Journal of Insects as Food and Feed, 2022; 8(9): 1015-1025

SPECIAL ISSUE: *Insects on the monogastric menu*

Wageningen Academic Publishers

Economic viability of insect meal as a novel ingredient in diets for broiler chickens

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Received: 13 October 2021 / Accepted: 24 February 2022

RESEARCH ARTICLE

Abstract

The study aimed to evaluate the economic efficiency of supplementation of *Tenebrio molitor* meal in the diet for broilers, from 1 to 35 days of age. For that, data from a preliminary study were used to evaluate the inclusion of *T. molitor* meal in the broiler production performance. Four treatments were adopted: a control group and three experimental diets with 4, 8 and 12% levels of inclusion of this meal. The economic viability indicators were calculated considering the cost of the feed (R$/kg), the price of live broiler (R$/kg), feed intake (kg) and body weight (kg) of the birds. The feed cost increased proportionally with the inclusion of insect meal in poultry diets while the gross margin decreased from 93 to 98%, with 4 to 12% of inclusion of this ingredient, compared to the control diet. In the previous study, the level of 4% resulted in better performance of the birds, so, to enable the inclusion of 4% meal in the diet, this ingredient should be priced at R$ 4.53/kg.

Keywords: insect, poultry, circular economy, gross margin

1. Introduction

The use of insects as an ingredient and/or additive by the animal feed industry is a promising approach because it combines nutritive value, nutraceutical properties and efficient rearing systems (Gasco *et al.*, 2020; Józefiak and Engberg, 2017; Van Huis, 2015; Van Huis *et al.*, 2013). Insects can be sustainable, requiring smaller areas for production, with low greenhouse gas emissions and water footprint, or when using by-products as substrate (Grau *et al.*, 2017; Miglietta *et al.*, 2015; Oonincx *et al.*, 2015). The main candidate insects are yellow mealworm *Tenebrio molitor* (Coleoptera: *Tenebrionidae*) (Ramos-Elorduy *et al.*, 2002; Van Broekhoven *et al.*, 2015) and black soldier fly *Hermetia illucens* (Diptera: *Stratiomyidae*) (Surendra *et al.*, 2016), which are especially interesting because they can be reared in organic side streams, which represent one-third of the food and agriculture waste in the world (Gustavsson *et al.*, 2011).

The poultry products market is one of the fastest growing sectors (Van Huis *et al.*, 2013). The fast production cycle and high feed efficiency characterise the socioeconomic value of this production chain. On the other hand, the growth in animal production intensifies the pressure on the use of environmental resources, including for the production of grains intended as animal feed for other livestock. The growing scarcity of raw material production resources to the manufacture of feed, with their associated high costs (Van Huis *et al.*, 2013) has accelerated the search for sustainable ingredients in animal feed (Gasco *et al.*, 2020).

Soybean meal and fish meal are sources of protein in animal feed. Soy is the most common source of plant protein in the formulation of diets for broilers and laying hens due to its quality and quantity of amino acid (Veldkamp *et al.*, 2012). Soybean meal shows a large variation in quality, due to a range of factors, such as soil nutrition, chemical processing to eliminate antinutritional factors, high water consumption, and deforestation (Biasato *et al.*, 2018). Currently, the price of soybean meal and its accessibility are the main obstacles to maintaining it as one of the main ingredients in poultry diet formulations.

Insects are considered promising as a sustainable source of nutrients for birds (Barroso *et al.*, 2014; Józefiak *et al.*, 2020; Nascimento-Filho *et al.*, 2020), as they have a high content of proteins and fats (Makkar *et al.*, 2014; Veldkamp *et al.*, 2012) and could replace 25 to 100% of conventional protein ingredients that make up animal feed (Veldkamp *et al.*, 2012).

Larvae of *T. molitor* have an important potential use as a source of protein in the feed of birds. The use of insect meal as an ingredient in animal feed has been widely studied in poultry nutrition in recent years, due to its excellent nutritional composition (Biasato *et al.*, 2018; Bovera *et al.*, 2015; Ramos-Elourdy *et al.*, 2002), and nutrient digestibility (Mwaniki and Kiarie, 2018); and recently some studies point to the inclusion of insect meal in feed as an additive, in order to modulate intestinal microbiota (Józefiak *et al.*, 2020) and assist the immune system of broilers (Benzertiha *et al.*, 2019).

