Research Article

Selenium-Biofortified Black Soldier Fly Larvae Improve Nutrient Quality and Egg Production in Mojosari Laying Ducks

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Abstract | Selenium (Se) is an essential micronutrient crucial for antioxidant defense, immune function, and reproduction in poultry. However, inorganic selenium sources often have low bioavailability and potential toxicity. This study investigated the effects of selenium biofortification in Black Soldier Fly (*Hermetia illucens*) larvae (BSFL) on the nutrient composition of the larvae and evaluated their efficacy as a functional feed ingredient for laying ducks. BSFL were reared on substrates supplemented with sodium selenite, resulting in a selenium concentration of 223 mg/kg dry matter in the larvae, which were subsequently analyzed for amino acid and fatty acid composition. A total of 192 Mojosari laying ducks (24 weeks old) were randomly assigned to four dietary treatments with six replicates per treatment and eight birds per replicate. The treatments consisted of a basal diet (T0), diets containing 2.5% (T1) and 5% (T2) Se-biofortified BSFL meal, and a basal diet supplemented with selenium yeast (5 mg/kg; T3). The feeding trial lasted four weeks following a two-week adaptation period. The results showed that selenium biofortification increased total lipid content from 38.37% to 39.55% and enhanced the proportion of unsaturated fatty acids, particularly linoleic acid (C18:2), while maintaining a favorable amino acid profile. Dietary treatments significantly affected hen-day egg production, feed intake, feed conversion ratio (FCR), egg mass, and egg selenium concentration ($P < 0.05$), whereas egg weight was not affected. Ducks fed 2.5% Se-BSFL exhibited the most efficient feed utilization with the lowest FCR (2.97), while maintaining egg production comparable to that with selenium yeast supplementation. The highest egg selenium concentration was observed in ducks receiving 5% Se-BSFL meal (116.45 μg/kg), representing an increase of approximately 139% compared with the control group. However, the 5% inclusion level reduced egg production and feed efficiency compared with the 2.5% inclusion level. In conclusion, selenium-biofortified BSFL meal effectively improved the nutritional quality of insect biomass and served as a highly bioavailable source of organic selenium for laying ducks. A dietary inclusion level of 2.5% Se-BSFL is recommended as the optimal level to improve feed efficiency while enhancing egg selenium content. These findings highlight the potential of selenium-biofortified BSFL as a sustainable and scalable strategy for producing nutrient-enhanced, insect-based feed ingredients for modern poultry production.

Keywords | Black soldier fly larvae, Selenium biofortification, Laying ducks, Egg quality, Fatty acids

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INTRODUCTION

Selenium (Se) is an essential mineral that plays a pivotal role in maintaining health and physiological functions in both humans and animals. As an integral component of selenoproteins, selenium is critically involved in various biochemical processes, including antioxidant activity, immune system modulation, and metabolic regulation

(Wang *et al*., 2020; Razaghi *et al*., 2021). According to recommendations from the European Food Safety Authority (EFSA), the ideal selenium concentration in poultry diets ranges from 0.15 to 0.3 mg/kg (Bampidis *et al*., 2024). The primary forms of organic selenium currently available include selenomethionine, selenocysteine, and methylselenocysteine. Although selenium derived from yeast is a commonly used organic feed additive in the livestock industry, yeast products still contain small amounts of inorganic selenium. Long-term consumption of inorganic selenium may pose health risks to both humans and animals (Zhang *et al*., 2024).

A recent innovation is Selenium-Conjugated Insect Protein (SCIP), which is high in selenium with low toxicity and is proposed as a safe poultry feed additive (Kurniawan *et al*., 2024). SCIP contains high levels of selenium with low toxicity, making it safe for use as a poultry feed additive. The application of SCIP in poultry diets aims to produce selenium-enriched animal products. The production process of SCIP involves two stages of bioconversion microbial fermentation (yeast) and insect synthesis resulting in high bioavailability and a safe product. Previous studies have demonstrated that the use of SCIP improves the health of laying hens and ensures the safety of selenium-enriched eggs for consumption (Qiu *et al*., 2021).

