Research Article

Effect of Dietary Mealworm Meal Inclusion as a Replacement for Soybean Meal on Growth, Physiological, and Economic Efficiency of Broiler Chickens

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Abstract | The current study was conducted to explore the possible impact of soybean replacement with various levels of mealworm meal (MWM), *Tenebrio molitor*, on growth performance, carcass traits, meat quality, physiological status, and economic efficiency of broiler chickens. The study included 360 unsexed Cobb500™ commercial broiler chicks aged 1 day and weighing 46±1.5 g. Starting from the 22nd to the 42nd d of age, the chicks were randomly distributed according to the dietary inclusion levels of MWM into six treatment groups (6 replicate pens per group × 10 chicks per replicate, considering the equal ratio of males to females in each replicate). The first group of birds was fed a control finisher diet containing soybean-corn meal (0% MWM), while the remaining five groups of birds were provided with a finisher diet in which the soybean meal was partially replaced with 2%, 4%, 6%, 8%, and 10% MWM, respectively. Data were analyzed using the one-way analysis of variance (ANOVA) with a polynomial test to explore the linear and quadratic effects of increasing the MWM levels into the broiler diets. The results of this study showed a linear increase ($p < 0.05$) in the final body weight, body weight gain, carcass weight, dressing, and meat yellowness (b*) of broilers as the dietary MWM level increased. In addition, linear and quadratic increasing yields of liver, abdominal fats, and intestines were recorded with the increased levels of MWM. The carcass breast yield and the water retention capacity and the shear force of the broiler meat were linearly and quadratically ($p < 0.05$) increased, while the thawing and cooking loss of meat were decreased ($p < 0.05$) in response to the increase in the dietary MWM levels, up to 6%. Furthermore, some physiological aspects of the broilers, such as total protein, albumin, globulin, triiodothyronine hormone, triglycerides, and cholesterol profile concentrations in the serum were significantly ($p < 0.05$) improved by increasing the level of MWM into broiler diets up to 6%. In contrast, some traits of carcass composition and meat quality as well as physiological parameters deteriorated when adding higher levels of the MWM (8-10%) to the diets, compared to the control. Economically, there was a linear and quadratic ($p < 0.05$) decrease in the protein cost of the diet and a linear increase in birds' total revenue and profit margin in response to increasing MWM levels in the broiler diet. However, MWM linearly ($p < 0.05$) decreased the cost-benefit-ratio (CBR) and the return-on-investment outcomes (RoI) due to the restrictive production and the high prices of MWM in the global market. In conclusion, the dietary inclusion of MWM as a replacement of the soybean meal has a beneficial effect on the growth performance, carcass and meat characteristics, and physiological aspects of broiler chickens provided that it is used within the recommended levels, i.e., not exceeding 6% in the broiler diets. However, the economic feasibility of MWM inclusion into broiler diets remains at low CBR and RoI rates at the current time because of the restrictive marketing and the excessive cost of MWM production.

Keywords | Mealworm meal, Broiler chickens, Growth, Carcass traits, Meat quality, Physiological aspects, Economic efficiency

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INTRODUCTION

Poultry meat is an essential product for supplying people and communities with their animal-protein demands, and it is predicted that the global consumption of poultry meat will double in the coming 30 years (Kleyn and Ciacciariello, 2021). However, the intensive production of poultry meat would encounter another challenge, the prohibitive cost, if it continues to rely on expensive conventional ingredients in poultry diets, especially the corn and soybean meals that represent more than 60% of protein and energy requirements in poultry feed (Ahiwe et al., 2018). Thus, it is a sustainable option to seek efficient and inexpensive alternative sources of providing protein and energy in the poultry feed industry (van Huis, 2013). In this context, insect meals have been successfully inserted in poultry feeds due to their high nutritional value of proteins, polyunsaturated fatty acids, dietary fibers, and a variety of micronutrients in comparison with conventional feedstuffs (Al-Qazzaz and Ismail, 2016).

Mealworms are the worm-like larvae stage of the darkling beetle which belongs to the species of *Tenebrio molitor* within the order Coleoptera. They live in warm, dark, and damp places and can be raised on various types of fresh or decaying organic matter and foods (Elahi et al., 2022). It can be observed that mealworms have high protein (45-65%) and fat (25-45%) contents in comparison with the other species within the same order which have a wide range of protein (8.8-71.1%) and fat (0.7-69.8%) contents (Rumpold and Schlüter, 2013). They also have a balanced-profile of amino acids, minerals and vitamins (Liu et al., 2020; Rumpold and Schlüter, 2013). In addition, mealworms have other potential benefits, including low-gas release (Oonincx and de Boer, 2012), low-water footmark (Miglietta et al., 2015), limited-space occupation, and available mass production technology (Cortes Ortiz et al., 2016).

