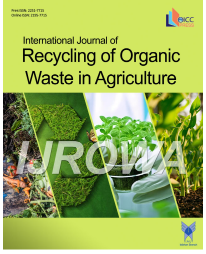

Volume 14, Issue 4, 142538 (1-7)

International Journal of Recycling of Organic Waste in Agriculture (IJROWA)

https://doi.org/10.57647/ijrowa.2025.16869

Enhancing agricultural waste bioconversion by Black Soldier Fly larvae through wheat bran supplementation

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Original Research

Received:
23 December 2024
Revised:
8 January 2024
Accepted:
12 April 2025
Published online:
28 May 2025

Abstract:

Purpose: The growing global challenge of waste management, amplified by population growth, demands sustainable solutions. Insect-based bioconversion, specifically using *Hermetia illucens* (Black Soldier Fly, BSF), offers an effective method for converting organic waste into protein-rich biomass.

Method: Various agricultural and food wastes were used as diets for BSF larvae and analyzed for their chemical composition. Pistachio hulls had the highest dry matter (94.27%) and ash content (9.60%), while date fruit waste had the highest carbohydrate content (91.55%). Cafeteria food waste had the highest crude protein (15.32%) and fat content (11.33%). Due to the high adhesiveness of date paste, larvae growth was restricted. Wheat bran was added to improve texture, reduce stickiness, and enhance larval feeding. The diets were evaluated based on growth indices such as weight gain (WG), specific growth rate (SGR), protein efficiency ratio (PER), and lipid efficiency ratio (LER).

Results: BSF larvae could not thrive on pure date paste due to its physical properties. However, the addition of wheat bran improved the substrate, resulting in better growth and survival rates. The best growth indices were observed in treatments with wheat bran alone or mixed with date paste, where WG and SGR were significantly enhanced. PER and LER also showed improved feed utilization.

Conclusion: An appropriate dietary balance is essential for optimizing BSF larvae growth, efficient mass rearing, and promoting sustainable waste management and protein production. Combining date by-products with wheat bran reduces waste, enhances sustainability, and provides a local protein source for poultry and aquaculture.

Keywords: Insect bioconversion; Protein production; Sustainable feed production; Waste reduction; Sustainable agriculture

1. Introduction

The Black Soldier Fly (BSF), *Hermetia illucens* L. (Diptera: Stratiomyidae), has emerged as one of the most effective organisms for the bio-conversion of organic waste into high-quality protein and lipids (Kim et al., 2011; Banks, 2014). BSF larvae are capable of thriving on a variety of substrates, including agricultural by-products and food waste, making them an effective solution for waste management and resource recovery (Caligiani et al., 2018). Their ability to convert low-quality biomass into valuable nutrients positions them as a sustainable source of feed for species such as fish, poultry, and pets (Kroeckel et al., 2012; Bosch et al., 2014; Li et al., 2016). BSF larvae contain protein levels ranging from 40 – 44% and fat content up to 49%, making them a promising alternative to conventional protein sources like fishmeal and soy (Gamero-Barraza et al., 2022; Silva et al., 2024). Furthermore, the antimicrobial peptides (AMPs) produced by BSF larvae are being explored as potential alternatives to traditional antibiotics, with antibacterial properties that could combat antibiotic-resistant bacteria (Di Somma et al., 2022; Scieuzo et al., 2023b).

