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RESEARCH ARTICLE

An innovative continuous self-separation reactor to process rural food waste using black soldier fly larvae

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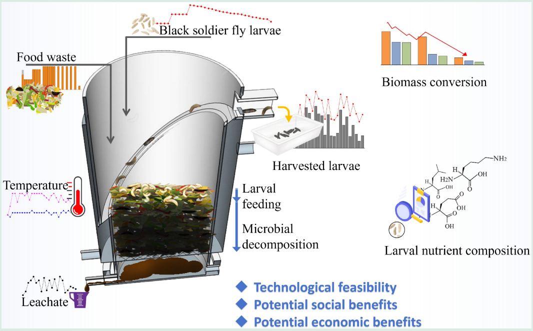
HIGHLIGHTS

- Rural food waste has stable properties and is suitable as a food source for BSFL.
- An innovative BSFL continuous self-separation reactor was developed.
- The single-batch mode operated for 10 d, reducing food waste by 38.9%.
- The continuous multi-batch mode operated for 32 d, reducing food waste by 56.6%.



ABSTRACT: The utilization of black soldier fly larvae (BSFL) in food waste treatment has garnered significant attention because of its alignment with the principles of a circular economy. However, in rural areas, inadequate management of waste segregation and a high proportion of difficult-to-decompose materials in food waste have reduced the treatment rate by BSFL. After a year-long investigation into rural food waste, we designed a BSFL continuous self-separation reactor, which incorporated microorganisms to enhance waste degradation. The reactor also maintained heat retention, facilitated leachate collection, and enabled the continuous feeding and automated separation of adult black soldier flies. Both single-batch and multi-batch continuous operation modes of the reactor consistently and effectively treated food waste. In the single-batch mode, operation for 10 d resulted in a 38.9% reduction in the wet weight of food waste, with a larval biomass yield of 80.9 g/kg. In the multi-batch continuous mode, operation for 32 d led to a 56.6% reduction in the wet weight of food waste, with a larval biomass yield of 64.7 g/kg. In addition, a 24-h sufficient consumption experiment revealed that the degradation of organic matter in rural food waste was significantly affected by the combined efforts of BSFL and microorganisms. The harvested larvae exhibited high levels of crude protein and crude fat, making them a valuable high-protein, high-fat animal feed. Overall, the reactor demonstrated notable space efficiency and effective waste reduction, providing key insights into the use of BSFL for food waste management.

KEYWORDS: Food waste, Black soldier fly larvae, Self-separation reactor, Biomass yield, High-protein animal feed

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1 Introduction

With the development of society, the amount of waste generated has substantially increased (Parra-Orobio et al., 2023). According to the United Nations Environment Programme, a colossal 1.05 billion tons of global food waste was generated in 2022, which is a substantial contributor to carbon emissions (Zhao et al., 2022; Programme, 2024). Several methods of food waste management are available (Salemdeeb et al., 2017; Siddiqui et al., 2022; Wang et al., 2023); among these, the application of resource-orientated insects stands out for its ability to transform waste into biomass energy (Nguyen et al., 2015). This strategy has gained increasing attention as it adheres to the principles of a circular economy (Wald, 2017; Lalander et al., 2019). The black soldier fly (BSF), a notable species in this regard, significantly reduces waste and promotes harmless disposal through larval consumption (Zhan et al., 2020; Mohan et al., 2023). Moreover, BSF larvae (BSFL) collected after treatment can be used as a high-protein insect feed that has significant economic value (Isibika et al., 2023). Thus, the application of BSFL is a promising approach for sustainable waste management (Singh et al., 2021; Zulkifli et al., 2023).

Currently, the majority of food waste processed by BSFL comprises urban food waste. In urban areas, the high proportion of leftover food in waste and effective waste sorting processes result in nutrient-rich waste materials, allowing BSFL to achieve a degradation rate of 70%–90% with minimal residue (Gold et al., 2020). In contrast, in rural areas, the lower living standards and relatively poor waste sorting strategies impact the generated food waste, resulting in waste containing a higher proportion of hard-to-degrade components. This also reduces the amount of material suitable for BSFL consumption and in turn lowers the overall efficiency of waste processing (Du et al., 2024).

Furthermore, most current methods for processing food waste using BSFL rely on turnover boxes or breeding racks as reactors (Singh et al., 2021). Such systems require continuous external operations, including temperature regulation, material distribution, turning, collection, and separation, to maintain functionality (Cheng et al., 2017; Falabella et al., 2018). As a result, these systems require substantial initial investment, have high operational maintenance demands, and are impractical for food waste management in rural areas with limited economic resources. Therefore, it is essential to develop BSFL processing methods that are better suited for disposing off rural food waste.

Rural food waste typically includes fruits, vegetables, straw, and food scraps. The primary component that is difficult for BSFL to digest of such waste is crude fiber (Hopkins et al., 2021; Xiang et al., 2024). However, the rigid chemical structure of crude fiber can be broken down by microorganisms in natural environments (Bai et al., 2020). Thus, adding microorganisms to a BSFL processing system to degrade components indigestible by BSFL can significantly enhance waste degradation. Additionally, to meet the specific needs of rural food waste processing, modifying the reactor design to incorporate features such as heat retention, leachate collection, continuous feeding, and automated separation of adult BSF will lead to the development of a user-friendly and cost-effective reactor that uses BSFL for waste management.

In this study, we aimed to develop a continuous self-separating reactor involving BSFL consumption and microbial breakdown to substantially reduce rural food waste. We performed experiments on single-batch, continuous multi-batch, and 24-h sufficient consumption of food waste to assess a range of indicators, including operational stability, waste processing efficacy, and larval production rates. The findings hold substantial implications for guiding the practical engineering application of BSFL in food waste treatment.

2 Materials and methods

2.1 Reactor construction

A novel continuous self-separating reactor involving the use of BSFL was autonomously designed (Fig. 1). The reactor, fabricated using organic glass, had a cylindrical shape, with dimensions of 20 cm in diameter and 50 cm in height. It comprised two principal sections: the upper treatment area, measuring 45 cm in height and 2 cm in width, a 45° sloped surface surrounding the inner wall that formed an extended outlet at its apex. The space between the outer and inner walls was hollow and could be filled with warm water to achieve insulation. The lower section featured a detachable base of 5 cm in height and equipped with a leachate outlet and 10 equidistant holes that were 1.5 cm in diameter along its outer edge. Affixed to the interface between the treatment area and the base was a 304 stainless steel mesh with a mesh size of 50. Finally, accounting for the influence of the slope, the effective bottom surface area of the container was 310 cm^2.