The MWM has been investigated as a feed additive or as a replacement of the conventional protein sources in broiler diets. Positive effects were evidenced for supplementing low levels of MWM (0.3-5.0 %) to broiler diets on the growth rate, feed conversion, carcass traits, intestinal microbiota and haemato-chemical profile (Benzertiha et al., 2019, 2020; Elahi et al., 2020; Sedgh-Gooya et al., 2021a). In contrast, Biasato et al. (2018) found that MWM addition to broiler diets at 5-15 % improved the body weight and feed intake, while it negatively affected the feed efficiency and intestinal morphology and did not affect the carcass traits' haemato-chemical parameters. Furthermore, corn gluten meal in broiler diets was successfully replaced by 7.5% MWM without any effect on broiler performance (Biasato et al., 2016). Soybean meal replacement by 29.65% MWM improved feed conversion, intestinal digestibility, and spleen weight (Bovera et al., 2016). It was also reported that MWM inclusion into broiler diets regulated the meat quality and contents of amino acids and fatty acids (Ballitoc and Sun, 2013; de Marco et al., 2015; Kim et al., 2014).

Although considerable studies have been reported on the feeding value of the MWM in broiler chickens, there is still a need to explore the appropriate doses, the effectiveness, the functional mechanisms, and the feasibility of its application. There is a scarcity of research that investigates the use of MWM as a replacement of the traditional protein sources in the nourishment of broiler chickens. Therefore, the present study aimed to evaluate the possible impact of soybean replacement by incremented levels of MWM on growth performance, carcass composition, meat quality, physiological profile, and profitability of broiler production.

MATERIALS AND METHODS

Birds and treatments

The study included 360 unsexed Cobb500™ commercial broiler chicks aged 1 day and weighing 46±1.5 g. The chicks were raised on a 5 cm-deep wood-shaving litter in floor pens that measured 90 × 90 × 38 cm (10 chicks per pen, considering the equal ratio of males to females). The chicks were kept under standard environmental conditions and provided with a corn–soybean-basal-diet mash until they reached 21 d of age according to the Cobb-500 broiler management guidelines. Feed and water were provided *ad libitum* to all birds throughout the study. Starting on the 22nd d of age, the chicks were distributed into six treatment groups (6 replicate pens each) according to the dietary inclusion levels of MWM. Throughout the consecutive 3 weeks, the first group of birds was fed on a finisher diet of soybean-corn meal and served as a control (0% MWM). The remaining five groups of birds were fed on a finisher diet in which the soybean-corn meal was partially replaced by 2%, 4%, 6%, 8%, and 10% MWM, respectively. The experimental diets were composed to be isonitrogenous, isocaloric, and as mash, following the nutritional recommendations of the Cobb-500 broilers, while the nutritional values of the formulated diets were determined using the international methods of the official analysis chemists (AOAC, 2005) (Table 1).

Table 1: Ingredients and nutritional values of the experimental diets included with mealworm meal.

Ingredients (g/kg as fed)	Mealworm meal groups					
	0%	2%	4%	6%	8%	10%
Mealworm meal	0.0	20.0	40.0	60.0	80.0	100.0
Soybean meal	300.0	274.0	251.0	226.0	204.0	182.0
Yellow corn	620.0	626.0	630.0	631.0	633.0	635.0
Vegetable oil	40.0	38.0	35.0	35.0	35.0	32.0
Dicalcium phosphate	15	16	17	18	18	20
Limestone	10	10	10	10	10	10
Salt (NaCl)	4.5	4.5	5.5	5.5	5.5	5.5
Premix [1]	5.5	5.5	5.5	5.5	5.5	5.5
Methionine	2.5	2.5	2.5	2.5	2.5	2.5
Lysine	1.5	1.5	1.5	2.5	2.5	2.5
Threonine	0.5	1.5	1.5	2.5	2.5	2.5
Tryptophan	0.5	0.5	0.5	1.5	1.5	2.5
Calculated nutrients						
Metabolizable energy (MJ/kg)	13.8	13.8	13.8	13.8	13.8	13.8
Crude protein (g/kg)	182.1	182.1	182.1	182.1	182.1	182.1
Calcium (g/kg)	8.3	8.3	8.3	8.3	8.3	8.3
None phytase phosphorus, NPP (g/kg)	4.7	4.7	4.7	4.7	4.7	4.7
Determined nutrients						
Crude protein (g/kg)	178.5	179.3	181.3	182.2	184.4	186.7
Crude fat (g/kg)	62.8	65.7	67.6	72.3	77.0	78.8
Crude fiber (g/kg)	32.8	32.9	33.3	33.4	33.7	34.1
Calcium (g/kg)	7.9	8.1	8.3	8.4	8.4	8.8
NPP (g/kg)	4.1	4.5	4.8	5.2	5.4	5.9