In recent years, there has been growing interest in supplementing BSF larvae diets with agricultural by-products, such as wheat bran, to enhance the nutritional value of organic waste. Wheat bran, a by-product of wheat milling, is a valuable nutrient source that, when added to BSF larvae diets, has been shown to improve larval growth and the overall nutritional composition of the biomass (Danieli et al., 2019; Zolfaghari et al., 2022). The use of wheat bran not only enriches the larvae's nutritional content but also promotes more sustainable protein production by recycling agricultural waste (Mannaa et al., 2024). At the same time, achieving the Sustainable Development Goal (SDG) of "zero hunger" has led to large-scale agricultural and food production, resulting in an increase in agro-food waste (AFW) generation and higher handling costs to prevent environmental pollution (Ezeorba et al., 2024). Agro-food waste, which includes heterogeneous materials such as food scraps and agricultural residues like pomace, peels, and hulls, represents a significant global challenge. These wastes are often discarded through incineration, landfilling, or low-efficiency applications, but their potential for bioconversion using BSF larvae remains underutilized (Zolfaghari et al., 2022). Several studies have examined the impact of food and agricultural waste on BSF growth and bioconversion efficiency, highlighting both the advantages and challenges of using these substrates (Liu et al., 2018; Danieli et al., 2019; Scala et al., 2020; Zolfaghari et al., 2022; Kawasaki et al., 2022; Niknia et al., 2023; Scieuzo et al., 2023a). However, the suitability of specific waste materials requires further research to optimize their use in BSF farming systems.

One of the major agricultural wastes is date waste, which, in recent years, has contributed to global production reaching approximately 9.8 million metric tons of dates (FAO, 2022). The production process leads to significant fruit losses, estimated at around 30% (Najjar et al., 2020). These losses occur during harvesting, storage, or conditioning due to factors such as mechanical damage, improper handling, and environmental conditions. This waste contributes to serious environmental issues, including the emission of greenhouse gases (Amicarelli et al., 2021). Date palm waste possesses significant potential for conversion into valuable products. However, it is often discarded or utilized inefficiently, resulting in the production of low-value by-products.

This study aims to assess the effects of food and agricultural waste-based diets, particularly those supplemented with wheat bran, on the survival, growth, and development of BSF larvae. By addressing challenges related to the variability of waste materials and optimizing substrate composition, this research seeks to contribute to the development of sustainable protein production systems. Moreover, it aims to mitigate the environmental impact of organic waste accumulation while enhancing the efficiency of bioconversion processes, ultimately supporting the widespread use of BSF larvae in agricultural and livestock industries.

2. Materials and methods

Insect rearing and larvae preparation

Black soldier fly larvae were obtained from Babaei's insectarium in Sari, Mazandaran Province, and transported to the insectarium at Shahid Bahonar University of Kerman. The insectarium was divided into three sections: larval rearing, adult maintenance, and egg collection.

Larvae were reared in trays ($10 \times 40 \times 50$ cm) under controlled conditions ($25-30$ °C, 65 ± 5% relative humidity), feeding on fruit, vegetable, and cafeteria waste. Upon reaching the prepupal stage, they were transferred to separate containers and subsequently to adult cages.

Adults were kept in mesh cages ($1 \times 1 \times 1.5$ m) under similar conditions ($25-30$ °C, $50-70$% relative humidity). They were provided with water but no food. Mating was facilitated with natural light supplemented by artificial lighting (12 h light: 8 h dark). Egg-laying was promoted using a fruit waste container covered with mesh and bundled wooden sticks.

Collected eggs were placed on mesh screens above a dilute wheat bran and water mixture as larval feed. Optimal conditions ($25-28$°C, $65-80$% relative humidity) were maintained for egg hatching. Hatchlings were fed on the mixture for three days before being transferred to rearing trays. Five-day-old larvae were then moved to the entomology lab for experimental studies.

Preparation of insect diets

Twelve dietary treatments were prepared for the experiment (Table 1).

All treatments were sun-dried, ground, and sieved before being mixed with distilled water to achieve a paste-like consistency.

