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RESEARCH ARTICLE

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Chrysomya chloropyga (copper-tailed blowfly) larvae reared on abattoir waste as a protein source for broiler production: carcass traits, meat quality and sensory attributes

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The larvae of the copper-tailed blowfly (*Chrysomya chloropyga*) have the potential to break down high-risk waste such as abattoir waste and ameliorate the nutrients to be reintroduced into the food chain by including them in broiler feeds. *Chrysomya chloropyga* larvae were grown on abattoir waste, harvested, processed, and included in broiler diets at inclusion rates of either 5, 10 or 15%. Thereafter the carcass traits, meat quality characteristics and descriptive sensory attributes were determined. Further to this the mineral content of the tibia, as well as the tibia bone strength were determined. The highest inclusion rate of 15% resulted in broiler carcass and meat characteristics that were on par with a formulated soya-based control diet. The chemical composition of the meat was predominantly not significantly affected by the dietary larval meal inclusion ($p > 0.05$). In terms of its sensory attributes, meat from broilers fed *C. chloropyga* meal showed some significant differences for chicken aroma and initial juiciness ($p \leq 0.05$). However, no significant differences were observed for any of five other sensory attributes of importance. Interestingly, the dietary inclusion of *C. chloropyga* meal was significantly related to increased tibia potassium and iron content, which could be linked to the insects' accumulating these minerals present in the abattoir waste. The results indicate that *C. chloropyga* larval meal could be included in broiler diets at up to 15% without any negative effects on the aforementioned characteristics and could even influence them positively.

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INTRODUCTION

The world population is growing at a rapid rate, especially in parts of Africa and Asia (UN 2022). This growth places more strain on our already thinly stretched global food resources (FAO 2023). One of the crucial effects of population growth is the increased need for protein, which will require an additional 0.2 to 1 billion hectares of agricultural land under present agricultural activities (Tilman et al. 2011). Most of the productive areas are already being cultivated, which may result in the need to use low-productivity marginal lands and forested areas (Wang et al. 2018). However, this conversion of currently unfarmed land to cultivated land conflicts with the need for conservation and negatively impacts the environment, with pressure being increased through land degradation (Maeda et al. 2021). To meet the protein requirements of both humans and farmed animals, enough crops need to be cultivated, which inevitably leads to increased crop waste accumulation. It is therefore imperative that alternative, more sustainable protein sources, for feeding either humans or animals, be investigated.

Another prominent issue that arises with increased agricultural activities is the large amounts of organic waste that are produced, which poses a health risk if not managed correctly. One such waste stream that has proven to be challenging to ameliorate or valorise is produced during the slaughter of animals. Abattoir waste has a large pollution risk as it includes fat, feathers, rejected carcasses, hides, hooves, feed digesta, heads, trimmings, intestines, blood and associated with these the potential of bacterial and viral disease. For example, 25–30% of a broiler chicken's weight is classified as being inedible and processes need to be developed to treat this waste stream – these processes need to be economically viable and have a low environmental footprint (Ozdemir & Yetilmezsoy 2019). A proposed method for reducing this risk while also recirculating nutrients from the waste is the use of insects (Lalander et al. 2019). The insects (or their larvae) of interest contain high levels of protein and fat, with amino acid profiles that compare well with the ideal amino acid profile for humans and various farmed animals, and favourable fatty acid compositions. These characteristics make them ideal for animal feed (Oonincx & Finke 2021).

Chrysomya chloropyga (CC) Wiedemann (Calliphoridae) is a coprosarcosaprophagous fly species of forensic importance (Villet 2017). The larvae of this species complete the larval stage in around 63 h, depending on environmental conditions (Richards et al. 2009), during which time their live weight increases from 0.5 mg at hatch to 61.5 mg at harvest (Parry et al. 2017). This characteristic, among others, makes CC a potential candidate species for the valorisation of abattoir waste (Parry et al. 2021). The use of CC larval meal in broiler diets might influence chemical, physical, production and sensory characteristics of poultry meat. This could in turn influence the consumer's choice to purchase the poultry product. The consumer's initial selection is predominantly influenced by the product appearance, while repurchase decisions are based on sensory attributes. At the time of publication, no literature was found regarding the use of CC larval meal in broiler production with a focus on the influence of the CC meal on sensory attributes. However, literature has been published on the use of other insect species in broiler nutrition (Pieterse et al. 2014; Cullere et al. 2016;

Pieterse et al. 2019). Reported studies have focused on carcass and slaughter characteristics and reported that the use of insect meal either had no effect on these characteristics or had a positive effect. Therefore, the objective of this study was to determine the effect of CC meal inclusion in broiler diets, as a protein source, on carcass traits, meat quality and sensory attributes.