[1]Premix (contents per kg of the diet): 10 KIU vit A, 5 KIU vit D_3, 65 IU vit E, 3 mg vit K, 3 mg vit B_1, 9 mg vit B_2, 4 mg vit B_6, 0.02 mg vit B_{12}, 0.20 mg biotin, 20 mg niacin, 15 mg pantothenic acid, 2 mg folic acid, 500 mg choline chloride; 100 mg Mn, 100 mg Zn, 40 mg Fe, 15 mg Cu, 1 mg Iodine, and 0.35 mg Se.

The whole-dried MWM was obtained from a commercial supplier, (Beta Hatch, Inc., Cashmere, Washington, United States) and was finely ground with a blender. The MWM powder was manually mixed with a part of the diet, then added to the rest of the diet to reach the desired MWM concentration in the experimental diets. These steps were repeated every feeding time to assure the complete consumption of the MWM by the birds. The chemical analyses of the MWM and soybean meal (SBM) were performed using the international methods of AOAC (2005), and the results are demonstrated in Table 2.

Table 2: The chemical analysis of mealworm and soybean meals (per 100 g).

Item	Mealworm meal	Soybean meal*
Approximate analysis		
Dry matter (g)	95	90
Crude protein (g)	59.2	44
Crude fat (g)	24	0.5
Crude fiber (g)	9.3	7.0
Gross energy (MJ)	2.8	1.7
Calcium (g)	0.06	0.25
Phosphorus (g)	1.10	0.20
Amino acids		
Isoleucine (g)	2.92	2.5
Leucine (g)	3.45	3.5
Valine (g)	0.83	2.40
Lysine (g)	2.97	2.70
Methionine (g)	1.80	0.65
Tyrosine (g)	3.28	1.70
Arginine (g)	4.27	3.40
Glycine (g)	3.17	1.09
Fatty acids (g)		
Linoleic acid, C18:2 (g)	5.52	0.30
αLinolenic acid, C18:3 (g)	0.51	0.06
Oleic acid, C18:1 (g)	9.34	0.14
Palmitic acid, C16:0 (g)	4.41	0.21

*According to the pamphlet of the supplier (not analyzed).

Productive performance

The birds were weighed from each replicate on the 22nd and 42nd days of age to record the initial and final body weight. The body weight gain was then calculated per replicate. Feed intake was determined every day for each replicate in the treatment groups, (the total amount introduced – feed remains). The feed conversion ratio (FCR) was then determined per replicate based on the feed intake consumed per unit of body weight gain.

Carcass composition

Two birds per replicate were individually weighed and slaughtered at the end of the trial, (12 birds per treatment group). The birds were heated in a 54°C-water for 2 min, then plucked, and the heads, necks, and feet were removed. The internal organs, intestines, and abdominal fats were immediately separated from the hot carcass. The dressing percentage was obtained by calculating the clean carcass weight as a percentage of the live weight. The breast, thigh, spleen, liver, gizzard, heart, abdominal fat, and intestine were weighed separately and calculated as a percentage of the carcass weight using an electronic sensitive balance of 0.1 g (Atrontec Electronic Tech Co., Ltd., Jiangsu, China).

Meat quality

Twelve samples of the breast muscles per replicate in each treatment group were used to assess the meat quality parameters according to previous works (Moustafa et al., 2021; Sabikun et al., 2019). The pH value at 1 cm depth of the meat was measured 24 h postmortem using a pH meter, (Hanna Instruments, Inc., Smithfield, RI, USA). Meat colors were determined 45 min postmortem using a colorimetric reader (Minolta CR-10, Konica Minolta, Tokyo, Japan). The results were presented following the CIELAB color system as L^*, a^*, and b^* which coordinate with the sample lightness, redness, and yellowness, respectively (Luo, 2015). To measure the thawing loss, the sample was dabbed with paper towels then weighed. The sample was put in a plastic bag and maintained in a chilling room at 4°C for 24 h, and then weighed again to obtain the drip loss percentage during the storage. After that, the bagged sample was cooked at 75°C for half an hour, then allowed to cool at room temperature. The cooking loss was obtained by calculating the weight loss after cooking as a percentage of the initial weight. In addition, a piece of the meat sample (3.0 g) placed in a Whatman filter-paper (grade 1, diam 110 mm) with two thin plastic films was compressed by a 2.5 kg load for 5 min. The water released from the meat was measured by the difference in weights of the filter paper with the plastic films before and after this application. The water-retention capacity of the sample was then calculated using the following equation: (100 water released/meat weight %). Finally, the shear force intensity was determined in the sample after cooking as previously mentioned by using a C-LM3 texture analyzer (Northeast Agricultural University, Harbin, China).