Furthermore, insects can efficiently convert a wide variety of organic waste into protein of high biological value, contributing positively with food waste (Makkar *et al.*, 2014; Van Huis *et al.*, 2013) and in waste reduction, which constitutes a new approach and a notable example of a sustainable circular economy (Meneguz *et al.*, 2018).

In the circular economy concept, the implementation of insects in the production chain can also favour small producers by providing a solution in the management of organic waste generated on the farm (Chaalala *et al.*, 2018), in addition to reducing costs (Chia *et al.*, 2019b). Recent studies have shown good results and encourage the production of insects on an industrial scale as well as their use in animal feed (Biasato *et al.*, 2018; Cappellozza *et al.*, 2019; Veldkamp and Bosch, 2015).

The inclusion of ingredients in feed formulation not only aims at a balanced diet of nutrients for optimal performance, but also considers profitability in the production process (Spring, 2013). However, there is little research on the economic perspectives regarding the use of insects as an ingredient in animal feed, especially in poultry diets. Therefore, the study aimed to evaluate the economic aspects of the inclusion of *T. molitor* meal in broiler diets in the period from 1 to 35 days of age.

2. Material and methods

Data for economic analysis were obtained from a feeding trial carried out at the Poultry facility of the Department of Animal Science, University of São Paulo, Piracicaba, state of São Paulo, Brazil. The experimental procedures were approved by the Institutional Animal Care and Use Committee (2017.5.2568.11.5).

Database

A growth performance trial was conducted with 480 one-day male Ross AP95 broilers that were distributed in a completely randomised design with 4 dietary treatments (6 replicates/treatment of 20 birds each). The treatments consisted of three different levels of inclusion of *T. molitor* meal (4, 8 and 12%), compared to the control diet without the inclusion of insect meal. Experimental diets were formulated to be isoenergetic and isonitrogenous, following the nutritional requirements of Rostagno *et al.* (2017).

One-day-old male Ross AP 95 chicks were weighed individually and per pen for equal weight distribution and placed into 24 pens, totalling 480 birds, with an initial body weight of 46.6±0.2 g. Birds were assigned to 4 treatment groups with 6 replicates pens (20 birds/pen) in a completely randomised design, and reared for 35 days.

Four iso-nutritional diets were formulated to contain different levels of full-fat *T. molitor* larvae meal (TM): Control, 4% TM, 8% TM and 12% TM. The nutritional program consisted of 3 diets: pre-starter (1-7 d), starter (8-21 d), and grower (22-35 d). All diets were formulated to meet or exceed the nutritional requirements of broilers according to Rostagno *et al.* (2017).

Economic analysis

In order to analyse the economic viability of using insect meal in broiler diets, the prices of corn and soybean meal obtained from a five-year historical average (from May 2015 to May 2020) were obtained from IEA (2020), and the price of live broilers obtained from JOX (2020). A price survey was carried out for the preceding five years, also between May 2015 and May 2020, with agribusinesses in the state of São Paulo, representing approximately 50% of chicken production of the state, for calcitic limestone, common salt, dicalcium phosphate, amino acids, and mineral and vitamin supplements for broilers at different stages of production. All prices were deflated using the values of the General Price Index (GPI), Indice Geral de Preços – Disponibilidade Interna – (IGP-DI) of Fundação Getúlio Vargas/FGV Brazil for the month of May 2020 (Table 1), according to the formula:

$$PI_{corrected} = PI_{nominal} \times \frac{IGPDI_{May/20}}{IGPDI_t} \quad (1)$$

where $PI_{corrected}$ is the actual price of the ingredient in month t, corrected to May 2020; $PI_{Nominal}$ is the price of

Table 1. Corrected prices of feed ingredients for the month of May 2020, using the IGP-DI/FGV index.

Ingredients[1]	Price (R$/kg)[2]
Corn, ground[a]	0.61
Soybean, meal[a]	1.70
Tenebrio, meal[b]	135.00
Dicalcium phosphate[b]	2.40
Calcitic limestone[b]	0.20
Soybean, oil[b]	3.26
Salt[b]	0.63
DL-methionine[b]	11.70
L-lysine HCL 77%[b]	2.85
Pre-starter and starter vitamin supplement	16.16
Vitamin supplement growth[b]	9.10
Pre-starter and starter mineral supplement[b]	6.22
Mineral growth supplement[b]	4.55
Chloride choline 70%[b]	5.92
Salinomycin 12%[b]	12.00
L-threonine[b]	7.90
Broiler[c]	3.24

[1] Data from: [a] IEA (2020); [b] Survey of prices carried out for the preceding five years, also between February 2015 and February 2020; [c] JOX (2020).
[2] Exchange index for the data period considered (Feb/2015 to Feb/2020) was 1 US$ = R$ 3,5625, or considering the period of time of the experiment it was 1 US$ = R$ 5,1572 (May/2020).

the ingredient in the month; $IGPDI_{May/20}$ index for the month of May 2020, and the $IGPDI_t$ the index for month t.