To determine the nutritional composition and analyze the nutrient content of the diets utilized in this study, completely homogeneous samples from each treatment were sent to the Central Laboratory of Shahid Bahonar University of Kerman, where they underwent standard chemical analyses. The crude fat content was determined using the Soxhlet extraction method with ether as the solvent. A sample ($1-2$ g) was wrapped in filter paper, weighed, and subjected to extraction for 6 hours. After solvent evaporation and drying in an oven, the final weight was recorded, and crude fat was calculated based on the weight difference (Helrich, 1990). Crude protein content was measured using the Kjeldahl method with an automatic Kjeldahl apparatus (model K-370). One gram of the sample was digested with sulfuric acid, and nitrogen content was determined. The crude protein percentage was calculated by multiplying the nitrogen content by a conversion factor of 6.25 (Helrich, 1990). Ash content was determined by weighing 2 g of the sample into a crucible and incinerating it at 550 °C for 5 hours. After cooling in a desiccator, the crucible was reweighed, and ash percentage was calculated (Helrich, 1990). Total carbohydrate content was estimated by difference, subtracting the sum of crude fat, crude protein, ash, and moisture percentages from 100 (Helrich, 1990). The results derived from these analyses served as the foundation for assessing the effects of the various diets on the growth parameters of the soldier fly larvae.

Effect of different diet regimens on survival rate and growth indices of Black Soldier Fly larvae

In this experiment, 15 five-day-old black soldier fly larvae were introduced to 15 grams of different dietary regimens in containers measuring 5 centimeters in diameter and height, with 10 replicates (ten repetitions were considered for each of the dietary treatments in the experiments). The petri dishes were covered with mesh. The experiment was conducted over a period of 10 days in a growth chamber located in the Entomology Laboratory of the Faculty of Agriculture at Shahid Bahonar University of Kerman. Environmental conditions were maintained at 26 ± 2 °C, 60 ± 5% relative

Table 1. Composition and description of dietary treatments used in the experiment.

No.	Dietary treatment	Abbreviation	Source	Preparation process
1	University cafeteria food waste	F	Shahid Bahonar University cafeteria	Collected over one week, sun-dried, ground, and sieved
2	Sour grape pomace	G	Local fruit juice vendors	Pomace obtained from juice extraction, sun-dried, ground, and sieved
3	Lemon peel residue	L	Local fruit juice vendors	Peel residue after juice extraction, sun-dried, ground, and sieved
4	Pistachio hull	P	Pistachio processing companies	Collected from processing factories, sun-dried, ground, and sieved
5	Wheat bran	B	Commercial sources	Purchased ready-made, sun -dried, ground, and sieved
6	Date fruit waste	D	Parsun Dey Symbol Co., Kerman	Includes varieties such as Rabbi, Mazafati, and Zahedi; sun-dried, ground, and sieved
7	Equal mixture of wheat bran and cafeteria food waste	BF	Combination of B and F	Prepared separately and mixed in equal proportions
8	Equal mixture of wheat bran and sour grape pomace	BG	Combination of B and G	Prepared separately and mixed in equal proportions
9	Equal mixture of wheat bran and lemon peel residue	BL	Combination of B and L	Prepared separately and mixed in equal proportions
10	Equal mixture of wheat bran and pistachio hull	BP	Combination of B and P	Prepared separately and mixed in equal proportions
11	Equal mixture of wheat bran and date fruit waste	BD	Combination of B and D	Prepared separately and mixed in equal proportions
12	Equal mixture of wheat bran, cafeteria food waste, sour grape pomace, lemon peel residue, pistachio hull, and date fruit waste	BFGLPD	Combination of B, F, G, L, P, and D	Prepared separately and mixed in equal proportions

humidity, and full light intensity. To prevent the substrate from drying out and to ensure the larvae could continue feeding, water was added to the substrate every other day. After a 10-day period, the larvae were collected from the rearing substrate and subjected to a 24-hour fasting period to facilitate the clearance of their intestines. Subsequently, the final weight of the larvae was recorded, and the larvae were counted. They were then frozen and stored at −18 °C for further analysis.

