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Meta-analysis of the effect of black soldier fly larvae meal in diet on broiler performance and prediction of its metabolisable energy value

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ABSTRACT

The aims of the present work were to determine by meta-analysis the responses of broiler performance to increasing dietary levels of black soldier fly larvae meal (BSFLM) and to develop prediction models of the apparent metabolisable energy corrected to zero nitrogen balance (AMEn) of BSFLM. Eighteen studies from 12 countries that sum up to 20 experiments and involved a total of 63 treatments with 468 replicates and 4229 birds fulfilled the requirements for the meta-analysis. Four papers from three countries that investigated eight different samples of BSFLM were selected for development of AMEn prediction by means of regression analysis or artificial neural network (ANN) modelling. Growth performance results were not affected ($p > .05$) by the presence of BSFLM at levels of 5.7 ± 2.3 and $15.5 \pm 6.0\%$ in the diet. Multiple linear regression and ANN models showed high precision and accuracy, were unbiased and performed almost identically in the evaluation dataset ($R^2 = 0.856$ and 0.858 and root mean square error of prediction as percentage of the observed mean = 5.216 and 5.241%). Feeding broilers with diets containing 15% BSFLM is not expected to have negative effects on growth performance. The following regression model could be useful for the estimation of AMEn in BSFLM: $\text{AMEn} = 4.08\ (\pm\ 0.330) + 0.295\ (\pm\ 0.0158) \times \text{GE} + 0.186\ (\pm\ 0.0021) \times \text{EE}$; where AMEn and gross energy (GE) are MJ/kg dry matter and crude fat (EE) is % dry matter.

HIGHLIGHTS

- Feeding broilers 15% black soldier fly larvae meal in the diet does not affect performance results.
- Metabolisable energy value of black soldier fly larvae meal can be accurately predicted from its composition.

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Introduction

The majority of poultry meat production (92%) comes from specialised broiler systems where high-energy high-protein diets mostly based (>75% of total ingredients) on cereal grains and oilseed cakes are fed to promote rapid growth in a short period of time (Mottet and Tempio 2017). This feeding system not only directly competes for human edible crops but also might have a negative environmental impact, thus it should be revised with the goal of achieving sustainable food systems in the future (Vauterin et al. 2021). In this context, the substitution of traditional protein sources by insects could greatly aid to achieve more sustainable broiler production systems (Khan 2018), without increasing or even reducing feed costs (Onsongo et al. 2018), provided an adequate and cost-effective supply from well-organised large-scale production facilities is available (Van Phl et al. 2020).

Dried black soldier fly larvae meal (BSFLM) is one of the most promising and studied alternatives to provide a sustainable protein source in poultry diets (Wang and Shelomi 2017; Dörper et al. 2021). The BSFLM has a higher crude protein content than soybean meal and other common vegetal protein sources and contains comparable amounts of most essential amino acids (Abd El-Hack et al. 2020).

The replacement of soybean meal and/or fish meal with BSFLM in a protein or weight basis in diets for broilers have been widely studied in the last few years (Opoku et al. 2018; Affedzie-obresi et al. 2020;

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Hartinger et al. 2021). Full fat, partially defatted or highly defatted BSFLM has been included in broiler diets at concentrations between 2 and 40% (Yaseen Kareem et al. 2018; Murawska et al. 2021), 5 and 25% (Dabbou et al. 2018; Neumann et al. 2018) and 4.1 and 15% (Hartinger et al. 2021; Kim et al. 2022), respectively. The inclusion level has been kept constant or has been decreased throughout the successive stages of the fattening cycle (Onsongo et al. 2018; Velten et al. 2018; Kim et al. 2022; Van der Heide et al. 2021). The observed responses seem to depend on the amount of BSFLM included in the diet, with poorer results reported generally at levels higher than 10% (Velten et al. 2018; Murawska et al. 2021), although in many cases responses above and below this threshold are inconsistent with no change, reduction or increase of one or several performance parameters at similar rates of supplementation (Dabbou et al. 2018; Onsongo et al. 2018; Yaseen Kareem et al. 2018; Attivi et al. 2020). The negative effects found have been attributed to a lower crude protein (CP) digestibility due to chitin in BSFLM and to changes in intestinal morphology (Dabbou et al. 2018; Hartinger et al. 2021). Again, the published reviews on the use of BSFLM in poultry diets summarise scientific literature in a descriptive and qualitative approach (Abd El-Hack et al. 2020; Sverguzova et al. 2021). However, the contradictory findings in the literature could be clarified by submitting published results on the inclusion of BSFLM in broiler diets to meta-analysis (Sauvant et al. 2020).

To the best of our knowledge, except for the work of Dabbou et al. (2018), published papers on BSFLM in broiler diets do not mention how metabolisable energy value of the BSFLM assayed was derived to formulate the experimental diets. Digestibility studies are the gold standard to determine the metabolisable energy content of poultry feeds and feedstuffs, but they are time consuming, labour intensive and costly; hence, several efforts have been made to develop empirical prediction equations based on regression models (Carré et al. 1984; Alvarenga et al. 2011). In the last decade, neural network based-models have joined to the classical regression models (Mariano et al. 2013). Developing either regression or neural network models for prediction of metabolisable energy value of BSFLM batches from their measured chemical composition could be helpful in broiler feed formulation.