Feed costs (FC) for each production phase (pre-starter, starter and growth) were calculated by adding the product between the amount of the feed ingredients (QI), defined at the time of the formulation of the feed, and their respective prices (PI):

$$FC = \sum (PI \times QI) \tag{2}$$

The total cost of the diet (CD) was calculated considering the cost of the feed and the feed intake in each feeding phase, from 1 to 35 days of age of the broiler.

To determine the economic viability indicators, the following variables were considered: final body weight (FW – kg); feed/bird/phase consumption (kg); price of live broiler (R$/kg); and the price of the feed/phase (R$/kg). Based on these variables, gross revenue (GR) per bird was calculated:

$$GR_i = FW_i \times PB_i \tag{3}$$

where FWi represents the final weight of the broiler (kg) in the accumulated period of 35 days; PBi the price of live broiler (R$/kg) i.

The gross selling margin (GMi) was calculated according to Gameiro (2009); CIAS (2020), using the following calculation:

$$GM_i = GR_i - \frac{FC_i}{0.7} \tag{4}$$

where GRi represents the gross revenue and FCi is the feed cost (R$/kg).

To estimate the cost of production of broiler (CPi), it was considered that feed represents 70% total production cost (CIAS, 2020).

The cost-benefit ratio (CB) was determined considering the calculation proposed by Chia *et al.* (2019b), in which:

$$CB_i = \frac{GR_i}{CP_i} \tag{5}$$

In (R$/kg), where GR$i$ represents gross revenue and CPi the cost of production, which in this study was considered as CDi (diet cost), with 70% total production cost (CIAS, 2020):

$$CP_i = \frac{CD_i}{0.7}$$

In order to calculate the viable price of insect meal and the simulations proposed in this study, an optimisation spreadsheet was created using the 'Solver' tool from Microsoft Excel® (Microsoft Corp., Redmond, WA, USA). For this, the costs of ingredients and live broilers were inserted, as well as the data of feed consumption and body weight and, subsequently, the price of insect meal for different scenarios was calculated.

Data obtained from the growth performance of the broilers identified that the group which received 4% of insect meal in their diets, showed the higher weight at 35 days (+154 g/chicken). The total volume of diets consumed by each animal of this experimental group was considered to determine the projection of the volume of insect meal required to meet the potential market for this ingredient for broilers. For this calculation the volume of broilers slaughtered under federal inspection (SIF) was also considered, as released by the Ministério da Agricultura, Pecuária e Abastecimento (MAPA, 2020). Both numbers were multiplied following the calculation:

$$IM = VB \times \Sigma FIC \quad (6)$$

Where IM represents the amount of insect meal (kg); VB total volume of broilers slaughtered (MAPA data), and ΣFIC the total insect meal feed consumption (kg) estimated for this broiler volume during the period of 35 days of rearing.

From these data, the volume of insects necessary to produce the insect meal to serve the market was calculated, considering 30% dry matter yield of insects for the production of the meal considering the average body weight of 145 mg/insect (Makkar *et al.*, 2014).

3. Results

There was an increase in the total cost of the diet (CD) with increasing inclusion levels of insect meal, resulting in a reduction in the gross margin of the broiler (GM) (Table 2).

In this analysis (Table 2), the costs of ingredients and the sale of live broilers were the only source of costs and profits, respectively, so the feed cost (FC) was considered to be 70% total production cost. Additionally, for the calculations, the feed intake and final weight of broilers were used.

The result of the economic analysis revealed a higher, which means better, gross margin for the control group. The feed cost increased, and proportionally decreased the gross margin 93, 97 and 98% for the groups 4, 8 and 12% of insect meal inclusion, respectively, in relation to the control group.

