[b]	1.5 ± 0.0[ab]	<0.001
Finisher phase (days 21–42)					
Weight at day 21 (g)	785.8 ± 11.5[a]	667.6 ± 11.8[c]	687.4 ± 10.3[bc]	719.9 ± 9.9[b]	<0.001
Average weight at day 42 (g)	2,015.9 ± 42.9[a]	2,027.2 ± 24.6[a]	1,990.0 ± 50.3[a]	1,990.0 ± 35.9[a]	0.879
ADBWG (g/day)	61.7 ± 1.73[a]	64.4 ± 1.2[a]	65.0 ± 2.1[a]	60.5 ± 1.9[a]	0.221
ADFI (g/day)	120.8 ± 0.0[b]	120.6 ± 0.0[b]	120.4 ± 0.0[a]	120.6 ± 0.0[ab]	0.003
FCR	2.0 ± 0.0[a]	1.9 ± 0.0[a]	1.9 ± 0.0[a]	2.0 ± 0.0[a]	0.212
Overall period (days 7–42)					
Average weight at day 7 (g)	167.1 ± 0.5[a]	167.4 ± 1.2[a]	168.1 ± 1.0[a]	167.2 ± 1.4[a]	0.917
Average weight at day 42 (g)	1,999.6 ± 43.8[a]	2,033.9 ± 139.2[a]	1,990.0 ± 50.3[a]	1,990.0 ± 35.9[a]	0.847
ADBWG (g/day)	52.4 ± 1.2[a]	53.2 ± 0.7[a]	52.0 ± 1.4[a]	52.0 ± 1.0[a]	0.865
ADFI (g/day)	91.3 ± 0.0[d]	90.2 ± 0.0[b]	88.8 ± 0.2[a]	90.8 ± 0.0[c]	<0.001
FCR	1.7 ± 0.0[a]	1.7 ± 0.0[a]	1.7 ± 0.0[a]	1.8 ± 0.3[a]	0.6089

Within a row, means followed by different letters are significantly different by multiple comparisons test (*P* value < 0.05).

T1 = 25% *D. intortum* + 75% BSFL, T2 = 50% *D. intortum* + 50% BSFL, T3 = 75% *D. intortum* + 25% BSFL, and control = commercial feed.

Abbreviations: ADBWG, average daily body weight gain; FCR, feed conversion ratio.

fodders have been shown to positively improve the performance of both layer and broiler chickens due to high fiber content, which boosts digestion and metabolism and thus leads to an increased rate of feed conversion (Krauze and Grela, 2010). The CP level of FM in our current study was 42.6%, an amount that is way lower compared to previous reports by Leiber et al. (2017) who found CP levels of 60.3%. The ash content of FM was also higher (49%) according to the same study. This suggest that the FM in this study was of lower quality which could be ascribed to adulteration by feed millers or suppliers (high sand content, use of poor quality fish, and long storage) as frequently reported in East Africa (Nalwanga et al., 2009).

Our findings suggest that the inclusion of *Desmodium* might have played an important role in the performance of the chickens as observed in previous feeding experiments with other livestock (Kaitho and Kariuki, 1998; Kariuki et al., 1999; Larbi et al., 2000; Jones and Jones, 2003; Dierenfeld and King, 2008). Leiber et al. (2017) also reported similar results using BSFL and legume fodders of alfalfa and pea.

Although the dressed weight of the chickens did not differ significantly at the end of the 42-day rearing period, T1, which had the highest percentage of BSFL, had the highest carcass weights followed by T2. The digestibility of *Desmodium* was not tested; however, reports have confirmed high digestibility of BSFL (Dierenfeld and King, 2008). In broiler chickens, most meat is deposited around the thighs and breast muscles (Kokoszynski et al., 2017). In T1 and T2, the thighs and breasts recorded the highest weights, and this must have contributed to the increased weights of these 2 treatments. Although the neck and wing weights of T3 and the control diets seemed to be higher compared to those of T1 and T2, meat deposition around these areas is usually low, and this explains their low overall weights compared to the other 2 treatments.

Chickens fed diets T1 and T2 recorded the highest internal organ weights, that is the liver, heart, and gizzard,

Table 4. The effect of replacing fish meal with black soldier fly larvae and *Desmodium intortum* meal in broiler chicken diets on mean (±SE) weekly growth rates of body length, thigh length, wing length, body width, and relative weight of internal organs at 6 wk.

Variables	Control	T1	T2	T3	*P*-values
Body length (cm)	1.87 ± 0.02[c]	1.85 ± 0.02[c]	2.05 ± 0.02[a]	1.97 ± 0.04[b]	<0.0001
Thigh length (cm)	0.58 ± 0.02[a]	0.54 ± 0.01[a]	0.54 ± 0.01[a]	0.61 ± 0.02[b]	0.025
Wing length (cm)	0.99 ± 0.06[a]	0.91 ± 0.10[b]	0.91 ± 0.04[b]	0.96 ± 0.05[ab]	0.003
Body width (cm)	3.18 ± 0.03[a]	3.08 ± 0.03[a]	3.16 ± 0.02[a]	3.12 ± 0.04[a]	0.309
Dressed carcass weight (g)	1,816.0 ± 55.96[a]	1,874.0 ± 38.11[a]	1,833.0 ± 52.42[a]	1,805.0 ± 74.25[a]	0.836
Relative weight: liver (%)	2.18 ± 0.55[a]	2.28 ± 0.11[a]	2.25 ± 0.37[a]	2.21 ± 0.48[a]	0.934
Relative weight: intestines (%)	5.07 ± 0.25[a]	4.44 ± 0.19[a]	4.85 ± 0.25[a]	4.69 ± 0.27[a]	0.322
Relative weight: gizzard (%)	3.65 ± 0.14[a]	3.77 ± 0.13[a]	3.82 ± 0.14[a]	3.88 ± 0.19[a]	0.738
Relative weight: heart (%)	0.61 ± 0.02[a]	0.62 ± 0.02[a]	0.59 ± 0.03[a]	0.58 ± 0.04[a]	0.386
Relative weight: spleen (%)	0.08 ± 0.01[a]	0.09 ± 0.01[a]	0.10 ± 0.01[a]	0.11 ± 0.02[a]	0.703

Within a row, means followed by different letters are significantly different based on a multiple comparisons test (*P* value < 0.05).