The objective of the present work was double. Firstly, to determine by meta-analysis the effects of the inclusion of BSFLM in the diet on broiler growth performance. Secondly, to develop prediction models of the metabolisable energy value of BSFLM.

Materials and methods

Peer-reviewed studies written in English were searched in Google Scholar using the operator 'allintitle:' and introducing several combinations of the keywords: 'poultry', 'broiler/s', 'chicken/s', '*Hermetia illucens*', 'black soldier fly' and 'metabolizable energy'. The search was limited between year 2000 and March 2022. The PRISMA flow diagram is shown in Figure 1.

Meta-analysis of the effects of BSFLM on growth performance

Studies retrieved by the search were selected if: (1) they clearly described the experimental design; (2) they included a control group not fed BSFLM; (3) the treatment diets with BSFLM were fed throughout all the feeding phases of the fattening cycle and (4) they reported the detailed composition of the experimental treatments, BSFLM level of inclusion in the diets, days on experimental treatments and at least two of the following three parameters: feed intake (FI), body weight gain (BWG) and feed conversion ratio (FCR). Experiments or treatments with explicitly declared interference factors due to environmental conditions or diet composition were discarded. If not reported, dietary dry matter was estimated at 90% (11 studies) and apparent metabolisable energy corrected to zero

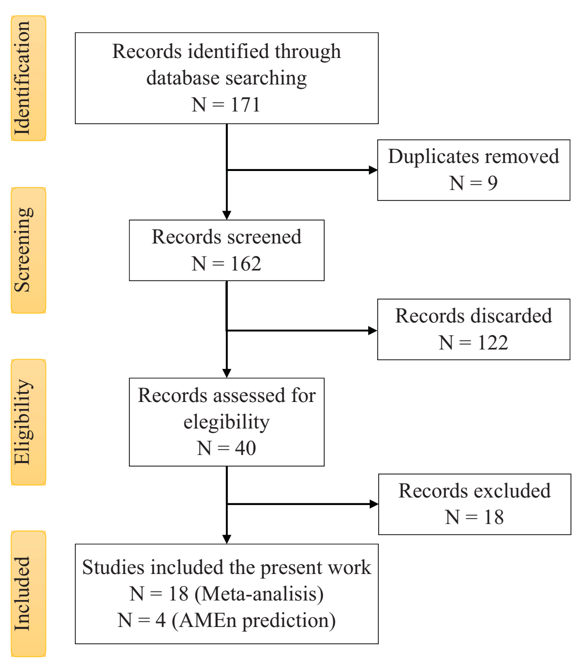

Figure 1. PRISMA flow diagram (AMEn: apparent metabolisable energy corrected to zero nitrogen balance).

nitrogen balance (AMEn) was calculated from proximal composition according to equation (8) of Carré et al. (1984) (two studies). Within each treatment, the contents of AMEn, CP and BSFLM were averaged according to each feeding phase duration. Finally, treatments were coded either as 'Control' or as 'BSFLM' when the diet did not contain or included BSFLM. Visual inspection of the data indicated that BSFLM diets could be further coded as $BSFLM_{low}$ and $BSFLM_{high}$ when the averaged BSFLM level was lower and equal or higher than 10%, respectively, following the results of Moula and Detilleux (2019).

Prediction of the metabolisable energy value of BSFLM

Four papers that reported the measured values of gross energy (GE), CP, crude fat (EE) and apparent or true metabolisable energy, corrected or not to zero nitrogen balance, of eight different samples of BSFLM were found in the search (Table 1). In all the four papers CP was reported as total nitrogen content multiplied by the conversion factor value of 6.25. The AMEn was selected as the target variable. A conversion factor of 0.86 was derived from the results in the work by Wolynetz and Sibbald (1984) to calculate AMEn from true metabolisable energy corrected to zero nitrogen balance when necessary.

Statistical analyses

In all analyses, statistical significance was declared at $p < .05$. Random-effects meta-analysis was performed with the MIXED procedure of SAS OnDemand for Academics (SAS Institute, Cary, NC, USA), according to the models proposed by St-Pierre (2001). Firstly, we compared Control and BSFLM diets to investigate the effects of inclusion of BSFLM in the diet on FBW, ADG, FI and FCR. The linear mixed model used was: $Yijk = \mu + Si + Tj + STij + eijk$, where Yijk is the dependent variable, μ is the overall mean, Si is the random effect of the ith experiment (Table 2), Tj is the fixed effect of the jth level of treatment (Control, $BSFLM_{low}$ and $BSFLM_{high}$), STij is the random interaction between the ith experiment and the jth level of treatment, and eijk is the residual error. The data were weighed with the square root of the number of replicates in each treatment using the WEIGHT statement. Orthogonal polynomial contrasts were used to test for linear and quadratic trends with the CONTRAST statement. The contrast coefficients for unequally spaced treatments (0, 5.7 and 15.5% averaged BSFLM content in the diet) were generated with the ORPOLY function in the IML procedure.