Exploiting the natural behavior of BSFL in their pre-

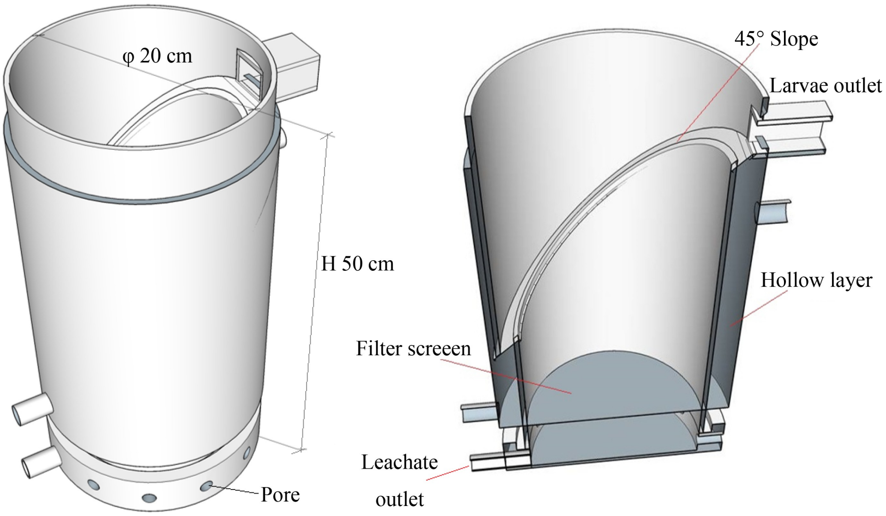

Fig. 1 Blueprint of the integrated reactor.

pupal stage to seek a sheltered and dry environment for pupation, we manually gathered the larvae as they emerged from slopes and exits. Leachate was collected via the mesh, base, and leachate outlet. Furthermore, the outer wall of the reactor incorporates a hollow interlayer, allowing for the infusion of warm water for insulation, thereby ensuring operational viability during low-temperature seasons.

This new reactor does not require an external oxygen supply as the processing area is connected to the base by a 304 stainless steel filter mesh; furthermore, the hollow base has ventilation holes in its outer wall. This allows oxygen to enter the reactor through the holes and the mesh at the bottom. Additionally, the constant movement of BSFL in the reactor stirs the kitchen waste, making the material structure relatively soft and enabling oxygen diffusion. Therefore, this reactor can maintain aerobic conditions independently without an external oxygen supply. For individual reactors, this experiment did not collect the gases produced during treatment. In actual production, the gases in the workshop can be collected through negative pressure ventilation and treated accordingly.

2.2 Experimental material

The food waste was obtained from a waste management facility located in a specific township in China (Changxing, Zhejiang Province). The waste included 65% vegetable and fruit waste, 15% straw waste, 10% kitchen waste, 5% livestock and poultry carcasses, and 5% nonbiodegradable impurities. Subsequently, these materials were subjected to impurity sorting, crushing, and moisture adjustment before being used as substrates for BSFL experiments. The final experimental substrates were < 3 cm in length and had a moisture content of approximately 80%.

Experimental BSFL were aged for 4 d and hatched from the eggs obtained from a BSF breeding farm located in China (Nanning, Guangxi, China). Following hatching, they were fed with a diet of bran and water for 4 d.

2.3 Experimental procedure

2.3.1 Single-batch mode experiment

In the single-batch mode experiment (Experiment A), 9000 4-d-old BSFL were introduced into the reactor on day 0, with a larval density of 29.0 larvae/cm^2. Another reactor without BSFL was set as the control (CK). Concurrently, 0.2 kg of residue from BSFL-processed food waste was used as the strain additive for these two reactors. The added residue served to introduce initial microbial strains for food waste decomposition and accelerate microbial breakdown processes. The residue used was the leftover material from the previous batch of BSFL treatment of food waste. This residue was rich in microbial strains that were capable of degrading proteins, carbohydrates, fats, and complex organic matter, including species from the families *Enterococcaceae*, *Lactobacillaceae*, and *Corynebacteriaceae*. *Enterococcaceae* are typically involved in the decomposition of organic matter, including proteins, carbohydrates, and fats. They can also promote the formation of complex organic matter. *Lactobacillaceae* play an important role in mineralization and decomposition of substances and can degrade carbohydrates to organic acids such as lactic acid. *Corynebacteriaceae* are capable of degrading various complex organic compounds, including hydrocarbons and phenols.

A daily addition of 1.26 kg of food waste, equivalent to 140 mg/(larva·d), was maintained. The experiment was conducted under ambient temperature conditions, with daily monitoring and recording of room temperature, heap temperature, and leachate volume. Termination criteria were met when 5% of the BSFL reached the prepupal stage. Then, the larvae were separated from the residue, and the larval quantity and weight were measured. Subsequently, the weight, moisture content, organic matter, crude protein, crude fat, crude fiber, and ash content of the residue at the container's bottom (consumed over 2 to 10 d) were measured for compositional analysis.

2.3.2 Multi-batch continuous mode experiment

In the multi-batch continuous mode experiment (Experiment B), 3500 4-d-old larvae were added in treatment reactor in each of three batches on day 0, 5 and 10. On day 0, 0.2 kg of the residue from BSFL-processed food waste was added as the strain additive for this reaction. Food waste was fed to the BSFL every 1 to 2 d, with the feeding amount adjusted according to actual operational conditions. The daily count, weight of BSFL emerging from the reactor, and leachate volume were recorded. Feeding ceased once the reactor reached capacity, and the experiment was concluded 1 week later. Then, the larvae and residue were separated, and the residue weight, moisture content (segmented detection), larval quantity, and larval weight were measured.

