frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 09 October 2025
DOI 10.3389/fsufs.2025.1673188

OPEN ACCESS

EDITED BY
Mohamed Ait-El-Mokhtar,
University of Hassan II Casablanca, Morocco

REVIEWED BY
Emmanuel O. Anedo,
International Centre of Insect Physiology and Ecology (ICIPE), Kenya
Zeleke Arke Ashango,
Wolaita Sodo University, Ethiopia

*CORRESPONDENCE
Cédrique L. Solofondranohatra
✉ lovacedrique@gmail.com

RECEIVED 25 July 2025
ACCEPTED 23 September 2025
PUBLISHED 09 October 2025

CITATION
Solofondranohatra CL, Ony CA, Burza S and Fisher BL (2025) Preliminary field evaluation of black soldier fly frass as an organic fertilizer on maize (*Zea mays* L.) growth and yield in southeastern Madagascar.
Front. Sustain. Food Syst. 9:1673188.
doi: 10.3389/fsufs.2025.1673188

Preliminary field evaluation of black soldier fly frass as an organic fertilizer on maize (*Zea mays* L.) growth and yield in southeastern Madagascar

Cédrique L. Solofondranohatra[1]*, Clarcky Andrianorosoa Ony[1], Sakib Burza[2,3] and Brian L. Fisher[1,4]

[1]Madagascar Biodiversity Center, Antananarivo, Madagascar, [2]Health In Harmony, Portland, OR, United States, [3]Department of Infectious Biology, London School of Hygiene & Tropical Medicine, London, United Kingdom, [4]Department of Entomology, California Academy of Sciences, San Francisco, CA, United States

Food insecurity remains a critical challenge for many farming communities in Madagascar, underscoring the need for sustainable strategies to improve crop yields. Black soldier fly frass (BSFF) is an emerging organic fertilizer, and composting may enhance its agronomic effectiveness. This study evaluated the effects of composted BSFF (CBSFF), fresh BSFF (FBSFF), cattle manure (CM), and a no-fertilizer control on maize (*Zea mays* L.) germination, height growth, grain yield, and agronomic efficiency of nitrogen (AE_N) in southeastern Madagascar's acidic sandy clay soils. Fertilizers were applied at 43 kg N/ha, reflecting actual farmer practices in the region. This rate represents one-third of the recommendation by FOFIFA (Madagascar's national agricultural research institute). Farmers in this region rarely apply the full recommended dose due to limited access, high input costs, and low return on investment, factors that contribute to persistent yield gaps even where recommended rates are followed. Maize treated with FBSFF had significantly lower germination rate than all other treatments. In contrast, there were no statistically significant differences in final plant height or grain yield among CBSFF and CM. However, CBSFF-treated plants were on average 6 and 13% taller than those receiving CM and FBSFF, respectively, and produced 38% more grain than CM. All fertilizer treatments yielded significantly more grain than the unfertilized control, which produced no harvestable maize. CBSFF also showed the highest agronomic efficiency of nitrogen (AE_N: 46 kg grain/kg N), although this difference was not statistically significant. These results suggest that BSFF, particularly in composted form, can supply sufficient nitrogen to support maize growth. Overall trends point to composted BSFF as the most agronomically effective option. Timing of application should depend on the frass form: composted BSFF is better suited for pre-planting use, while fresh BSFF may be more appropriate after germination. Even at sub-recommended doses, BSFF has the potential to enhance maize productivity and contribute to local food security. Further research across diverse agroecological zones, including trials comparing BSFF with the full recommended fertilizer dose, and economic analyses incorporating frass cost, labor, and transport are recommended to identify optimal application strategies and support widespread adoption by smallholder farmers.

KEYWORDS

black soldier fly frass, organic fertilizer, maize (*Zea mays* L.), field trial, grain yield, soil fertility, sustainable agriculture, smallholder farmers in Madagascar

1 Introduction

Sustainable agricultural practices are crucial to address the increasing challenge of soil degradation and to improve the food security and livelihoods of the small-scale farmers who produce a significant portion of the food supply in sub-Saharan Africa (FAO, 2017). In Madagascar, where food security remains a critical challenge (Schipanski et al., 2016), increasing agricultural production is essential. However, sustainable agricultural methods such as improved rice cultivation, have seen limited adoption, often due to socioeconomic constraints and lack of access to resources (Stoop et al., 2002). This makes it harder to improve food systems and build resilience among smallholder farmers. As agricultural productivity is a key determinant of food security for these farmers (Herrera et al., 2021), promoting the wider implementation of sustainable practices is essential. The southeastern region is one of the most food-insecure areas of Madagascar, where smallholder farmers face significant challenges in achieving food security and contributing to local food availability (Randrianarison et al., 2020).

