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Effects of processing methods of dried black soldier fly larvae as top-dressing replacement in layer diets on performance, egg quality, and economic returns

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Abstract

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Feed cost is a major egg production expense. This study evaluated the effects of differently processed dried black soldier fly larvae (BSFL) on laying performance, egg quality, and economic returns. Forty commercial brown laying hens (30 weeks old) were assigned to four treatments with 10 replicates each in a completely randomized design for 6 weeks. Treatments comprised a commercial diet (control) and diets with 10% top-dressing replacement using hot-air dried larvae (T2), boiled and hot-air dried larvae (T3), or autoclaved and hot-air dried larvae (T4). Data were analyzed using repeated measures ANOVA. Hen-day egg production, egg weight, egg mass, and feed conversion ratio were significantly affected by treatment, time, and treatment × time interaction ($p<0.001$). T2 and T3 generally showed improved production performance and feed efficiency compared with the control. Egg weight was affected by treatment ($p=0.003$) and treatment × time interaction ($p=0.025$), whereas albumen and yolk proportions were unaffected ($p>0.05$). Shell proportion ($p=0.024$), yolk color ($p=0.035$), and shell thickness at the sharp end ($p=0.045$) differed among treatments, whereas most internal egg quality and eggshell traits were unaffected. BSFL reduced feed cost per egg by 0.25, 0.37, and 0.05 THB per egg, equivalent to approximately 0.008, 0.012, and 0.002 USD per egg, for T2, T3, and T4, respectively, compared with the control. Net return increased by 109.44, 119.90, and 42.36 THB, equivalent to approximately 3.50, 3.83, and 1.35 USD, respectively. T3 had the highest benefit–cost ratio. Because top-dressing increased dietary protein and fat contents relative to the control, responses may partly reflect differences in nutrient density among treatments. Overall, the results suggest that replacing 10% of commercial feed with dried BSFL using a top-dressing approach can maintain laying performance and may improve economic efficiency, particularly with boiled and hot-air dried larvae, under the conditions of this study.

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1. Introduction

The egg production industry plays an important role in food security, as eggs are a highly nutritious, affordable, and accessible source of protein. However, egg production is currently facing challenges from increasing production costs, particularly feed costs, which account for more than 60-70% of total costs [1, 2]. Fluctuations in the prices of major feed ingredients, such as soybean meal and fish meal, affect competitiveness and long-term sustainability of production systems [3 - 5]. Therefore, the development of alternative protein sources that are low-cost, nutritionally adequate, and practically applicable in commercial production systems is essential.

Black soldier fly larvae (*Hermetia illucens* L.) have gained attention as an alternative protein source for animal feed due to their high protein and lipid content, suitable essential amino acid profile for poultry, and the ability to be produced from organic waste, aligning with sustainable production and circular economy concepts [6, 7]. Numerous studies have reported that black soldier fly larvae can replace conventional protein sources in poultry diets without negatively affecting production performance and product quality [8 - 10].

However, most previous studies have focused on incorporating black soldier fly larvae into reformulated diets designed to achieve equivalent nutrient compositions. Although this approach is appropriate from a nutritional

perspective, it does not fully reflect practical conditions in commercial layer farms, where pelleted diets are commonly used and on-farm feed formulation is limited. Consequently, limited information is available regarding the practical use of whole dried black soldier fly larvae as a direct top-dressing replacement in commercial pelleted diets. In addition, processing methods such as hot-air drying, boiling, and autoclaving may influence nutrient availability, protein structure, lipid stability, microbial safety, and nutrient digestibility, which may subsequently affect laying performance and egg quality [11 - 13]. Although many studies have evaluated black soldier fly larvae in poultry diets, comparative information on different processing methods under direct replacement or top-dressing conditions remains limited [6, 12]. Furthermore, high inclusion levels may affect nutrient digestibility and gut microbiota in laying hens [14]. Therefore, a replacement level of 10% was selected, as it has been reported to be used without negative effects on production performance.

Accordingly, this study aimed to evaluate the effects of differently processed dried black soldier fly larvae, including hot-air drying, boiling followed by hot-air drying, and autoclaving followed by hot-air drying, used as a 10% top-dressing replacement in commercial pelleted layer diets on production performance, egg quality, and economic returns of commercial laying hens.

2. Materials and Methods

Experimental animals

A total of 40 commercial brown laying hens at 30 weeks of age, with an initial average body weight of 1.68 ± 0.23 kg, were used. The study was conducted from 17 November 2025 to 4 January 2026, including a 1-week acclimation period followed by a 6-week experimental period. The hens were individually housed in battery cages (1 hen per cage; 40 × 40 × 35 cm) in an open-house system, provided with 16 hours of light per day and ad libitum access to drinking water. The hens were acclimated to the experimental diets for 1 week prior to a 6-week experimental period. The experiment was conducted under Animal Use License No. U1-03142-2559 and followed ethical principles and guidelines for animal care and use.