2.3.3 24-h sufficient consumption experiment

The 24-h sufficient consumption experiment (Experiment C) was conducted in a 17 cm × 12 cm × 7 cm polypropylene plastic box, with 0.2 kg of food waste and 6000 4-d-old BSFL. The BSFL were fed at a rate of 33.3 mg/(larva·d) to consume the material fully. The feeding took place at room temperature (30 °C) for 24 h. The organic matter, crude protein, crude fat, crude fiber, ash content, and moisture content of the fresh food waste and separated residue were measured for compositional analysis.

2.4 Analysis methods

The moisture content of the samples was determined using the drying method at 102 °C, and the ash content and organic matter were determined using the muffle furnace incineration method. Electrical conductivity (EC) and pH of food waste were determined in fresh waste-to-water ratios of 1:10 (w/v) using a conductometer (FE38, METTLER TOLEDO, Switzerland) and a pH meter (FE28, METTLER TOLEDO, Switzerland), respectively. Subsequently, the crude fat content of the air-dried samples was determined by Soxhlet extraction method, crude fiber content was determined using a fiber analyzer (ANKOM 220, ANKOM, USA), and Kjeldahl nitrogen content was determined using a fully automatic Kjeldahl nitrogen analyzer (k9860, Jinan Ocean energy Instrument, China). Thereafter, the obtained Kjeldahl nitrogen values were multiplied by a factor of 6.25 to calculate the crude protein content.

The following terms are defined as per Siddiqui et al. (2022). Larvae count was the estimated number of larvae based on the weight of 100 BSFL using weighing methods. Feeding rate was the amount of food waste per BSFL fed per day, expressed in g/(larva·d). Larvae density was defined as the ratio of the number of larvae to the bottom surface area of the rearing container, measured as larvae/cm^2. Material to larvae conversion rate (larvae productivity) was defined as the ratio of the harvested weight of BSFL to the total mass of material fed, presented in g/kg. System weight reduction was defined as the total weight of food waste added minus the weight of residue, larvae, and leachate; it represented the total loss of material due to microbial activity, BSFL metabolism, and system water evaporation, among other factors. The component proportion was defined as the percentage of different components in wet weight (WM) or dry weight (DM) relative to the total weight of the system; leachate was considered only in wet weight, with dry weight recorded as zero. Survival rate was defined as the ratio of the number of BSFL separated at the end of the experiment to the initial number of larvae introduced into the experiment.

Data analysis and visualization were conducted using Microsoft Excel 2019 (Microsoft Corp., USA), Origin 2021 (Origin Laboratory Corp., USA), and Adobe Illustrator 2022 (Adobe Corp., USA).

3 Results and discussion

3.1 Characteristics of rural food waste

This study involved a year-long sampling and analysis of food waste from a waste management facility located in a specific township in China (Changxing, Zhejiang

Province), taking samples bimonthly from each quarter to ascertain its suitability as a feedstock for BSFL. As illustrated in Fig. 2(a), the moisture content of the rural food waste fluctuated between 72.9% and 80.7%, which is consistent with the dietary needs of BSFL. Therefore, it was readily consumable with almost no need for additional moisture adjustment. Consistent moisture content levels throughout the year supported the operational feasibility of using BSFL for food waste management. The pH levels varied from 4.6 to 6.0, reflecting a mildly acidic environment that was conducive to the feeding habits of BSFL typically without the need for artificial adjustment (Fig. 2(b)). A stable pH provides favorable conditions for the industrial cultivation of the larvae. The EC values ranged from 1.5 to 3.8 mS/cm, signifying a substantial presence of inorganic salts that could supply essential ions for the growth of the BSFL. The organic matter content ranged from 81.4% to 86.8%, indicating a sufficiently high nutritive value for the growth of BSFL (Fig. 2(c)). Nutritious components, such as crude protein and crude fat, which were readily absorbed by BSFL, accounted for 27.1%–32.3% of the waste (Fig. 2(d)). In contrast, more recalcitrant components, such as crude fiber, which are less digestible, accounted for 3.6%–6.5% of the waste. This finding suggested that although rural food waste contained some indigestible components, the proportion of usable constituents significantly outweighed that of the less digestible ones. Therefore, the application of BSFL for food waste processing holds considerable merit for further research.

3.2 Reactor operation status

3.2.1 Single-batch mode experiment

The single-batch mode experiment spanned a duration of 10 d (Table 1). In experimental group A, 0.2 kg of residue from BSFL-processed food waste was added on day 0. Between days 0 and 7, 1.26 kg of food waste was added daily, and only 0.85 kg was added on day 8 owing to container height limitations, resulting in a total of 11.13 kg food waste. By day 10, with the BSFL reaching 14 d of age, approximately 5% of them had progressed to the prepupal stage; thus, the experiment was concluded. Overall, 5% of the larvae have grown to the prepupal stage, as observed from the color of the