Organic fertilizer inputs are vital for improving soil health and boosting crop productivity, providing a sustainable solution for future agriculture (Vanlauwe et al., 2014; Vanlauwe et al., 2015). Organic fertilizers provide a valuable source of nitrogen, a key nutrient that is often deficient in soils and limits crop production in many regions of sub-Saharan Africa (Tully et al., 2015). The Black Soldier Fly (BSF) (*Hermetia illucens*, L.) is an effective recycler of organic waste, converting it into nutrient-rich organic fertilizer that can support crop production and soil health management (Lalander et al., 2015; Beesigamukama et al., 2021a), contributing to circular bioeconomy (Lopes et al., 2022). While BSF frass fertilizer (BSFF) is a relatively new organic fertilizer product, it is increasingly being studied for its agronomical performance and potential benefits in sustainable agriculture (e.g., Beesigamukama et al., 2020a; Anyega et al., 2021; Menino et al., 2021; Rehan et al., 2024), and forest restoration (Solofondranohatra et al., 2025). Many studies have demonstrated that BSFF has a positive impact on plant growth and yields (e.g., Choi and Hassanzadeh, 2019; Coudron et al., 2019; Menino et al., 2021), but negative effects of frass application such as stunted growth have also been reported due to phytotoxic properties (e.g., Temple et al., 2013; Setti et al., 2019). Lopes et al. (2022) highlighted that the main limitation of using freshly produced BSFF as a fertilizer is its lack of maturity and stability. Compost maturity and stability describes the extent to which the composting process has been completed, indicating that the material is free from phytotoxic substances and harmful plant or animal pathogens that could hinder seed germination, plant development, or overall soil health (Bernal et al., 2009, 2017). The immaturity of BSFF is primarily due to the rapid bioconversion of organic waste by BSF larvae–usually completed in less than 20 days, which leaves insufficient time for the frass to fully stabilize and mature (Setti et al., 2019; Song et al., 2021). The application of immature and unstable compost may result in nutrient immobilization and phytotoxic effects, which can negatively affect seed germination and restrict plant growth (Emino and Warman, 2004; Luo et al., 2018). Therefore, it is important to adopt post-treatments such as thermophilic composting, which has been shown to improve the suitability of BSFF as a fertilizer for cultivation (Lopes et al., 2022). Thermophilic composting is the decomposition of organic waste by heat-loving microorganisms at high temperatures (40–70 °C), resulting in rapid breakdown and pathogen reduction (Epstein, 1997), making the final product safe and nutrient-rich for soil application (FAO, 1980). A recent study by Lopes et al. (2024) showed that recirculating BSFF by incorporating it as a diet component for BSF larvae increased its degree of decomposition and ensured a better quality of the subsequent frass obtained. The frass produced from recirculation process is more mature and stable as evidenced by the reduction of its self-heating, gas volatilization, and a better seed germination (Lopes et al., 2024).

BSFF has been shown to have great potential to support the growth of maize (Beesigamukama et al., 2020a, 2020b; Gärttling et al., 2020; Tanga et al., 2022; Risman et al., 2025), the world's most important cultivated food crop (Rouf et al., 2016). Beyond BSFF, recent work in Madagascar's agroclimatological conditions has also demonstrated that other insect frass types, such as cricket frass, can significantly enhance crop performance, including green bean growth and pod production (Andrianorosoa Ony et al., 2024). In Madagascar, maize is among the top three food crops that farmers typically rely on, along with rice and cassava—for both home consumption and income generation, (Harvey et al., 2014). Maize is essential for the rural poor, as it serves as a key source of nutrition, especially during the lean season when food supplies are limited (Harvey et al., 2014). The use of BSFF could play an important role in supporting maize production in Madagascar, offering a promising solution to improve soil health and crop yields, for a sustainable and productive agricultural system. Here, we experimentally evaluate the comparative impact of the application of thermophilic composted BSFF, fresh BSFF, cattle manure, and no fertilizer on the germination, growth, yield and nitrogen use efficiency of maize in the farming systems of agricultural communities in southeastern Madagascar. This study provides information essential to integrate BSFF into existing local farming practices.

