Research Article

Feeding strategies for small-scale rearing black soldier fly larvae (*Hermetia illucens*) as organic waste recycler

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Abstract
Processing organic waste using black soldier fly (BSF)-based technology offers a promising alternative for sustainable organic waste management and urban sanitation. This study was conducted to assess the influence of feeding strategies on the efficacy of BSF larvae to recycle organic wastes into value products. Fruit waste and chicken manure were used as organic waste samples while commercial chicken feed was used as a control, and were processed for 15 days in circular plastic containers (Ø 30 × 12 cm) with 50; 100; 150; and 200 mg/larva/day continuous and batch feeding diets, using 500 four-day-old larvae per diet, repeated four times. Larval survival rates were not significantly affected by the feeding strategies. However, average larval biomass of 83.69 ± 13.04 g and 82.46 ± 08.52 g was achieved for the continuous and batch feeding strategies, respectively, under favorable conditions. Larval feed reduction rates ranged from 24.65 ± 03.48% to 72.78 ± 01.48% and 24.52 ± 0.27% to 72.25 ± 12.13% with continuous and batch feeding strategies, respectively, and were significantly affected by the different daily diets. On the other hand, the bioconversion rates ranged from 13.34 ± 0.26% to 50.82 ± 02.27%, and the highest values were observed with the continuous feeding diets. This study confirms the efficacy of BSF larvae to thrive in different organic substrates and shows that the continuous feeding strategy can be better and enhance a sustainable small-scale organic waste management.

Keywords Animal feed · Bioconversion · Larval biomass · Waste management

1 Introduction

In low- and middle-income countries, indiscriminate disposal, poor-quality treatment and uncontrolled landfilling of organic waste contribute to negative environmental and public health outcomes [1, 2]. Up to 85% of household wastes are biodegradable while about half of the wastes are from food. Globally, about 1.3 billion tonnes of food are wasted each year, which equates to an annual economic loss of about $ 1 billion [3]. Poor organic waste management practices also waste energy and the nutrients that could be used to meet the increasing global resource demand [4, 5]. Therefore, there is a pressing need for developing multiple potential food waste valorization technologies to reduce as well as mitigate the adverse effects of food waste. Processing of organic waste using fly larvae is a relatively new concept which is currently attracting interest [6–9].

As detritivores, the diversity of holomtabolous insects includes black soldier fly (BSF) larvae specializing in their

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ability to thrive on different organic substrates as food sources [10–12]. These substrates are most often food waste from agriculture and food processing industries. BSF larva is one of the detritivores dipterans studied to convert organic waste into biofertilizers and larval biomass, which can be used, respectively, to improve poor soils and as sources of proteins and dietary fats for animal feed [13, 14]. BSF is a complete metamorphosis insect which, during its larval stage, feeds voraciously on a varied range of organic waste and efficiently converts nitrogen compounds and carbohydrates into larval biomass. Their nutritional values have been evaluated and can be compared with those of animal protein sources usually used in animal feed [15, 16]. In the literature, this is recognized as insects-based technology and represents an economically viable method for recycling large quantities of food waste into valuable products.

Sustainable organic waste management is classified among the priorities of countries wishing to ensure the best living conditions for their citizens [17]. In Cameroon, like in most African countries, composting is one of the most advanced techniques for recycling and recovering food waste [18–20]. Composting is the decomposition of organic matter and their transformation into humus by the action of a great number of microorganisms in a hot, humid and ventilated environment [21, 22]. This process can take several months and produce compost as the only valuable product. In contrast, organic waste management using BSF larvae does not require specific microorganisms and only takes about two weeks to produce organic fertilizers which can be used in production of crops, and larval biomass which can be used as a source of proteins for livestock or as a biofuel precursor for diesel engines [15, 23, 24]. It should also be noted that the treatment of organic waste based on BSF larvae offers a promising alternative for environmental safety. Because by converting nitrogen compounds and carbohydrates from organic waste, it contributes to the reduction of greenhouse gas emissions and therefore leading to global warming [25–27].