MATERIALS AND METHODS

Animals and rearing conditions

Ethical clearance for this study was obtained from Stellenbosch University's Animal Care and Ethics Committee (SU-ACUM13-00026). Three hundred and twenty unsexed, one-day-old broiler chickens were used in the rearing trial. The chickens were randomly allocated to 32 cages (0.9 m × 0.6 m), each housing 10 chickens. Management followed the guidelines for primary breeders as described by Cobb Vantress (2008). Ventilation was set to provide a minimum of six air changes per minute. Chickens were provided water and feed *ad libitum*. A three-phase feeding system was utilised, which included: 900 g starter feed, 1200 g grower feed and finisher feed until slaughter per chicken. Chickens were reared until 35 days of age.

Diets

The CC used in this study were reared and processed at Stellenbosch University's experimental farm Mariendahl, Stellenbosch, Western Cape, South Africa. The larvae were reared on abattoir waste (consisting predominately of lungs, trachea, liver, intestines, carcass/bruise trimmings and intestinal fat) procured from a commercial pig abattoir (Winelands pork, Western Cape, South Africa). *Chrysomya chloropyga* eggs were collected from a breeding colony and placed on the abattoir waste at a density of 0.1 g eggs to 10 kg waste. The larvae fed on the waste for 3 days at which point they self-harvested by climbing out of the feeding containers into collection containers. The collected larvae were subsequently washed and then frozen at –20 °C until processing. Prior to processing the larvae were thawed and dried at 60 °C for 24 h. Processing included milling and mixing the larvae into the broiler feed. Table 1 indicates the nutritional composition of CC in terms of proximate composition and amino acid profile.

Four treatment feeds were formulated for each of the three feeding phases. Treatment feeds within each phase differed in terms of CC inclusion, which was 0, 5, 10, or 15%, respectively. Table 2 describes the formulated diets in terms of ingredient and nutritional composition. There were four treatment groups.

Slaughter and sample preparation

On Day 35, the chickens were slaughtered by an experienced technician at Stellenbosch University's experimental chicken abattoir according to the standard slaughtering method for commercial broilers (DAFF 2006). Briefly, chickens were stunned electrically (50–70 volts, 3–5 s), and exsanguinated for two minutes. Thereafter the carcasses were scalded in a rotating 60 °C water bath for five minutes, de-feathered and eviscerated. One representative carcass was selected from each cage for measurements and analysis.

Carcass and meat characteristics

Initial pH (pH_i) of the thigh and breast muscles were measured 15 min post-mortem using a Crison PH25 pH meter (Allela, Barcelona, Spain). Carcasses were then chilled overnight (2–4 °C). Ultimate pH (pH_u) was measured 24 h post-mortem. This was followed by portioning. The dressing percentage was calculated as the cold carcass weight as a percentage of the live slaughter weight. The carcasses were cut in half. The thighs and drumsticks were removed by cutting above the thigh towards the acetabulum and behind the pubic bone. The thighs and drumsticks were then separated by cutting perpendicular to the joint that connects them. The wings were removed by cutting the joint between the scapula and the coracoid. Each portion was weighed individually. The skin was removed from the breast portion and the muscle separated from the bone. These weights were used to calculate the skin and fat, muscle and bone portions of the breast cut and are expressed as percentage of the total breast portion. Breast muscles were allowed to bloom by exposure to atmosphere at 8 °C for one hour (Honikel 1998). Thereafter the surface colour measurements were taken in triplicate using a colourimeter (Catelogue no. 6805, BYK-Gardner GmbH, Gerestried, Germany). The breast muscles were then individually vacuum packed and frozen at –18 °C until time of analysis. Left breasts were used for sensory analysis and right breasts for chemical analysis.

Chemical analysis

Each treatment group used for the chemical analysis consisted of eight replicates (one per cage). Before analysis, samples were thawed at 4 °C for 12 h and homogenised. For proximate composition analysis, homogenised right breast samples were cooked and analysed using the methods described by the Association of Analytical Chemists International. All proximate analyses were performed in duplicate at the Department of Animal Sciences, Stellenbosch University, South Africa. Amino acid analysis was conducted at the Central Analytical Services Centre of Stellenbosch University. Moisture and ash contents (%) were determined according to AOAC Official Methods 934.01 and 942.05, respectively. The intramuscular fat (IMF) content (%) of 5 g homogenised samples was determined by chloroform/methanol (1:2, v/v) extraction (Latimer 2016). Crude protein (CP) content (%) was determined using the Dumas nitrogen

Table 1. Proximate composition and amino acid profile of *Chrysomya chloropyga* larvae reared on abattoir waste

Proximate composition (%)		
	As is basis	Dry matter basis
Dry matter	36.19	–
Moisture	63.81	–
Ash	11.65	32.20
Crude protein (CP)	13.21	48.01
Crude fibre (CF)	2.23	6.16
Crude fat (EE)	6.90	19.07
Amino acid composition (g/kg CP)		
Arginine	3.60	
Serine	1.92	
Aspartic acid	0.99	
Glutamic acid	1.96	
Glycine	2.08	
Threonine	1.90	
Alanine	1.69	
Tyrosine	1.96	
Proline	1.89	
Hydroxy-proline	0.02	
Methionine	1.04	
Valine	1.95	
Phenylalanine	2.80	
Isoleucine	1.55	
Leucine	2.21	
Histidine	1.43	
Lysine	2.32	