Calculated parameters

Following the experimental procedures, the parameters including Survival Rate (SR), Body Weight Gain (WG), Specific Growth Rate (SGR), Protein Efficiency Ratio (PER), and Lipid Efficiency Ratio (LER) were calculated using the methods outlined below (Hamza et al., 2008; Zamani and Goli, 2021).

$$\mathrm{SR} = \left(\frac{N_t}{N_0}\right) \times 100$$

$$\mathrm{WG} = W_t - W_0$$

$$\mathrm{SGR} = \left(\frac{\ln(W_t) - \ln(W_0)}{t}\right) \times 100$$

$$\mathrm{PER} = \frac{\mathrm{WG}}{\mathrm{TP}}$$

$$\mathrm{LER} = \frac{\mathrm{WG}}{\mathrm{TL}}$$

where:

- N_t = Number of larvae at the end of the experiment
- N_0 = Number of larvae at the beginning of the experiment
- W_t = Final weight of the larvae
- W_0 = Initial weight of the larvae
- t = Number of days of the experiment
- F = Amount of food consumed by each larva
- Total protein ingested (TP) = F × Percentage of protein in the diet
- Total lipid ingested (TL) = F × Percentage of lipid in the diet

Data analysis

To assess the validity of the underlying assumptions, the data were initially evaluated for normality and homogeneity of variance using Bartlett's test (Köhler et al., 2012). Data that did not meet the assumption of normality were transformed using the Box-Cox transformation to satisfy the necessary assumptions. The transformed data were then analyzed using one-way ANOVA in Statplus statistical software (version 4.9, 2007), with Fisher's Least Significant Difference (LSD) post-hoc test applied for pairwise mean comparisons. All statistical analyses were conducted at a significance level of 0.05.

3. Results and discussion

Results and discussion of the chemical analysis of dietary treatments

The results of the chemical analysis for dry matter, crude protein, crude fat, carbohydrates, and ash content are presented in Table 2. As shown in the Table, the highest dry matter content was observed in treatment P (94.27%), while the lowest was recorded in treatment B (92.54%). Regarding crude fat, the highest and lowest values were found in treatments F and BD, respectively, with 11.33% and 2.52%. Treatment F had the highest crude protein content (15.32%), while treatment D had the lowest (2.38%). For ash content, treatments P and D exhibited the highest and lowest values, respectively, with 9.60% and 1.61%. Finally, treatment D had the highest total carbohydrate content (91.55%), whereas treatment F had the lowest (68.32%).

Table 2. Chemical analysis of the dietary treatments.

Dietary treatment (Abbreviation)	Dry matter (%)	Crude fat (%)	Crude protein (%)	Ash (%)	Total carbohydrates (%)
F	93.77	11.33	15.32	5.03	68.32
G	93.92	3.58	10.79	4.09	81.54
L	94.17	4.62	6.90	7.64	80.84
P	94.27	6.05	10.08	9.60	74.27
B	92.54	4.04	14.39	7.53	74.04
D	93.75	4.46	2.38	1.61	91.55
BF	93.19	7.12	15.15	5.06	72.67
BG	93.53	5.25	11.89	6.72	76.14
BL	92.92	3.81	10.46	7.45	78.28
BP	93.52	5.50	11.57	6.25	76.68
BD	93.17	2.52	8.12	6.61	82.75
BFGLPD	93.88	4.20	10.04	6.00	79.76

The dietary treatments included food waste in the university cafeteria (F), sour grapes pomace (G), lemon peel residue (L), pistachio hull (P), wheat bran as the control (B), date fruit waste (D) wheat bran combined with food waste in the university cafeteria (BF), wheat bran with sour grapes pomace (BG), wheat bran with lemon peel residue (BL), wheat bran with pistachio hull (BP), wheat bran with date fruit waste (BD), and a comprehensive mixture of wheat bran, cafeteria food waste, sour grapes pomace, lemon peel, pistachio hull, and date fruit waste (BFGLPD).