Experimental diet preparation

Black soldier fly larvae were reared on cabbage waste, which consisted mainly of discarded cabbage leaves and trimmed cabbage heads rejected during pre-market quality sorting. This material was continuously available throughout the year in the study area and was chopped into small pieces before being used as the larval substrate. Black soldier fly eggs were placed in plastic rearing trays (45 × 30 ×16 cm; width × length × height). After hatching, larvae were reared on organic waste, consisting mainly of food waste, vegetables, and fruits. Feed was provided in four age-based feeding periods, with 1.5 kg of substrate supplied during each period. At 15 days of age, larvae reached the prepupal stage and were harvested, cleaned, and prepared as whole dried larvae without grinding. The larvae were processed using three methods: (1) hot-air drying at 60 °C, (2) boiling at 100 °C for 20 minutes followed by hot-air drying at 60 °C, and (3) autoclaving at 121 °C for 20 minutes followed by hot-air drying at 60 °C. For all treatments requiring hot-air drying, larvae were dried at 60 °C for a minimum of 24 hours, and drying was continued until the moisture content did not exceed 10%, following the method of Rodríguez-Rodríguez *et al.* [11]. These methods were selected because they represent practical thermal processing approaches with different processing intensities, while maintaining the use of whole dried black soldier fly larvae for direct top-dressing application. A commercial layer diet containing 17% crude protein was used as the control (T1). Experimental diets were prepared by replacing 10% of the commercial diet with dried black soldier fly larvae on a weight basis (10% w w^{-1}; as-fed basis), consisting of T2 = hot-air dried larvae, T3 = boiled and hot-air dried larvae, and T4 = autoclaved and hot-air dried larvae. Samples of larvae and experimental diets were analyzed for chemical composition, including dry matter (DM), crude protein (CP), crude fiber (CF), ether extract (EE), and ash, according to AOAC [15], as shown in Table 1.

Table 1 Chemical composition of dried black soldier fly larvae and experimental diets (%).

Item	DM (%)	% of DM			
		CP	CF	EE	Ash
Dried black soldier fly larvae					
Hot-air dried larvae	97.89	39.32	6.15	41.30	8.91
Boiled and hot-air dried larvae	98.47	38.04	8.46	41.31	8.68
Autoclaved and hot-air dried larvae	98.48	37.72	7.24	42.16	8.81
Experimental diets					
T1	88.56	17.54	5.90	5.45	5.94
T2	89.49	19.72	5.93	9.03	6.24
T3	89.55	19.49	6.16	9.04	6.21
T4	89.55	19.46	6.03	9.12	6.23

Note: T1 = commercial layer diet (control); T2–T4 = commercial diet replaced with 10% dried black soldier fly larvae processed by hot-air drying, boiling and hot-air drying, and autoclaving and hot-air drying, respectively; DM = dry matter; CP = crude protein; CF = crude fiber; EE = ether extract; Ash = ash content.

Experimental design

A completely randomized design (CRD) was used with four treatments, each with 10 replicates, using one laying hen as the experimental unit. The treatments consisted of T1 = commercial diet, T2 = commercial diet replaced with 10% hot-air dried larvae, T3 = commercial diet replaced with 10% boiled and hot-air dried larvae, and T4 = commercial diet replaced with 10% autoclaved and hot-air dried larvae (Fig. 1).