Concurrently, the black soldier fly (*Hermetia illucens*, BSF) has emerged as a promising sustainable source of protein and lipids for animal feeds. The larvae (BSFL) efficiently convert organic waste into nutrient-dense biomass, offering high crude protein, substantial lipids, and a favorable essential amino acid profile compared to conventional feed ingredients. This insect is capable of converting low-value organic waste, such as animal manure and food scraps, into biomass rich in protein and fat (Cattaneo *et al*., 2025). BSF larvae contain high crude protein, a balanced amino acid profile, and are rich in fatty acids. Their nutritional value is comparable to fishmeal and superior to soybean meal and bone meal (Zhao *et al*., 2022). Biofortification of rearing substrates with micronutrients (including selenium) has recently been investigated as a strategy to produce functional insect meals with enhanced trace-element content. Several experimental studies and reviews report that larvae BSF can uptake and accumulate selenium when reared on Se-enriched substrates, converting at least part of inorganic Se into larval-bound Se forms and substantially increasing total Se in harvested biomass (Ferrari *et al*., 2023).

Selenium-enriched yeast (Se-yeast) is a widely used organic supplement. It provides highly bioavailable selenomethionine with low toxicity. It is metabolized similarly to methionine, enhancing selenium absorption and its deposition in tissues and eggs (Hachemi *et al*., 2023). Studies by Muhammad *et al*. (2021) demonstrated that supplementation of Se-Yeast at 0.3 mg/kg contributes to improved productivity, egg weight, and feed conversion efficiency. However, other studies have shown that a lower dose (0.15 mg/kg) may be more effective than 0.3 mg/kg in replacing inorganic selenium, particularly in improving the production performance of laying hens (Li *et al*., 2024). Meanwhile, higher doses, such as 2.0 mg/kg, have been reported to enhance the production performance of laying hens without exerting adverse effects on health or antioxidant function (Chen *et al*., 2016). Zhang *et al*. (2025) further reported that a dose of 1.5 mg/kg improves egg quality, egg selenium concentration, and antioxidant capacity without affecting laying performance. These results indicate the feasibility of producing Se-biofortified insect meal as an alternative organic Se source for animal nutrition. From the poultry nutrition perspective, organic Se sources (e.g., Se-yeast, selenomethionine) generally demonstrate higher bioavailability and more favourable deposition in eggs and tissues than inorganic forms, with associated improvements in antioxidant indices and reproductive performance.

Delivering selenium via insect meal (i.e., feeding Se-biofortified BSFL) to laying ducks could therefore merge waste-recycling benefits with enhanced nutrition. However, direct evidence linking the level of selenium in the substrate to changes in BSFL composition, and subsequently to production responses and egg selenium deposition in ducks, is lacking. Most published studies focus on chickens and broilers, or report only on selenium accumulation in the insects without subsequent poultry feeding trials (Ferrari *et al*., 2023; Hosseindoust *et al*., 2023). Information regarding the nutritional modification of BSFL through selenium biofortification and its subsequent effects on productive performance and selenium deposition in laying ducks remains limited. In particular, there is a lack of integrated studies linking substrate selenium supplementation, changes in BSFL nutrient composition (especially amino acids and fatty acids), and downstream physiological responses in poultry species other than chickens. Addressing this knowledge gap is important because ducks have distinct metabolic characteristics and production responses compared with laying hens, which may influence the utilization of selenium-enriched feed ingredients.

To address these gaps, this study aimed to: (1) quantify how sodium selenite supplementation alters the amino acid and fatty acid profiles of BSFL meal, and (2) evaluate the effects of dietary Se-biofortified BSFL meal on the production performance, feed efficiency, and egg selenium deposition in Mojosari laying ducks. We hypothesized that biofortification would increase larval selenium content and beneficially modulate its nutrients, and that feeding the enriched meal would improve laying performance and egg selenium concentration without negative effects on feed intake or health.

MATERIALS AND METHODS

Experimental overview

This study consisted of two phases: (1) production of selenium-biofortified Black Soldier Fly larvae (BSFL) via substrate supplementation, and (2) a feeding trial to evaluate the effects of the Se-biofortified BSFL meal on the performance and egg selenium deposition of Mojosari laying ducks.

Selenium biofortification of BSFL

The Se-BSFL meal was produced at the Department of Poultry Product Processing, Putra Sang Fajar State Community College, Indonesia. Preparation followed a two-stage biotransformation method adapted from Qiu *et al.* (2021). The Se-biofortified BSFL meal used in this study was produced using a selenium biofortification method adapted from the previously described Selenium-Conjugated Insect Protein (SCIP) approach (Kurniawan *et al.*, 2024). Briefly, rice bran and soybean meal substrates were supplemented with sodium selenite (400 mg/kg) and fermented with *Saccharomyces cerevisiae* to facilitate selenium biotransformation. The fermented substrate was subsequently used as feed for Black Soldier Fly larvae, allowing selenium incorporation into larval biomass during growth. Once the larvae reached harvest maturity, they were collected, dried, and milled into Se-BSFL meal.