These differences in the composition of the raw materials used in each treatment can be attributed to the varying nutrient content. The student cafeteria waste likely contains richer sources of fat and protein, while date and wheat bran waste primarily provide carbohydrates and fiber, with lower fat and protein content. This disparity in nutrient composition explains the observed variations in fat, protein, and carbohydrate levels across the treatments. Given the contrasting levels of protein, fat, and carbohydrates in date waste and student cafeteria food waste, these differences offer an opportunity to assess the impact of each nutrient on larval growth. Previous studies have indicated that protein plays a critical role in the structural development and metabolic processes of insects (Sharma et al., 2024), while fat serves as an energy source during various growth stages, carbohydrates provide immediate energy for daily activities and growth (Arrese and Soulages, 2010). By evaluating larval growth factors and survival rate across different treatments, the specific role of protein, fat, and carbohydrates in larval development can be better understood.

The findings revealed that the larvae of this insect are incapable of growing, developing, or surviving on date waste paste (D). This incompatibility between the feeding substrate and larval survival in date waste substrate can primarily be attributed to the physical characteristics of the substrate, such as its structural integrity and adhesiveness, rather than its nutritional composition. In contrast, the incorporation of wheat bran into the feeding substrates of black soldier fly larvae, due to its high fiber content, improved the texture of the substrate, reduced its stickiness, and facilitated larval movement and feeding. These modifications enhanced the larvae's access to nutrients, thereby promoting better survival and growth. Zolfaghari et al. (2022) further emphasized that the survival rate of the larvae of this insect is strongly influenced by the physical properties of the feeding substrate, particularly its texture and fiber content. Their findings suggest that substrates with higher fiber content significantly contribute to the structural integrity of the medium, which in turn enhances the larvae's ability to feed, grow, and ultimately survive.

Results and discussion of the experimental treatments

In this study, treatment D was excluded as none of the 150 larvae tested survived. The lowest survival rate (SR) was observed in treatment F ($55.66 \pm 7.52\%$), showing a significant difference compared to all other treatments ($p < 0.0049$) (Table 3). In contrast, the highest SR was recorded in treatment BG ($95.99 \pm 2.03\%$). Additionally, SR values in treatments L, B, BF, BG, BL, BP, BD, and BFGLPD were significantly higher than those in treatments F, G, and P ($p < 0.0099$).

Body weight gain (WG) data depicted in Table 3 revealed that treatment P exhibited the lowest WG (0.006 ± 0.0002 g), significantly different from treatments L, B, BF, BG, BL, BP, and BD ($p < 0.0002$), but not significantly different from treatments F, G, and BFGLPD. Conversely, the highest WG was observed in treatment B (0.068 ± 0.0029 g), which was significantly different from all other treatments ($p < 0.00001$).

Specific growth rate (SGR) results shown in Table 3 indicated that treatment F had the lowest SGR ($24.48 \pm 0.007\%$), significantly different from treatments L, B, BF,

Table 3. Comparison of mean (± SE) of Larval Survival Rates (SR), Weight Gain (WG), Specific Growth Rate (SGR), Protein Efficiency Ratio (PER), and Lipid Efficiency Ratio (LER) of the Black Soldier Fly across various dietary treatments.