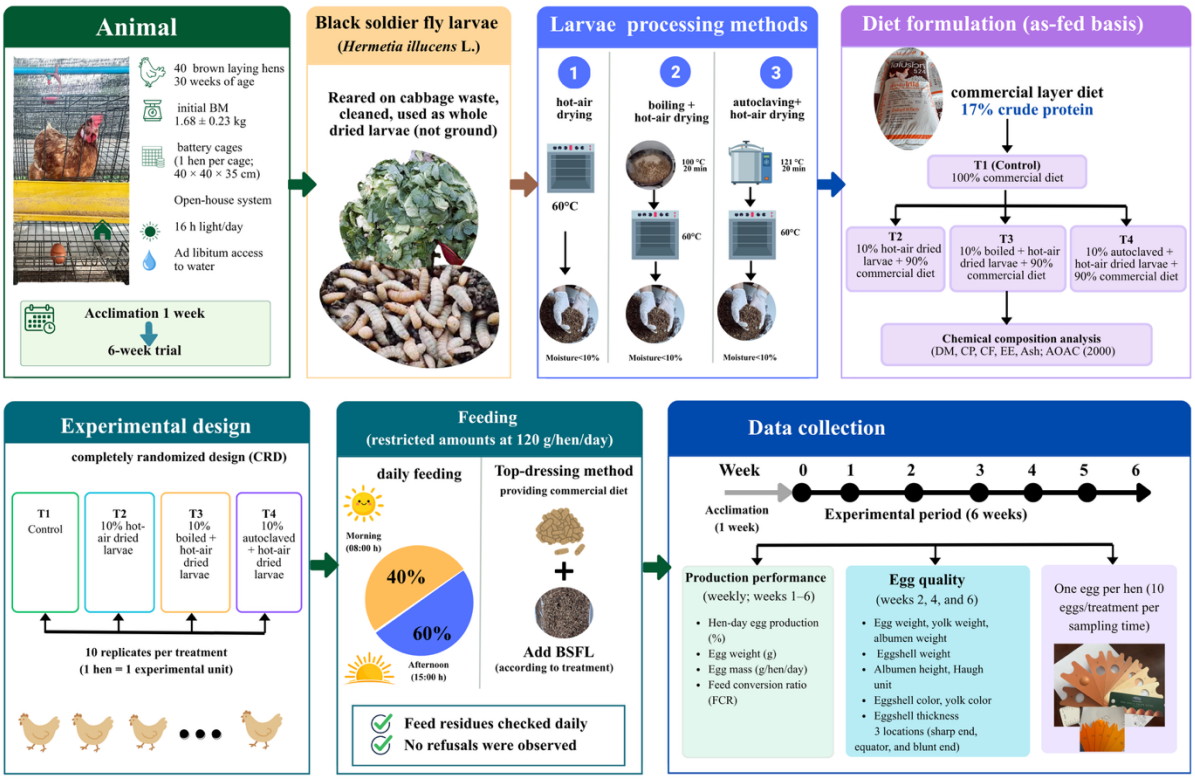


Fig. 1 Experimental workflow showing larvae processing, diet preparation with 10% top-dressing, feeding, and data collection.

Feeding and data collection

Feed was provided in restricted amounts at 120 g per hen per day for all treatments, following the recommendation of Dale [16]. The daily ration was divided into two meals: 40% in the morning and 60% in the afternoon. The top-dressing method was applied by first providing the commercial diet, followed by adding black soldier fly larvae according to the designated proportion. Feed residues were checked daily, and no refusals were observed throughout the experiment. Eggs were collected daily at 16:00 h, and the following data were recorded.

Production performance

Data were recorded weekly for 6 consecutive weeks (weeks 1-6), using each hen as the experimental unit, and the data were calculated as weekly means. The variables studied included hen-day egg production, egg weight, egg mass, and feed conversion ratio. These variables were calculated using standard equations commonly applied in laying hen performance studies [17, 18], as follows (1 - 4);

$$\text{HDEP (\%)} = \frac{\text{E}}{(\text{H} \times \text{D})} \times 100 \quad (1)$$

$$\text{EW (g)} = \frac{\text{TEW}}{\text{NE}} \quad (2)$$

$$\text{EM (g per hen per day)} = \frac{(\text{HDEP} \times \text{EW})}{100} \quad (3)$$

$$\text{FCR} = \frac{\text{ADFI}}{\text{EM}} \quad (4)$$

Where: HDEP is hen-day egg production (%), E is the total number of eggs collected, H is the number of hens, D is the number of experimental days, EW is egg weight (g), TEW is total egg weight (g), NE is the total number of eggs, EM is egg mass (g per hen per day), FCR is feed conversion ratio, and ADFI is average daily feed intake (g per hen per day).

Egg quality

Egg quality was evaluated every two weeks (weeks 2, 4, and 6). One fresh egg per hen was randomly collected at each sampling time, totaling 10 eggs per treatment per sampling. The parameters analyzed included egg weight, yolk weight, albumen weight, eggshell weight including membranes, albumen height, Haugh unit, eggshell color, yolk color, and eggshell thickness. Eggshell thickness was measured at three locations (sharp end, equator, and blunt end), and the average value was used to represent each egg. Eggshell color was measured using the Egg Shell Color Guide for Laying Hens (Zinpro Performance Minerals®, USA), which provides a visual color score ranging from 1

to 8. Lower scores indicate lighter eggshell color, whereas higher scores indicate darker brown eggshell color. Each egg was visually compared with the guide under the same lighting conditions, and the corresponding score was recorded. Yolk color was determined using the DSM Yolk Color Fan (DSM Nutritional Products, Netherlands). Data were summarized as treatment means for each sampling period, and values from weeks 2, 4, and 6 were averaged to obtain overall means per hen for the entire experimental period.

Economic analysis

Economic evaluation was conducted over the entire experimental period. All economic values were expressed in Thai Baht (THB), and an approximate exchange rate during the experimental period was applied (1 USD = 31.28 THB). The following components were considered:

1) Feed cost was calculated based on the actual feed consumption for each treatment. The price of the commercial layer diet was set at 16.00 THB per kg. For the black soldier fly larvae treatments, processing-adjusted unit costs were estimated based on the relative complexity of each preparation method. The baseline cost of dried black soldier fly larvae was set at 10.00 THB per kg, based on a reported cost estimate for black soldier fly larvae in Thailand derived from the energy cost of pilot-scale drying [19]. This baseline value was then adjusted using relative processing-complexity indices of 1.00 for hot-air drying (T2), 1.10 for boiling followed by hot-air drying (T3), and 1.20 for autoclaving followed by hot-air drying (T4). Accordingly, the estimated unit costs of dried black soldier fly larvae were 10.00, 11.00, and 12.00 THB per kg for T2, T3, and T4, respectively. Feed cost was calculated according to the 10% replacement level of the commercial diet with dried black soldier fly larvae (10% w w^{-1}; as-fed basis).