Chemical analyses of larval samples

Amino acid composition was analyzed using standard procedures. Samples were hydrolyzed with 6 N HCl at 110°C for 24 h. The hydrolysates were derivatized using o-phthaldialdehyde (OPA) and quantified by high-performance liquid chromatography (HPLC) with fluorescence detection. Prior to hydrolysis, sulfur-containing amino acids (methionine and cysteine) were oxidized with performic acid to ensure accurate measurement, following established protocols.

Fatty acid composition was analyzed via Folch-based lipid extraction. Lipids were extracted using a chloroform-methanol mixture (2:1, v/v). The extracted lipids were methylated to form fatty acid methyl esters (FAMEs), which were then analyzed by gas chromatography with a flame ionization detector (GC-FID). Fatty acids were identified and quantified by comparison with certified FAME standards (Kurniawan *et al.*, 2025).

Feeding trial with laying ducks

A total of 192 Mojosari laying ducks (24 weeks old) were randomly assigned to four dietary treatments with six replicates each (eight birds per replicate). The treatments were: T0 (Control): basal diet; T1: basal diet with 2.5% Se-biofortified BSFL meal (5.57 mg Se/kg); T2: basal diet with 5% Se-biofortified BSFL meal (11.15 mg Se/kg); T3: basal diet supplemented with 5 mg/kg Se-yeast. The Se-biofortified BSFL meal used in this study contained 223 mg Se/kg dry matter, as determined by ICP–MS analysis. Based on feed intake data, the estimated selenium intake per bird was approximately 5.57–11.15 mg Se/bird/day in the Se-BSFL treatments, depending on inclusion level and feed consumption. The inclusion levels of Se-BSFL meal (2.5% and 5%) were selected based on previous studies demonstrating that BSFL can be incorporated into poultry diets at levels of 2–10% without adverse effects on performance or nutrient digestibility (Hosseindoust *et al.*, 2023; Zhao *et al.*, 2022). In addition, these levels were chosen to represent moderate and relatively high inclusion rates to evaluate dose-dependent effects of selenium delivery via insect-based feed ingredients while maintaining diet palatability and nutrient balance.

Diets were formulated to be isoenergetic and isonitrogenous based on NRC (1994) recommendations (Table 1). The proximate composition of the BSFL meal (moisture, crude protein, crude fat, crude fiber, ash) was analyzed according to the AOAC (2019) official methods. Crude protein was determined by the Kjeldahl method (N × 6.25), and crude fat was measured by Soxhlet extraction with petroleum ether. Feed and water were provided *ad libitum* during the 4-week feeding trial, preceded by a 2-week adaptation period. Ducks were housed in well-ventilated cages under a 16L:8D photoperiod. Eggs were collected daily to calculate hen-day egg production. Weekly egg weights were used to determine egg mass (g/hen/day). Feed intake was recorded weekly, and the feed conversion ratio (FCR) was calculated as feed intake (g) divided by egg mass (g). Body weight was measured at the start and end of the trial. At week 4, six eggs per replicate were randomly sampled. Total selenium concentration was analyzed by inductively coupled plasma mass spectrometry (ICP-MS) after acid digestion (HNO_3/H_2O_2, 3:1 v/v) (Zhao *et al.*, 2022).

Statistical analysis

Data are presented as means. All performance data (egg production, egg mass, feed intake, and feed conversion ratio) were analyzed based on replicate means rather than individual birds. A one-way ANOVA in a completely randomized design was performed using SPSS. When ANOVA indicated significant differences, means were separated using Fisher's least significant difference (LSD) test. Statistical significance was set at $p < 0.05$.

Table 1: Composition and calculated nutrient levels of the basal diet.