2 Materials and methods

2.1 Study site and climate

The experiment was carried out in Morafeno village, Ankarana Commune, Farafangana District, in the southeastern region (23.018°S, 47.769°E) of Madagascar from November 2024 to February 2025. The region is characterized by a humid tropical climate, receiving roughly 2,000 mm of annual rainfall mostly during the rainy season from November to April (CREAM, 2013).

Climatic conditions during the early cropping season (November–December 2024) were broadly consistent with long-term monthly averages (1970–2000; Fick and Hijmans, 2017). November rainfall totaled 167 mm (vs. 149 mm normal), with a mean temperature of 25.1 °C (vs. 24.6 °C); December rainfall was 284 mm (vs. 294 mm normal), and mean temperature 26.5 °C (vs. 25.6 °C) (Supplementary Table S1).

Soil was sandy clay with strong acidity (Table 1). Soil acidity was corrected by applying dolomite at a dose of 0.25 t/ha, based on guidance from a local agronomic expert with long-term experience in diverse Malagasy soil types. While this dosage is below the general recommendation for strongly acidic soils (e.g., Chairiyah et al., 2021), it reflects field-level constraints and local agronomic practice. Table 1 presents the soil analysis results.

TABLE 1 Site soil properties (me% = milliequivalent percentage).

Soil parameter	Value
pH	5.42
C/N	17.9
Total nitrogen (%)	0.17
Total organic carbon (%)	3.05
Phosphorus	4.01
Potassium (me%)	0.06
Calcium (me%)	1.1
Magnesium (me%)	0.85
Sodium (me%)	0.31
Clay (%)	31
Silt (%)	20
Sand (%)	49

TABLE 2 Characteristics of fresh BSFF and composted BSFF.

Parameter	Fresh BSFF	Composted BSFF
pH	6.06	7.12
Organic carbon (%)	37.97	25.59
Total nitrogen (%)	2.48	2.41
NH_4^+–N (mg/kg)	4,700	1,750
NO_3^-–N (mg/kg)	4,550	1,680
Phosphorus (%)	1.31	3.13
Potassium (%)	0.21	1.38
Calcium (%)	0.29	0.93
Magnesium (%)	0.38	2.58
Iron (mg/kg)	977.3	7,853.6
Manganese (mg/kg)	214.3	536.6
C/N ratio	15.31	10.61

2.2 Experimental design and treatments

This study examined how (*Zea mays* L.), variety IRAT200, responds to different fertilizer treatments. The experiment was arranged in a Randomized Complete Block Design with three replicates. Each replicate consisted of 24 plants, arranged at a spacing of 80 × 60 cm.

Four treatments were applied: composted BSFF (CBSFF), fresh BSFF (FBSFF), cattle manure (CM), and no fertilizer (Control). Fertilizers were applied at rates equivalent to 43 kg of total N per hectare, based on the usual dose locally used (cattle manure), which corresponds to the third of the recommended dose for the region (FOFIFA, 2024), and half of the commonly recommended dose in Sub-Saharan Africa (Tetteh et al., 2018).

Fresh BSFF was included to assess its agronomic effects under field conditions, given the limited data on its direct application and the possibility that smallholder farmers may use it without composting due to time or resource constraints.

2.3 BSFF production and characterization

BSFF was obtained from Valala Farm Research Lab at MBC—Antananarivo. Black soldier flies were reared on conventional chicken feed during the first 7 days, then on spent grain until harvest.

Fresh BSFF was sun-dried for 4 days and not sifted before application. Composted BSFF was prepared for 5 weeks using the heap method (FAO, 1980). Both FBSFF and CBSFF were analyzed for macro- and micronutrient content (Table 2).

2.4 Crop management

Following the practices of local smallholder farmers in the region, the fertilizer was applied once, in holes of 15 cm diameter and 15 cm deep, and mixed with the removed soil. Two seeds of maize were planted per hole.

Plants were watered twice a day, in the morning and in the evening. Weeds were removed manually whenever they appeared.