Table 2. Formulated ingredient and calculated nutrient composition of broiler diets containing *Chrysomya chloropyga* (CC) larvae

		Starter				Grower				Finisher			
		Control	5% CC	10% CC	15% CC	Control	5% CC	10% CC	15% CC	Control	5% CC	10% CC	15% CC
Formulated ingredient composition													
CC	%		5.00	10.00	15.00		5.00	10.00	15.00		5.00	10.00	15.00
Fine Yellow maize	%	50.09	50.33	49.64	56.94	45.68	47.11	48.53	49.96	47.16	47.10	47.04	47.84
Full fat soya bean meal	%	15.39	15.13	15.87	11.24	44.17	39.09	34.00	28.91	48.89	43.99	39.09	33.29
Soya oilcake meal (50% CP)	%	30.14	25.40	20.07	12.03	6.15	4.76	3.38	2.00				
L-lysine HCl	%	0.14	0.18	0.21	0.47	0.05	0.10	0.15	0.20				0.02
DL methionine	%	0.13	0.11	0.09	0.12	0.15	0.12	0.10	0.08	0.13	0.10	0.06	0.03
Vitamin and mineral premix	%	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Limestone	%	1.66	1.66	1.66	1.70	1.63	1.64	1.65	1.66	1.64	1.64	1.64	1.64
Salt	%	0.13	0.22	0.11	0.06	0.28	0.26	0.25	0.23	0.29	0.28	0.28	0.27
Monocalcium phosphate	%	1.64	1.64	1.64	1.65	1.63	1.63	1.64	1.64	1.63	1.63	1.63	1.63
Sodium bicarbonate	%	0.54	0.19	0.56	0.64	0.12	0.14	0.16	0.18	0.10	0.11	0.11	0.13
Calculated ingredient composition													
AMEn chick	MJ/kg	11.90	11.92	11.90	11.90	12.90	12.75	12.59	12.43	13.13	12.94	12.76	12.56
Crude protein	%	20.69	20.25	19.88	16.43	19.53	18.95	18.37	17.79	18.22	18.33	18.45	18.25
Lysine	%	1.53	1.52	1.52	1.50	1.39	1.39	1.38	1.38	1.29	1.29	1.28	1.28
Methionine	%	0.50	0.50	0.500	0.52	0.49	0.49	0.49	0.48	0.47	0.46	0.45	0.44
Cysteine	%	0.42	0.42	0.42	0.39	0.40	0.40	0.40	0.40	0.38	0.39	0.40	0.40
TSAA	%	0.92	0.92	0.92	0.91	0.89	0.89	0.89	0.88	0.85	0.85	0.85	0.85
Threonine	%	0.97	0.97	0.97	0.86	0.92	0.91	0.91	0.91	0.87	0.89	0.91	0.93
Tryptophan	%	0.30	0.30	0.30	0.27	0.28	0.28	0.28	0.28	0.26	0.27	0.28	0.29
Arginine	%	1.73	1.73	1.73	1.52	1.64	1.62	1.62	1.61	1.54	1.58	1.63	1.65
Isoleucine	%	1.16	1.12	1.08	0.90	1.08	1.03	0.99	0.95	1.02	1.01	0.10	0.97
Leucine	%	2.16	2.09	2.01	1.76	2.02	1.95	1.88	1.80	1.94	1.91	1.87	1.83
Crude fibre	%	3.00	3.08	3.18	3.06	3.65	3.61	3.57	3.53	3.73	3.71	3.70	3.65
Crude fat	%	5.20	6.00	6.94	7.15	10.00	10.00	10.00	10.00	10.84	10.84	10.80	10.70
Calcium	%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Phosphorous	%	0.84	0.84	0.84	0.81	0.83	0.83	0.83	0.83	0.82	0.83	0.83	0.83
Available phosphorous	%	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Sodium	%	0.22	0.16	0.22	0.22	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Chloride	%	0.16	0.22	0.16	0.16	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

AMEn – Apparent metabolisable energy, corrected for nitrogen retention.
TSAA – Total sulphur containing amino acids

combustion method (AOAC 992.15). Nitrogen content was analysed using a LECO FP828 (LECO Corporation, St Joseph, Michigan, U.S.A.). Ethylenediamine tera acetate was used for calibration. Amino acid hydrolysis was performed according to the AOAC Official method 994.12 (AOAC 2002). In short, 6 ml 6 M hydrochloric acid containing 15% phenol solution was added to each sample and sealed under nitrogen. Samples were left to hydrolyse for 24 h at 110 °C. Samples were then removed and allowed to cool before being transferred to Eppendorf tubes. Thereafter they were frozen at –18 °C until analysis. Amino acid analysis was performed using a Waters API Quattro Miro instrument with samples being subjected to the Waters AccQ Tag Ultra derivatisation kit for cleaning. Amino acid standard was purchased from Waters (P/N: WAT088122) and prepared by mixing 40 µl standard, 760 µl water and 200 µl of internal standard. Samples were diluted according to protein content, where 8–20% CP was diluted 10 times, 20–60% CP 20 times and 60–100% CP 50 times. Samples were prepared by adding 10 µl sample, 70 µl borate buffer and 20 µl reconstituted AccQ Tag reagent to a tube. Tubes were then vortexed and allowed to stand at room temperature (28 °C) for one minute. Thereafter they were placed in a heating block at 55 °C for 10 min. After preparation, 1µl of each sample was used for analysis.