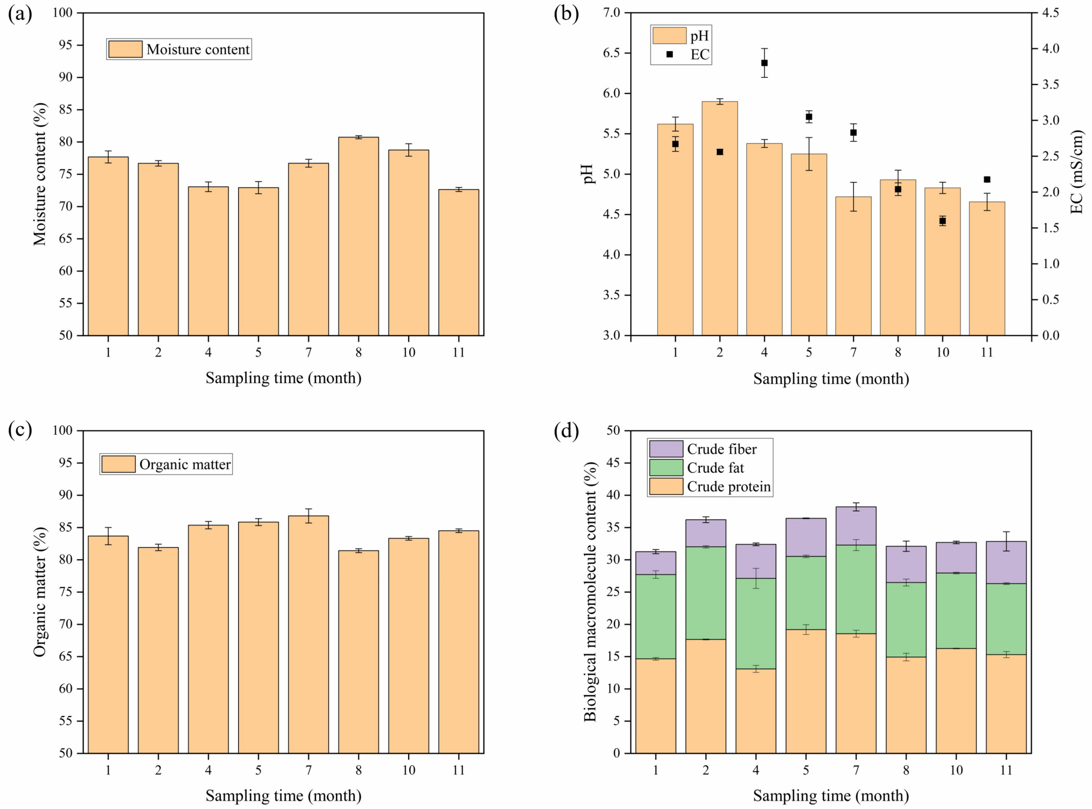

Fig. 2 Properties of rural food waste in different months: (a) Moisture content; (b) pH and EC; (c) organic content; (d) crude fiber, crude fat and crude protein. EC, electrical conductivity.

Table 1 Operation during the single-batch mode treatment.

Time (d)	Ambient temperature (°C)	Experimental group A			Control group (CK)	
		Larvae age (d)	Feeding amount of food waste (kg)	Heap temperature (°C)	Feeding amount of food waste (kg)	Heap temperature (°C)
0		4	Residue 0.2		Residue 0.2	
0	29	4	1.26	29	1.26	29
1	28	5	1.26	36	1.26	30
2	30	6	1.26	39	1.26	39
3	30	7	1.26	39	1.26	43
4	30	8	1.26	39	1.26	39
5	30	9	1.26	39	1.26	40
6	30	10	1.26	39	1.26	40
7	30	11	1.26	39		39
8	30	12	0.85	39		39
9	30	13		39		39
10	30	14		37		38
Total			11.13		9.02	

Notes: In experimental group A, 8200 larvae were harvested, with a larval density of 26.5 larvae/cm^2 and an average feeding rate of 133.3 mg/(larva·d).

larvae inside the reactor. In the control (CK) group, 0.2 kg of residue was added on day 0. Because of the limited height of the reactor, 1.26 kg of food waste was added daily from days 0 to 6, resulting in a total of 9.02 kg food waste. Throughout the experiment, the ambient temperature was maintained at 30 °C. In group A, the heap temperature gradually increased from 30 to 39 °C by day 2 and remained stable thereafter. In contrast, the heap temperature in the CK group increased from 30 to 43 °C by day 3, gradually returning to 39 °C and stabilizing.

Approximately 8200 BSFL, with a survival rate of 91.11%, were harvested from experimental group A on day 10; these findings were similar to those of Lalander et al. (2019), who reported a survival rate of 90%–96%. The separated BSFL weighed 0.90 kg, with a moisture content of 64.0% and an average weight of 0.110 g/larva, which was lower than that reported by Lalander et al. (2019) (approximately 0.212 g/prepupa). Since this experiment was terminated when only 5% of the BSFL reached the prepupal stage, most BSFL had not reached their maximum size. The actual larval density was 26.5 larvae/cm^2, with an average feeding rate of 133.3 mg/(larva·d). In group A, 1350 mL of leachate was collected, which was significantly more than that collected from the CK group (600 mL), indicating that the introduction of BSFL stimulated microbial activity and metabolism in the composting system, thereby enhancing water production.

3.2.2 Multi-batch continuous mode experiment

The multi-batch continuous mode experiment ran continuously for 32 d (Fig. 3(a)). The room temperature was maintained at approximately 30 °C, whereas the heap temperature gradually increased from 30 to 39 °C on day 2 and fluctuated between 35 and 39 °C, before gradually cooling down to 33 °C on day 24. On day 0, 0.2 kg of residue was added, with food waste added according to the consumption rates (Fig. 3(b)). Additionally, 0.434 kg/d from days 0 to 4, 0.868 kg/d from days 5 to 8, 1 kg/d from days 10 to 14, 1 kg every 2 d from days 15 to 26, and 0.16 kg on day 27 were added, totaling 17.00 kg.

Throughout the operational period from days 10 to 32, the daily yield of BSFL crawling out of the outlet ranged between 100 and 400, amounting to 5500 larvae (Fig. 3(c)). On day 32, 4200 BSFL were isolated and collected, resulting in a cumulative larvae count of 9700 and a survival rate of 92.38%. The separated larvae collectively weighed 1.10 kg, with a moisture content of 64.0%, and an average weight of 0.113 g/larva, which was slightly higher than that observed in experiment A. Leachate was collected daily from days 12 to 32, totaling 2740 mL (Fig. 3(b)). The estimated larval density during the operation ranged from 11.3 to 33.9 larvae/cm^2, with the highest density observed from days 10 to 14, exceeding 30 larvae/cm^2 (Fig. 3(d)). The estimated feeding rates were 124 mg/(larva·d) from days 0 to 7, 62–104.2 mg/(larva·d) from days 8 to 26,