The cost-benefit ratio of 0.38 indicates that the inclusion of 4% insect meal may be more economically interesting, when compared to the inclusions of 8 and 12%. Despite this, the gross margin is negative, because of the high cost of R$ 135.00/kg insect meal, considering prices at that experimental moment. The ratio of revenue to production cost represents the cost-benefit, and a value greater than 1 (one) suggests that the benefits of production exceeded the costs, and vice versa (Chia *et al.*, 2019b).

In order to illustrate the economic viability of using insect meal in feed for broilers, using the optimisation worksheet, different scenarios have been proposed to simulate the viable price of insect meal, in principle for two different scenarios (Table 3).

Scenario I showed a gross margin of R$ 1.56/bird, obtained from the control treatment. Based on that gross margin, the viable value of insect meal was determined for three different levels of inclusion of insect meal (4, 8 and 12%) using the optimisation spreadsheet with the aid of the Microsoft Excel® Solver tool.

Scenario II showed that the price of insect meal must be R$ 4.53/kg. This cost was obtained following from Scenario I and was considered as the maximum cost of the insect meal, to be viable as an ingredient, maintaining a positive gross margin. Based on that ingredient cost, economic viability was determined for the three levels of inclusion with the optimisation worksheet using the Microsoft Excel® Solver tool.

Based on Scenario I, to meet the gross margin of R$ 1.56/bird (obtained from the control group calculations), the price of insect meal would have to decrease at all levels of inclusion, reaching the maximum prices found of resulting in values of R$ 4.53/kg, R$ 2.80/kg and R$ 3.65/kg, respectively, for diets with 4, 8 and 12% levels of insect meal inclusion. The response in broiler growth performance obtained with 4% insect meal was the greatest (154 g in final weight) and for this reason the price at this level was considered the standard for comparisons in Scenario II.

Table 2. Variables considered for economic analysis in the four compared groups, with different insect meal percentage of inclusion.

Variables[1]	Insect meal inclusion[2]				*P*-value[3]
	0%	4%	8%	12%	
Average feed cost of diet (R$/kg), CD	1.43	6.70	11.98	16.95	–
Total feed consumption (kg/bird), FC	3.482	3.619	3.536	3.547	0.431
Total cost of diet (R$/bird), TCC	4.89	24.09	42.18	60.78	–
Live final weight (kg/bird), FW	2.637b	2.791a	2.649b	2.668b	0.069
Gross revenue (R$), GR	8.55	9.05	8.59	8.65	–
Gross margin (R$), GM	1.56	-25.37	-51.67	-78.18	–
Cost-benefit ratio (R$), CB	1.75	0.38	0.20	0.14	

[1] CD (R$/kg) average feed costs for the three rearing phases; Insect meal price (R$/kg)=135.00; live broiler price, PB (R$/kg)=3.24; CD=FC×CD; GR=FC×PB; GM=GR–(FC/0.70), considered the participation of 70% costs with nutrition (CIAS, 2020); CB=RB/CP (Chia *et al.*, 2019a). CR, PV are expressed by the average sum of each treatment of 20 birds/pen in the pre-starter, starter and growth phases.
[2] Levels of inclusion of insect meal (*Tenebrio molitor*) in the diet: 0 (control), 4, 8 and 12%.
[3] Two-way ANOVA, and Tukey test, with $P<0.10$; (–) not calculated values.

Table 3. Economic viability (GR, GM, and CB) of insect meal in the two scenarios considered.

Variables[1,2]	Scenario I[3]			Scenario II[3]		
	Inclusion of insect meal[4]					
	4%	8%	12%	4%	8%	12%
Insect meal cost (R$/kg)	4.53	2.80	3.65	4.53	4.53	4.53
Total cost of diet (R$/broiler), FC	5.24	4.92	4.96	5.24	4.92	4.96
Gross revenue (R$), GR	9.05	8.59	8.65	9.05	8.59	8.65
Gross margin (R$), GM	1.56	1.56	1.56	1.56	0.86	1.02
Cost-benefit ratio (R$), CB	1.73	1.75	1.74	1.73	1.59	1.62

[1] Price of live broiler, PB (R$/kg)=3.24; CD=FC×CD; GR=FC×PB; GM=GR–(CD/0.70), considered the 70% variation in nutrition costs (CIAS, 2020); CB=GR/CP (Chia *et al.*, 2019a).
[2] CD is the total cost of the diet, GR is gross revenue from the sale of live broilers, GM is the gross margin of the broiler, CB is the cost-benefit of including insect meal in the broiler diet.
[3] Scenario I: viable value of insect meal when GM is equal to R$ 1.56/bird; Scenario II: economic viability, when the value of insect meal is R$ 4.53/kg (optimisation spreadsheet using the Solver tool from Microsoft Excel® (Microsoft Corp., Redmond, WA, USA) for all inclusions.
[4] Levels of inclusion of insect meal in the diet: 0 (control), 4, 8 and 12%.