2.5 Measurements and sampling schedule

Maize was planted on 9 November 2024 and harvested on 21 February 2025, with a total crop duration of approximately 3.5 months. Growth measurements were carried out until physiological maturity, prior to final grain harvest, but phenological stages were not formally recorded in this trial.

Data on maize germination were collected at day 14 after sowing, and was defined as seedling emergence, indicated by the visible appearance of the coleoptile above the soil surface (ISTA, 2020). Data on plant height were collected every 4 weeks, from day 14 after sowing up to the harvest. Plant height was measured using a tape measure, from ground level to the tip of the shoot.

Maize grain data were collected at maturity by harvesting all plants per treatments. Maize ears were threshed to determine grain weights using a weighing scale. Grains were air dried to 12.5% moisture to determine grain yield per plant (g/plant), and calculated on a hectare basis to obtain the total grain yield (t/ha). Agronomic nitrogen efficiency (AE_N), a measure of economic yield produced per unit amount of N supplied from each treatment, was calculated using the grain yield from each treatment using the following equation (Baligar et al., 2001).

$$AE_N \left(kg / kg\ N\right) = \frac{\left[Grain\ yield_F \left(kg / ha\right) - Grain\ yield_C \left(kg / ha\right)\right]}{Quantity\ of\ N\ applied \left(kg\ N / ha\right)}$$

where F represents fertilizer treatment and C represents the control.

2.6 Statistical analysis

All statistical analyses were conducted in R (R Core Team, 2020). Each dataset was tested for normality using Shapiro–Wilk test and residual diagnostics. Where necessary, data were log- or square-root transformed to meet model assumptions. Germination proportion, grain yield per plant, total grain yield, and agronomic nitrogen use efficiency (AE_N) were analyzed using a one-way analysis of variance

(ANOVA) with treatment as the independent variable. Pairwise comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at $p < 0.05$. Maize plant height, which was measured repeatedly at 4-week intervals, was analyzed using a linear mixed-effects model with treatment, time (day), and their interaction as fixed effects, and replication as a random effect. Post-hoc comparisons were performed using Tukey's HSD. All analyses were conducted with the "lme4" and "multcomp" packages in R. Model outputs and pairwise comparisons are provided in Supplementary Tables S2–S9. Raw data are available via Figshare (Doi: 10.6084/m9.figshare.30103666).

3 Results

3.1 Maize germination

The different fertilizer treatments caused significant differences in maize germination proportion ($p < 0.001$) (Figure 1). Germination was highest in cattle manure (CM) (95.8%) and similar to plants treated with CBSFF (91.7%). FBSFF treatment significantly lowered maize germination compared to all other treatments (19.44%, all $p < 0.001$).

3.2 Plant height

Fertilizer treatments resulted in significant differences in plant height during the experiment ($p < 0.001$) (Figure 2). At day 14, mean plant height ranged between 4.9 and 14.09 cm, with plants treated with FBSFF being significantly shorter than the other treatments. The GLMM indicated a strong effect of sampling time ($p < 0.001$, Supplementary Table S5), as plant height increased steadily across days 14, 42, 77, and 102. While the main effect of treatment alone was not significant, significant treatment × time (day) interactions were detected for the control treatment. For all treatments but the control, plant height increased significantly up to day 77, then increased slightly to reach peak values at day 102. From day 42 to the end of the experiment, maize grown using fertilizer treatments were significantly taller compared to the control. At day 102, CBSFF-treated maize reached the greatest mean height (171 cm), although this was not statistically different from CM or FBSFF. By contrast, control plants were 138% shorter than CBSFF.

3.3 Maize grain yield

The final number of plants alive for each treatment, from which maize grain yield was measured is 64, 13, 64, and 35 for CBSFF, FBSFF, CM and Control, respectively. Different treatments caused significant differences in maize grain yield per plant and total yield ($p < 0.001$ and $p = 0.02$, respectively) (Figures 3A,B). Maize yield was positively affected by all fertilizer treatments compared to control. Grain yield per plant was highest with CBSFF (106 g), with no significant difference compared to FBSFF (85 g) and CM (82 g) (Figure 3A). The highest total grain yield (1.98 t/ha) was produced from maize grown with CBSFF, and this was 38 and 388% times