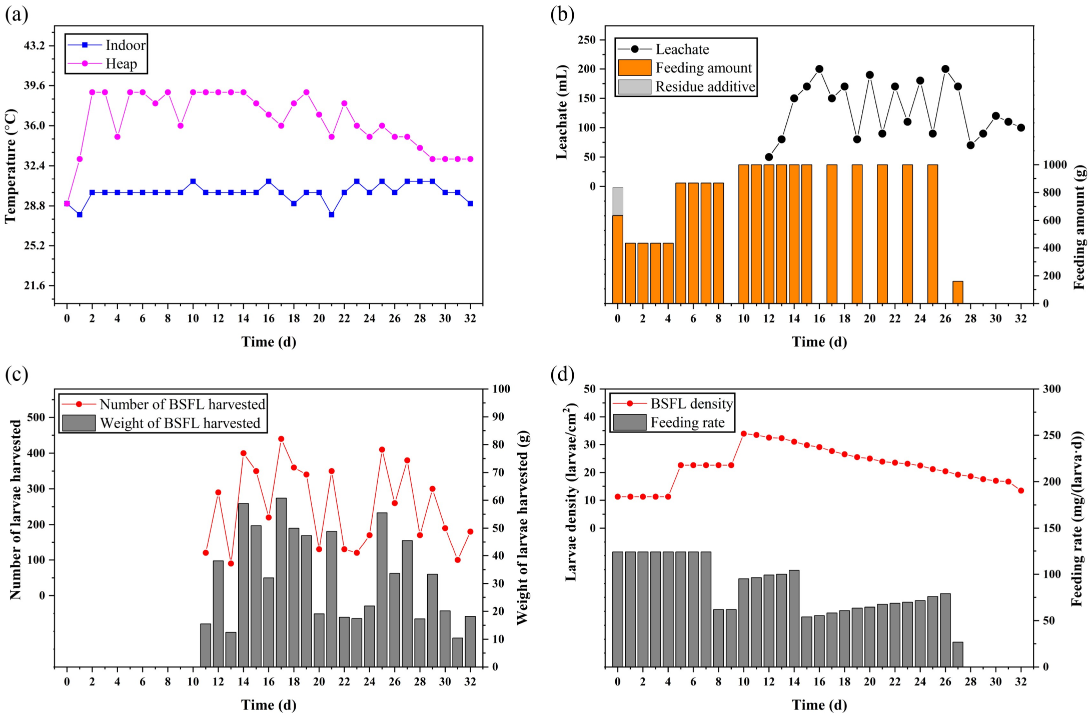

Fig. 3 Operation status of multi-batch continuous mode experiment: (a) Indoor and heap temperature; (b) residue additive amount, feeding amount, and leachate volume; (c) number and weight of BSFL harvested; (d) BSFL density and feeding rate. BSFL, black soldier fly larvae.

and 26.9 mg/(larva·d) on day 27. During the 32-d operational period, the mean larval density averaged 22.2 larvae/cm^2, and the mean feeding rate reached 73.5 mg/(larva·d). These data suggest that the reactor is capable of efficient operation in both single-batch and continuous multi-batch modes.

3.3 Waste reduction and larval production

3.3.1 Single-batch mode experiment

In group A, 11.13 kg of food waste with an 80.2% moisture content, and a 2.20 kg calculated dry matter weight was added (Fig. 4(a)). In the CK group, 9.02 kg of food waste with an 80.2% moisture content and 1.79 kg calculated dry matter weight was added (Fig. 4(b)). After 10 d of treatment, the residual feed weight for the CK group was 7.25 kg with an 80.4% moisture content and 1.42 kg calculated dry matter weight. For group A, the residual feed weight was 6.8 kg with a 79.4% moisture content and 1.40 kg calculated dry matter weight. The CK group demonstrated a wet weight reduction of 19.7% and a dry weight reduction of 20.4%. In contrast, group A exhibited a wet weight reduction of 38.9% and dry weight reduction of 36.4%, indicating increases of 97.46% and 78.43%, respectively, compared with the CK group. This finding indicates that the addition of BSFL significantly enhanced food waste reduction. The observed reduction rates were consistent with those documented by Gold et al. (2020), who showed a 37.9% reduction in food waste, and surpassed the findings of another study (Lalander et al., 2019). Thus, a further exploration of reactors is warranted.

The leachate to wet weight ratio in group A (12.1%) was higher than that in the CK group (6.7%), indicating that the addition of BSFL facilitated organic matter decomposition and water generation. Furthermore, the system weight reduction to wet weight ratio in group A (18.7%) was higher than that in the CK group (13.0%), whereas the system weight reduction to dry weight ratio in group A (21.7%) slightly surpassed that in the CK group (20.4%). This observation suggested that larval feeding significantly impacted the emission of water vapor but minimally affected the gaseous emission of non-aqueous substances (Taufek et al., 2024). In Group A, the proportion of residue dry weight was 63.6%, which is 16.0% lower than that of the CK group (79.6%). Among them, the proportion of system weight reduction was only 1.3% higher, and the proportion of harvested BSFL dry weight was 14.7%. The conversion rate of food waste into biomass growth by larvae