When this price, of R$ 4.53/kg was applied for all treatments in Scenario II, the gross margin for 8 and 12% treatments was reduced, but was still positive.

Therefore, other scenarios were proposed using the level of 4% inclusion of insect meal (Tables 3 and 4). In addition, economic contexts were defined to analyse market prices for soybean meal with values from March 2020 (Table 5). This month was selected due to the COVID-19 global pandemic, which resulted in a higher price than usual for animal feed.

In Table 4, in Scenario 1, the gross margin (GM) of the 4% insect meal was considered to be 70% of R$ 1.56/bird (gross margin obtained from the control group). In Scenario 2, the gross margin (GM) of the 4% insect meal was considered to be 50% of R$ 1.56/bird. In Scenario 3, the gross margin of the 4% insect meal was considered to be 30% of R$ 1.56/bird. In Scenario 4, the cost of insect meal was determined by changing the value of soybean meal (considering the month of March 2020) (Table 5).

In Scenario 5, the cost of soybean meal was determined by simulation, and then replaced by 4% insect meal with the price of R$ 4.53/kg and the gross margin of R$ 1.56/bird. In Scenario 6, the cost of soybean meal was determined by simulation, then replaced by 4% insect meal, considering the price of R$ 135.00/kg and the gross margin of R$ 1.56/bird. In the scenario simulation process, we proposed challenging market cases with a worse gross margin than the initial gross margin found (R$ 1.56/broiler) in this study, considering the control group that did not use insect meal.

We found a feasible result, in the simulation, considering this gross margin of R$ 1.09/broiler in Scenario 1, which represented a proposal of 30% decrease of the initial gross margin, the price of R$ 7.56/kg, when 4% of insect meal was included in the diet. Even though with R$ 3.03/kg more for the cost of insect meal, this R$ 7.56/kg generates a positive cost-benefit context.

On the other hand, in Scenarios 2 and 3, considered as a simulation proposal, when the gross margin decreases by 50 and 70% (R$ 0.78/bird and R$ 0.47/bird, respectively), the viable cost of insect meal could be increased to R$ 4.47/kg and R$ 6.00/kg, which could cost R$ 9.10/kg in Scenario 2 and R$ 10.63/kg in Scenario 3; but in both conditions, the cost-benefit ratio indicates that the use of insect meal is less profitable when compared to Scenarios 1 and 2, as showed in Table 4.

In Scenario 4, for the gross margin of R$ 1.56/bird, with soybean meal at R$ 1.87/kg, the viable cost of insect meal was calculated to be R$ 5.16/kg. The analysis of Scenario 5 shows that the cost of soybean meal should be at least R$ 1.48/kg to obtain a margin of 1.56/bird; in this case, soybean was replaced by 4% insect meal. This scenario is cost-effective, and the inclusion of insect meal is economically viable.

Nevertheless, in Scenario 6, when the cost of insect meal is increased to R$ 135.00/kg, the replacement of soybean by insect meal is impractical. The insect meal cost at R$ 135.00/kg resulted in a negative gross margin per kg live broiler (GM = -R$ 173.94/broiler).

Considering the cost of insect meal at 135.00/kg, in Scenario 7 and 8, the price of live broiler should be R$ 13.05/kg to obtain a gross margin equal to zero, and when the gross margin is equal to the control group, R$ 1.56/bird, in Scenario 8, the price of live broiler should be at least R$ 13.64/kg (Table 6).

Table 4. Simulation of different gross margin scenarios (R$/bird) to determine the economic viability of the cost of insect meal (R$/kg) in the diets of broilers aged 35 days.