Various studies have investigated into the effects of different organic waste streams on laboratory-reared BSF [28–30], as well as the influence of animal manure or food waste on the development and survival of BSF larvae using experimental prepared diets [8, 28]. Other studies have investigated the potential of BSF larvae to recycle these organic wastes into useful products [31–33]. However, most of these studies focus on the waste stream-based diets and lack information on the effects of feeding strategy. For example, what will happen if a given amount of organic waste is defined and fed to the BSF larvae once at the start for the entire development period? Would providing BSF larvae with small amounts of waste every day improve their recycling and conversion efficiencies? To the best of our knowledge, no study so far has investigated the combined effect of different organic wastes stream-based diets and feeding strategy on the recycling and converting activities of BSF larvae in a given facility. Therefore, this study aimed to investigate the influence of feeding strategy on the efficacy of BSF larvae to thrive in different organic wastes stream-based diets with an overview of their recycling and converting activities. Information from this study is important for improving small-scale organic waste management using BSF-based technology, as well as the production of environmentally sustainable livestock feed for smallholder farmers.

2 Materials and method

2.1 Black soldier fly colony

This study was carried out in a greenhouse at the Agri-Business vocational training Center (ABC), Dschang, Cameroon. BSF colony was established in 2017 from larvae of wild-trapped *Hermetia illucens* populations breed since 2016 at the International Institute of Tropical Agriculture (IITA), Yaoundé, Cameroon. BSF egg clusters from the pre-established colony were incubated according to the method described by Dzepe et al. [9]. After hatching, a total number of 48 000 four-day-old larvae were collected and divided into two equal groups used to test two feeding strategies (continuous and batch feeding strategies). The continuous feeding strategy consisted of a treatment in which the organic substrate was continuously supplied in different diets to the larvae every two days, while in the batch feeding strategy, the different daily diets were calculated for 15 days and supplied to the larvae once at the start of the experiment.

2.2 Organic waste sample

Fruit waste and chicken manure were used as organic waste samples, while chicken feed was used as a control substrate. Fruit waste was constituted mainly with papaya, pineapple and orange and was collected in the bins of fruit sellers in the Dschang market, while fresh chicken manure was collected from a broiler farm at the University of Dschang. Chicken feed was purchased from a commercial animal feed company in Cameroon, and its composition is: 22% crude protein, 6% fat, 3.5% crude fiber and 5% crude ash. The collected fruit waste and fresh chicken manure were stored for two days to reduce the water content, and a 50 g sample was taken from each and oven-dried for 24 h at 100 °C to determine their humidity rate using relation (Eq. 1).

$$\text{Humidity rate (\%)} = \left[1 - (\text{dried weight}/50)\right] \times 100. \quad (1)$$

The dry chicken feed on the other hand was moistened at 60% with fresh water before use. The water contents of the first two substrates were 90.42 ± 1.05% and 69.87 ± 2.85%, respectively, for fruit waste and chicken manure. These values are within the suitable range for BSF organic waste processing as recommended by Cammack et al. [34] and Dortmans et al. [35].

2.3 Experimental design

2.3.1 Continuous feeding treatment

The experiments were carried out in circular plastic containers (Ø 30 × 12 cm), covered with mosquito nets to prevent BSF larvae predators. Four seeded containers of 500 four-day-old larvae each were used for each organic substrate sample. The different containers were supplied every two days with 50; 100; 150; and 200 g of their respective substrates, in order to achieve the daily diets of 50; 100; 150; and 200 mg per larva, respectively. Each treatment was repeated four times and the duration of the experiment was determined according to the required time of BSF larvae to reach maturity which was approximately 15 days.