Dietary Treatment (Abbreviation)	Survival rate (SR) (%)	Weight gain (WG) (g)	Specific growth rate (SGR) (%)	Protein efficiency ratio (PER)	Lipid efficiency ratio (LER)
F	56.66 ± 7.52^{a}	0.006 ± 0.0004^{a}	24.48 ± 0.007^{a}	0.211 ± 0.0142^{a}	0.286 ± 0.0191^{a}
G	71.99 ± 6.11^{b}	0.006 ± 0.0003^{a}	24.49 ± 0.005^{a}	0.282 ± 0.0132^{ab}	0.851 ± 0.039^{ab}
L	93.33 ± 1.72^{c}	0.019 ± 0.0011^{c}	24.66 ± 0.014^{de}	1.385 ± 0.0898^{e}	2.069 ± 0.119^{e}
P	73.33 ± 4.66^{b}	0.006 ± 0.0002^{a}	24.49 ± 0.0037^{a}	0.295 ± 0.0115^{ab}	0.492 ± 0.0191^{a}
B	95.33 ± 1.73^{c}	0.068 ± 0.0029^{f}	25.24 ± 0.0225^{e}	2.368 ± 0.1009^{f}	8.436 ± 0.359^{g}
D	0	NA	NA	NA	NA
BF	93.33 ± 1.72^{c}	0.027 ± 0.0031^{d}	24.81 ± 0.02^{cd}	0.894 ± 0.1026^{d}	1.903 ± 0.2183^{de}
BG	95.99 ± 2.03^{c}	0.016 ± 0.0008^{c}	24.63 ± 0.011^{bc}	0.677 ± 0.0321^{cd}	1.533 ± 0.0728^{cde}
BL	94.66 ± 1.33^{c}	0.03 ± 0.0012^{d}	24.79 ± 0.016^{cd}	1.442 ± 0.0564^{e}	3.961 ± 0.1548^{f}
BP	89.99 ± 2.48^{c}	0.014 ± 0.0011^{bc}	24.6 ± 0.014^{b}	0.642 ± 0.461^{c}	1.35 ± 0.0969^{bcd}
BD	89.99 ± 2.67^{c}	0.06 ± 0.0023^{e}	25.11 ± 0.027^{de}	3.707 ± 0.1418^{g}	11.947 ± 0.4569^{h}
BFGLPD	87.33 ± 3.50^{c}	0.01 ± 0.0008^{ab}	24.54 ± 0.008^{ab}	0.502 ± 0.0392^{bc}	1.202 ± 0.0936^{bc}

The dietary treatments included food waste in the university cafeteria (F), sour grapes pomace (G), lemon peel residue (L), pistachio hull (P), wheat bran as the control (B), date fruit waste (D) wheat bran combined with food waste in the university cafeteria (BF), wheat bran with sour grapes pomace (BG), wheat bran with lemon peel residue (BL), wheat bran with pistachio hull (BP), wheat bran with date fruit waste (BD), and a comprehensive mixture of wheat bran, cafeteria food waste, sour grapes pomace, lemon peel, pistachio hull, and date fruit waste (BFGLPD), (Means were compared using Fisher's Least Significant Difference (LSD) test at the 5% significance level).

BG, BL, BP, BD, and BFGLPD ($p < 0.004$), but not from treatments G and P. Treatment B exhibited the highest SGR ($25.24 \pm 0.0225\%$), significantly differing from all other treatments ($p < 0.00001$).

Treatment F exhibited the lowest protein efficiency ratio (PER) at 0.211 ± 0.0142 (Table 3), significantly differing from treatments L, B, BF, BG, BL, BP, BD, and BFGLPD ($p < 0.0046$), but showing no significant variation compared to treatments G and P. Conversely, treatment BD recorded the highest PER at 3.707 ± 0.1418, with statistically significant differences observed against all other treatments ($p < 0.00001$).

As illustrated in Table 3, the lipid efficiency ratio (LER) was lowest in treatment F (0.286 ± 0.0192), significantly differing from treatments L, B, BF, BG, BL, BP, BD, and BFGLPD ($p < 0.0018$), but not from treatments G and P. Treatment BD showed the highest LER (11.947 ± 0.4569), significantly exceeding all other treatments ($p < 0.00001$).