For the development of prediction models of AMEn, Monte-Carlo simulation was used to overcome the few number of observations in the original dataset (Escobar-Bahamondes et al. 2017). A synthetic dataset containing 5000 cases was constructed from the original data with the Simulation procedure of SPSS 25 for Windows (SPSS Inc., Chicago, IL, USA). The simulation model assumed normal distribution of variables and included Pearson's correlation coefficients between them, as well as their mean, standard deviation and minimum and maximum values (the latter calculated as the mean plus ± three times the standard deviations) (Table 3). The synthetic dataset was randomly split in three subsets namely training (60% of cases), testing (20% of cases) and evaluation (20% of cases). The training dataset was used in multiple regression analysis and artificial neural network (ANN) modelling. The regression model was developed by stepwise regression analysis with the GLMSELECT procedure of SAS OnDemand for Academics. Independent variables were GE, CP and EE and both linear and

Table 1. Summary the of studies used to develop prediction models of the metabolisable energy value of black soldier fly larvae meal (BSFLM).

Author	Country	Type of BSFLM tested	Assayed energy value	Methodology
De Marco et al. (2015)	Italy	Full fat	AME, AMEn	25% substitution in a maize-soybean meal based diet (34 day-old chicks)
Matin et al. (2021)	USA	Partially defatted	TMEn	Precision feeding (25–35 g) in conventional roosters fasted for 26 h
Mwaniki and Kiarie (2019)	Canada	Highly defatted	AME, AMEn	35% substitution in a nitrogen-free diet (17 day-old chicks)
Schiavone et al. (2017)	Italy	Partially defatted and highly defatted	AME, AMEn	25% substitution in a maize-soybean meal based diet (32 day-old chicks)

Note: AME: apparent metabolisable energy; AMEn: apparent metabolisable energy corrected to zero nitrogen balance; TMEn: true metabolisable energy corrected to zero nitrogen balance.

Table 2. Summary of the studies included in the meta-analysis.

Author	Country	Line	BSFLM[a] tested	Age at data collection	Time on feeding the experimental diets
Affedzie-obresi et al. (2020)	Ghana	Cobb 500	N.A.[b]	56	56
Attivi et al. (2020)	Togo	Ross 308	N.A.	42	42
Brede et al. (2018)	Germany	Ross 308	Partially defatted	35	35
Cockcroft (2018)	South Africa	Cobb 500	Full fat and partially defatted	32	28
Dabbou et al. (2018)	Italy	Ross 308	Partially defatted	35	35
Hartinger et al. (2021)	Austria	Ross 308	Highly defatted	35	35
Kim et al. (2022)	Korea	Ross 308	Highly defatted	35	35
Murawska et al. (2021)	Poland	Ross 308	Full fat	42	42
Neumann et al. (2018)	Germany	Ross 308	Partially defatted	34	34
Oluokun (2010)	Nigeria	Native	Full fat	70	70
Onsongo et al. (2018)	Kenya	Cobb 500	Full fat	49	42
Opoku et al. (2018)	Ghana	Cobb 500	Full fat	56	56
Schoor (2017)	South Africa	Cobb 500	Full fat	29	29
Uushona (2015)	South Africa	Cobb 500	Full fat	35	32
Van der Heide et al. (2021)	Denmark	Ross 308	Highly defatted	35	35
Van Emmenes (2021)	South Africa	Ross 308	Full fat	42	35
Velten et al. (2018)	Germany	Ross 308	Partially defatted	34	34
Yaseen Kareem et al. (2018)	India	Cobb 500	Full fat	42	42

[a]Black soldier fly larvae meal.
[b]Not available.

Table 3. Descriptive statistics of the synthetic dataset built to develop prediction models of apparent metabolisable energy corrected to zero nitrogen balance (AMEn) in black soldier fly larvae meal (values on dry matter basis).

Parameter	Mean	Standard deviation	Minimum	Maximum
Gross energy, MJ/kg	22.39	1.15	18.82	25.90
Crude protein, %	53.41	8.28	28.23	80.21
Crude fat, %	17.67	8.36	0.02	44.46
AMEn, MJ/kg	13.96	1.93	8.80	20.45

quadratic terms were investigated. The best model was chosen according to the PRESS option (minimum true prediction error through leave-one-out validation). The ANN model was constructed using SPSS 25 for Windows. The architecture of the ANN was a feed-forward multilayer perceptron with three inputs (GE, CP and EE), 1 output (AMEn), with linear activation function, and one hidden layer of one, two or three hidden units per hidden layer, with hyperbolic tangent activation function. For many practical problems, there is no reason to use more than one hidden layer and as rule of thumb the number of hidden units should be between the size of the input layer and the size of the output layer (Heaton 2008). Initialisation value for the random number generator was fixed at 12,345, variables were standardised, and training was carried out with the batch option. The optimisation algorithm was scaled conjugate gradient with initial lambda and sigma values set at 0.0000005 and 0.00005, respectively (Møller 1993). Criteria to stop the model training were set at the first reached, either one step without decreasing error ratio more than 0.001 or a maximum of 10,000 training epochs. Models' performance was studied in the evaluation dataset. The coefficient of determination (R^2), the root mean square error of prediction (RMSEP), the standardised RMSEP (RSR), and the concordance correlation coefficient (CCC) (Lin 1989) were used to assess prediction adequacy. The higher the values of R^2 and CCC and the lower the values of RMSEP and RSR, the better precision and accuracy. Moreover, to investigate biases, the mean square error of prediction was decomposed in central tendency error, that measures mean bias (the better, the nearer to zero), linear error or error due to regression (the better, the nearer to zero) and random error due to disturbances (Tedeschi 2006).