2.3.2 Batch feeding treatment

This treatment was carried out under the same conditions as with continuous feeding treatment while the only difference was that for each substrate, the diets were calculated for 15 days according to the different daily diets of 50; 100; 150; and 200 mg/larva and supplied to the containers in batches once at the start of the experiment. The different containers each seeded with 500 four-day-old larvae received, respectively, 375; 750; 1125; and 1500 g of their respective substrate for the duration of the treatment. Table 1 summarizes the different treatments performed in this study.

2.4 Organic waste recycling parameters

For each treatment, the larvae were harvested on the 15th day in the containers, counted and weighed using an electronic weighing balance readable to 0.01 g, after washing with fresh water. Residual substrates were also collected from the containers and weighed using an electronic scale of precision ± 0.1 g, and subsequently, a sample of 50 g of each residual substrate was taken into an oven for 24 h at 100 °C to determine its dry weight. To take into account both the sustainable organic waste recycling and the larval biomass production, the efficacy of BSF larvae to thrive in the different organic waste samples according to the continuous and batch feeding treatments was assessed using parameters such as larval survival rate (1); larval wet weight (2); waste reduction rate (3); waste reduction index (4); and larval bioconversion rate (5). These parameters were calculated using the following formulas:

1. The larval survival rate (SR) was calculated for each treatment as follows (Eq. 2).

$$\text{SR}\,(\%) = \frac{\text{Number of larvae harvested}}{\text{Number of four days old larvae added}} \times 100 \quad (2)$$

2. The larval wet weight was considered as the final weight of the larvae harvested in each treatment at the end of the experiment and was measured using an electronic weighing balance readable to 0.01 g
3. The waste reduction rate (WR) was estimated for each treatment based on the dry weight of the substrates using the formula (Eq. 3).

$$\text{WR}\,(\%) = \left[1 - (\text{Substrate residue}/\text{Substrate added})\right] \times 100 \quad (3)$$

The substrate residue is the substrate obtained after larval conversion.

4. The waste reduction index (WRI) takes into account not only the overall material reduction but also the time require by the larvae to reduce this amount of waste and was estimated as follows (Eq. 4).

$$\text{WRI} = (\text{WR}/t) \times 100 \quad (4)$$

Table 1 Description of the different treatments performed during the study

	Continuous feeding				Batch feeding			
Diets (mg/larva/jour)	50	100	150	200	50	100	150	200
Nomber of larvae (n)	500	500	500	500	500	500	500	500
Quantity of substrate (g)	375	750	1125	1500	375	750	1125	1500
Feeding occasions (n)		Every two days				Once at the start		
Treatment replicates (n)	4	4	4	4	4	4	4	4

WR represents the total amount of organic material reduces during the time t. High WRI values indicate good reduction efficiency.

5. The bioconversion rate (BR) was estimated for each treatment using the formula (Eq. 5).

$$\mathrm{BR}(\%) = \frac{\text{Wet weight of havested larvae}}{\text{initial dry weight of substrate added}} \times 100 \tag{5}$$

Like the waste reduction index, a high bioconversion rate indicates good bioconversion efficiency.

2.5 Statistical analysis

The collected data were analyzed statistically using R 3.5.0 software. One-way analysis of variance followed by the Tukey post hoc test was performed to determine the differences between the treatments according to the substrates, while the Student t test was performed to compare the variation of the different parameters between the continuous and batch feeding strategies. A p value < 0.05 was considered to indicate a significant difference between the values compared.

3 Results

3.1 Larval survival rate

The survival rates recorded during continuous and batch feeding treatments were not significantly affected by the daily diet ($p > 0.05$), except those of the larvae subjected to continuous feeding diets with fruit waste which recorded significant variations ($p < 0.05$). Furthermore, for each daily diet these survival rates varied significantly depending on the type of substrate ($p < 0.05$), and the larvae subjected to chicken manure recorded the highest values during both continuous and batch feeding treatments (Fig. 1). The comparison of both treatments does not show significant difference ($p > 0.05$).