Physiological parameters

At 42 d of age, 12 blood samples per treatment were taken from the brachial vein and centrifuged (2000× g, 10 min, 4 °C) to separate the serum. The total protein (TP), albumin (ALB), globulin (GLB), creatinine (CRT), and uric acid (UA) concentrations, and the activities of aspartate transferase (AST) and alanine transferase (ALT) enzymes were determined by using an automated scanning spectrophotometer (CE1010, Cecil Instruments Limited, Cambridge, UK) and commercial colorimetric kits (BioDiagnostic, Giza, Egypt). The serum triiodothyronine (T_3) hormone was determined using chicken ELISA kits (MyBioSource, San Diego, CA, USA). The serum triglyceride (TG), total cholesterol (CH), and high-density lipoprotein cholesterol (HDL-CH) were assayed following the instructions of the commercial diagnostic kits, (Diamond Diagnostics Company, Cairo, Egypt), while the low-density lipoprotein cholesterol (LDL-CH) was detected using the formulae: (LDL = CH – HDL – TG/5).

Economic efficiency

The feed cost was the only factor considered in the analysis while the other cost factors, including labor, medication, water, electricity, housing, etc., were presumed to be the same for all the treatments. Feed costs were estimated based on the quantity of ingredients in each experimental diet and their prices during the time of the experiment. The benefits were considered as the revenue gained from selling the birds at the slaughter age (42 d). The cost benefit ratio (CBR) represents the ratio between the total revenue and the total cost of production. The return on investment (RoI) measures the gain/loss of the invested money in production. The CBR and RoI were considered in the current study to analyze the economic efficiency of the broilers (Onsongo et al., 2018).

Statistical analysis

Data were analyzed using the one-way analysis of variance (ANOVA) of the SPSS software package, (version 22.0; IBM corp., NY, USA, 2013). The variances in the data were homogeneous, as indicated by results with use of the Levene's test. A polynomial test was carried out to explore the linear and quadratic contrasts of increasing the MWM levels into the broiler diets on all the parameters of the productive performance, carcass composition, meat quality, physiological aspects, and economic efficiency. The experimental unit for the productive performance and the economic efficiency data was the pen, (n= 6), while the bird was considered as the experimental unit for the other parameters (n= 12). The statistical power was explored by G*Power software (Kiel University, Germany), resulting in 97% for this analysis. The level of statistical significance was set at $p < 0.05$.

RESULTS

Productive performance

Results of the productive performance as affected by the MWM inclusion into the broiler diets are shown in Table 3. The MWM diets did not affect the feed intake of the broilers. There was a linear increase ($p < 0.05$) in the final body weight and body weight gain, and a linear decrease in the feed conversion ratio associated with the increase in the MWM inclusion levels into the broiler diets. The maximum improvement in the broiler performance was obtained in the 10%-MWM group.

Table 3: Effect of dietary mealworm meal (MWM) inclusion on the productive performance of broiler chickens.

Parameters	Dietary MWM levels							P-value	
	0%	2%	4%	6%	8%	10%	SEM	Linear	Quadratic
Initial body weight (g)	1003.8	1002.0	1002.3	1005.8	1000.7	1003.2	13.05	0.961	0.997
Final body weight (g)	2858.3	2970.8	3011.7	3097.7	3163.3	3175.8	56.94	< 0.001	0.286
Body weight gain (g)	1854.5	1968.8	2009.3	2091.8	2162.7	2172.7	58.41	< 0.001	0.299
Feed intake (g/d)	160.8	159.2	161.7	163.3	162.5	160.5	5.45	0.758	0.674
Feed conversion ratio	1.82	1.70	1.70	1.64	1.58	1.55	0.046	< 0.001	0.402

Each mean represents the averaged data of 10 birds × 6 replicates per treatment group (n = 6). SEM: pooled standard error of means. Statistical significance was considered at p-value < 0.05.

Table 4: Effect of dietary mealworm meal (MWM) inclusion on the carcass composition of broiler chickens.