Descriptive sensory analysis

For the sensory analysis, the remaining right breasts were thawed at 4 °C for 12 h, blotted dry and weighed. Unseasoned breasts, individually packed in oven bags, were placed on stainless steel roasting pans fitted with grids. Thermocouple probes attached to a digital temperature monitor (Hanna Instruments, South Africa) were secured in the centre of each sample. The meat samples were cooked in a conventional oven (Defy, model 835), which was connected to a computerised monitoring and temperature regulation system. The oven was preheated at 160 °C and the meat samples were cooked until their core temperature reached 75 °C. Samples were cooled for 15 min to allow equilibration to ambient temperature. The cooked samples were blotted dry and weighed. The cooked meat

samples were each cut into 32 cubes, each cube being 1 cm^3 in size. The sample cubes were individually wrapped in aluminium foil, and in groups of four, placed into glass ramekins coded with a randomised three-digit code. Prior to the sensory analysis session, the ramekins containing the meat sample cubes were places in a preheated industrial oven (Hobart, France) at 70 °C for 7 min. For the duration of the session the ramekins were kept in a preheated water bath at 70 °C. Descriptive sensory analysis was performed by eight experienced panellists and were trained according to guidelines for sensory analysis of meat (AMSA 1995). The panellists undertook five training sessions during which each panellist received four 1 cm^3 cubes from the four treatments. During the training sessions the panel decided on the sensory attributes that would be evaluated (Table 3). For the sensory analysis session, the panellists each received four cubes per treatment replicate; thus each panellist assessed eight replicates for each of the four treatment groups.

The panellists carried out the descriptive sensory analysis while seated at individual booths with computers fitted with Compusense 5 software (www.compusense.com, Guelph, Canada). The samples were analysed for the respective sensory attributes using an unstructured linear scale where zero indicated "low intensity" and 100 indicated "high intensity". The sensory analysis sessions took place in a temperature-controlled room at 21 °C with artificial daylight in accordance with the guidelines (AMSA 1995). The panellists were supplied with room temperature distilled water, apple pieces and wafer biscuits in order to cleanse and refresh their palates between testing of samples. Six sensory analysis sessions on three different consecutive days were performed, with two sessions per day.

Tibia bone strength and mineral composition

After carcass dressing, the tibia bones were removes and stored at –18 °C until analysis. The right tibias were thawed at 4 °C for 12 h and all adherent tissue was removed prior to analysis. Tibia length was measured with a digital calliper. The tibia weight and bone breaking strength was measured with a Instron tensile/compression machine with a 50 kg load cell. The bones were individually placed in the machine with the mid-diaphyseal diameter in the middle of the probe. The bone bending force was measure using a 10 mm probe that move at a constant speed of 30 mm/s. Bone strength was measured in Newtons per square millimetre. The mineral composition of the tibia samples was determined at the Institute of Animal Production (Western Cape Department of Agriculture, Elsenburg, South Africa) according to the combustion method 6.1.1 as described by the Agriculture Laboratory Association of Southern Africa (AGRILASA 2007). In short, 6 ml of 6 M hydrochloric acid was added to 0.5 g of sample. The samples were then placed in an oven at 50 °C for 30 min. Thereafter, 35 ml of distilled water was added, and the mixture was filtered into a 50 ml bottle. The bottles were then filled up to 50 ml with distilled water. The mineral content was determined with an iCAP 6000 series Inductive Coupled Plasma (ICP) spectrophotometer (Thermo Electron Corporation, Strada Rivoltana, 20090 Rodana, Milan, Italy) fitted with a vertical quartz torch and Cetac ASX-520 autosampler. The mineral concentrations were calculated with iTEVA Analyst software (https://tools.thermofisher.com/content/sfs/brochures/D01575~.pdf).

Statistical analysis

Statistical analyses of carcass characteristics, chemical analysis and physical measurements were analysed using the general linear model (GLM) procedure on SAS (2009). The Shapiro-Wilk test for normal distribution of data and a Levene's test for homoscedasticity were performed. Significance was declared at $p \leq 0.05$. A one-way analysis of variance (ANOVA) and Bonferroni's post hoc test was used for statistical analysis. In cases where the assumption of homoscedasticity was not satisfied, a Welch's analysis of variance for unequal variances was performed. Sensory analysis data was analysed with multivariate analyses using XLSTAT (www.xlstat.com, Addisoft, New York, U.S.A.). In the event of significant non-normality, outliers were identified and residuals greater than three standard deviations were removed.