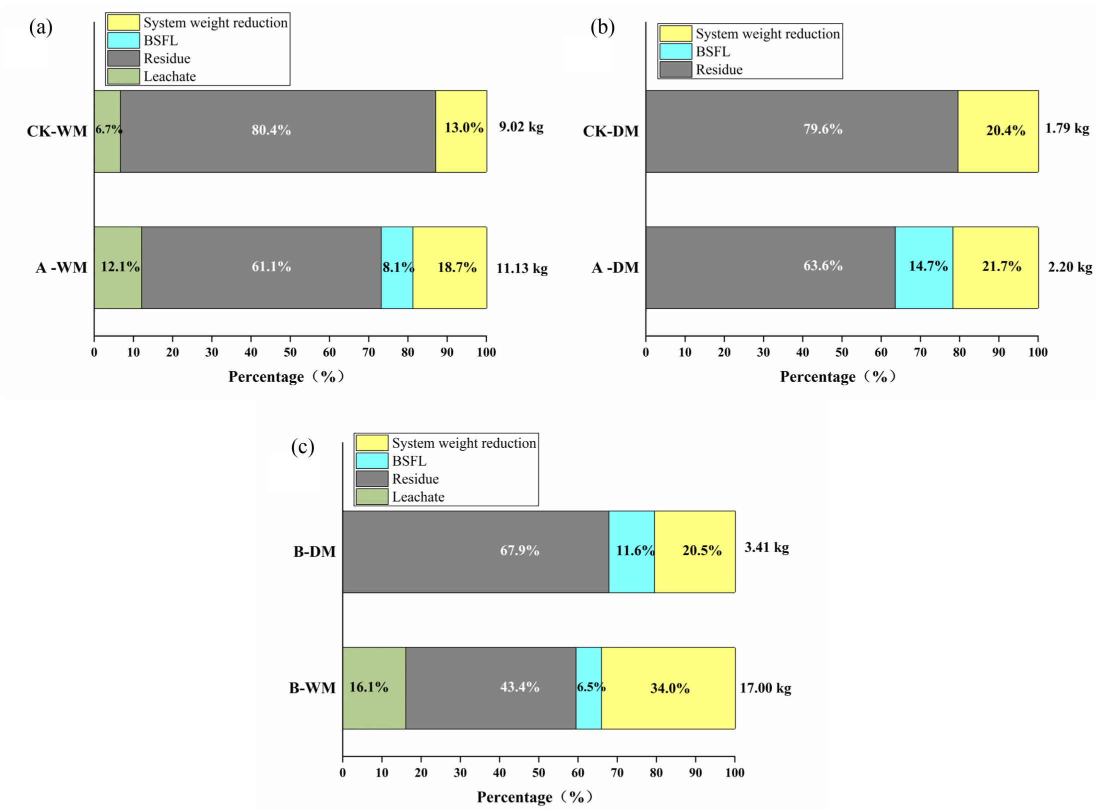

Fig. 4 System weight reduction, BSFL, residue, and leachate proportion of dry and wet weights in different treatment groups at the end of the reaction: (a) Wet weight proportions in the A and CK groups; (b) dry weight proportions in the A and CK groups; (c) dry and wet weight proportions in group B. BSFL, black soldier fly larvae.

reached 91.88%, indicating exceptionally high resource utilization efficiency (Gold et al., 2020; Taufek et al., 2024). After 10 d of operation, the separated BSFL weighed a total of 900 g, which was 8.1% of wet weight ratio, yielding a material-to-larvae production rate of 80.9 g/kg in wet weight.

3.3.2 Multi-batch continuous mode experiment

In group B, 17.00 kg of food waste with a moisture content of 79.9% and calculated dry matter weight of 3.42 kg was introduced (Fig. 4(c)). Following 32 d of treatment, the residual feed weight was 7.38 kg with a moisture content of 68.6% and calculated dry weight of 2.32 kg. Wet weight proportions comprised 43.4% residue (7.38 kg), 16.1% leachate (2.74 kg), 6.5% BSFL (1.10 kg), and 34.0% in system weight reduction (5.79 kg). Meanwhile, dry weight proportions comprised 67.9% residue (2.32 kg), 11.6% BSFL (0.40 kg), and 20.5% in system weight reduction (0.70 kg).

After 32 d of processing, group B demonstrated a wet weight reduction of 56.6%, significantly higher than that of group A (38.9%). The dry weight reduction reached 32.1%, slightly lower than that in group A (36.4%). The proportion of leachate in group B (16.1%) was higher than that in group A (12.1%). This difference might be attributed to the longer operation time in the multi-batch continuous mode, which increased water production from the continuous degradation of organic matter by BSFL and microorganisms. The calculated larvae production rate in group B was 64.7 g/kg, markedly lower than that in group A (80.9 g/kg). The survival rate and average larvae weight in group B were 92.38% and 0.113 g, respectively, comparable to those in group A (91.11% and 0.110 g, respectively). This reason could be attributed to the heightened intraspecific competition in group B, adversely impacting early and middle larval growth. However, with a prolonged growth period in group B, the average weight of late-stage larvae matched that in group A. These data suggested that the continuous self-separating reactor using BSFL is capable of achieving waste reduction and harvesting larvae in both single-batch and continuous multi-batch modes.

3.4 Biomass conversion rate

In experiment C, after 24 h, 100 g of fresh food waste, initially with a moisture content of 80.2% (Fig. 5(a)), was converted into 69.36 g of residue by BSFL with a moisture content of 76.1% (Fig. 5(b)), achieving a 30.6% reduction in wet weight and 16.3% reduction in dry weight and indicating that the reduced substance was primarily water. Similarly, in the single-batch mode, the same fresh food waste, consumed over a period of 2–10 d, produced 61.1 g of residue with a moisture content of 79.4% (Fig. 5(c)), representing a 38.9% reduction in wet weight and 36.4% reduction in dry weight. Notably, the reductions in wet and dry weight, especially the reduction in dry weight, were more significant after 2–10 d of consumption than those observed after 24-h sufficient consumption. The higher moisture content in the residue after 2–10 d might be due to leachate percolation from the upper layers of food waste. In the 24-h sufficient consumption experiment, the primary reduction pathway was consumption by BSFL. However, in the 2–10 d consumption experiment, which had an extended fermentation time, waste reduction involved both larval consumption and microbial decomposition. On the other hand, previous studies have demonstrated a notable decrease in microbial diversity within heaps after introducing BSFL into food waste. Over time, the structure of the microbial community in the heap and the BSF gut becomes increasingly similar (Jiang et al., 2019; Xiang et al., 2024). Consequently, influenced by BSF and their gut microbiota, the microbial community in the heap is reshaped (Ma et al., 2024). These findings suggest that the addition of BSFL further optimizes the microbial population, enhancing the competitive advantage of functional microorganisms.

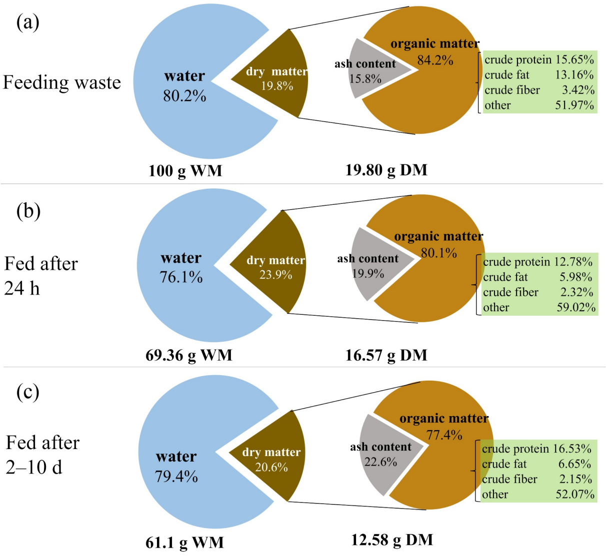

Fig. 5 Composition of wet and dry matter in different components: (a) Feeding waste (100 g); (b) fed after 24 h (per 100 g of feeding waste); (c) fed after 2 to 10 d (per 100 g of feeding waste).