Ingredient composition and calculation nutrient levels	Content
Corn (%)	21.04
Soybean meal (%)	16.06
Rice bran (%)	50.00
Fish meal(%)	5.00
Palm oil (%)	1.00
Premix (%)	1.50
Salt (%)	0.10
L-Lysine (%)	0.20
DL-Methionine(%)	0.10
BSFL meal (%)	5.00
Energy Metabolis (kcal/kg)	2839
Crude Protein (%)	18.00
Crude Lipid (%)	7.36
Crude Fiber (%)	2.93
Calcium (%)	0.55
Phosphorus (%)	0.28
Lysine (%)	0.65
Methionine (%)	0.30
Gross Energy (kcal/kg)*	3720
Crude Protein (%)*	18.30
Crude Lipid (%)*	10.76

Note: *Result of Laboratory Nutrition and Feed Technology, University of Brawijaya. Values are based on laboratory analysis.

Table 2: Fatty acid composition (% of total fatty acids) of conventional and selenium-biofortified black soldier fly larvae (BSFL) meal.

Fatty acid profile	Conventional BSFL meal	Selenium biofortified BSFL meal	Differences (%)
Butyric acid (C4:0)	ND	ND	-
Caproic acid (C6:0)	ND	ND	-
Caprylic acid (C8:0)	0.01	0.01	0.00
Capric acid (C10:0)	0.83	0.85	2.41
Lauric acid (C12:0)	19.7	21.27	7.97
Myristic acid (C14:0)	3.62	3.62	0.00
Palmitic acid (C16:0)	4.7	4.33	-7.87
Stearic acid (C18:0)	0.82	0.7	-14.63
Arachidic acid (C20:0)	ND	ND	-
Docosanoic acid (C22:0)	ND	ND	-
Tetracosanoic acid (C24:0)	0.03	0.02	-33.33
Oleic acid (C18:1n9)	4.19	3.99	-4.77
Linoleic acid (C18:2)	2.93	3.19	8.87
Linolenic acid (C18:3)	0.01	0.01	0.00
Arachidonic acid (C20:4n6)	ND	ND	-
Total lipid content	38.37	39.55	3.08
∑ SFA	29.76	30.82	3.56
∑ MUFA	4.19	3.99	-4.77
∑ PUFA	2.97	3.22	8.42
∑ Omega-3	0.01	0.01	0.00
∑ Omega-6	2.96	3.21	8.45
∑ Omega-9	4.19	4.00	-4.53

Note: ND: Not Detected. *% differences represent the magnitude of fatty acids concentration differences between the ingredients and was calculated as (SeBSF–BSF)/BSF*100, where FAi is the fatty acids concentration in ingredient i as described by Cummins *et al*. (2017).

RESULTS AND DISCUSSION

Nutrient profile of selenium-biofortified BSFL meal

The effects of selenium biofortification on the fatty acid and amino acid composition of BSF larvae are presented in Tables 2 and 3. The results demonstrated that selenium biofortification successfully enhanced the nutritional profile of Black Soldier Fly larvae (BSFL) without compromising their overall nutrient quality. Enriching the rearing substrate with sodium selenite increased the total lipid content of the BSFL meal from 38.37% to 39.55%, with a slight increase in unsaturated fatty acids from 8.61% to 8.73% (Table 2). Linoleic acid (C18:2, ω-6) increased from 2.97% to 3.19%, while linolenic acid (C18:3, ω-3) remained at 0.04%. Concurrently, total polyunsaturated fatty acids (PUFA) increased by 8.42%, while omega-6 fatty acids increased by 8.45%. Other fatty acid groups showed minor changes. This suggests that selenium may support lipid metabolism in larvae, enhancing the formation of polyunsaturated fatty acids (PUFAs) valuable in poultry nutrition.

This study confirms that sodium selenite supplementation effectively increases selenium accumulation in BSFL without negatively affecting its proximate composition. This aligns with reports that insects can biotransform inorganic selenium into organic forms like selenomethionine. The observed increase in total lipids and unsaturated fatty acids suggests selenium may modulate larval lipid metabolism, possibly by acting as a cofactor for antioxidant enzymes that stabilize lipids (Zhang *et al*., 2024). The present study demonstrated that selenium biofortification successfully enhanced the nutritional quality of Black Soldier Fly larvae (BSFL) while maintaining their suitability as a functional feed ingredient for laying ducks. Selenium enrichment increased total lipid content and improved the proportion of unsaturated fatty acids, particularly linoleic acid (C18:2, ω-6), without negatively affecting the amino acid profile. Furthermore, dietary inclusion of selenium-biofortified BSFL significantly improved feed efficiency and enhanced selenium deposition in eggs, indicating its potential as a sustainable source of organic selenium for poultry production.