2) Egg revenue was calculated from the number of eggs produced, classified by egg size, and multiplied by farm-gate prices (THB per egg). Eggs were classified into seven sizes: size 0 (≥70 g), size 1 (65-69 g), size 2 (60-64 g), size 3 (55-59 g), size 4 (50-54 g), size 5 (45-49 g), and size 6 (≤44 g), with prices of 3.50, 3.40, 3.30, 3.20, 3.10, 3.00, and 2.90 THB per egg, respectively.

3) Net return, feed cost per egg, and benefit-cost ratio (BCR) were calculated using standard poultry economic evaluation approaches reported in previous studies [20, 21], as follows (5-7);

$$\text{NR (THB per hen)} = \text{TER} - \text{FC} \quad (5)$$

$$\text{FCE (THB per egg)} = \frac{\text{FC}}{\text{NE}} \quad (6)$$

$$\text{BCR} = \frac{\text{TER}}{\text{FC}} \quad (7)$$

Where: NR is net return (THB per hen), TER is total egg revenue, FC is feed cost, FCE is feed cost per egg (THB per egg), NE is the total number of eggs, and BCR is the benefit-cost ratio.

Statistical analysis

Production performance and egg quality data were analyzed using repeated measures analysis of variance (repeated measures ANOVA) under a completely randomized design (CRD). Treatment was considered the between-subject factor, whereas time (week) was considered the within-subject factor. The model included the main effects of treatment and time, as well as the treatment × time interaction. When significant treatment effects were detected ($P<0.05$), overall treatment means were compared using Duncan's new multiple range test (DMRT). When significant time effects or treatment × time interactions were detected, pairwise comparisons of estimated marginal means were performed using the Least Significant Difference (LSD) test to compare treatments within each time point and/or time points within each treatment. Statistical analyses were performed using SPSS version 29.0.1.1 (IBM Corp., Armonk, NY, USA).

3. Results and Discussion

Production performance of laying hens

The effects of replacing commercial diets with 10% dried black soldier fly larvae processed using different methods are presented in Table 2. Production performance parameters, including hen-day egg production, egg weight, egg mass, and feed conversion ratio (FCR), were significantly affected by treatment, time, and their interaction ($p<0.001$). For hen-day egg production, T3 showed the highest overall mean, followed by T2, T4, and T1, respectively ($p<0.001$), with an increasing trend toward the end of the experiment. Egg weight was significantly higher in T2 and T4 than in T1 and T3 ($p<0.001$). Egg mass was highest in T2, followed by T3 and T4, and lowest in T1 ($p<0.001$). For FCR, T2 showed the best feed efficiency, followed by T3 and T4, while T1 had the highest value ($p<0.001$), with FCR showing a decreasing trend toward the end of the experiment.

The results indicate that replacing commercial diets with 10% dried black soldier fly larvae processed using different methods significantly affected the production performance of laying hens. T2 and T3 showed better overall performance than the control, particularly in terms of egg production and egg mass, while T2 also exhibited the best feed efficiency (FCR). However, although statistically significant differences were observed, the magnitude of these differences was relatively small in biological terms and did not indicate any negative impact on production performance. This suggests that the use of black soldier fly larvae at this level can effectively replace commercial diets under the conditions of this experiment. This is consistent with previous reports indicating that the inclusion of black soldier fly larvae at low to moderate levels (approximately 3-12% of diet) can replace conventional protein sources without adversely affecting egg production, egg weight, or feed efficiency in laying hens [10, 22 - 24]. These findings indicate that the nutritional composition of black soldier fly larvae is adequate to meet the requirements of laying hens. The increased egg production and egg mass observed in

treatments receiving black soldier fly larvae, particularly T2 and T3, may be associated with higher nutrient density, as the larvae contain high levels of protein and fat, including medium-chain fatty acids such as lauric acid, which play a role in gut health and nutrient utilization in poultry [25]. In addition, although differences in FCR were observed among treatments, the values remained within a similar range, indicating that protein and energy from black soldier fly larvae were utilized with efficiency comparable to that of commercial diets [26]. However, it should be noted that the experimental diets supplemented with black soldier fly larvae contained higher levels of protein and fat than the control diet (Table 1), due to the use of a top-dressing approach without reformulating the diets to be nutritionally equivalent. Therefore, the comparable production performance observed may have been influenced by the increased nutrient density of the experimental diets, particularly protein and energy, which are key factors affecting egg production and feed efficiency [27].

Table 2 Laying performance of hens fed commercial diets partially replaced (top-dressing) with differently processed dried black soldier fly larvae.