Results and discussion

Meta-analysis of the effects of BSFLM on growth performance

Eighteen studies (14 papers and four thesis) from 12 countries that sum up to 20 experiments and involved a total of 63 treatments with 468 replicates and 4229 birds fulfilled the requirements (Table 2). Within the 18 studies selected for the meta-analysis, 9 were carried out in Africa, 7 in Europe and 2 in Asia (Table 2). Most studies were published in years 2018, 2021 and 2020 (eight, five and two, respectively). The most represented genetic line was Ross 308 (12 experiments). The 20 experiments in the 18 studies summed up to 22 Control treatments and 41 BSFLM treatments, with between three and 18 replicates per treatment. A total of 21, 10 and 5 BSFLM treatments tested full fat, partially defatted and highly defatted BSFLM, respectively, and 5 did not mention the type used. Only 10 studies gave details on the chemical composition of the BSFLM used. BSFLM mainly replaced protein of soybean mean, fish meal or a combination of them in 28, 6 and 7 treatments, respectively. Lysine and methionine levels in the experimental diets were adjusted in

16 out of the 20 experiments. None of the studies included in the meta-analysis reported the chitin content of the experimental diets.

Table 4 shows the descriptive statistics of the production parameters in the studies included in the meta-analysis. Averaged CP and AMEn contents did not differ between treatments ($p > .05$). Averaged BSFLM level was 5.7 ± 2.3 and $15.5 \pm 6.0\%$ in the $BSFLM_{low}$ and $BSFLM_{high}$ treatments, respectively. Except for the work of Oluokun (2010), days to reach FBW (39 ± 7 d), average energy consumed (1.21 ± 0.19 MJ/d) and growth performance results were for the most part in line with expected outcomes in the modern poultry industry (Tallentire et al. 2017; Baracho et al. 2019).

Growth performance results were not affected ($p > .05$) by the presence of BSFLM in the diet at any level of inclusion (Table 5). The results for FI and FCR agreed with the findings of a previous meta-analysis that evaluated the effects of including several insects in the diet on poultry performance (Moula and Detilleux 2019). On the contrary to our results, those authors found a negative effect of insects on ADG at dietary levels of equal to or higher than 10%; however, they did not investigate possible interactions between insect species and amounts supplied. Now the question arises why some studies have found different effects on broiler performance after BSFLM inclusion in the diet at contrasting levels, e.g. a poorer performance at an average inclusion level of 13.5% in the study of Velten et al. (2018) and no negative effects at an average inclusion level of 22.3% in the study of Brede et al. (2018). Inadequate amino acid balance, lower CP digestibility, negative effects on intestinal morphology and/or inaccurate assessment of AMEn of the diets containing BSFLM might help explain the negative effects found in some studies.

Replacing conventional protein sources by BSFLM in the experimental diets in a protein or weight basis might not result in a comparable balance of the amino acids supplied to the animals, hence negatively affecting growth performance. All but one experimental treatments of the studies included in the meta-analysis were isonitrogenous and most of them, including the latter, incorporated at least L-lysine and DL-methionine in the formula composition to adjust the amino acid supply. Moreover, Fuso et al. (2021) reported a profile of essential amino acids in the protein of black soldier fly prepupae reared on several substrates comparable with that of soybean meal and fish meal, except for lysine and methionine, which showed lower contents than in fish meal protein (Sauvant et al. 2004). However, the results of Neumann et al. (2018) and Velten et al. (2018) suggest that similar levels of essential amino acids in standard diets and BSFLM diets migth not suffice always to achieve the same production results, due to a decreased net protein utilisation with BSFLM diets (Neumann et al. 2018), which ultimately could be related to a lower digestibility of essential amino acids in such diets (Brede et al. 2018; Hartinger et al. 2021).

Table 4. Descriptive statistics of several parameters in the studies selected for the meta-analysis.

Parameter	n	Mean	Standard deviation	Minimum	Maximum
Averaged BSFLM, % diet	41	11.40	6.80	2.00	34.80
Averaged AMEn, MJ/kg dry matter	63	13.97	0.81	12.64	15.08
Averaged CP, % dry matter	63	23.27	2.13	19.08	29.60
Average AMEn intake, MJ/d	63	1.21	0.19	0.72	1.64
Average CP intake, g/d	63	20.00	3.80	11.30	27.70
Initial body weight, g	37	43.70	4.80	35.30	55.00
Final body weight, g	55	2216.00	443.00	1369.00	3182.00
Average daily gain, g/d	63	55.20	13.10	20.90	76.00
Average feed intake, g/d	63	95.40	15.70	58.50	127.60
Feed conversion ratio, g/g	63	1.79	0.36	1.34	2.80

Note: BSFLM: black soldier fly larvae meal; AMEn: apparent metabolisable energy corrected to zero nitrogen balance; CP: crude protein.

Table 5. Effects of feeding diets with increasing levels of black soldier fly larvae meal (BSFLM) on the growth performance parameters of broilers.