T1 = 25% *D. intortum* + 75% BSFL, T2 = 50% *D. intortum* + 50% BSFL, T3 = 75% *D. intortum* + 25% BSFL, and control = commercial feed.

Table 5. Cost-benefit analysis on the sale (US$) of chickens fed with insect *Desmodium*-based feed between a push-pull adopter and non-push-pull adopter according to various commercial pathways.

Full chicken fed with insect *Desmodium*-based feed between a push-pull adopter and non-push-pull adopter at doorstep and retail										
	Doorstep (p/u)					Retail (p/kg)				
	Production cost (US$)	Total selling price (US$)	Profit/loss (US$)	Cost-benefit ratio	Return on investment (%)	Production cost (US$)	Total selling price (US$)	Profit/loss (US$)	Cost-benefit ratio (%)	Return on investment (%)
Push-pull adopters										
T1	6.15	6.50	0.35	1.06	5.69	6.15	8.82	2.67	1.43	43.41
T2	5.37	6.50	1.13	1.21	21.05	5.37	8.67	3.30	1.61	61.45
T3	4.52	6.50	1.98	1.44	43.81	4.52	8.56	4.04	1.89	89.38
Control	6.10	6.50	0.40	1.06	6.56	6.10	8.61	2.51	1.41	41.14
Non-push-pull adopters										
T1	6.50	6.50	0.00	1.0	15.38	6.50	8.82	2.31	1.36	35.54
T2	5.89	6.50	0.61	1.10	10.36	5.89	8.69	2.80	1.48	47.54
T3	5.37	6.50	1.13	1.21	21.04	5.37	8.56	3.18	1.59	59.22
Control	6.10	6.50	0.40	1.07	6.55	6.10	8.61	2.50	1.41	40.98
Assorted chickens fed with insect *Desmodium*-based feed between a push-pull adopter and non-push-pull adopter										
	Push-pull adopters					Non-push-pull adopters				
T1	6.16	13.46	7.31	2.19	118.67	6.50	13.46	6.96	2.07	107.08
T2	5.37	13.07	7.70	2.43	143.39	5.89	13.07	7.19	2.22	122.07
T3	4.52	13.32	8.80	2.95	194.69	5.37	13.32	7.95	2.48	148.04
Control	6.10	12.88	6.78	2.11	111.14	6.10	12.88	6.78	2.11	111.14

Push-pull: a farming strategy for controlling agricultural pests by using repellent "push" plants and trap "pull" plants.
1US$ = 100 Kenyan Shilling.
T1 = 25% *Desmodium intortum* + 75% BSFL, T2 = 50% *D. intortum* + 50% BSFL, T3 = 75% *D. intortum* + 25% BSFL, and control = commercial feed.
Abbreviations: p/kg, price per kg; p/u, price per unit.

although there were no significant differences. T1 and T2 feeds had the highest levels of fats, probably from the BSFL that was used, and the levels were considerably higher than that of the conventional feed. This could have contributed to the large livers as an adaptation to digest the fats, as reported by Zaefarian et al. (2019). The similarity in the concurrent increase in gizzard and liver sizes in this study also concurs with the findings of Møller et al. (2019), who found similar results as a chicken's response to diets containing antioxidants. This can be ascribed to the antioxidant properties of *Desmodium*, as demonstrated by Govindarajan et al. (2003). Compared to the various treatments, the gizzards of the control chickens were relatively smaller compared to those of BSFL-*Desmodium*-fed chickens. The low levels of sand and grit in the test diets could have directly caused the gizzard to be overworked, thus getting enlarged in the process (Sacranie et al., 2012).

The results of this study provide chickens with marketable sizes. There was a considerable variation in terms of the weight of the different body parts that is directly linked to commercial value or market price. It was found that the sale of full chicken meat at retail prices provided higher profits compared to sales at doorstep. This study also demonstrated that backyard production systems with regular feeding regimes were less profitable due to the high input cost incurred. The doorstep approach to the sale of chicken meat is a common practice among smallholder farmers at the farm level, whereby the price of the chicken does not depend on its live weight. Contrarily, for retail sales, the chicken prices are usually determined by the weight of the chicken or its assorted parts, and the prices are usually fixed. The retail sale of chicken meat is commonly practised in supermarkets, which largely depend on the principle of willing seller, willing buyer. Equally, backyard chicken production is profitable, especially if the farmer is a push-pull adopter due to own *Desmodium* sourcing. Generally, the sale of assorted chicken is mainly practised on a retail basis. When compared to the sale of whole chicken, this method of selling is highly profitable for both farmers who use *Desmodium* and BSFL feeds and those who use conventional feeds.

In summary, this study demonstrated that a *Desmodium*-BSFL mix could act as a poultry feed protein substitute. The cost-benefit analysis indicated that the use of insects and *Desmodium* is cost-effective, especially when farmers have free access to *Desmodium*. The approach used in this study needs to be promoted along with push-pull technology for rapid uptake.

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DISCLOSURES

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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