Regarding the dry matter only, 100 g of food waste contained 16.67 g of organic matter, including 3.10 g of crude protein, 2.61 g of crude fat, 0.68 g of crude fiber, and 10.28 g of other organic matter, such as monosaccharides, starch, and small molecular organic compounds (Fig. 6). After 24-h sufficient consumption, the organic matter decreased to 13.30 g, and the crude protein, crude fat, crude fiber, and other organic matter correspondingly reduced to 2.12, 0.99, 0.39, and 9.80 g, respectively. Thus, the degradation rate of organic matter was 20.22%, and the corresponding degradation rates of crude protein, crude fat, crude fiber, and other organic matter were 31.61%, 62.07%, 42.65%, and 4.67%, respectively. Following consumption for 2–10 d, the organic matter decreased to 9.75 g, and the crude protein, crude fat, crude fiber, and other organic matter correspondingly reduced to 2.08, 0.84, 0.27, and 6.56 g, respectively. Thus, the degradation rate of organic matter was 41.51%, and the corresponding degradation rates of crude protein, crude fat, crude fiber, and other organic matter are 32.90%, 67.82%, 60.29%, and 36.19%, respectively.

Notably, the reduction in organic matter during the initial 24 h accounted for 48.7% of the total reduction over 2–10 d. In addition, the reductions in crude protein, crude fat, crude fiber, and other organic matter during the initial 24 h represented 96.1%, 91.5%, 70.7%, and 12.9% of the reductions over 2–10 d, respectively. In particular, the reduction in crude

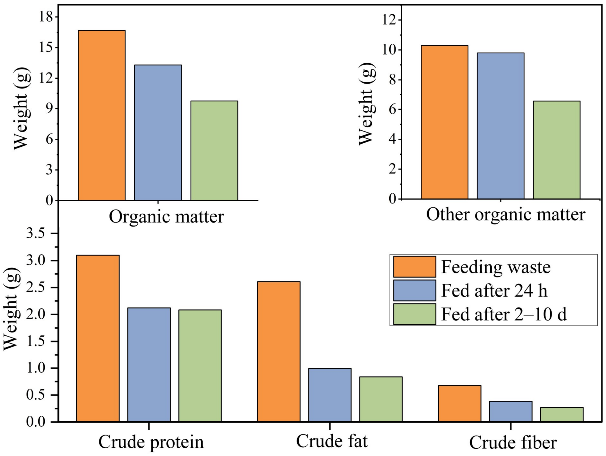

Fig. 6 Content of organic matter, crude protein, crude fat, crude fiber, and other organic matter in feeding waste, fed after 24 h, and fed after 2–10 d (per 100 g of feeding waste).

protein, and crude fat was predominantly influenced by BSFL activities during the first 24 h, whereas the reduction in other organic matter was mainly influenced by the combined activities of BSFL and microorganisms throughout the entire process (Shumo et al., 2019; Xue et al., 2023). In addition, we can also observe that the degradation rate of crude fiber over 2–10 d of feeding was 1.41 times that of crude fiber after 24-h sufficient consumption, indicating that the addition of microorganisms can significantly promote the degradation of crude fiber. These observations highlighted the significant influence of both BSFL and microorganisms on the overall reduction of organic matter in food waste throughout the experiments.

3.5 Nutritional components of BSFL

The collected BSFL samples were subjected to nutritional analysis. The moisture content of the BSFL was 63.7%. The dried and milled BSFL meal had a crude protein content of 45.21%, crude fat content of 33.45%, crude fiber content of 1.21%, and ash content of 14.3% (Table 2). These findings suggested BSFL meal is a rich source of both protein and fat and thus an excellent animal feed.

An additional analysis was performed on 17 amino acids present in the BSFL meal (Table 3). The cumulative content of these amino acids was 40.032%, highly consistent with the crude protein content, indicating that the majority of the crude protein was derived from protein nitrogen. The optimal application of BSFL meal is in the aquaculture industry. According to the “Compound Feed for Aquatic Products” (GB/T 22919-2008) standards, the lysine content in the feed for *Litopenaeus vannamei* should exceed 1.8%. The BSFL meal contained 2.987% lysine, exceeding this requirement. Consequently, BSFL meal is recognized as a superior high-protein feedstock.

Table 2 Composition content of dried black soldier fly meal

Component	Content (%)
Crude protein	45.21
Crude fat	33.45
Crude fiber	1.21
Ash	14.3

Table 3 Content of 17 amino acids in dried black soldier fly meal

Essential amino acids (%)		Non-essential amino acids (%)	
Lysine	2.987	Glycine	2.912
Methionine	0.879	Alanine	3.716
Leucine	3.465	Serine	0.089
Isoleucine	2.031	Aspartate	4.156
Threonine	0.641	Glutamate	4.365
Valine	3.165	Proline	3.132
Phenylalanine	2.031	Arginine	2.066
		Histidine	1.879
		Tyrosine	2.416
		Cystine	0.102

Notes: The total content of 17 amino acids is 40.032%.

In summary, the innovative continuous self-separating reactor using BSFL has demonstrated stable operation in both single-batch and continuous multi-batch modes. This system effectively processes rural food waste while yielding high-quality insect proteins.

4 Conclusions

We developed an innovative continuous self-separating reactor for processing rural food waste using BSFL. The reactor incorporates functions such as heat retention, leachate collection, continuous feeding, and automatic separation of adult BSF and feed materials. Experiments were conducted using both single-batch and multi-batch continuous modes, demonstrating the reactor’s stable operation. In the single-batch mode, a 10-d operation resulted in a 38.9% reduction in the wet weight of the food waste, with a larval biomass yield of 80.9 g/kg. In the multi-batch continuous mode, an operation for a total of 32 d led to a 56.6% reduction in the wet weight of the food waste, with a larval biomass yield of 64.7 g/kg. Comparative analysis of a 24-h sufficient consumption experiment revealed that the degradation of organic matter in rural food waste was significantly affected by the combined effect of BSFL and microorganisms throughout the process. The harvested larvae contained high levels of crude protein and crude fat, rendering them to be a valuable high-protein, high-fat animal feed. This study has demonstrated the feasibility of using BSFL and microorganisms for the continuous processing of food waste; this approach is space-saving and can lead to efficient waste reduction and insect protein production. Moreover, the findings of this study provide insights into the application of BSFL in food waste treatment engineering.