In this study, the results indicated that both the wheat bran treatment and the combination of wheat bran and date waste produced the most favorable outcomes across all four growth factors (WG, SGR, PER, and LER). Despite lower levels of crude fat and crude protein in these diets compared to other treatments, they were rich in carbohydrates and fiber, showing higher relative palatability. This suggests that elevated levels of protein and fat do not significantly influence larval growth. Similarly, Scala et al. (2020) found that adding spent grain to fruit waste positively impacted the biomass production of *H. illucens* larvae. In their study, larvae fed a mixture of apple and spent grain produced twice the biomass compared to those fed apples alone. This suggests that elevated levels of protein and fat do not significantly influence the growth of larvae. In the study by Kawasaki et al. (2022), increasing protein levels in the diet of black soldier fly larvae negatively impacted their survival, growth, and development. Additionally, Liu et al. (2018) demonstrated that the role of carbohydrates in the growth and development of these larvae is equally as crucial as that of protein. Danieli et al. (2019) found that although the protein and fat content in the diet did not directly impact the concentration of these compounds in the larvae's body, diets rich in carbohydrates and fiber significantly increased fat accumulation in the larvae. This highlights the significant role of dietary composition in lipid deposition (Franco et al., 2024). In line with the findings of Niknia et al. (2023), the mixed diet of day-old chick feed and hemp seed meal, with its well-balanced composition of protein, fat, and carbohydrates, proved to have the most beneficial effect on the growth and development of *H. illucens* larvae. In addition to protein and fat, other factors such as ash, micronutrients, fiber, and fatty acids play a significant role in the growth and development of *H. illucens* larvae. Scieuzo et al. (2023a) found that *H. illucens* larvae thrived on fruit waste, with strawberry being the most effective for growth. Although the protein and lipid levels were similar, significant differences were observed in ash content, micronutrients, and other compounds. The analysis of various dietary treatments and their resulting outcomes reveals that the appropriate balance of these key components plays a pivotal role in the effectiveness of the diets on the larvae's biological performance. This optimal balance not only promotes the growth and development of the larvae but also enhances the overall efficiency of *H. illucens* mass rearing. Furthermore, aside from the aforementioned factors, the physical structure of the feeding substrate, secondary metabolites present in plant materials, as well as essential minerals and vitamins, play an integral role in the nutritional quality of different diets. These elements can influence nutrient absorption by the larvae, thereby affecting their growth and development. Consequently, a more in-depth investigation of these factors is warranted to improve the efficacy of the diets and enhance productivity in *H. illucens* rearing.

4. Conclusion

This study demonstrates that wheat bran supplementation significantly enhances the bioconversion of agricultural waste by *H. illucens* larvae. Among the diets tested, the combination of wheat bran and date waste yielded the best results in weight gain, specific growth rate, protein efficiency ratio, and lipid efficiency ratio. Although this diet contains lower protein and fat levels, its optimal balance of carbohydrates and fiber is crucial for improved larval development and nutrient conversion. While date waste alone is insufficient, its supplementation with wheat bran proves effective. Further research is needed to explore alternative byproducts that can replace wheat bran without compromising performance. The findings hold significant implications for sustainable waste management and insect-based feed production, offering a cost-effective, nutrient-efficient alternative for livestock and aquaculture feeds. Additionally, factors such as substrate structure, micronutrient availability, and secondary metabolites may influence larval growth, necessitating further investigation along with large-scale feasibility studies to evaluate economic and environmental impacts.

Acknowledgment
Thanks are extended to Mr. Ebrahim Babaei for providing the insect larvae and to Parsun Dey Symbol Company for supplying the date by-products for this research.

Authors contributions
Conceptualization: K. Ahmadi; Methodology: K. Ahmadi, M. Asadi; Data Collection: Z. Raeiszadeh; Formal Analysis: Z. Raeiszadeh, K. Ahmadi; Writing – Original Draft: Z. Raeiszadeh, K. Ahmadi; Writing – Review & Editing: Z. Raeiszadeh, K. Ahmadi, M. Asadi; Scientific Analysis: K. Ahmadi, M. Asadi; Preparation of Final Draft: K. Ahmadi; Funding Acquisition: K. Ahmadi, Z. Raeiszadeh. All authors have read and approved the final version of the manuscript.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
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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