RESULTS

Carcass and meat characteristic

The influence of the dietary inclusion of CC on broiler carcass characteristics is shown in Table 4. The live slaughter weight ($p = 0.052$) and cold carcass weight ($p = 0.067$) were similar although there was a tendency ($0.10 > p > 0.05$) toward differences with the 10% inclusion having higher values in both cases. However, the dressing percentage did not differ between dietary treatments. In terms of the different meat cuts that are of commercial importance, the only cut that was significantly affected by CC meal inclusion was the breast meat cut, where a 10% inclusion delivered the highest breast meat yield ($p \leq 0.05$). Like the slaughter weight and dressing percentage, the other commercial cut yields were not significantly affected by any inclusion percentage of CC meal, indicating that CC meal could be included in broiler diets up to 15% without a negative effect on the various yields and could have a positive effect by increasing the breast meat yield. There were also no significant differences regarding the tissue yields (skin and fat, muscle, and bone), which again reiterates that the inclusion of CC meal does not have a negative effect on the yield. The initial pH (pH_i) and

Table 3. Definition and scale of attributes used for descriptive sensory analysis of chicken breast

Sensory attribute	Description	Scale
Chicken aroma	Aroma associated with the chicken meat, as soon as the aluminium foil is removed.	0 = None 100 = Prominent
Chicken flavour	Flavour associated with chicken prior to swallowing while chewing.	0 = None 100 = Prominent
Metallic aroma	Aroma associated with raw meat and/or blood-like, as soon as the aluminium foil is removed	0 = None 100 = Prominent
Metallic flavour	Taste associated with raw meat and/or blood-like taste prior to swallowing while chewing.	0 = None 100 = Prominent
Initial juiciness	Amount of fluid extruded on surface of meat sample when pressed between the thumb and forefinger (pressed perpendicular to fibres).	0 = Dry 100 = Extremely juicy
Sustained juiciness	Amount of moisture perceived during mastication, after the first five chews using the molar teeth.	0 = Dry 100 = Extremely juicy
Tenderness	The impression of tenderness perceived after the first five chews using the molar teeth.	0 = Tough 100 = Extremely tender

ultimate pH (pH_u) for both the breast and thigh muscles and the colour measurements taken on the breast muscles are indicated in Table 5. The thigh pH_u was the only measurement where a significant difference was found, with the control group showing the highest pH_u and the 5% inclusion and the 15% inclusion groups showing the lowest pH_u values.

Chemical analysis

The proximate composition analysis results of the cooked breast meat are indicated in Table 6. The moisture content of all the treatment groups were lower than those reported by other studies that performed the analysis on raw meat. This is expected as the cooking process is known to reduce the moisture content of meat (Shaarani et al. 2006). The moisture content was the only proximate component that showed a significant difference between the treatment groups, with the control group having the highest moisture content (p = 0.002). There were no significant differences in moisture content between the other three treatment groups. This suggests that the inclusion of CC meal at any inclusion between 5% and 15% will have a similar effect on the moisture content. Neither protein, fat nor ash contents were significantly affected by the CC inclusion, although there was a tendency (p = 0.054) for the ash content to increase as the level of CC in the diet increased. This similarity in proximate analyses is expected as all the treatment diets were formulated to be balanced (Table 2) and should not cause differences in the protein or fat contents of the broiler meat. The amino acid content of the broiler breast meat showed no significant differences between treatment groups for any of the amino acids that were analysed (Table 7).

Descriptive sensory analysis

As pertaining to the descriptive sensory analyses, no significant differences were observed for chicken flavour, metallic aroma, metallic flavour, sustained juiciness, or tenderness (Table 8). In terms of chicken aroma, a difference (p = 0.008) was seen between the control group and the 5% CC inclusion group, with the 5% CC inclusion group showing the highest value. Initial juiciness also showed significant differences between treatment groups, with the control group and the 5% CC inclusion group showing the highest initial juiciness. However, as mentioned, there were no significant differences between the treatments in terms of sustained juiciness.

Tibia bone strength and mineral content

The results of the tibia bone breaking force and breaking strength are shown in Table 9. The treatments did not have a significant effect on either parameter. Significant differences in tibia mineral contents were observed between treatment groups for two of the minerals that were analysed, potassium and iron. The three CC inclusion treatment groups all had significantly higher potassium content compared to the control group. The iron content of the 5% inclusion treatment group was observed to be the highest and the control group and the 15% CC inclusion groups were observed to have the lowest iron content.