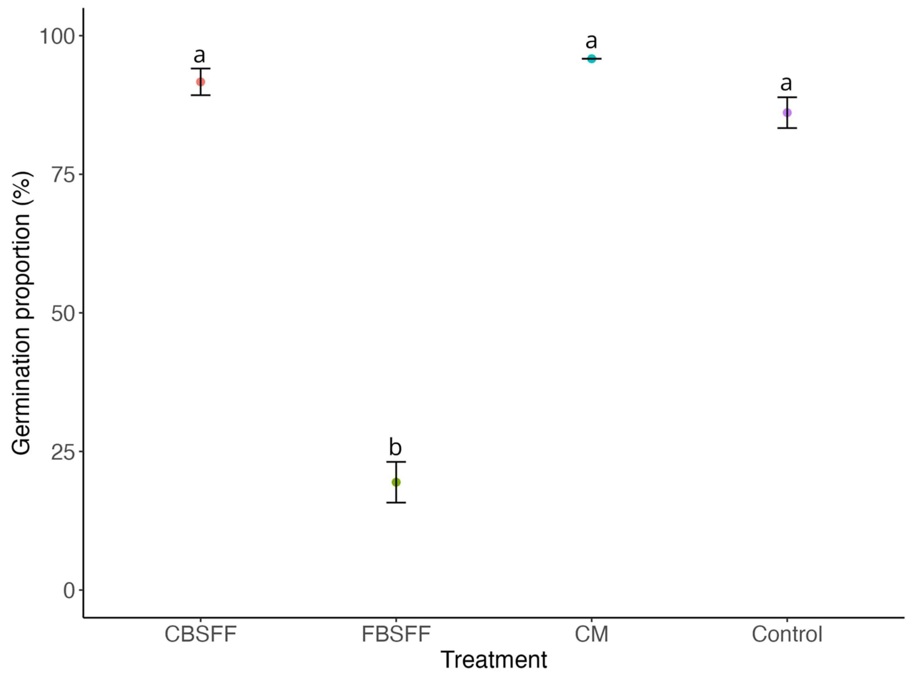

FIGURE 1
Germination proportion across four different fertilizer treatments. CBSFF, composted black soldier fly frass; FBSFF, fresh black soldier fly frass; CM, cattle manure; Control, no fertilizer. Letters above each treatment level represent statistically significant differences at $p \leq 0.05$. Error bars indicate standard error of the mean.

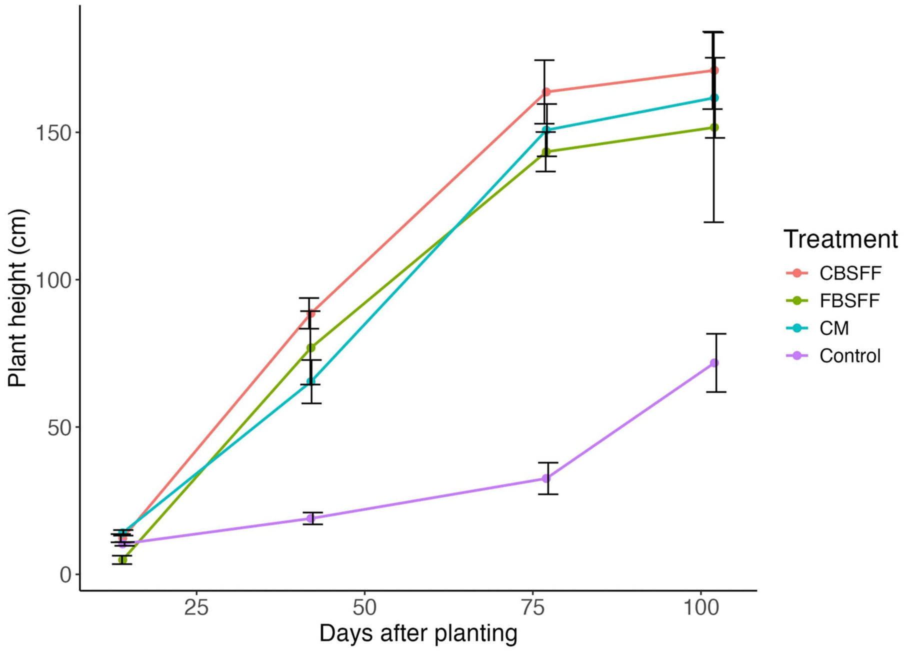

FIGURE 2
Maize height growth over time across four different fertilizer treatments. CBSFF, composted black soldier fly frass; FBSFF, fresh black soldier fly frass; CM, cattle manure; Control, no fertilizer. Letters above each treatment level represent statistically significant differences at $p \leq 0.05$. Error bars indicate standard error of the mean.