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	p-value		
						Treatment	Week	Treatment ×Week
Hen-day egg production (%)								
T1	71.43±9.22^{c}	65.08±9.56^{c}	60.32±12.32^{c}	68.25±11.18^{b}	79.37±4.55^{a}	< 0.001	< 0.001	< 0.001
T2	79.37±3.46^{b}	79.37±4.20^{a}	73.02±6.02^{b}	76.30±9.13^{ab}	76.19±4.29^{a}			
T3	87.30±3.72^{a}	79.48±5.29^{a}	80.95±3.09^{a}	82.54±9.42^{a}	77.78±7.28^{a}			
T4	71.43±6.30^{c}	69.84±10.16^{bc}	74.60±9.99^{b}	76.19±9.28^{ab}	77.78±10.39^{a}			
Egg weight (g)								
T1	51.11±2.26^{b}	49.23±2.82^{b}	52.95±1.82^{b}	52.67±2.97^{b}	53.03±2.3^{b}	< 0.001	< 0.001	< 0.001
T2	55.36±1.64^{a}	54.83±2.17^{a}	57.94±1.78^{a}	58.95±1.17^{a}	58.85±1.56^{a}			
T3	48.31±1.60^{c}	49.12±1.90^{b}	51.96±1.20^{b}	52.99±1.51^{b}	53.36±1.1^{b}			
T4	55.30±1.04^{a}	57.29±1.17^{a}	57.10±1.18^{a}	59.18±1.16^{a}	58.27±1.04^{a}			
Egg mass (g per hen per day)								
T1	36.37±5.11^{c}	32.14±5.24^{c}	31.08±6.38^{c}	36.00±4.55^{b}	41.68±2.2^{b}	< 0.001	< 0.001	< 0.001
T2	43.82±1.83^{a}	43.70±3.12^{a}	42.90±4.53^{a}	44.89±4.44^{a}	45.03±2.76^{a}			
T3	42.41±3.32^{ab}	39.03±2.44^{b}	41.56±0.70^{a}	44.02±4.69^{a}	41.57±3.6^{b}			
T4	39.89±3.35^{b}	39.78±6.14^{b}	42.33±5.13^{a}	45.03±5.21^{a}	45.10±4.83^{a}			
FCR								
T1	3.36±0.49^{a}	3.83±0.65^{a}	4.02±0.90^{a}	3.38±0.45^{a}	2.88±0.16^{a}	< 0.001	< 0.001	< 0.001
T2	2.74±0.11^{c}	2.76±0.19^{b}	2.83±0.30^{b}	2.70±0.28^{b}	2.68±0.16^{ab}			
T3	2.84±0.22^{bc}	3.08±0.20^{b}	2.89±0.05^{b}	2.75±0.30^{b}	2.90±0.26^{a}			
T4	3.02±0.25^{b}	3.09±0.49^{b}	2.88±0.35^{b}	2.70±0.32^{b}	2.70±0.30^{ab}			

Means within the same column and parameter with different superscripts differ significantly (P<0.05).
Note: T1 = commercial diet (control); T2–T4 = commercial diet replaced with 10% dried black soldier fly larvae processed by hot-air drying, boiling followed by hot-air drying, and autoclaving followed by hot-air drying, respectively. FCR = feed conversion ratio.

Egg quality

The evaluation of egg quality is presented in Tables 3 and 4. Egg weight was significantly affected by treatment (p=0.003), with the highest overall mean observed in T4, followed by T2, T1, and T3. A significant treatment × week interaction was also observed for egg weight (p=0.025), whereas the main effect of week was not significant (p=0.324). This indicates that the treatment response in egg weight varied across the experimental periods. In particular, T2 and T4 showed higher egg weights in week 4, while T3 showed the lowest value in week 6. For egg component proportions, albumen and yolk proportions were not significantly affected by treatment, week, or treatment × week interaction (p>0.05). In contrast, shell proportion was significantly affected by treatment (p=0.024), with T3 showing the highest overall value and T2 showing the lowest value, whereas week and treatment × week interaction were not significant (p>0.05). For other internal egg quality parameters, including albumen height and Haugh unit, no significant effects of treatment, week, or treatment × week interaction were observed (p>0.05). However, yolk color showed a significant treatment effect (p=0.035), with T4 having a higher overall value than the other treatments, while the effects of week and treatment × week interaction were not significant (p>0.05). For eggshell structural quality parameters, shell thickness at the sharp end was significantly affected by treatment (p=0.045), with T1 and T4 showing higher overall values than T2. However, shell thickness at the equator and blunt end did not differ significantly among treatments (p>0.05). No significant week effects or treatment × week interactions were observed for shell thickness at any measured position (p>0.05). Eggshell color was not significantly affected by treatment, week, or treatment × week interaction (p>0.05). Overall, the results indicated that time had no significant effect on the measured egg component proportions, internal quality traits, or eggshell structural parameters, whereas treatment × week interaction was observed only for egg weight.