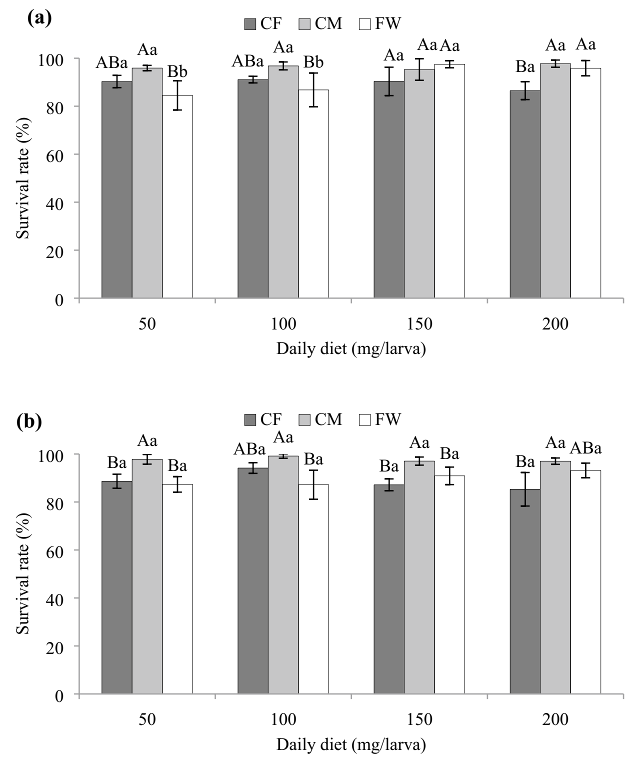

Fig. 1 Survival rates of BSF larvae subjected to different substrates using continuous (**a**) and batch (**b**) feeding diets. Means (±SE) followed by different upper-case letters are significantly different among substrates ($p < 0.05$). Means followed by different lower-case letter are significantly different among diets ($p < 0.05$). CF, chicken feed; CM, chicken manure; FW, fruit waste

3.2 Larval biomass

The BSF larval biomass from different treatments varied significantly according to the substrate and daily diet ($p < 0.05$). The values from continuous feeding treatments were directly proportional to the different daily diets with chicken manure and fruit waste. Those of the larvae from chicken feed do not show significant variation at 100, 150 and 200 mg/larva daily diets ($p > 0.05$). The same trends were observed with batch feeding treatments. However, regardless of the daily diet, the highest larval biomass was recorded with chicken feed, followed by chicken manure and fruit waste (Fig. 2). When the two feeding strategies were compared, the larval biomasses from continuous feeding treatments were relatively higher than those from batch feeding treatments.

3.3 Waste reduction rate

The reduction rate of different substrates subjected to BSF larvae using continuous and batch feeding strategies was all significantly affected by the daily diets ($p < 0.05$). The values recorded ranged from 24.65 ± 3.48% to 72.78 ± 1.48% and from 24.52 ± 0.27% to 82.45 ± 2.55%, respectively, with continuous and batch feeding diets, regardless of the substrate. Fruit wastes recorded the highest values, followed by the chicken feed and chicken manure (Fig. 3). The reduction rate of the chicken feed did not show significant variation according to the daily diet ($p > 0.05$). However, when the two feeding strategies are compared, the reduction rates of substrates subjected to batch feeding diets were significantly higher than those