Table 4. Means (± standard errors) of carcass characteristics of broilers fed diets with different inclusions of *Chrysomya chloropyga* larval meal

Parameters	Treatments diets				*P*-value
	Control	5% CC	10% CC	15% CC	
Live slaughter weight (g)	2067.50 ± 10.65	2047.50 ± 0.04	2172.50 ± 0.04	2095.00 ± 0.04	0.052
Cold carcass weight (g)	1364.50 ± 11.32	1388.73 ± 30.99	1472.27 ± 38.55	1399.50 ± 25.36	0.067
Dressing percentage (%)	66.00 ± 0.50	67.86 ± 0.01	67.78 ± 0.01	66.83 ± 0.01	0.525
Breast (g)	267.58 ± 8.12^{b}	277.45 ± 5.18^{ab}	299.35 ± 9.33^{a}	270.91 ± 7.68^{ab}	0.031
Thigh (g)	352.65 ± 5.27	348.93 ± 11.63	373.36 ± 10.44	365.10 ± 10.72	0.290
Drumstick (g)	195.04 ± 4.82	209.65 ± 6.52	213.20 ± 9.76	205.55 ± 5.38	0.293
Wing (g)	172.60 ± 9.41	178.15 ± 7.96	178.73 ± 5.62	179.19 ± 5.78	0.091
Back (g)	93.29 ± 3.37	94.61 ± 2.78	99.61 ± 4.76	98.00 ± 5.56	0.704
Breast portion					
Skin and fat (%)	5.73 ± 0.38	6.93 ± 0.55	6.28 ± 0.35	6.87 ± 0.48	0.212
Muscle (%)	74.25 ± 0.91	74.21 ± 1.39	72.79 ± 1.56	71.33 ± 1.35	0.366
Bone (%)	18.54 ± 0.77	17.55 ± 1.02	20.00 ± 1.61	20.72 ± 0.87	0.205

(^{a,b}) Means with different superscripts within the same row differ significantly ($p \leq 0.05$)

Table 5. Means (± standard errors) of meat characteristics of broilers fed diets with different inclusions of *Chrysomya chloropyga* larval meal

Parameters	Treatments diets				*P*-value
	Control	5% CC	10% CC	15% CC	
pH_i breast	6.38 ± 0.04	6.35 ± 0.06	6.38 ± 0.06	6.41 ± 0.03	0.890
pH_u breast	6.13 ± 0.04	6.06 ± 0.04	6.13 ± 0.03	6.06 ± 0.02	0.261
pH_i thigh	6.65 ± 0.06	6.57 ± 0.06	6.58 ± 0.04	6.52 ± 0.04	0.302
pH_u thigh	6.65 ± 0.04^{a}	6.46 ± 0.03^{b}	6.52 ± 0.04^{ab}	6.47 ± 0.04^{b}	0.006
L* breast	54.35 ± 0.71	53.35 ± 1.26	53.94 ± 1.22	54.03 ± 0.87	0.922
a* breast	0.74 ± 0.30	-0.35 ± 0.23	0.22 ± 0.32	0.14 ± 0.33	0.105
b* breast	12.31 ± 0.26	9.97 ± 0.71	10.54 ± 0.76	12.15 ± 1.04	0.085
Hue breast	86.70 ± 1.25	92.88 ± 2.08	89.33 ± 1.44	90.36 ± 1.77	0.093
Chroma breast	12.35 ± 0.28	10.01 ± 0.68	10.57 ± 0.77	12.18 ± 1.03	0.083

(^{a,b}) Means with different superscripts within the same row differ significantly ($p \leq 0.05$)
pH_i – initial pH
pH_u – ultimate pH

Table 6. Means (± standard errors) of proximate analysis (g/100g; cooked breast meat) of broilers fed diets with different inclusions of *Chrysomya chloropyga* larval meal

Parameters	Treatments diets				*P*-value
	Control	5% CC	10% CC	15% CC	
Moisture	68.9 ± 0.58[a]	66.1 ± 0.50[b]	66.2 ± 0.50[b]	66.0 ± 0.50[b]	0.002
Protein	28.4 ± 0.57	28.9 ± 0.50	29.3 ± 0.50	29.4 ± 0.50	0.568
Fat	2.1 ± 0.24	2.8 ± 0.21	2.8 ± 0.21	2.7 ± 0.21	0.090
Ash	1.1 ± 0.09	1.2 ± 0.08	1.2 ± 0.08	1.4 ± 0.08	0.054

([a,b]) Means with different superscripts within the same row differ significantly ($p \leq 0.05$)

Table 7. Means (± standard errors) of amino acid composition (g/100g; cooked breast meat) of broilers fed diets with different inclusions of *Chrysomya chloropyga* larval meal