	Diet				*p*		
Parameter	Control $n = 22$	$BSFLM_{low}$ $n = 17$	$BSFLM_{high}$ $n = 24$	SEM	Model	Linear	Quadratic
Final body weight, g	2234.00	2204.00	2166.00	61.30	.64	.39	.89
Average daily gain, g/d	57.10	56.60	55.40	1.99	.63	.39	.77
Average feed intake, g/d	97.20	94.30	94.60	1.54	.34	.35	.85
Feed conversion ratio, g/g	1.76	1.76	1.77	0.04	.95	.83	.82

Note: $BSFLM_{low}$ and $BSFLM_{high}$: $5.7 \pm 2.3\%$ and $15.5 \pm 6.0\%$ BSFLM in the diet; SEM: standard error of the mean.

Lower diet CP digestibility due to chitin consumption, a polysaccharide composed of a long-chain polymer of N-acetyl-glucosamine that is the major component in insect exoskeleton, has been blamed as the responsible of lowering performance results when BSFLM is included at high levels in broiler diets (Dabbou et al. 2018). Broilers show activities of mucosal chitinase and N-acetyl-β-D-glucosaminidase in the proventriculus (Koh and Iwamae 2013), but it has been found that chitin from crustaceans negatively affect CP digestibility and nitrogen retention at levels above 5 and 2.8% in the diet, respectively, while reducing overall ADG (Hossain and Blair 2007; Khempaka et al. 2011). Hartinger et al. (2021) and Kim et al. (2022) found significantly lower CP digestibility in coincidence with lower FBW and ADG when fed diets containing 8.9 and 13.8% BSFLM on average, respectively, as compared with their controls and lower BSFLM diets. However, BSFLM levels of 22.3% on average and up to 10% in the diets of Brede et al. (2018) and Yaseen Kareem et al. (2018), respectively, did not elicit negative responses of diet CP digestibility, FBW and ADG. Furthermore, Murawska et al. (2021) observed lower FI and reduced FBW and ADG as compared to a control group in treatments containing 17.3, 25.8 and 34.8% BSFLM on average. Assuming a chitin content of 5.65% in BSFLM as fed (Smets et al. 2021), the calculated dietary percentages of chitin in the highest BSFLM treatments of Hartinger et al. (2021), Kim et al. (2022) and Murawska et al. (2021) were ∼0.50, 0.78 and 1.97%, respectively. Those values are well below the thresholds found by Hossain and Blair (2007) and Khempaka et al. (2011), which would not support the chitin content in the BSFLM diets as the only cause of the poorer results in those studies.

Changes in intestinal morphology have been also related to poorer performance of broilers at high dietary levels of BSFLM, yet results are contradictory and inconclusive. Dabbou et al. (2018) in their 15% BSFLM treatment and Velten et al. (2018) in their basic BSFLM treatment (13.5% BSFLM on average) found shorter villi along the small intestine and in jejunum, respectively; hence a lower absorption of nutrients could justify the observed lower FBW and ADG in those treatments. However, the reduced FBW and ADG at the highest dietary level of BSFLM (8.9%) in the work of Hartinger et al. (2021) was not accompanied by morphological changes at jejunum or ileum. Furthermore, Uushona (2015) and Schoor (2017) did find neither reduced performance nor alterations of intestinal morphology after feeding diets with up to 15% BSFLM.

Finally, inaccurate assessment of AMEn value of BSFLM in the experimental diets should not be ruled out as a cause of the negative effects on growth performance observed in some studies. Only 10 out of the 18 studies included in the meta-analysis reported full or partial chemical composition of the BSFLM assayed and none of them stated how its AMEn was assessed, except for Dabbou et al. (2018). Merely assuming a published value of the AMEn in BSFLM could lead to a high error in feed formulation because of the great variability of its chemical composition, due not only to the rearing substrate of the larvae (Tschirner and Simon 2015; Spranghers et al. 2017; Meneguz et al. 2018) but also to their processing after harvesting (Uushona 2015; Schiavone et al. 2017; Cockcroft 2018).

Developed models for the prediction of the metabolisable energy value of BSFLM

Published research on metabolisable energy value of BSFLM is scarce (De Marco et al. 2015; Schiavone et al. 2017; Mwaniki and Kiarie 2019; Matin et al. 2021). Therefore, in order to develop a prediction model, we built a synthetic dataset from the data of the eight observations in the original dataset compiled from published studies. Variability of CP and EE contents in the observations of the synthetic dataset (Table 3) was large enough as compared to published data on BSFLM chemical composition (Tschirner and Simon 2015; Spranghers et al. 2017; Smets et al. 2021). Moreover, within the studies included in the meta-analysis of the present work, CP and EE contents ranged 36.3–71.2% and 6.3–42.4% dry matter basis, respectively. The best multiple regression model included GE and EE as predictors in equation (1), but the latter accounted for more than 98% of the total variance explained by the model. In the ANN analysis, models with one, two or three hidden units were trained up to 10 times each. A model with one hidden layer and two hidden units minimised the sum of squares error and the relative error in the testing dataset and was retained. In this model, the relative importance of EE, GE and CP as predictors were 74.2, 19.3 and 6.5%, respectively.

AMEn $= 4.08\ (\pm\ 0.330) + 0.295\ (\pm\ 0.0158) \times$ GE $+$ $0.186\ (\pm\ 0.0021) \times$ EE; where AMEn and GE are MJ/kg dry matter and EE is % dry matter. Values in parenthesis are the standard errors of the respective means (1)

Both models obtained in the present work showed high precision and accuracy, were unbiased and

Table 6. Performance of the models developed for prediction of apparent metabolisable energy corrected to zero nitrogen balance (AMEn).