Parameters	Dietary MWM levels							P-value	
	0%	2%	4%	6%	8%	10%	SEM	Linear	Quadratic
Live weight, LW (g)	2873.4	2975.9	3027.1	3095.0	3179.0	3214.4	20.74	< 0.001	0.134
Carcass weight, CW (g)	2020.8	2163.3	2211.7	2287.5	2374.2	2400.8	31.86	< 0.001	0.043
Dressing (CW/LW %)	70.34	72.71	73.02	73.92	74.69	75.77	0.951	< 0.001	0.457
Breast (% CW)	34.04	34.50	34.81	35.67	33.65	31.77	0.705	0.003	< 0.001
Thigh (% CW)	20.46	19.67	20.33	19.86	20.58	20.14	0.485	0.827	0.529
Spleen (% CW)	0.19	0.18	0.19	0.19	0.18	0.17	0.006	0.002	0.043
Liver (% CW)	2.11	2.15	2.23	2.25	2.33	2.42	0.061	< 0.001	0.572
Gizzard (% CW)	3.10	2.94	3.01	3.12	3.08	3.01	0.072	0.791	0.994
Heart (% CW)	1.56	1.30	1.23	0.97	0.95	0.94	0.059	< 0.001	< 0.001
Fat (% CW)	2.00	2.04	2.03	2.11	2.24	2.40	0.067	< 0.001	0.008
Intestine (% CW)	6.56	6.17	6.89	7.98	8.50	8.99	0.301	< 0.001	0.070

Each mean represents 2 birds × 6 replicates per treatment group (n = 12). SEM: pooled standard error of means. Statistical significance was considered at p-value < 0.05.

Carcass composition

The effect of MWM inclusion into broiler diets on the carcass composition was presented in Table 4. There was a linear increase (p < 0.05) in the live weight, carcass weight, and dressing of broilers as the dietary MWM levels increased. A linear and quadratic increase (p < 0.05) in the breast yield was obtained as the dietary level of MWM increased to the amount of 6%, while higher levels of MWM (8-10%) decreased the breast yield, compared to the control group. In addition, linear and quadratic increasing yields of liver, abdominal fats, and intestines were recorded with increasing the MWM levels in the diet. In contrast, the heart yield was linearly and quadratically decreased (p < 0.05) as the MWM levels increased, while the spleen yield was also decreased when adding MWM at 10% into the broiler diets. The MWM diets did not affect the thigh or the gizzard yield of the broiler carcass.

Meet quality

The meat quality traits as affected by the MWM meal inclusion into broiler diets are summarized in Table 5. The meat pH, lightness (L^*), and redness (a^*) were not influenced by the MWM treatments, whereas the meat yellowness was linearly increased (p < 0.05) by increasing the MWM level inclusion to 10% into broiler diet. The thawing and cooking loss of meat were linearly and quadratically decreased (p < 0.05) as the dietary inclusion levels of the MWM increased to 6%. In contrast, a quadratic increase in the water retention capacity and a linear and quadratic increase in the shear force of broiler meat was obtained as a result of the increase in the dietary MWM levels up to 6% (p < 0.05). When adding higher levels of the MWM (8-10%) to the diets, the thawing and cooking loss increased again, while the water retention capacity and the shear force decreased.

Physiological traits

The effects of the dietary inclusion of the MWM on the broilers' physiological traits are summarized in Table 6. The TP and ALB concentrations in the serum were linearly and quadratically (p < 0.05) enhanced by increasing the MWM levels up to 8%, and the GLB concentration was enhanced by increasing the MWM up to 6%; however, they decreased again when higher levels of MWM were introduced. The T_3 hormone concentration was linearly increased (p < 0.05) with the increase of MWM levels, recording the maximum

T_3 concentration with 8% MWM. In contrast, increasing the MWM levels up to 6% quadratically reduced (p < 0.05)

Table 5: Effect of dietary mealworm meal (MWM) inclusion on the meat quality of broiler chickens.

Parameters	Dietary MWM levels							P-value	
	0%	2%	4%	6%	8%	10%	SEM	Linear	Quadratic
pH	5.97	5.88	5.94	5.98	5.93	6.04	0.157	0.527	0.602
Lightness (L^*)	51.41	51.34	50.48	51.54	52.34	51.81	1.493	0.493	0.655
Redness (a^*)	4.93	4.75	4.83	4.54	4.72	4.71	0.198	0.201	0.323
Yellowness (b^*)	4.99	5.15	5.47	5.73	6.03	6.06	0.157	< 0.001	0.464
Thawing loss (%)	3.88	3.34	3.27	2.69	2.92	2.96	0.132	< 0.001	< 0.001
Cooking loss (%)	19.62	18.52	17.71	16.98	17.09	17.42	0.367	< 0.001	< 0.001
Water retention capacity (%)	87.68	88.78	89.63	89.63	87.83	87.90	0.249	0.235	< 0.001
Shear force (kg)	2.13	2.14	2.23	3.18	2.98	2.64	0.112	< 0.001	< 0.001

Each mean represents 2 birds × 6 replicates per treatment group (n = 12). SEM: pooled standard error of means. Statistical significance was considered at p-value < 0.05.