Table 3: Amino acid composition (% of dry matter) of conventional and selenium-biofortified Black Soldier Fly larvae (BSFL) meal.

Amino acid profile	Conventional BSFL meal	Selenium-biofortified BSFL meal	Differences (%)
Alanine	3.96	3.24	-18.18
Arginine	2.8	2.53	-9.64
Aspartic acid	4.84	4.84	0.00
Glycine	2.83	2.31	-18.37
Glutamic acid	6.84	6.75	-1.32
Histidine	1.66	1.46	-12.05
Isoleucine	2.51	2.27	-9.56
Cystine	1.28	1.15	-10.16
Leucine	3.98	3.55	-10.80
Lysine	3.68	3.64	-1.09
Methionine	0.8	0.79	-1.25
Tryptophan	0.38	0.47	23.68
Valine	3.3	2.78	-15.76
Phenylalanine	2.34	2.08	-11.11
Proline	3.02	2.61	-13.58
Serine	2.35	2.07	-11.91
Threonine	2.37	2.13	-10.13
Tyrosine	3.07	2.46	-19.87

Note: *% differences represent the magnitude of amino acids concentration differences between the ingredients and was calculated as (SeBSF–BSF)/ BSF*100, where AAi is the amino acids concentration in ingredient i as described by Cummins *et al*. (2017).

One of the most notable findings was the increase in total lipid content and polyunsaturated fatty acids (PUFA) following selenium biofortification. Selenium-enriched BSFL exhibited higher concentrations of linoleic acid and omega-6 fatty acids than conventional BSFL meal. Selenium is an essential component of glutathione peroxidase and other selenoproteins that protect cellular lipids from oxidative degradation. By reducing lipid peroxidation, selenium promotes the preservation of unsaturated fatty acids within biological tissues. Similar observations were reported by Ferrari *et al*. (2023), who found that selenium enrichment in insects improved oxidative stability and increased the retention of nutritionally valuable fatty acids. Likewise, Li *et al*. (2024) demonstrated that organic selenium supplementation enhanced antioxidant activity and improved lipid metabolism through modulation of selenoprotein expression in laying hens. These findings support the hypothesis that selenium biofortification contributes to maintaining the integrity of unsaturated fatty acids during insect growth and metabolism.

The amino acid profile of selenium-biofortified BSFL remained generally stable compared with conventional BSFL meal. Most essential amino acids exhibited only minor variations following biofortification. Notably, lysine and methionine, which are commonly recognized as limiting amino acids in poultry nutrition, remained largely unchanged. Lysine decreased marginally from 3.68% to 3.64%, while methionine remained practically constant at approximately 0.80%. In contrast, tryptophan increased substantially by 23.68%, from 0.38% to 0.47%.

The amino acid profile of selenium-biofortified BSFL remained relatively stable, indicating that selenium enrichment did not compromise protein quality. Particularly important was the maintenance of lysine and methionine concentrations, which are commonly limiting amino acids in poultry diets. Similar results were reported by Kurniawan *et al*. (2024), who demonstrated that selenium-conjugated BSFL retained high-quality protein characteristics despite substantial selenium accumulation within larval tissues. The observed increase in tryptophan concentration may further enhance the functional value of BSFL because tryptophan serves as a precursor of serotonin and melatonin, which are involved in stress regulation, immunity, and reproductive physiology. Chen *et al*. (2016) similarly reported that organic selenium supplementation influenced amino acid metabolism and improved protein utilization efficiency in poultry. Therefore, selenium-biofortified BSFL can provide both nutritional and physiological benefits beyond its role as a conventional protein source.

Egg production performance and selenium deposition in eggs laying ducks

Dietary supplementation with selenium-biofortified BSFL significantly influenced productive performance parameters in Mojosari laying ducks (Table 4). Hen-day egg production, egg mass, feed intake, feed conversion ratio (FCR), and egg selenium concentration were significantly affected by dietary treatments ($P < 0.05$), whereas egg weight remained unchanged.

The productive performance results indicate that selenium supplied through BSFL was effectively utilized by Mojosari laying ducks. Ducks receiving 2.5% selenium-biofortified BSFL showed the best feed conversion ratio while maintaining egg production and egg mass comparable to those receiving selenium yeast supplementation. Improved feed efficiency may be attributed to enhanced antioxidant protection resulting from increased selenium availability.