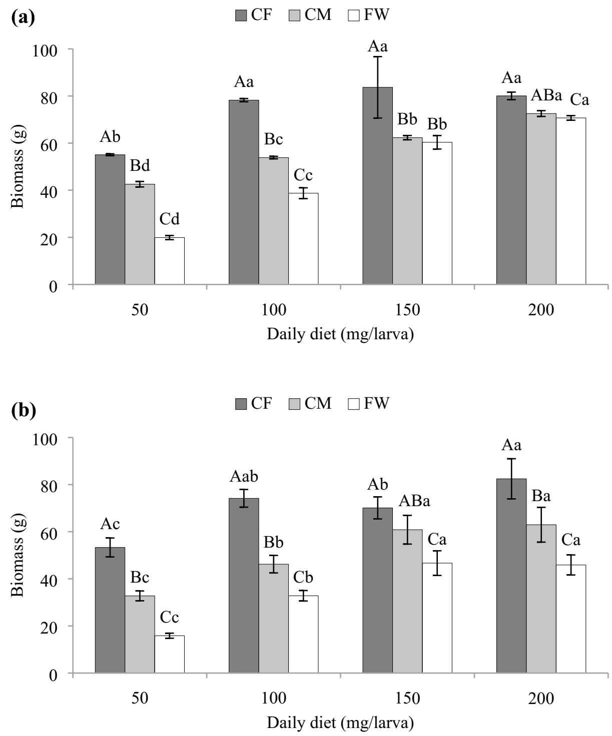

Fig. 2 Biomass of BSF larvae subjected to different substrates using continuous (**a**) and batch (**b**) feeding diets. Means (± SE) followed by different upper-case letters are significantly different among substrates ($p < 0.05$). Means followed by different lower-case letter are significantly different among diets ($p < 0.05$). CF, chicken feed; CM, chicken manure; FW, fruit waste

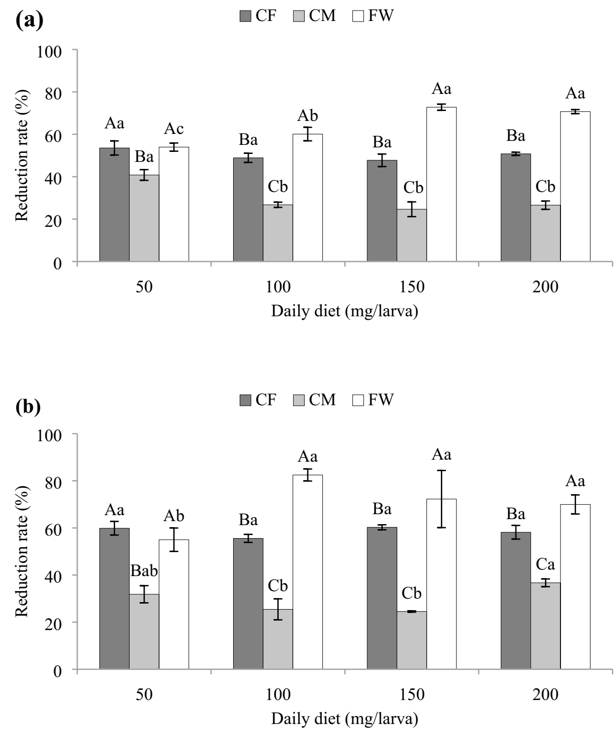

Fig. 3 Reduction rates of organic substrates subjected to BSF larvae using continuous (**a**) and batch (**b**) feeding diets. Means (± SE) followed by different upper-case letters are significantly different among substrates ($p < 0.05$). Means followed by different lower-case letter are significantly different among diets ($p < 0.05$). CF, chicken feed; CM, chicken manure; FW, fruit waste

from continuous feeding diets ($p < 0.05$). The same trends were observed with the reduction indices (Table 2).

3.4 Bioconversion rate

Figure 4 shows the bioconversion rates of BSF larvae obtained in this study. They were significantly affected by the type of substrate, regardless of the feeding strategy and fruit waste recorded the highest values ($p < 0.05$). The daily diets also influenced the conversion of the different substrates with the exception of fruit waste which did not show any significant variation with the diets 50, 100 and 150 mg/larva/day ($p > 0.05$). When the two feeding strategies are compared, the bioconversion rates recorded with continuous feeding diets were relatively higher, although no significant difference was observed ($p > 0.05$).