Table 6: Effect of dietary mealworm meal (MWM) inclusion on the physiological traits of broiler chickens.

Parameters	Dietary MWM levels							P-value	
	0%	2%	4%	6%	8%	10%	SEM	Linear	Quadratic
TP (g/dL)	4.74	5.17	5.58	6.35	6.43	5.57	0.220	< 0.001	< 0.001
ALB (g/dL)	2.98	3.33	3.56	3.64	4.18	3.87	0.153	< 0.001	0.041
GLB (g/dL)	1.76	1.84	2.01	2.71	2.19	2.04	0.164	0.002	< 0.001
T_3 (μmol/mL)	5.60	5.86	6.30	8.26	8.57	8.23	0.404	< 0.001	0.186
ALT (U/mL)	13.31	12.16	12.05	10.17	12.97	14.06	0.753	0.339	< 0.001
AST (U/mL)	29.35	28.51	25.07	22.09	25.07	30.02	1.249	0.182	< 0.001
CRT (mg/dL)	0.28	0.27	0.26	0.25	0.26	0.29	0.010	0.581	< 0.001
UA (mg/dL)	5.66	5.48	5.18	4.92	5.14	5.02	0.112	< 0.001	0.002
TG (mg/dL)	182.44	181.83	180.38	179.13	176.37	173.31	1.652	< 0.001	0.106
CH (mg/dL)	129.57	128.75	128.62	127.90	123.54	120.71	1.536	< 0.001	0.009
LDL-CH (mg/dL)	98.89	94.08	93.31	90.81	86.48	86.29	2.735	< 0.001	0.619
HDL-CH (mg/dL)	44.02	48.30	51.42	53.44	55.84	56.48	1.257	< 0.001	0.012

Each mean represents 2 birds × 6 replicates per treatment group (n = 12). SEM: pooled standard error of means. Statistical significance was considered at p-value < 0.05. Parameters: TP, total protein; ALB, albumin; GLB, globulin; T3, triiodothyronine; ALT, alanine transferase; AST, aspartate transferase; CRT, creatinine; UA, uric acid; TG, triglycerides; CH, cholesterols; LDL-CH, low-density lipoprotein cholesterol; HDL-CH, high-density lipoprotein cholesterol.

Table 7: Effect of dietary mealworm meal (MWM) inclusion instead of soybean meal (SBM) on the economic performance of broiler chickens.

Parameters	Dietary MWM levels							P-value	
	0%	2%	4%	6%	8%	10%	SEM	Linear	Quadratic
SBM replacement (%)	0	8.7	16.3	24.7	32.0	39.3	-	-	-
SBM per unit MWM (%)	0	4.33	4.08	4.11	4.00	3.93	-	-	-
Total feed intake (g/bird)	3377.5	3342.5	3395.0	3430.0	3412.5	3370.5	114.37	0.758	0.674
SBM cost (US$/bird)	1.47	1.33	1.24	1.12	1.01	0.89	0.042	< 0.001	0.937
MWM cost (US$/bird)	0.00	0.19	0.39	0.59	0.78	0.96	0.016	< 0.001	0.577
Protein cost in feed (%)	61.27	59.23	58.00	56.61	55.84	55.17	0.000	< 0.001	< 0.001
Total feed cost (TFC)	2.40	2.56	2.80	3.02	3.20	3.35	0.095	< 0.001	0.647
Live weight at slaughter (g)	2858.3	2970.8	3011.7	3097.7	3163.3	3175.8	56.94	< 0.001	0.286
Total revenue (TR)	19.01	19.76	20.03	20.60	21.04	21.12	0.379	< 0.001	0.286
Profit margin (PM)	16.61	17.19	17.23	17.58	17.84	17.77	0.336	< 0.001	0.282
CBR	7.95	7.72	7.17	6.83	6.60	6.30	0.194	< 0.001	0.465
RoI	694.81	671.54	617.09	582.90	559.59	530.04	19.441	< 0.001	0.465

Each mean represents the averaged data of 10 birds × 6 replicates per treatment group (n = 6). SEM: pooled standard error of means. Statistical significance was considered at p-value < 0.05. Cost (US$/kg) of the basal diet = 0.71, SBM = 1.45, and MWM = 2.85; broiler price = 6.65 US$/kg live weight; PM = TR – TFC; CBR = TR/TFC; RoI = PM/TFC%; currency exchange for 1 US$ = 3.76

SAR during the study.

the serum ALT, AST and CRT, while using higher levels of MWM elevated ALT, AST and CRT again. The UA was linearly and quadratically reduced ($p < 0.05$) by increasing the levels of the MWM, recording the minimum UA concentration with 6%. Furthermore, the serum TG and LDL-CH concentrations were linearly decreased, and the total CH was linearly and quadratically decreased ($p < 0.05$) as the dietary MWM levels increased. Moreover, a linear and quadratic ($p < 0.05$) increase in the HDL-CH concentration was recorded as the MWM levels increased in the broiler diet.