Table 3 Egg component proportions and internal quality parameters of laying hens fed commercial diets partially replaced (top-dressing) with differently processed dried black soldier fly larvae.

Treatment	Week 2	Week 4	Week 6	Overall	p-value		
					Treatment	Week	Treatment × Week
Egg weight (g)							
T1	54.37±5.10^{ab}	48.71±4.15^{b}	56.77±3.33^{a}	53.28^{bc}	0.003	0.324	0.025
T2	52.63±4.83^{ab}	58.93±2.24^{a}	56.43±5.70^{a}	56.00^{ab}			
T3	49.17±2.27^{b}	56.05±2.45^{ab}	47.31±2.54^{b}	50.84^{c}			
T4	56.53±3.33^{a}	58.15±7.98^{a}	59.69±3.17^{a}	58.13^{a}			
Albumen proportion (%)							
T1	61.14±3.06	60.53±0.66	61.80±2.46	61.15	0.110	0.215	0.169
T2	60.72±1.67	63.43±2.37	60.50±0.94	61.55			
T3	59.61±1.70	62.87±2.42	58.50±2.01	60.33			
T4	61.67±2.11	61.93±3.64	63.39±1.08	62.33			
Yolk proportion (%)							
T1	25.30±2.40	25.09±0.45	24.64±2.39	25.01	0.206	0.142	0.430
T2	26.26±1.27	24.32±1.90	26.08±0.99	25.55			
T3	26.19±1.02	23.84±1.83	26.71±1.31	25.58			
T4	25.17±1.91	24.60±2.11	23.77±0.44	24.51			
Shell proportion (%)							
T1	13.56±0.83	14.39±0.97	13.56±0.86	13.84^{ab}	0.024	0.758	0.357
T2	13.02±0.55	12.26±0.55	13.42±1.15	12.90^{c}			
T3	14.20±1.66	13.29±0.67	14.79±1.53	14.09^{a}			
T4	13.16±0.74	13.47±1.70	12.85±0.76	13.16^{bc}			
Albumen height (mm)							
T1	6.44±1.58	5.25±1.56	5.40±0.71	5.69	0.555	0.218	0.647
T2	6.78±0.95	6.07±0.14	5.50±1.03	6.11			
T3	5.91±0.88	5.38±1.12	5.63±0.69	5.64			
T4	5.45±0.83	5.22±1.28	6.08±0.98	5.58			
Haugh unit							
T1	80.84±10.10	73.98±12.64	72.94±5.60	75.92	0.417	0.153	0.645
T2	83.98±6.97	77.51±0.74	73.55±8.35	78.34			
T3	79.64±5.65	72.59±8.94	78.43±5.45	76.89			
T4	73.18±7.88	70.61±8.61	76.94±6.38	73.58			
Yolk color							
T1	12.25±0.96	11.25±0.50	12.00±0.82	11.83^{b}	0.035	0.182	0.365
T2	11.75±0.50	11.50±0.58	12.25±0.50	11.83^{b}			
T3	11.25±0.50	11.50±0.58	12.50±0.58	11.75^{b}			
T4	12.50±1.29	12.25±0.50	12.00±0.82	12.25^{a}			

Means within the same column and parameter with different superscripts differ significantly (P<0.05).
Note: Albumen, yolk, and shell proportions were calculated relative to whole egg weight.

Table 4 Eggshell structural quality parameters of laying hens fed commercial diets partially replaced (top-dressing) with differently processed dried black soldier fly larvae.

Treatment	Week 2	Week 4	Week 6	Overall	p-value		
					Treatment	Week	Treatment × Week
Shell thickness at sharp end (mm)							
T1	0.42±0.04	0.42±0.03	0.39±0.03	0.41^{a}	0.045	0.498	0.306
T2	0.37±0.05	0.39±0.05	0.40±0.03	0.38^{b}			
T3	0.40±0.01	0.43±0.03	0.38±0.03	0.40^{ab}			
T4	0.39±0.02	0.41±0.03	0.43±0.02	0.41^{a}			
Shell thickness at equator (mm)							
T1	0.41±0.05	0.43±0.03	0.40±0.05	0.41	0.200	0.212	0.758
T2	0.38±0.05	0.41±0.04	0.40±0.03	0.40			
T3	0.41±0.02	0.41±0.02	0.39±0.03	0.40			
T4	0.39±0.01	0.42±0.03	0.43±0.04	0.41			
Shell thickness at blunt end (mm)							
T1	0.42±0.04	0.40±0.05	0.40±0.03	0.40	0.280	0.434	0.436
T2	0.37±0.06	0.40±0.03	0.40±0.03	0.39			
T3	0.39±0.03	0.41±0.02	0.38±0.03	0.39			
T4	0.39±0.02	0.42±0.04	0.44±0.04	0.42			
Shell color							
T1	5.75±1.50	7.00±0.82	4.75±1.50	5.83	0.150	0.352	0.104
T2	6.00±1.63	6.75±0.96	5.25±1.50	6.00			
T3	7.00±0.82	5.50±1.29	7.00±0.00	6.50			
T4	6.25±1.26	4.75±0.96	5.25±1.71	5.42			