4 Discussion

Black Soldier Fly offers a promising solution to improve the collection and recycling of organic waste, which is actually responsible for many unsanitary problems encountered in urban areas. During their larval stage, the BSF feeds voraciously on various types of organic waste and converts carbohydrates and nitrogen compounds into secondary protein products [32, 36, 37]. In the present study, the larval survival rates of the BSF were not significantly influenced, both during continuous and batch feeding strategies, except for those of larvae fed on continuous diets with fruit waste. These different survival rates were, however, higher compared to those obtained by Nguyen et al. [38] for BSF larvae in household waste (47%), fruit and vegetable waste (77%). Some authors attribute the low survival rates to the intraspecific competition between individuals for the feed source [39–41] and to the type of substrate [42]. However, Devon [43] obtained low survival rates at the optimal daily diet of 100 mg/larva as recommended by Diener et al. [36] compared to the 125 mg/larva/day diet. This could suggest that, in a production system, the daily diet should be adjusted according to the evolution of the larval biomass. It is very important to know at what stage of larval development these mortalities most often occur, in order to determine for how long the larvae must be fed with a specific diet in a given treatment.

Table 2 Reduction indices of substrates subjected to BSF larvae using continuous and batch feeding diets

	Daily diet (mg/larva)	CF	CM	FW
Continuous feeding	50	3.57 ± 0.22^{Aa}	2.72 ± 0.16^{Ba}	3.59 ± 0.12^{Ac}
	100	3.26 ± 0.14^{Bab}	1.78 ± 0.08^{Cb}	4.01 ± 0.21^{Ab}
	150	3.18 ± 0.19^{Bb}	1.64 ± 0.23^{Cb}	4.85 ± 0.09^{Aa}
	200	3.38 ± 0.05^{Bab}	1.77 ± 0.13^{Cb}	4.71 ± 0.06^{Aa}
Batch feeding	50	3.99 ± 0.19^{Aa}	2.12 ± 0.24^{Bab}	3.66 ± 0.33^{Ab}
	100	3.70 ± 0.11^{Ba}	1.69 ± 0.29^{Cb}	5.49 ± 0.17^{Aa}
	150	4.01 ± 0.07^{Ba}	1.63 ± 0.01^{Cb}	4.81 ± 0.80^{Aa}
	200	3.87 ± 0.19^{Ba}	2.44 ± 0.10^{Ca}	4.66 ± 0.27^{Aa}

Means (± SE) followed by different upper-case letters are significantly different among substrates ($p < 0.05$). Means followed by different lower-case letter are significantly different among diets ($p < 0.05$). *CF* Chicken feed; *CM* Chicken manure; *FW* Fruit waste

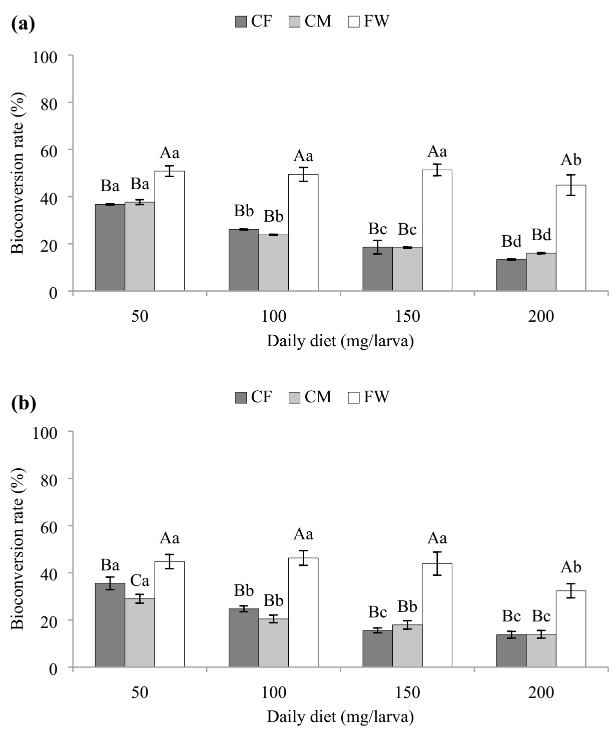

Fig. 4 Conversion rates of organic substrates subjected to BSF larvae using continuous (**a**) and batch (**b**) feeding diets. Means (± SE) followed by different upper-case letters are significantly different among substrates ($p < 0.05$). Means followed by different lower-case letter are significantly different among diets ($p < 0.05$). CF, chicken feed; CM, chicken manure; FW, fruit waste