Economic efficiency

Data of Table 7 show the profitability of replacing SBM by MWM in the broilers' diet. Although MWM did not affect the total feed intake of the birds, the total feed cost was linearly ($p < 0.05$) increased with the increase of the MWM levels in the broiler diet, while the protein cost in the feed was linearly and quadratically decreased. In contrast, increasing the dietary MWM inclusion levels into the broiler diets linearly ($p < 0.05$) increased the live weight at the slaughter age (42 d), the total revenue, and the profit margin of birds. However, a linear ($p < 0.05$) decrease in the CBR and RoI outcomes was obtained as the MWM levels increased in the diets.

DISCUSSION

The variation in protein and fat contents of edible insects, including mealworms, may be originated from differences between species, developmental stages, feed sources, and measuring methods (Rumpold and Schlüter, 2013). The MWM used in the present study has a higher crude protein and fat than that presented in the soybean meal (SBM) (59.2% *vs.* 44% and 24% *vs.* 0.5%, respectively) (Table 2). To obtain isonitrogenous and isocaloric experimental diets for the broiler chickens, around 8.7, 16.3, 24.7, 32.0, and 39.3% of the soybean meal (SBM) as a common protein ingredient in the finisher diet was partially substituted with 2, 4, 6, 8, and 10% of the MWM, respectively (Table 1). Our target was to study the prospective effects of the MWM supplementation as an alternative source of protein in broiler diets on their growth, carcass composition, meat quality, physiological aspects, and profitability.

Increasing the MWM levels in the broiler diets improved their growth performance and feed conversion ratio; However, it did not affect the feed intake of broilers (Table 3). In addition, the dressing percentage was increased by the MWM treatment at all levels. Indeed, there is a wide variation in the results concluded from other studies on the addition of MWM to broiler diets that may be due to several factors, including broiler species, broiler age, MWM doses, MWM source, and type of replaced meal (Elahi et al., 2022; Tavares et al., 2022). Biasato et al. (2018) found that introducing 5-15% MWM as a replacement of SBM in the diets linearly increased the body weight and daily body weight gain in male Ross broilers. Ballitoc and Sun (2013) reported that broilers fed with 0.5-10% MWM showed higher weight gain, improved feed conversion ratio, and enhanced dressing and eviscerated weights of the carcass. The growth enhancement in the MWM-treated broilers may be attributed to the high-quality protein of the MWM as an animal protein type that supplies the broilers with substantial amounts of balanced amino acids when compared with plant protein types (Jin et al., 2016; Vieira et al., 2004). However, we observed that the increase in the carcass weight may refer to the increase in the liver, abdominal fat, and intestine weights against the breast and thigh muscles of the carcass (Table 4). The increase occurred in the liver and fat weight could be justified by the high amount of unsaturated fatty acids in the mealworm compared to the soybean meal (Finke, 2002). In accordance with the results reported by Marareni and Mnisi (2020), we observed that the meat color tended to yellowness as the dietary MWM levels increased. In the present study, the enhanced weight of breast muscle and the improvement of meat quality were obtained by using increased levels of MWM up to 6% in the broiler diet, while using higher levels of MWM (8-10%) into broiler diets decreased the breast muscle yield in the carcass and caused a reduction in the weight of other internal organs, such as the spleen which is considered as an indicator for strength of the avian immune system (Smith and Hunt, 2003) and the heart which supplies the oxygen required for metabolism (Tůmová and Chodová, 2018). Moreover, the high levels of MWM worsened some characteristics of the meat quality, such as water retention capacity and shear force, which are reflected in the meat tenderness, flavor and consumer acceptability (Mir et al., 2017). Some studies attributed the increased releasing of water from the breast muscle to the oxidative deterioration of fats and the degradation of proteins in the 8-10% MWM groups (Huff-Lonergan and Lonergan, 2005).