Scenarios[1]	Variables[2]					
	Insect meal R$/kg	Soybean meal R$/kg	CD R$/bird	GR R$/bird	GM R$/bird	CB
1 (70% of control group GM)	7.56	1.70	5.57	9.05	1.09	1.62
2 (50% of control group GM)	9.10	1.70	5.79	9.05	0.78	1.56
3 (30% of control group GM)	10.63	1.70	6.00	9.05	0.47	1.51

[1] It was determined in Scenarios 1, 2 and 3: the gross margin considering 70, 50 and 30% reduction of R$ 1.56/kg, gross margin obtained in the diet without the inclusion of insect meal, respectively. For the elaboration of the studied scenarios, only the treatment with 4% inclusion of insect meal was considered for the proposed simulations.
[2] Price of live broiler, PB (R$/kg)=3.24; CD=FC×CD; GR=FC×PB; GM=GR–(CTD/0.70), considered the 70% variation in nutrition costs (CIAS, 2020); cost benefit ratio CB= B/CP (Chia *et al.*, 2019a). CB is the cost-benefit of including insect meal in the broiler diet; CD is the total cost of the diet; GM is the gross margin of the broiler; GR is gross revenue from the sale of live broilers.

Table 5. Simulation of different scenarios considering different soybean and/or insect meal costs to determine the economic viability of the cost of insect meal (R$/kg) in the diets of broilers aged 35 days.

Scenarios[1]	Variables[2]					
	Insect meal R$/kg	Soybean meal R$/kg	CD[3] R$/bird	GR[3] R$/bird	GM[3] R$/bird	CB[3]
4	5.16	1.87	5.24	9.05	1.56	1.73
5	4.53	1.48	5.52	8.55	1.56	1.73
6	135.00	Not possible to calculate	128.09	9.05	-173.94	0.07

[1] Scenario 4: viable price of insect meal considering the cost of soybean meal in March 2020; Scenario 5: the minimum cost of soybean meal to replace 4% inclusion of insect meal at R$ 4.53/kg, considering the GR of R$ 1.56/bird; Scenario 6: the minimum cost of soybean meal to replace 4% inclusion of insect meal at R$ 135.00/kg, considering the GM of R$ 1.56/bird. For the elaboration of the studied scenarios, only the treatment with 4% inclusion of insect meal was considered for the proposed simulations.
[2] Price of live broiler, PB (R$/kg)=3.24; CD=FC×CD; GR=FC×CD; GM=GR–(CD/0.70), considered the 70% variation in nutrition costs (CIAS, 2020); CB=RB/CP (Chia *et al.*, 2019b).
[3] CD is the total cost of the diet, GR is gross revenue from the sale of live broilers, GM is the gross margin of the broiler, CB is the cost-benefit of including insect meal in the broiler diet.

Table 6. Simulation of the viable price of live broiler, (PB), (R$/kg live broiler) considering the price of R$ 135.00/kg for the insect meal, the different gross margin R$/bird (GM = GR–(FC/0.7)), equal to zero in Scenario 7 and, equal to the control group R$ 1.56/bird in Scenario 8.

Scenarios[1]	Variables[2]				
	Broiler price (PB) R$/kg	Total cost of diet (CD) R$/bird	Broiler final live weight (LW) kg/bird	Gross revenue (GR) R$/bird	Gross margin (GM) R$/bird
7	13.05	24.09	2.640	34.41	0.00
8	13.64	24.09	2.640	35.97	1.56

[1] Scenario 7 considers GM=0; Scenario 8 considers GM=1.56/bird.
[2] GR=FC×PB; GM=GR–(CD/0.70), considered the 70% variation in nutrition costs (CIAS, 2020).

The insect meal consumption (IMC) per bird and the projection of production of insect meal necessary to supply the production of broilers in the state of São Paulo are shown in Table 7 and 8, respectively. The state of São Paulo was chosen as the reference since it was the region where the feeding trial was carried out.

Table 7. Insect meal consumption (IMC) per bird, obtained in the previous experiment (kg/bird) considering the rearing period from 1 to 35 days old.

Variables[1]	
Total feed consumption, kg FC	3.612
Final broiler live weight, kg LW	2.743
Feed conversion ratio, FCR	1.316
Insect meal consumption/bird, kg IMC	0.144

[1] FC, LW and FCR data was obtained from experimental data for the group with 4% insect meal diet inclusion. IMC was obtained from experimental data, of group with 4% inclusion of insect meal, where IMC = FC × 0.04 (kg/bird).

When we observe the amount of insects estimated in this study to supply the actual market production in São Paulo, or even in Brazil, we could find a reduction in the amount of soybean meal necessary to be included in the broiler diet.

Based on the consumption of corn and soybean meal, in the different stages of bird development, it was observed that the replacement of soybean meal with insect meal may be feasible in the starter and growing phases.