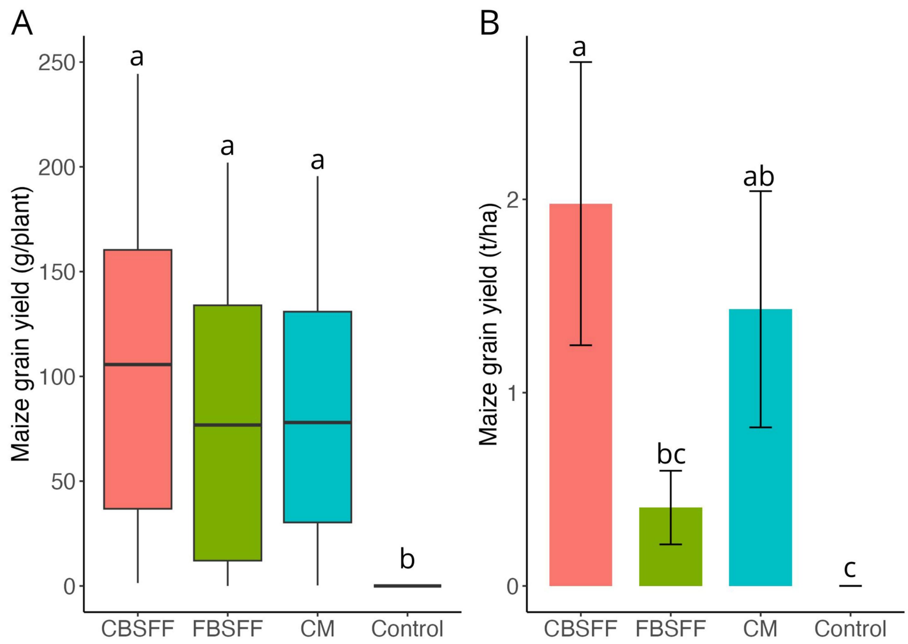

FIGURE 3
Maize grain yield per plant **(A)** and total yield **(B)** across four different fertilizer treatments. CBSFF, composted black soldier fly frass; FBSFF, fresh black soldier fly frass; CM, cattle manure; Control, no fertilizer. Final number of plants alive is 64, 13, 64, and 35 for CBSFF, FBSFF, CM and Control, respectively. Different letters above each treatment level represent statistically significant differences at $p \leq 0.05$. Error bars indicate standard error of the mean.

higher than maize total grain yield produced with CM and FBSFF, respectively (Figure 3B). Total grain yield was significantly higher for CBSFF compared to FBSFF ($p = 0.0502$; Supplementary Table S8). No significant difference was found between CBSFF and CM ($p > 0.05$), although CBSFF yielded consistently higher. Control treatment maize plants did not produce any grain.

3.4 Agronomic nitrogen use efficiency

The AE_N from maize produced using the different treatments are presented in Table 3. Maize grown using CBSFF had the highest AE_N (46 kg/kg N), which was similar to the AE_N obtained with CM (33.3 kg/kg N) and FBSFF (9.4 kg/kg N).

4 Discussion

In Madagascar, boosting the agricultural productivity of maize, a crop essential to food security, is crucial for enhancing the livelihoods and food security of smallholder farmers. In our study, we show that fertilizing maize with mature and stable BSFF increases plant growth and yield. These results highlight the potential of BSFF as a sustainable and locally available nutrient source for maize production, contributing to more environmentally friendly farming practices.

4.1 Effects of fertilizer types on maize germination

Our results showed that among the four treatments tested, maize germination proportion was highest with CM and CBSFF, which was significantly higher than the FBSFF treatment (Figure 1). The low germination observed in FBSFF treatment can be attributed to its lack of maturity and biological instability, due to the rapid processing time of organic waste by BSF larvae, which often results in the presence of phytotoxic compounds that inhibit seed germination (Setti et al., 2019). Compost maturity is a critical indicator of fertilizer quality, characterized by the absence of substances that can inhibit seed germination, hinder plant development, or negatively affect soil health (Bernal et al., 2009).