The results indicated that the physiological parameters were improved by the MWM inclusion into the broiler diets by up to 6% (Table 6). In agreement with previous studies (Sedgh-Gooya et al., 2021b), we found that the MWM treatment increased the concentrations of serum TP, ALB, and GLB. This increase in serum protein concentrations may be due to the higher contents of protein in the MWM compared to the SBM (Table 2). In addition, the MWM protein contained higher contents of some amino acids (1.80% versus 0.65% methionine, 3.28% versus 1.70% tyrosine, 4.27% versus 3.40% arginine, and 3.17% versus

1.09% glycine in MWM versus SBM, respectively), which in turn enhanced the body proteins (Mitchell et al., 2016). Furthermore, the doubled concentration of tyrosine in the MWM compared to the SBM, which is the precursor amino acid of thyroid hormones (Khaliq et al., 2015), could explain the linear increase of T_3 concentration in the MWM treatment in this study. In contrast, the observed effects of the MWM treatments on the AST and ALT activities and the CRT and UA levels in the current study assume a possible protective effect of the MWM on the hepatic and muscle cells (Giannini et al., 2005), and the renal function (Yadav et al., 2014). The hepatoprotective impacts of the MWM may also regulate the proteins and amino acids metabolism (Charlton, 1996), which in turn allow releasing of albumin from the liver to blood circulation (Chiu and Hua, 2016). This finding was evidenced by the linear increasing of serum ALB by increasing the MWM levels in the broiler diets. On the other hand, results displayed a significant decrease in the serum TG, CH, and LDL-CH with an increase in the HDL-CH in the broilers treated with increasing levels of MWM. These results agree with the results obtained by other researchers (Lee et al., 2022; Mahmoud et al., 2022) in Japanese quail supplemented with MWM. The hypolipidemic effect of the MWM was reported in a previous study in rats (Lee et al., 2022) whose authors suggested that the mealworm has good-quality fats with plentiful unsaturated fatty acids that positively affect the lipid profile in animals. These findings were supported by the chemical analysis of the MWM in the present study which presents high amounts of unsaturated fatty acids, such as α-linolenic, linoleic, and oleic acids, compared to those in the SBM (Table 2). Thus, the MWM could be also used as a valuable source of both protein and energy in the diets of chickens, (Kierończyk et al., 2018; de Marco et al., 2015).

The economic study showed that the protein cost in the feed was decreased, and the total revenue and profit margins were increased by the MWM treatment. However, the high cost of the MWM led to a significant increase in the total feed cost, and consequently, the CBR and RoI were significantly decreased after the replacement of the SBM by the MWM (Table 7). In other economic studies (Khan et al., 2016; Onsongo et al., 2018), it was reported that nutritional expenses can be reduced by utilizing insects in poultry diets. Regardless of the potential benefits of including the MWM in poultry nutrition, the cost of MWM production remains high because it is still at an early stage of adoption by farmers and the commercial poultry feed industry (Selaledi et al., 2021). The recent global forecast reports indicate that the mealworms market is expected to grow at a high rate of 28.6% from 2022–2030 (Mealworms Market, 2022). Therefore, the MWM inclusion into broiler diets could be efficiently economical and profitable by introducing cost-effective rearing technologies, developing processing methods, and further cooperating between stakeholders of the mealworm marketing (Tanga et al., 2021; van Huis, 2020).

CONCLUSIONS

The study concluded that soybean meal replacement by the MWM as an alternative source of protein in the finisher diet of broilers has a beneficial effect on the final body weight, body weight gain, and feed conversion. In addition, MWM inclusion into broiler diets improved some characteristics of carcass composition and meat quality. Some physiological parameters were also enhanced by the MWM treatment, such as increased serum proteins and T_3 hormone and decreased ALT, AST, CRT, UA, TG, and CH profiles. However, the recommended levels of MWM should not exceed 6% in broiler diets as higher levels of the MWM may reduce the carcass yield of breast and internal organs, scale down the meat quality, and deteriorate some physiological parameters in broilers. Furthermore, the CBR and RoI outcomes of broilers treated with the MWM remain low due to the restrictive marketing and the excessive cost of the MWM production.

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NOVELTY STATEMENT

The current work is a pioneer study that examines the effect of mealworm meal (MWM) inclusion as a replacement of soybean meal in broiler diets on their growth performance, carcass and meat properties, physiological aspects, and economic efficiency. The results concluded that soybean meal in broiler diets could be effectively replaced by MWM as a sustainable option in poultry meat production.

AUTHOR'S CONTRIBUTION

All authors contributed equally to the manuscript.

Ethical approval

The current animal study protocol was authorized by the research ethical committee of King Faisal University, Saudi Arabia, (Ref. No. KFU-REC-2022-AUG– ETHICS362).

Conflicts of interest

The authors declare no conflict of interest.

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