Means within the same column and parameter with different superscripts differ significantly (P<0.05)

The results indicate that replacing commercial diets with 10% black soldier fly larvae using a top-dressing approach can improve some internal egg quality parameters, particularly egg weight, albumen weight, and yolk weight. T2 and T4 showed significantly higher values in some periods and in the overall mean, reflecting that supplementation with black soldier fly larvae increased the nutrient density of the diet and enhanced the deposition of egg components. These findings are consistent with previous reports [28, 29], which indicated that the use of black soldier fly larvae can increase egg weight and internal egg components. The increase in egg weight and internal components may be related to adequate protein and amino acid content, as black soldier fly larvae contain amino acid profiles suitable for poultry, which play an important role in egg protein synthesis and nutrient deposition [5]. In addition, the high fat and energy content of black soldier fly larvae may enhance nutrient utilization, leading to increased deposition of albumen and yolk mass in supplemented treatments. For other internal egg quality parameters, including albumen height and Haugh unit, no differences were observed among treatments, indicating that supplementation with black soldier fly larvae at this level did not affect egg freshness or protein quality. These findings are consistent with Zhao *et al.* [10], who reported no significant effect of black soldier fly larvae on Haugh unit in laying hens. Regarding eggshell quality, differences were observed in shell weight and shell thickness at the sharp end, while thickness at the equator and blunt end was not different, suggesting that supplementation with black soldier fly larvae may influence mineral deposition in the eggshell to some extent. However, considering the overall structural parameters, including shell thickness at multiple positions and eggshell color, which were not significantly different among treatments ($p>0.05$), it can be concluded that supplementation with black soldier fly larvae at this level did not negatively affect overall eggshell quality, which is consistent with Zhao *et al.* [10].

Economic returns

The analysis of economic returns from egg production is presented in Table 5. T3 showed the highest total egg production, egg revenue, net return, and benefit–cost ratio (BCR), while having the lowest feed cost per egg, followed by T2. Compared with the control group, the use of dried black soldier fly larvae reduced feed cost per egg by 0.25, 0.37, and 0.05 THB per egg, equivalent to approximately 0.008, 0.012, and 0.002 USD per egg, for T2, T3, and T4, respectively. Net return increased by 109.44, 119.90, and 42.36 THB, equivalent to approximately 3.50, 3.83, and 1.35 USD, respectively. Among the black soldier fly larvae treatments, T3 showed the greatest economic benefit, with the lowest feed cost per egg (2.51 THB peregg) and the highest BCR (1.23). In contrast, T1 showed the lowest net return and BCR. Considering egg size distribution, treatments using black soldier fly larvae, particularly T2 and T4, had a higher proportion of medium to large eggs (sizes 2–4) than the control, which contributed to increased total revenue.

These results indicate that replacing commercial diets with 10% dried black soldier fly larvae tends to improve the economic efficiency of egg production, particularly in T3 and T2, which showed higher net return and BCR than the control. The main contributing factors were the higher number of eggs and greater proportion of medium to large eggs, together with reduced feed cost per egg, especially in T3, which had lower cost than the control under the condition that the cost of dried black soldier fly larvae was lower than that of commercial feed. This reduction in cost per unit of production reflects that black soldier fly larvae can be used as an alternative feed ingredient to partially replace commercial diets, with the potential to reduce production costs and improve the economic efficiency of egg production systems, consistent with previous reports indicating that insects can serve as alternative feed resources to reduce feed costs and enhance the sustainability of poultry production [5, 25, 30].

Table 5 Economic returns of egg production in laying hens fed commercial diets partially replaced with differently processed dried black soldier fly larvae.

Item	T1	T2	T3	T4
Total egg production, % (number of eggs)				
Size 0	1.43 (4)	2.71 (8)	0.96 (3)	1.08 (3)
Size 1	5.36 (15)	6.78 (20)	2.25 (7)	6.83 (19)
Size 2	5.71 (16)	23.73 (70)	5.14 (16)	21.58 (60)
Size 3	21.07 (59)	44.07 (130)	16.08 (50)	43.17 (120)
Size 4	34.29 (96)	17.63 (52)	46.95 (146)	25.54 (71)
Size 5	13.57 (38)	1.69 (5)	22.19 (69)	1.80 (5)
Size 6	18.57 (52)	3.39 (10)	6.43 (20)	0.00 (0)
Total egg, % (number of eggs)	100.00 (280)	100.00 (295)	100.00 (311)	100.00 (278)
Economic parameters				
Egg revenue (THB)	869.00	948.20	963.70	891.20
Feed cost (THB)	806.40	776.16	781.20	786.24
Net return (THB)	62.60	172.04	182.50	104.96
Feed cost per egg (THB per egg)	2.88	2.63	2.51	2.83
Benefit–Cost Ratio (BCR)	1.08	1.22	1.23	1.13

Note: Commercial layer feed price was 16.00 THB per kg. The estimated unit costs of dried black soldier fly larvae were 10.00, 11.00, and 12.00 THB per kg for T2, T3, and T4, respectively. Egg revenue was calculated based on egg size classes and farm-gate prices.