Amino acids	Treatments diets				*P*-value
	Control	5% CC	10% CC	15% CC	
Histidine*	2.5 ± 0.09	2.5 ± 0.08	2.5 ± 0.09	2.5 ± 0.08	0.995
Serine	3.0 ± 0.08	3.0 ± 0.07	3.1 ± 0.08	3.0 ± 0.07	0.860
Arginine*	5.2 ± 0.12	5.3 ± 0.11	5.3 ± 0.11	5.4 ± 0.10	0.883
Glycine	3.3 ± 0.07	3.5 ± 0.06	3.3 ± 0.07	3.4 ± 0.06	0.266
Aspartic acid	7.2 ± 0.18	7.0 ± 0.15	7.2 ± 0.16	7.2 ± 0.14	0.916
Glutamic acid	11.3 ± 0.24	11.1 ± 0.21	11.3 ± 0.23	11.4 ± 0.20	0.865
Threonine*	3.6 ± 0.09	3.5 ± 0.08	3.5 ± 0.08	3.5 ± 0.07	0.945
Alanine	4.2 ± 0.08	4.3 ± 0.07	4.2 ± 0.07	4.2 ± 0.07	0.782
Proline	2.8 ± 0.06	2.8 ± 0.05	2.7 ± 0.05	2.8 ± 0.05	0.542
Cysteine	0.4 ± 0.02	0.4 ± 0.02	0.4 ± 0.02	0.4 ± 0.02	0.683
Lysine*	7.5 ± 0.55	7.6 ± 0.48	7.5 ± 0.51	6.7 ± 0.45	0.543
Tyrosine	3.1 ± 0.11	3.0 ± 0.10	3.1 ± 0.11	3.1 ± 0.09	0.723
Methionine*	2.0 ± 0.10	2.3 ± 0.08	2.3 ± 0.09	2.3 ± 0.08	0.086
Valine*	4.2 ± 0.09	4.2 ± 0.07	4.1 ± 0.08	4.1 ± 0.07	0.466
Isoleucine*	3.7 ± 0.08	3.8 ± 0.07	3.7 ± 0.07	3.7 ± 0.06	0.758
Leucine*	6.4 ± 0.13	6.3 ± 0.12	6.3 ± 0.12	6.3 ± 0.11	0.946
Phenylalanine*	3.5 ± 0.12	3.4 ± 0.10	3.5 ± 0.11	3.4 ± 0.10	0.717

* Essential amino acids for humans

DISCUSSION

Carcass and meat characteristics

The inclusion of CC meal up to 15% had minimal influence on the final live weight, cold carcass weight or dressing percentage of broilers (Table 4). These results are similar to those reported when Black soldier fly (*Hermetia illucens* L. (Stratiomyidae)) prepupae meal was included in broiler diets (Pieterse et al. 2019). Although diet can have an effect on these parameters, the similarity between the different treatments is likely due to the similarities between the chemical compositions of the diets that had been formulated to be iso-energetic and isonitrogenous. Therefore, the inclusion of CC meal up to 15% neither negatively nor positively influenced these parameters.

The only carcass characteristic that was significantly influenced by the diets was the breast yield, where treatment 10% CC resulted in the highest yield. These results are like those reported by Pieterse et al. (2014) who reported increased breast and thigh yields for broilers reared on house fly (*Musca domestica* L. (Muscidae)) larvae meal diets at 10% inclusion. The breast portion is generally the most expensive cut, and these results indicate the use of CC meal at an inclusion of 10% could have a financially advantageous impact on production – although this aspect warrants further research. Schiavone et al. (2019) reported a quadratic increase in broiler breast meat yield with the inclusion of *H. illucens* meal although the inclusion of *H. illucens* meal did not have a significant effect on the breast meat yield of broiler quails (Cullere et al. 2016). Hwangbo et al. (2009) found that including up to 15% *M. domestica* larvae in broiler feed significantly increased breast meat yield. Although there are some differences in literature regarding the effect of insect meals on broiler breast meat yields, the results of the present study indicate that CC meal could be used to substitute the protein source in broiler diets without a negative effect on the yield of economically important meat cuts.

As shown in Table 5, the only meat characteristic that was significantly influenced by the treatments was the ultimate pH of the thigh portion. However, these values are still within the normal range for cooked broiler meat (Husak et al. 2008).

Chemical analysis

As expected, there were no significant differences in either the protein, fat, or ash content between the different diet groups (Table 6). Interestingly, there was a significant difference between the treatment groups in terms of the breast moisture content. The moisture content differences together with the numerical differences in fat content might indicate that the insect-fed groups were further along on the growth curve than the control group. Altmann et al. (2020) reported that partially replacing soybean meal with insect meal (*H. illucens*) did not have any significant effects on the proximate composition of broiler breast meat. Similarly, there were no significant differences found for any of the analysed amino acids. Although other studies have found that the inclusion of insect meal can alter the amino acid profile of broiler meat (Cullere et al. 2018), the aforementioned results are likely caused by the diets that were formulated to be as similar as possible in terms of their composition. The amino acid profile of broiler meat is also largely genetically predetermined

Table 8. Means (± standard errors) of descriptive sensory attributes of breast meat from broilers fed diets with different inclusions of *Chrysomya chloropyga* larval meal.