We could observe a reduction in the consumption of soybean meal by 40 g in the starter phase, and 10 g in the growth phase per bird, amounting to 50 g of soybean meal savings per bird over the 35 days of rearing, in this study (Table 9).

This reduction in soybean meal consumption of 50 g/broiler means a saving of 63,129 tonnes of soybean in the state of São Paulo, and 764,366 tonnes in Brazil, which represents a decrease of 0.8% in soybean meal required for broiler production (Table 10). This percentage considers a Brazilian soybean harvest of 126 million tonnes, based on yield data from 2019/2020.

Table 8. Projection of production of insect meal necessary to supply the production of broilers in the state of São Paulo (SP) and Brazil (BR), considering the feasible results found in this study, during rearing period from 1 to 35 days of age.

Variables	Values
Number of broilers slaughtered – São Paulo in 2019[1]	436,976,338
Number of broilers slaughtered – Brazil in 2019[1]	5,291,136,629
Total meal for number of broilers slaughtered in SP at 4% insect meal inclusion[2], *t*	63,126
Total meal for number of broilers slaughtered in BR at 4% insect meal inclusion[2], *t*	764,366
Amount of insects required to meet the market for insect meal in broiler production in SP *(t)*[3] VT	107,340
Amount of insects required to meet the market for insect meal in broiler production in BR *(t)*[3] VT	1,299,422

[1] Data obtained from the sum of slaughters under Federal Inspection (SIF) in the state of São Paulo, where the experiment was conducted, and in the country (Brazil) according to the Ministry of Agriculture, Livestock and Food Supply (MAPA, 2020).
[2] Amount of insect meal needed to serve the market considering 4% inclusion in broiler diets in tons.
[3] VT = amount of insects needed to produce the volume of meal to serve the SP and Brazil market, considering the 4% inclusion, calculated considering 30% conversion of insects into meal (Makkar *et al.*, 2014).

Table 9. Total feed intake, and insect meal intake in kg/chicken in each phase.

Variables[1]	Total feed intake (kg/broiler) in each phase[2]					
	Control			4% insect meal		
	Pre-starter	Starter	Growth	Pre-starter	Starter	Growth
Corn, kg	0.056	0.481	1.095	0.060	0.535	1.119
Soybean meal, kg	0.062	0.485	0.935	0.055	0.449	0.927
Insect meal, kg	0.000	0.000	0.000	0.005	0.045	0.094

[1] Ingredient/bird/development phase.
[2] Broiler development phases: pre-starter (1-7 days); starter (8-21 days) and growth (22 to 35 days).

Table 10. Effect of including insect meal in broiler diet on the requirements for soybean meal.

Use of soybean meal in the poultry chain[1]	Amount of soybean
Reduction in soybean meal consumption kg/broiler	0.050
Estimated amount of soybean meal saved in the state of São Paulo in 2019[2], *t*	63.129
Estimated amount of soybean meal saved in Brazil in 2019[2], *t*	764.366

[1] Experimental values obtained from Table 7, the calculations only considered the treatment with 4% inclusion of insect meal.
[2] Reduced consumption of soybean meal for the number of broilers slaughtered in 2019 (MAPA, 2020).

4. Discussion

To the best of our knowledge, this is the first study to address the economic viability of including insect meal in the diet for broilers in Brazil.

Profitability in agribusiness is one of the most important indicators and is used to assess the capacity of maximum production with the minimum of inputs (Al-Sharafat *et al.*, 2020). The choice of gross margin for economic analysis in this study is due to the fact that processing costs (feed manufacture, mixing, transportation, among others) were not considered in the calculations.

From an economic perspective, the cost of insect meal at R$ 135.00/kg is impractical, despite the increase of 154 g in the final weight of broilers (Table 2). Although the cost-benefit calculation indicates an advantage with the inclusion of 4% insect meal, the gross margin is negative. This demonstrated the need to thoroughly investigate the viable price of insect meal as addressed in this study.

Khan *et al.* (2016) pointed out that the cost of diets in broilers can be reduced by the use of insect meal, if produced on a large commercial scale to replace fish and soybean meal, considering the analysis in their article.

In another study, Onsongo *et al.* (2018) in turn observed a 25% better cost-benefit when replacing 55% of soybean meal and fish meal with black soldier fly meal in starter and growing diets, considering the Kenyan market, where diet costs are higher than in Brazil, despite the high costs of this ingredient.