One key phytotoxic compound in fresh BSFF is ammonium-nitrogen (NH_4^+–N), which is often present in high concentrations (e.g., Green and Popa, 2012; Liu et al., 2020). In our study, FBSFF contained 4,700 mg/kg of NH_4^+–N (Table 2), well above the 400 mg/kg limit recommended by Bernai et al. (1998) for high-quality compost. This aligns with previous findings showing that fresh BSFF with high NH_4^+–N concentrations can significantly reduce germination (Bohm et al., 2023; Ramírez et al., 2008). After composting FBSFF for 5 weeks, the NH_4^+–N concentration dropped by 63%, which corresponded with a significant increase in germination (Figure 1). These results support earlier studies indicating that composting, as a follow-up step in BSF-based bioconversion can lower NH_4^+–N concentrations and mitigate the associated phytotoxicity of the frass (Lopes et al., 2019; Song et al., 2021; Lopes et al., 2022).

TABLE 3 Effect of composted BSF frass (CBSFF) fertilizer, fresh BSF frass (FBSFF) fertilizer and cattle manure (CM) on maize agronomic nitrogen use efficiency (AE_N).

Treatment	AE_N (kg/kg N)	Mean-separation
CBSFF	46 ± 17.03	a
FBSFF	9.4 ± 4.43	a
CM	33.3 ± 14.21	a
	ns	

4.2 Effects of fertilizer types on maize height growth

Despite the inhibition of maize germination observed with FBSFF treatment, plants that did germinate did not show any significant difference in height growth compared to CBSFF and CM (Figure 2). The final height of plants treated with FBSFF was only 6 and 13% shorter than those treated with CM and CBSFF, respectively. These results suggest that maize germination is the growth phase most sensitive to fresh frass toxicity, while subsequent plant growth remained unaffected. This effect may be attributed to the reactivation of biological activity in fresh frass upon its interaction with soil moisture after application (Hénault-Ethier et al., 2024). The relatively high carbon content in the soil (Table 1; Riquier, 1972) might have helped activate a spontaneous process of biodegradation by composting and stabilizing the organic matter in the frass, resulting in an improved fertilizing efficiency. However, maize treated with CBSFF exhibited the highest growth in terms of plant height compared to the other treatments, which is consistent with a growing body of research emphasizing the importance of composting in enhancing the growth-promoting effect of BSFF. For instance, Song et al. (2021) reported improved biomass production in *Brassica rapa* when BSFF was composted for 5 weeks, compared to stunted growth under fresh frass application. Similarly, Anyega et al. (2021) found that composted BSFF, whether applied alone or in combination with other fertilizers, significantly improved plant growth across various crops, including tomato, kale, and French beans. Wang et al. (2025) found that composted BSFF derived from pig manure promoted maize seedling growth more effectively than fresh frass, whereas no significant growth differences were observed between composted and fresh frass derived from chicken manure. These improvements can be attributed to the reduction of the C/N ratio during the composting process (from 15.31 in FBSFF to 10.61 in CBSFF, Table 2), indicating a higher degree of organic matter decomposition and nutrient mineralization (Chen et al., 2014). Lower C/N ratios in organic fertilizers are generally associated with improved nitrogen availability, as microbial immobilization is reduced and more nitrogen remains accessible for plant uptake (Raj and Antil, 2011; Chen et al., 2014). Additionally, Beesigamukama et al. (2021b) also showed that soils amended with BSFF have high mineralization, indicating a rapid availability of mineral nitrogen to support plant growth. These findings highlight the role of composting in stabilizing BSFF and increasing its effectiveness as an organic nutrient source in crop production systems.