	Training dataset		Evaluation dataset	
Statistics	Regression	Neural network	Regression	Neural network
R^2	0.858	0.856	0.859	0.858
RMSEP, MJ/kg dry matter	0.731	0.737	0.726	0.729
RMSEP, % mean	5.227	5.271	5.216	5.241
RSR, % standard deviation	19.410	19.580	19.480	19.580
CCC	0.924	0.920	0.924	0.921
Central tendency error, %	0.000	0.010	0.200	0.360
Linear error, %	0.000	0.370	0.000	0.350
Random error, %	100.000	99.620	99.800	99.290

Note: R^2: coefficient of determination; RMSEP: root mean square error of prediction; RSR: standardised RMSEP; CCC: concordance correlation coefficient.

performed almost identically in the training and evaluation datasets (Table 6). They were equally robust and might be able to generalise to new data with reasonable precision and accuracy. Again, ANN models are expected to perform better than regression models but not always. In the present work, the ANN model currently did not improve the prediction compared to the regression model, which might indicate that no interactions or non-linear terms needed to be modelled (Özesmi et al. 2006). Our results contrast with past studies that found better precision and accuracy of ANN models as compared to multiple regression models for prediction of metabolisable energy in poultry feedstuffs (Perai et al. 2010; Sedghi et al. 2011; Lotfi et al. 2020). Number of observations, criteria for selection of variables in the multiple regression analysis or parametrization of the ANN model might explain such differences (Özesmi et al. 2006; Kim 2008).

Conclusions

Based on the results of the present study, feeding broiler chickens with diets containing 15% BSFLM is not expected to have negative effects on growth performance, provided that AMEn content and amino acid supply of such diets do not differ from those based on conventional protein sources. Until more experimental results on metabolisable energy of BSFLM become available to develop better prediction models, the regression model obtained in the present work could be useful for the estimation of its AMEn value when formulation broiler diets.

Ethical approval

Not applicable.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [A. L. M. M.], upon reasonable request.

References

Abd El-Hack ME, Shafi ME, Alghamdi WY, Abdelnour SA, Shehata AM, Noreldin AE, Ashour EA, Swelum AA, Al-Sagan AA, Alkhateeb M, et al. 2020. Black soldier fly (*Hermetia illucens*) meal as a promising feed ingredient for poultry: a comprehensive review. Agriculture. 10(8):339.

Affedzie-Obresi S, Adu-Aboagye G, Nkegbe EK, Asuming-Bediako N, Ansah KO, Mensah-Bonsu A, Sarpong DB, Amegashie DPK, Kwadzo GTM, Wallace PA, et al. 2020. Black soldier fly (*Hermetia illucens*) larvae meal as alternative protein in broiler production in Ghana. Ghana J Agric Sci. 55(1):1–13.

Alvarenga RR, Rodrigues PB, Zangeronimo MG, Freitas RTF, Lima RR, Bertechini AG, Fassani EJ. 2011. Energetic values of feedstuffs for broilers determined with in vivo assays and prediction equations. Anim Feed Sci Technol. 168(3-4):257–266.

Attivi K, Agboka K, Mlaga GK, Oke O, Teteh A, Onagbesan O, Tona K. 2020. Effect of black soldier fly (*Hermetia illucens*) maggots meal as a substitute for fish meal on growth performance, biochemical parameters and digestibility of broiler chickens. Int J Poult Sci. 19(2):75–80.

Baracho MS, Nääs I, Lima NDS, Cordeiro AFS, Moura DJ. 2019. Factors affecting broiler production: a meta-analysis. Braz J Poult Sci. 21(3):1–10.

Brede A, Wecke C, Liebert F. 2018. Does the optimal dietary methionine to cysteine ratio in diets for growing chickens respond to high inclusion rates of insect meal from *Hermetia illucens*? Animals. 8(11):187.

Carré B, Prevotel B, Leclercq B. 1984. Cell wall content as a predictor of metabolisable energy value of poultry feedingstuffs. Br Poult Sci. 25(4):561–572.

Cockcroft B. 2018. The nutritional potential of black soldier fly (*Hermetia illucens*) larvae as a protein source for broiler chicken diets [MSc]. Stellenbosch: Stellenbosch University.

Dabbou S, Gai F, Biasato I, Capucchio MT, Biasibetti E, Dezzutto D, Meneguz M, Plachà I, Gasco L, Schiavone A. 2018. Black soldier fly defatted meal as a dietary protein source for broiler chickens: effects on growth performance, blood traits, gut morphology and histological features. J Anim Sci Biotechnol. 9(1):1–10.

De Marco M, Martínez S, Hernandez F, Madrid J, Gai F, Rotolo L, Belforti M, Bergero D, Katz H, Dabbou S, et al. 2015. Nutritional value of two insect larval meals (*Tenebrio molitor* and *Hermetia illucens*) for broiler chickens: apparent nutrient digestibility, apparent ileal amino acid digestibility and apparent metabolizable energy. Anim Feed Sci Technol. 209:211–218.

Dörper A, Veldkamp T, Dicke M. 2021. Use of black soldier fly and house fly in feed to promote sustainable poultry production. J Insects Food Feed. 7(5):761–780.