Ballitoc and Sun (2013) pointed out that the addition of insect meal to diets suggest a greater palatability of the diet, reflecting the innate behaviour of birds in a natural environment. Nascimento-Filho *et al.* (2020), demonstrated that after a few days of being offered insect meal in a cafeteria-type study, chickens developed a clear preference for this ingredient compared to the usual feed ingredients, especially extruded semi-whole soybean meal, and also indicated better feed conversion rates.

Moreover, in a study with different levels of dietary fat for broilers, from insects added at 0.2 and 0.3% added on top, Benzertiha *et al.* (2020) reported an increase in the levels of IgY and IgM, and in the values of IL-2 and TNF-α, demonstrating a potential immunomodulatory role in chickens.

The inclusion of insect meal as a protein and energy source in animal feed, due to the high content of crude protein and saturated and monosaturated fatty acids (Veldkamp *et al.*, 2012), represents a novel option for nutritionists.

In this sense, this study determined that the maximum cost of soybean meal must be R$ 1.48/kg to be replaced by 4% insect meal, costing R$ 135.00/kg, to obtain the same gross margin as the control group, of R$ 1.56/bird, as seen in Scenario 5, where the soybean costs R$ 1.70/kg. On the other hand, considering the cost of insect meal at R$ 135.00/kg, the optimisation of the price of soybean meal is impractical (Table 5), and may only be applicable if the price of a live broiler is higher than R$ 13.05/kg (Table 6). This is sometimes the case with special products on the market, sold as premium or organic chickens, which have higher gross margins and higher prices for final customers.

The way to make insects economically interesting as an ingredient and/or an additive for the animal industry is by scaling up the production systems to decrease the costs with insect meal, and to make it regularly available in large quantities. Many companies have arisen in the last five years in Europe, the United States, and Asia, such as Kreca (Netherlands), Ynsect (France), Protix Biosystems (Netherlands), AgriProtein (South Africa), Enviroflight (United States), Bioflytech (Spain), Entomotech (Spain), Entogreen (Portugal), and Nutrition Technologies (Malaysia), which are dedicated to animal and human nutrition. As an example, the market price for insect meal ranges from 8.4 to 9.3 US$/kg in China, 10.8 to 14 US$/kg in the USA, 12.9 to 20 US$/kg in the EU, and 65 to 70 US$/kg in South Korea, all of which are considerably higher than the US$0.34/kg soybean price (Hong *et al.*, 2020).

Although in Brazil there is still no large-scale industrial production of insects, the Brazilian Association of Insect Breeders (ASBRACIS) was recently created, aiming to organise and develop the sector.

It should be highlighted that other animal species can be candidates for insect meal consumption, including pet food for dogs and cats, or wild and ornamental birds and fishes, which might make the cost of R$ 135/kg feasible in other sectors. This is because these species, when compared to farm animals, do not require optimisation of productivity and do not necessarily return profit to their handlers (Van Huis, 2020). The same author points out that the number of consumers who take into account sustainable food and its most varied forms of 'organic' or 'premium' feed has grown with consumption options, also justifying the acceptance and viability of insect meal in the pet market.

5. Conclusions

The economic optimisation demonstrated that the maximum viable cost of insect meal should be R$ 4.53/kg to result in a gross margin of R$ 1.56/bird (defined for the control group, without insect meal, at the time of the experiment) in order to be acceptable to the current poultry diet market in Brazil. When the level of inclusion increases, the cost of meal needs to decrease in order to become profitable. A decrease in the gross margin was found with increasing levels of insect meal in the diets.

There was a 96.6% difference between the real market price for the insect meal applied in this study, and the viable price that could be accepted by the poultry market without affecting broiler gross margin. Therefore, anyone thinking of becoming an insect meal producer focusing on producing huge quantities for the poultry market, has to consider large-scale production to make production costs viable.

Another potential avenue for making insect meal production economically viable is to consider decreasing the inclusion level of insect meal in broiler diets, using the potential application of insect meal as a nutritional additive to enhance health, where feed intake beyond nutritional value could be explored.

Saving 0.8% of soybean meal solely on broiler chicken feed, just in Brazil, can mean the use of these grain quantities for human consumption. This demonstrates a big potential saving of this grain once it is truly possible to extend the scenario of insect meal use worldwide. This scenario could contribute considerably to sustainable development goals, and is also included in circular economy concepts.

Conflicts of interest

The authors declare no conflicts of interest.

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