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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References

Bai L, Deng Y, Li J, Ji M, Ruan W (2020). Role of the proportion of cattle manure and biogas residue on the degradation of lignocellulose and humification during composting. Bioresource Technology, 307: 122941

Cheng J Y K, Chiu S L H, Lo I M C (2017). Effects of moisture content of food waste on residue separation, larval growth and larval survival in black soldier fly bioconversion. Waste Management, 67: 315–323

Du S, Zhang M, Zhang S, Wen X, Wang Y, Wu D (2024). Evaluation of the quality of products from multiple industrial-scale composting treatment facilities for kitchen waste and exploration of influencing factors. Environmental Research, 262: 119899

Falabella P, Chia S Y, Tanga C M, Khamis F M, Mohamed S A, Salifu D, Sevgan S, Fiaboe K K M, Niassy S, Van Loon J J A, et al. (2018). Threshold temperatures and thermal requirements of black soldier fly Hermetia illucens: implications for mass production. PLoS One, 13(11): e0206097

Gold M, Cassar C M, Zurbrügg C, Kreuzer M, Boulos S, Diener S, Mathys A (2020). Biowaste treatment with black soldier fly larvae: increasing performance through the formulation of biowastes based on protein and carbohydrates. Waste Management, 102: 319–329

Hopkins I, Newman L P, Gill H, Danaher J (2021). The influence of food waste rearing substrates on black soldier fly larvae protein composition: a systematic review. Insects, 12(7): 608

Isibika A, Simha P, Vinnerås B, Zurbrügg C, Kibazohi O, Lalander C (2023). Food industry waste: an opportunity for black soldier fly larvae protein production in Tanzania. Science of the Total Environment, 858: 159985

Jiang C L, Jin W Z, Tao X H, Zhang Q, Zhu J, Feng S Y, Xu X H, Li H Y, Wang Z H, Zhang Z J (2019). Black soldier fly larvae (*Hermetia illucens*) strengthen the metabolic function of food waste biodegradation by gut microbiome. Microbial Biotechnology, 12(3): 528–543

Lalander C, Diener S, Zurbrügg C, Vinnerås B (2019). Effects of feedstock on larval development and process efficiency in waste treatment with black soldier fly (*Hermetia illucens*). Journal of Cleaner Production, 208: 211–219

Ma C, Huang Z, Feng X, Memon F U, Cui Y, Duan X, Zhu J, Tettamanti G, Hu W, Tian L (2024). Selective breeding of cold-tolerant black soldier fly (*Hermetia illucens*) larvae: gut microbial shifts and transcriptional patterns. Waste Management, 177: 252–265

Mohan K, Sathishkumar P, Rajan D K, Rajarajeswaran J, Ganesan A R (2023). Black soldier fly (*Hermetia illucens*) larvae as potential feedstock for the biodiesel production: recent advances and challenges. Science of the Total Environment, 859: 160235

Nguyen T T X, Tomberlin J K, Vanlaerhoven S (2015). Ability of black soldier fly (*Diptera: Stratiomyidae*) larvae to recycle food waste. Environmental Entomology, 44(2): 406–410

Parra-Orobio B A, Soto-Paz J, Hernández-Cruz J A, Gómez-Herreño M C, Domínguez-Rivera I C, Ocaña-Oviedo E R (2023). Evaluation of biochar as an additive in the co-composting of green waste and food waste. Sustainability, 15(9): 7437

Programme U N E (2024). Food Waste Index Report 2024. Nairobi: United Nations Environment Programme

Salemdeeb R, Zu Ermgassen E K H J, Kim M H, Balmford A, Al-Tabbaa A (2017). Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. Journal of Cleaner Production, 140: 871–880

Shumo M, Osuga I M, Khamis F M, Tanga C M, Fiaboe K K M, Subramanian S, Ekesi S, Van Huis A, Borgemeister C (2019). The nutritive value of black soldier fly larvae reared on common organic waste streams in Kenya. Scientific Reports, 9(1): 10110

Siddiqui S A, Ristow B, Rahayu T, Putra N S, Widya Yuwono N, Nisa K, Mategeko B, Smetana S, Saki M, Nawaz A, et al. (2022). Black soldier fly larvae (BSFL) and their affinity for organic waste processing. Waste Management, 140: 1–13

Singh A, Srikanth B H, Kumari K (2021). Determining the black soldier fly larvae performance for plant-based food waste reduction and the effect on biomass yield. Waste Management, 130: 147–154

Taufek N M, Mohamad Zulkifli N F N, Hamizah A N (2024). Upcycling of food waste generated from the fresh market by utilising black soldier fly larvae: influence on growth, bioconversion, and nutritional composition. Journal of Environmental Management, 349: 119467

Wald C (2017). The new economy of excrement. Nature, 549(7671): 146–148

Wang H, Qin Y, Xin L, Zhao C, Ma Z, Hu J, Wu W (2023). Preliminary techno-economic analysis of three typical decentralized composting technologies treating rural kitchen waste: a case study in China. Frontiers of Environmental Science & Engineering, 17(4): 47

Xiang F, Zhang Q, Xu X, Zhang Z (2024). Black soldier fly larvae recruit functional microbiota into the intestines and residues to promote lignocellulosic degradation in domestic biodegradable waste. Environmental Pollution, 340: 122676

Xue Y, Xiao K, Wu X, Sun M, Liu Y, Ou B, Yang J (2023). Insights into the changes of amino acids, microbial community, and enzymatic activities related with the nutrient quality of product during the composting of food waste. Frontiers of Environmental Science & Engineering, 17(3): 35

Zhan S, Fang G, Cai M, Kou Z, Xu J, Cao Y, Bai L, Zhang Y, Jiang Y, Luo X, et al. (2020). Genomic landscape and genetic manipulation of the black soldier fly *Hermetia illucens*, a natural waste recycler. Cell Research, 30(1): 50–60

Zhao S, Schmidt S, Gao H, Li T, Chen X, Hou Y, Chadwick D, Tian J, Dou Z, Zhang W, et al. (2022). A precision compost strategy aligning composts and application methods with target crops and growth environments can increase global food production. Nature Food, 3(9): 741–752

Zulkifli S, Jayanegara A, Pramudya B, Fahmi M R, Rahmadani M (2023). Alleviation of selected environmental waste through biodegradation by black soldier fly (*Hermetia illucens*) larvae: a meta-analysis. Recycling, 8(6): 83