Escobar-Bahamondes P, Oba M, Beauchemin KA. 2017. Universally applicable methane prediction equations for beef cattle fed high- or low-forage diets. Can J Anim Sci. 97(1):83–94.

Fuso A, Barbi S, Macavei LI, Luparelli AV, Maistrello L, Montorsi M, Sforza S, Caligiani A. 2021. Effect of the rearing substrate on total protein and amino acid composition in black soldier fly. Foods. 10(8):1773.

Hartinger K, Greinix J, Thaler N, Ebbing MA, Yacoubi N, Schedle K, Gierus M. 2021. Effect of graded substitution of soybean meal by *Hermetia illucens* larvae meal on animal performance, apparent ileal digestibility, gut histology and microbial metabolites of broilers. Animals. 11(6):1628.

Heaton J. 2008. Introduction to neural networks with Java. McKinnis M, editor. Chesterfield (MO): Heaton Research, Inc.

Hossain SM, Blair R. 2007. Chitin utilisation by broilers and its effect on body composition and blood metabolites. Br Poult Sci. 48(1):33–38.

Khan SH. 2018. Recent advances in role of insects as alternative protein source in poultry nutrition. J Appl Anim Res. 46(1):1144–1157.

Khempaka S, Chitsatchapong C, Molee W. 2011. Effect of chitin and protein constituents in shrimp head meal on growth performance, nutrient digestibility, intestinal microbial populations, volatile fatty acids, and ammonia production in broilers. J Appl Poult Res. 20(1):1–11.

Kim B, Kim HR, Baek YC, Ryu CH, Sy J, Jeong JY, Kim M, Jung H, Park SH. 2022. Evaluation of microwave-dried black soldier fly (*Hermetia illucens*) larvae meal as a dietary protein source in broiler chicken diets. J Insects Food Feed. 8(9): 977–987.

Kim YS. 2008. Comparison of the decision tree, artificial neural network, and linear regression methods based on the number and types of independent variables and sample size. Expert Syst Appl. 34(2):1227–1234.

Koh K, Iwamae S. 2013. Chitinolytic activity of mucosal enzymes in the different parts of the digestive tract in broilers. J Poult Sci. 50(1):65–67.

Lin LIK. 1989. A concordance correlation coefficient to evaluate reproducibility. Biometrics. 45(1):255–268.

Lotfi M, Shariatmadari F, Ahmadi H, Sharafi M. 2020. Estimation and prediction of metabolizable energy contents of wheat bran for poultry. J Agric Sci Technol. 22(4):965–976.

Mariano FCMQ, Paixão CA, Lima RR, Alvarenga RR, Rodrigues PB, Nascimento GAJ. 2013. Prediction of the energy values of feedstuffs for broilers using meta-analysis and neural networks. Animal. 7(9):1440–1445.

Matin N, Utterback P, Parsons CM. 2021. True metabolizable energy and amino acid digestibility in black soldier fly larvae meals, cricket meal, and mealworms using a precision-fed rooster assay. Poult Sci. 100(7):101146.

Meneguz M, Schiavone A, Gai F, Dama A, Lussiana C, Renna M, Gasco L. 2018. Effect of rearing substrate on growth performance, waste reduction efficiency and chemical composition of black soldier fly (*Hermetia illucens*) larvae. J Sci Food Agric. 98(15):5776–5784.

Møller MF. 1993. A scaled conjugate gradient algorithm for fast supervised learning. Neural Netw. 6(4):525–533.

Mottet A, Tempio G. 2017. Global poultry production: current state and future outlook and challenges. World Poult Sci J. 73(2):245–256.

Moula N, Detilleux J. 2019. A meta-analysis of the effects of insects in feed on poultry growth performances. Animals. 9(5):201.

Murawska D, Daszkiewicz T, Sobotka W, Gesek M, Witkowska D, Matusevičius P, Bakuła T. 2021. Partial and total replacement of soybean meal with full-fat black soldier fly (*Hermetia illucens* L.) larvae meal in broiler chicken diets: impact on growth performance, carcass quality and meat quality. Animals. 11(9):2715.

Mwaniki ZN, Kiarie E. 2019. Standardized ileal digestible amino acids and apparent metabolizable energy content in defatted black soldier fly larvae meal fed to broiler chickens. Can J Anim Sci. 99(2):211–217.

Neumann C, Velten S, Liebert F, Neumann C, Velten S, Liebert F. 2018. The graded inclusion of algae (*Spirulina platensis*) or insect (*Hermetia illucens*) meal as a soybean meal substitute in meat type chicken diets impacts on growth, nutrient deposition and dietary protein quality depending on the extent of amino acid supplementation. Open J Anim Sci. 8(2):163–183.

Oluokun JA. 2010. Upgrading the nutritive value of full-fat soyabeans meal for broiler production with either fishmeal or black soldier fly larvae meal (*Hermetia illucens*). Niger J Anim Sci. 3(2):51–61.

Onsongo VO, Osuga IM, Gachuiri CK, Wachira AM, Miano DM, Tanga CM, Ekesi S, Nakimbugwe D, Fiaboe KKM. 2018. Insects for income generation through animal feed: effect of dietary replacement of soybean and fish meal with black soldier fly meal on broiler growth and economic performance. J Econ Entomol. 111(4):1966–1973.