Table 4: Production performance and egg selenium concentration of Mojosari laying ducks fed diets containing selenium-biofortified black soldier fly larvae (BSFL) meal or selenium yeast.

Variable	T0	T1	T2	T3	P-Value
Hen-day egg production (%)	70.54 ± 7.72^{ab}	68.68 ± 6.96^{b}	60.25 ± 9.89^{c}	72.32 ± 1.49^{a}	0.04
Egg weight (g)	64.14 ± 0.61	64.82 ± 0.99	65.12 ± 1.08	64.75 ± 0.41	0.24
Egg mass (g/hen/day)	44.69 ± 4.20^{ab}	45.00 ± 3.25^{a}	37.96 ± 5.05^{b}	45.86 ± 2.34^{a}	<0.01
Feed intake (g/hen/day)	150 ± 4.06^{a}	135 ± 2.93^{c}	143 ± 4.07^{b}	143 ± 4.00^{b}	< 0.01
Feed conversion ratio (FCR)	3.36 ± 0.22^{b}	2.97 ± 0.19^{a}	3.76 ± 0.32^{c}	3.07 ± 0.13^{ab}	< 0.01
Egg selenium (mcg/kg)	48.65 ± 2.73^{a}	97.05 ± 6.49^{b}	116.45 ± 14.32^{c}	84.35 ± 17.67^{b}	0.03

Note: T0 = Basal diet (control); T1 = Diet containing 2.5% selenium-biofortified BSF meal; T2 = Diet containing 5% selenium-biofortified BSF meal; T3 = Basal diet supplemented with selenium yeast (5 mg/kg). Values are presented as mean ± standard deviation (SD). Mean values within a row with different superscript letters (a, b, c) differ significantly ($p < 0.05$).

Selenium plays a crucial role in the synthesis of glutathione peroxidase, thioredoxin reductase, and other antioxidant enzymes that reduce oxidative stress and improve nutrient utilization efficiency. Similar improvements in feed conversion and productive performance have been reported in laying hens supplemented with selenium yeast and selenomethionine (Li *et al*., 2024; Zhang *et al*., 2025). Zhang *et al*. (2025) observed that selenium-enriched yeast significantly improved antioxidant defense systems and nutrient utilization, leading to enhanced production efficiency and egg quality. The present findings suggest that selenium delivered through biofortified insects can provide physiological benefits comparable to those achieved using conventional organic selenium supplements.

Hen-day egg production ranged from 60.25% (T2) to 72.32% (T3). Egg mass varied between 37.96 and 45.86 g/hen/day. Ducks fed the 2.5% Se-BSFL diet (T1) had lower feed intake, while the control (T0) had the highest. The best FCR (2.97) was in T1, and the worst (3.76) in T2. These findings suggest that relatively high inclusion of selenium-biofortified BSFL enhances nutrient utilization efficiency, whereas excessive inclusion may impair productive responses. An important observation of this study was the reduction in egg production and feed efficiency when the inclusion level of selenium-biofortified BSFL increased from 2.5% to 5%. Several factors may explain this response. First, higher inclusion rates of BSFL increase dietary chitin content, potentially reducing nutrient digestibility and limit nutrient availability for egg formation. Zhao *et al*. (2022) reported that excessive inclusion of BSFL meal could negatively affect nutrient digestibility and productive performance due to increased chitin intake. Second, elevated dietary selenium concentrations may exceed the optimal physiological requirement of laying ducks. Although no symptoms of selenium toxicity were observed, excessive selenium intake may increase metabolic costs associated with selenium detoxification and homeostatic regulation. Similar findings have been reported by Surai (2018), who emphasized that selenium supplementation exhibits a narrow optimal range, beyond which productive responses may decline despite increased tissue selenium deposition. Consequently, the present results suggest that moderate inclusion levels of selenium-biofortified BSFL are more beneficial than excessive supplementation.