The larvae fed in continuous feeding diets tended to develop fast into large pre-pupae compared to those subjected to the batch feeding diets. Similar results were observed by Nana et al. [32], who argued that BSF larvae have preference for fresh diet as compared with rotten diet. Other authors also demonstrate that most organic wastes lose their nutritional value over time due to the action of microorganisms [31, 44]. This could explain the difference observed between the larval biomass from continuous and batch feeding diets. These larval biomasses were, however, directly proportional to the daily diet in both treatments, regardless of the different substrates used. These results confirm once again the importance of a balanced diet for small-scale rearing of BSF larvae.

Regardless of the different treatments, larval feed reduction rates were higher with fruit waste compared to chicken manure and chicken feed. The same observations were made by Nguyen et al. [33], who reported that reduction rates of fruits and vegetables by BSF larvae are higher compared to the standard chicken feed. These results could be explained by the texture of fruits wastes, which are generally full of water and easy to degrade. However, for all substrates the values were close to those obtained by various authors in the literature. For example, Cheng et al. [45], respectively, obtain 43% and 67% of the reduction rates of dry mass with fruits and vegetables, while Joly [46] obtains 65% with kitchen waste, and Diener et al. [47] obtain 46% to 76% with municipal organic waste. Chicken manure recorded the lowest reduction rates in this study. This could be due to its low energy content as it is a waste product of chicken digestion. Nguyen et al. [33] reported that the energy content of a substrate can affect its reduction efficiency by BSF larvae. Although there were no significant differences, the reduction rates obtained with the larvae subjected to the batch feeding diets were relatively higher as compared to those of the larvae subjected to the continuous feeding diets. This could be due to the action of microorganisms which compete with the larvae for old substrate. This type of substrate is generally characterized by the release of foul smells due to the microorganism's action. Gold et al. [48] have summarized all the degradation processes that occur in organic waste outside the larval organism in a given area. In the batch feeding strategy, the reduction rates of larvae subjected to the control diets (chicken feed) did not show significant variation. This contrast the results achieved by Diener et al. [47]

that 100 mg of the feed per larva per day is the best diet for organic waste reduction using BSF larvae.

The bioconversion rates recorded in this study were inversely proportional to the daily diets regardless of the different substrates, both continuous and batch feeding treatments. Fruit waste recorded the highest values compared to chicken manure and chicken feed. These results are similar to those obtained by Devon [43] who reports a significantly higher bioconversion rate and feed conversion ratio by the BSF larvae with a daily diet of 125 mg per larva. However, for chicken manure and chicken feed, the values obtained were substantially close to the values in the literature. Nyakeri et al. [31] obtained a bioconversion rate of 22.3% with human manure at 100 mg/larva/day diet, while Joly [46] obtained 20.73% with kitchen waste at 100 mg/larva/day. It is important to note that these values were calculated based on the dry weight of the different substrates. The bioconversion rates calculated based on the wet weights are much lesser than the values obtained in this study, due to the influence of the water content of the substrates [32, 47].

5 Conclusions

This study provides a context for understanding the efficacy of BSF larvae to recycle organic wastes according to different feeding strategies, with an overview on the larval biomass production which can be used as animal feed in livestock sector. The results showed that BSF larvae are more able to thrive in fresh substrates compared to old substrates and that the best recycling or conversion efficiency is obtained with low continuous daily diets. Regardless of the different treatments, the feed reduction rate varied between 24.52 and 72.78% and the bioconversion rate varied between 13.34 and 51.34%. This means that with BSF-based technology, a 100 kg of organic waste can be reduced to between 70.54 and 20.72 kg and also generate between 10.34 and 50.13 kg of biomass in just 15 days.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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