Considering the effects of processing methods of black soldier fly larvae, T3 (boiled and hot-air dried) tended to provide better overall results in terms of production performance, some egg quality parameters, and economic returns compared with T2 (hot-air dried) and T4 (autoclaved and hot-air dried). However, these differences were not observed in all parameters, indicating that the effects of processing methods are specific to the type of variable evaluated. These results may be related to the effects of heat on the structure and availability of nutrients, as wet heat can induce an appropriate level of protein denaturation, allowing digestive enzymes to access more easily and potentially improving amino acid utilization [31, 32], while also reducing microbial load and maintaining raw material quality [5, 33]. In contrast, hot-air drying alone may have less effect on protein structure [34], and high-temperature steaming may affect the availability of certain amino acids [35, 36]. However, this study did not directly evaluate nutrient digestibility or amino acid availability; therefore, further studies are needed to confirm these mechanisms.

Overall, the findings indicate that the inclusion of dried BSFL as a 10% top-dressing replacement in commercial layer diets can be implemented without detrimental effects on laying performance or egg quality under the conditions of this study. Among the processing methods evaluated, boiled and hot-air dried BSFL tended to provide the most favorable balance between productive performance and economic return. However, because the experimental diets were not formulated to be nutritionally equivalent and nutrient digestibility was not evaluated, the mechanisms underlying these responses remain uncertain. Further studies using isoenergetic and isonitrogenous diets, multiple inclusion levels, digestibility measurements, and longer production periods are necessary to confirm these findings.

Although dried black soldier fly larvae showed potential as a top-dressing replacement in layer diets, practical application requires careful consideration. The nutrient quality, microbial safety, and processing cost of dried black soldier fly larvae may vary depending on larval substrate, rearing conditions, drying method, and post-harvest handling. On-farm production may help farmers reduce feed cost and recycle organic waste, but it requires technical knowledge, labor, space, hygiene control, and consistent drying practices. Purchasing dried black soldier fly larvae from external suppliers may be more convenient for larger farms, but product quality, price stability, and supply consistency should be ensured. For industrial-scale application, stable supply chains, standardized processing, quality control, and clear cost accounting are required.

4. Conclusion

The present study suggests that replacing 10% of a commercial layer diet with dried black soldier fly larvae using a top-dressing approach can be implemented without detrimental effects on laying performance or overall egg quality under the conditions of this experiment. Among the experimental treatments, boiled and hot-air dried larvae (T3) appeared to be the most promising treatment, particularly in terms of egg production and economic return. However, because the experimental diets were not formulated to be nutritionally equivalent, the observed responses may partly reflect differences in dietary nutrient density rather than the effect of dried black soldier fly larvae or processing method alone. Further studies using nutritionally balanced diets, multiple inclusion levels, digestibility evaluation, long-term laying trials, and detailed cost accounting are required to confirm the practical and economic feasibility of dried black soldier fly larvae in commercial layer production systems.

5. Recommendations

Based on the results, the use of black soldier fly larvae at a level of 10%, particularly in the form of boiled and hot-air dried larvae, has the potential to be applied as a replacement for commercial feed in commercial laying hen farms in terms of production performance, some egg quality parameters, and economic efficiency. The present study was designed to evaluate the practical application of black soldier fly larvae as a top-dressing replacement under commercial feeding conditions rather than under nutritionally standardized experimental diets. Therefore, dietary nutrient composition differed among treatments, which should be considered when interpreting the observed responses. However, its application should consider the consistency of raw material quality and production cost in each context, together with appropriate feed formulation management. Since this study was conducted at only one replacement level, with a limited experimental period, and using a top-dressing method that resulted in differences in nutrient levels among the experimental diets, and did not directly evaluate nutritional mechanisms such as nutrient digestibility or amino acid availability, further studies should focus on comparing multiple replacement levels under nutritionally balanced diets, evaluating nutrient utilization mechanisms, and conducting long-term trials under practical farm conditions to clearly confirm effectiveness and economic feasibility in practical applications.

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7. Declaration of Generative AI in Scientific Writing

The authors used ChatGPT to assist with language editing only. All content was reviewed and approved by the authors, who take full responsibility for the final manuscript.

8. CRediT Author Statement

Panut Sooksoi: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Interpretation, Writing - review & editing. **Janejira Namee:** Conceptualization, Investigation, Data curation, Writing - original draft, Writing – review & editing, Supervision.

9. Research Involving Human and Animals Rights

This study involved animals only. All procedures were conducted in accordance with ethical principles and relevant guidelines for the care and use of animals.

10. Ethics Approval and Consent to Participate

The experiment was approved under Animal Use License No. U1-03142-2559.

11. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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