Parameters	Treatments diets				*P*-value
	Control	5% CC	10% CC	15% CC	
Chicken aroma	64.8 ± 7.65[b]	69.7 ± 9.27[a]	67.8 ± 7.50[ab]	66.2 ± 8.45[ab]	0.008
Chicken flavour	63.5 ± 7.28	67.1 ± 8.61	67.4 ± 8.28	66.5 ± 9.67	0.183
Metallic aroma	2.4 ± 4.76	1.1 ± 3.14	1.5 ± 3.63	1.8 ± 4.35	0.262
Metallic flavour	4.0 ± 5.95	2.6 ± 4.89	3.5 ± 4.77	2.3 ± 4.27	0.067
Initial juiciness	76.0 ± 9.79[a]	73.5 ± 11.04[ab]	70.1 ± 11.08[c]	71.4 ± 9.59[bc]	0.012
Sustained juiciness	69.4 ± 9.10	66.2 ± 7.87	66.5 ± 8.53	67.6 ± 9.08	0.059
Tenderness	84.4 ± 11.97	82.5 ± 9.24	83.4 ± 11.67	82.4 ± 9.84	0.525

([a,b]) Means with different superscripts within the same row differ significantly ($p \leq 0.05$)

Table 9. Means (± standard errors) of tibia breaking force, strength and bone mineral content of broilers fed diets with different inclusions of *Chrysomya chloropyga* larval meal.

Parameters		Treatments diets			*P*-value	*p*-value
		Control	5% CC	10% CC	15% CC	
Breaking force	N	357.8 ± 29.09	375.1 ± 29.09	359.9 ± 25.20	391.2 ± 26.95	0.805
Breaking strength	N/mm^2	75.4 ± 5.40	68.9 ± 5.40	66.1 ± 4.68	71.9 ± 5.00	0.615
Calcium	%	41.0 ± 1.14	38.6 ± 1.14	37.4 ± 1.00	38.1 ± 1.05	0.126
Phosphate	%	19.6 ± 0.44	19.3 ± 0.44	18.1 ± 0.38	18.8 ± 0.40	0.083
Potassium	%	1.0 ± 0.04[b]	1.6 ± 0.04[a]	1.5 ± 0.04[a]	1.4 ± 0.04[a]	< 0.001
Magnesium	%	0.7 ± 0.01	0.7 ± 0.01	0.7 ± 0.01	0.7 ± 0.01	0.080
Sodium	mg/kg	12.8 ± 0.78	28.3 ± 0.78	14.8 ± 0.68	13.7 ± 0.72	0.890
Copper	mg/kg	1.9 ± 1.53	1.7 ± 1.53	2.8 ± 1.33	4.2 ± 1.42	0.618
Zinc	mg/kg	303.1 ± 10.21	325.1 ± 10.21	322.8 ± 8.85	306.0 ± 9.46	0.287
Iron	mg/kg	234.0 ± 14.17[b]	288.5 ± 14.17[a]	263.6 ± 12.28[ab]	239.9 ± 13.12[b]	0.043

([a,b]) Means with different superscripts within the same row differ significantly ($p \leq 0.05$)

and if the dietary amino acid requirements are met by the feed, no changes should be observed in the meat amino acid profile (Aftab 2019).

Descriptive sensory analysis

Most of the sensory traits that were analysed were found to be unaffected by the treatments, with the exception of chicken aroma and initial juiciness. Other studies that analysed similar sensory attributes found that the inclusion of insect meals did not significantly affect the sensory attributes of broiler meat (Pieterse et al. 2014; Cullere et al. 2018). This study indicates that CC meal inclusion in broiler diets could enhance sensory attributes of the meat. The results are thus promising, and further research could be of value for ensuring sensory attributes are not negatively affected by the inclusion of insect meal in broiler diets.

Tibia bone strength and mineral content

The treatments had no effect on these parameters, which is in line with the results reported by Pieterse et al. (2019) when *H. illucens* pre-pupae meal was used as one of the dietary proteins. This indicates that CC meal at these inclusion levels will not have a negative effect on the bone parameters. The analysed mineral contents of the tibia bone can be seen in the same table. Potassium and iron were the only minerals that were significantly affected by the treatments and in both cases the control had the lowest content of the specific mineral. The increased iron content could be as a result of the abattoir waste that the larvae were reared on, which is high in iron. Although the mineral content of CC larvae was not analysed, it has been reported that many insects, especially fly larvae, contain adequate amounts of these two minerals to meet the animals' requirements (Oonincx & Finke 2021). It is possible that the minerals in the insect meal had higher bioavailability compared to the soya, which it replaced. This is likely due to the presence of phytate in soya, which reduces the bioavailability and is not present in the larvae (Hurrell 2003). Although no differences were observed in the colour and metallic flavour of the meat, the iron concentration of the tibia bones differed amongst treatments, and this could indicate increased mineral bioavailability. These effects on bioavailability warrants further research.

CONCLUSION

The carcass, meat and sensory characteristics of broilers fed diets containing CC larval meal at an inclusion rate of up to 15% were on par with the control soya-based diet. For some of the measured parameters, the experimental treatment groups even outperformed the control group, leading to the conclusion that CC larval meal can be used as a protein source in broiler diets at these inclusion levels without any negative effects on the aforementioned characteristics and could even have a positive effect on them. This opens the possibility of using CC larvae to convert abattoir waste into protein, to be used for either animals or perhaps humans.

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AUTHOR CONTRIBUTIONS

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