Opoku O, Atuahene CC, Adjei MB, Quaye B, Adu MA. 2018. Black soldier fly (*Hermetia illucens*) larvae meal (BSFLM) as alternative dietary protein source for broiler chickens; effects on growth performance, carcass and haematological parameters. Ghana J Anim Sci. 9(1):25–31.

Özesmi SL, Tan CO, Özesmi U. 2006. Methodological issues in building, training, and testing artificial neural networks in ecological applications. Ecol Modell. 195(1-2):83–93.

Perai AH, Moghaddam HN, Asadpour S, Bahrampour J, Mansoori G. 2010. A comparison of artificial neural networks with other statistical approaches for the prediction of true metabolizable energy of meat and bone meal. Poult Sci. 89(7):1562–1568.

Sauvant D, Letourneau-Montminy MP, Schmidely P, Boval M, Loncke C, Daniel JB. 2020. Review: use and misuse of meta-analysis in animal science. Animal. 14(S2):s207–s222.

Sauvant D, Perez JM, Tran G. 2004. Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses and fish. Wageningen: Academic Publishers.

Schiavone A, D, Marco M, Martínez S, Dabbou S, Renna M, Madrid J, Hernandez F, Rotolo L, Costa P, Gai F. 2017. Nutritional value of a partially defatted and a highly defatted black soldier fly larvae (*Hermetia illucens* L.) meal for broiler chickens: apparent nutrient digestibility, apparent metabolizable energy and apparent ileal amino acid digestibility. J Anim Sci Biotechnol. 8(1):1–9.

Schoor AV. 2017. The assessment of black soldier fly (*Hermetia illucens*) pre-pupae, grown on human faecal waste, as a protein source in broiler and layer diets [MSc]. Stellenbosch: Stellenbosch University.

Sedghi M, Ebadi MR, Golian A, Ahmadi H. 2011. Estimation and modeling true metabolizable energy of sorghum grain for poultry. Poult Sci. 90(5):1138–1143.

Smets R, Claes J, Van Der Borght M. 2021. On the nitrogen content and a robust nitrogen-to-protein conversion factor of black soldier fly larvae (*Hermetia illucens*). Anal Bioanal Chem. 413(25):6365–6377.

Spranghers T, Ottoboni M, Klootwijk C, Ovyn A, Deboosere S, D, Meulenaer B, Michiels J, Eeckhout M, D, Clercq P, De Smet S. 2017. Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. J Sci Food Agric. 97(8):2594–2600.

St-Pierre NR. 2001. Invited review: integrating quantitative findings from multiple studies using mixed model methodology. J Dairy Sci. 84(4):741–755.

Sverguzova SV, Shaikhiev IH, Sapronova ZA, Fomina EV, Makridina YL. 2021. Use of fly larvae *Hermetia illucens* in poultry feeding: a review paper. J Water Land Dev. 49(IV-VI):95–103.

Tallentire CW, Mackenzie SG, Kyriazakis I. 2017. Environmental impact trade-offs in diet formulation for broiler production systems in the UK and USA. Agric Syst. 154:145–156.

Tedeschi LO. 2006. Assessment of the adequacy of mathematical models. Agric Syst. 89(2-3):225–247.

Tschirner M, Simon A. 2015. Influence of different growing substrates and processing on the nutrient composition of black soldier fly larvae destined for animal feed. J Insects Food Feed. 1(4):249–259.

Uushona T. 2015. Black soldier fly (*Hermetia illucens*) prepupae as a protein source for broiler production [MSc]. Stellenbosch: Stellenbosch University.

Van der Heide ME, Nørgaard JV, Engberg RM. 2021. Performance, nutrient digestibility and selected gut health parameters of broilers fed with black soldier fly, lesser mealworm and yellow mealworm. J Insects Food Feed. 7(6):1011–1022.

Van Emmenes L. 2021. Exploring the potential health benefits from *Hermetia illucens* and *Chrysomya chloropyga* larvae meal in poultry diets [PhD]. Stellenbosch: Stellenbosch University.

Van PhI CP, Walraven M, Bézagu M, Lefranc M, Ray C. 2020. Industrial symbiosis in insect production—a sustainable eco-efficient and circular business model. Sustainability. 12(24):10333.

Vauterin A, Steiner B, Sillman J, Kahiluoto H. 2021. The potential of insect protein to reduce food-based carbon footprints in Europe: the case of broiler meat production. J Clean Prod. 320:128799–128799.

Velten S, Neumann C, Bleyer M, Gruber-Dujardin E, Hanuszewska M, Przybylska-Gornowicz B, Liebert F. 2018. Effects of 50 percent substitution of soybean meal by alternative proteins from *Hermetia illucens* or *Spirulina platensis* in meat-type chicken diets with graded amino acid supply. Open J Anim Sci. 08(02):119–136.

Wang Y-S, Shelomi M. 2017. Review of black soldier fly (*Hermetia illucens*) as animal feed and human food. Foods. 6(10):91.

Wolynetz MS, Sibbald IR. 1984. Relationships between apparent and true metabolizable energy and the effects of a nitrogen correction. Poult Sci. 63(7):1386–1399.

Yaseen Kareem K, Abdulla N, Ling Foo H, Shazali N. 2018. Effect of feeding larvae meal in the diets on growth performance, nutrient digestibility and meat quality in broiler chicken. Indian J Anim Res. 88(10):84–89.