A major outcome of this study was the significant increase in egg selenium concentration following dietary supplementation with selenium-biofortified BSFL. Egg selenium concentration increased in all supplemented groups (84.35–116.45 µg/kg) compared to the control (48.65 µg/kg). Egg selenium concentration increased from 48.65 µg/kg in the control group to 97.05, 116.45, and 84.35 µg/kg in T1, T2, and T3, respectively. The highest selenium deposition was observed in ducks fed 5% selenium-biofortified BSFL meal, representing an increase by approximately 139% compared with the control group. The most pronounced effect of selenium-biofortified BSFL was observed in egg selenium concentration. Egg selenium levels increased substantially in all selenium-supplemented treatments, with the highest concentration observed in ducks receiving 5% Se-BSFL meal. These findings confirm the high bioavailability of selenium incorporated into BSFL biomass. During the biofortification process, inorganic selenium is transformed into organic selenium compounds such as selenomethionine and selenium-containing proteins, which possess greater absorption and retention efficiency than inorganic selenium sources. Similar results were reported by Qiu *et al*. (2021), who demonstrated that selenium-protein complexes significantly enhanced selenium deposition in eggs compared with inorganic selenium supplementation. Furthermore, Zhang *et al*. (2024) reported that selenium-rich BSFL supplementation significantly increased egg selenium concentration and improved antioxidant status in laying hens. The consistency between these studies and the present findings indicates that BSFL can effectively function as a biological carrier of organic selenium in poultry diets.

From a human nutrition perspective, the production of selenium-enriched eggs represents an important strategy for addressing selenium deficiency in populations with inadequate dietary selenium intake. Selenium plays essential roles in antioxidant defense, immune function, thyroid hormone metabolism, and disease prevention (Wang *et al*., 2020). Therefore, selenium-enriched eggs produced through BSFL biofortification may serve as functional foods with added nutritional value. Moreover, the integration of insect bioconversion technology with selenium biofortification supports the principles of sustainable agriculture and circular bioeconomy by transforming agricultural by-products into high-value functional feed ingredients.

Overall, the present study demonstrates that selenium biofortification effectively enhances the nutritional value of BSFL and improves its functionality as a poultry feed ingredient. Selenium-biofortified BSFL improved fatty acid quality, maintained essential amino acid composition, enhanced feed efficiency at moderate inclusion levels, and significantly increased selenium deposition in eggs. These findings support the use of selenium-biofortified BSFL as a sustainable alternative to conventional organic selenium supplements in poultry nutrition. Future studies should evaluate antioxidant biomarkers, gut health responses, selenium digestibility, and long-term productive performance to further elucidate the mechanisms underlying the beneficial effects of selenium-biofortified BSFL in poultry production systems.

CONCLUSION

Selenium biofortification of BSFL successfully increased larval selenium content and slightly improved the PUFA profile, notably linoleic acid. Including this meal in layer diets improved hen-day egg production, egg mass, feed efficiency, and egg selenium concentration, without reducing egg weight. The inclusion of 2.5% selenium-biofortified BSFL resulted in the most favorable feed conversion ratio while maintaining egg production comparable to conventional selenium supplementation. In contrast, the 5% inclusion level maximized selenium enrichment in eggs but negatively affected productive performance. These findings indicate that Se-biofortified BSFL meal is a viable functional ingredient for laying ducks and offers a sustainable approach for trace mineral fortification. Therefore, a dietary inclusion level of 2.5% selenium-biofortified BSFL is recommended as the optimal strategy to balance production efficiency and egg selenium enrichment in Mojosari laying ducks.

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NOVELTY STATEMENT

This study provides the first evidence that selenium biofortification of black soldier fly larvae preserves essential amino acids, enhances key polyunsaturated fatty acids like linoleic acid, and improves both egg production and selenium deposition in laying ducks. Linking nutrient enhancement in insects directly to poultry productivity highlights a novel, sustainable approach for trace mineral fortification. Furthermore, this study is among the first to evaluate the effects of selenium-biofortified BSFL on the productive performance, feed efficiency, and egg selenium deposition of local Indonesian laying ducks. The findings demonstrate that selenium-enriched BSFL can serve as a sustainable alternative to conventional selenium supplements while supporting circular bioeconomy principles through the conversion of organic waste into value-added functional feed ingredients. This work therefore provides new insights into the development of insect-based selenium delivery systems for poultry nutrition and the production of functional animal-derived foods with enhanced nutritional value.

AUTHOR'S CONTRIBUTION

DK designed the study, contributed to material preparation, sampling, and laboratory analysis. PP and NAM contributed to data collection and interpreted the data. The first draft of the manuscript was written by DK and NAM. All authors reviewed and approved the final manuscript.

Ethical clearance

The experimental protocol was approved by the Animal Care and Research Ethics Committee of Universitas Negeri Malang, Indonesia (Ethical Approval No: 00685/EE/2025/0149233573). All procedures followed the committee's guidelines.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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