4.3 Effects of fertilizer types on maize grain yield and nitrogen use efficiency

In terms of maize grain yield, plants treated with CBSFF produced the highest average yield per plant, comparable to those obtained with FBSFF and CM (Figure 3A). Although CBSFF plots showed a 38% higher average total grain yield compared to CM, this difference was not statistically significant in Dunn's tests following the Kruskal–Wallis analysis, due to the limited number of field replicates ($n = 3$). Among the three organic fertilizer treatments, CBSFF demonstrated the highest yield, significantly outperforming FBSFF and outperforming CM in all metrics, though not at a statistically significant level. This suggests that composting BSFF not only improves nutrient availability but also delivers more consistent yield benefits than fresh frass or cattle manure. FBSFF can support maize productivity, particularly during the post-germination phase, by enhancing nutrient availability and soil fertility as it matures and stabilizes in the soil (Hénault-Ethier et al., 2024). Consistent with our findings, Tanga et al. (2022) reported in a greenhouse study that composted BSFF led to maize grain yield increases of up to 212% compared to other organic fertilizer sources. In line with this, Beesigamukama et al. (2020b) found that maize treated with composted BSFF produced grain yields up to 27% higher than those receiving equivalent amounts of commercial organic fertilizers. Notably, even at one-third of the recommended nitrogen input for optimum maize production, CBSFF achieved 57% of the yield obtained under the full recommended dose (FOFIFA).

Notably, control plots, despite maintaining approximately half the final number of plants treated with CBSFF and CM (64 plants, Figures 3A,B), and forming cobs, failed to produce any grain, highlighting the infertility of our soil (Table 1; Riquier, 1972). Studies have shown that under nutrient deficiencies, especially nitrogen shortage, developing kernels frequently abort, which reduces kernel set (Monneveux et al., 2005). The increased maize grain yields and growth observed across all fertilizer treatments relative to the control (Figures 3A,B) are consistent with findings from previous studies (Beesigamukama et al., 2020b; Tanga et al., 2022). These findings highlight low soil fertility as a major constraint to crop production across many regions of sub-Saharan Africa (Gachimbi et al., 2005; Muchena et al., 2005), underscoring that external nutrient inputs are extremely important.

In terms of agronomic nitrogen use efficiency, our results align with previous findings showing that maize grown with CBSFF performs better in nitrogen utilization compared to other organic fertilizers (Beesigamukama et al., 2020b; Tanga et al., 2022) due to the high N mineralization and nutrient release rates (Yéton et al., 2019). Beesigamukama et al. (2020b) reported an AE_N of 43.2 kg/kg N at their lowest BSFF application rate, which closely aligns with our results of 45.9 kg/kg N for CBSFF, suggesting an adequate nitrogen supply to support maize growth.

4.4 Recommendations to smallholder farmers

The results of this study indicate that BSFF, even when applied at a dose below the regional recommendations, can significantly enhance maize production in the southeastern farming systems of Madagascar. The timing of BSFF application should depend on its form, with fresh BSFF best applied after germination, while composting it beforehand improves its maturity for better growth and yield. Notably, composted BSFF (CBSFF) produced the highest total grain yield (1.98 t/ha), 38% higher than cattle manure and substantially higher than fresh BSFF, while the unfertilized control produced no harvestable maize. These outcomes highlight the superior agronomic performance of composted BSFF and support its use as the preferred organic fertilizer for maize in this region. The improvements observed in overall maize performance with composted BSFF underscore its value in addressing nutrient deficiencies commonly limiting crop productivity in sub-Saharan Africa and similar agroecological zones.

Based on our results, we recommend that smallholder farmers in southeastern Madagascar incorporate BSFF into their maize production systems as a sustainable and effective organic fertilizer. For maximum yield, composting the frass for before application is strongly advised, as this enhances seed germination, plant growth, and grain yield by reducing phytotoxicity and improving nutrient availability. Traditional organic fertilizers such as cattle manure (CM) can also be recommended, as they produced growth and yield comparable to composted BSFF (CBSFF) in our study. In situations where composting is not feasible and no other organic input is available, fresh BSFF (FBSFF) may be applied after germination to avoid inhibition, but it should be used with caution given its association with reduced early growth and significantly lower yield.

However, several questions remain to refine these recommendations such as: How does BSFF perform across different soil types and cropping systems in Madagascar? Can co-composting BSFF with crop residues or animal manure further enhance its quality and agronomic performance? Future trials should also evaluate how different doses of regional chemical fertilizer recommendations (e.g., full, half, and one-third—with different dolomite rates) compare to composted BSFF (CBSFF), fresh BSFF (FBSFF), and cattle manure (CM) in terms of maize growth, yield, and profitability. Incorporating cost–benefit and marginal rate of return analyses will be essential for identifying economically viable and agronomically effective nutrient management strategies for smallholder farmers. These will help tailor BSFF management practices for wider adoption among smallholder farmers and improve the resilience and productivity of maize farming systems in the region.

5 Conclusion

As this study was conducted over a single season at one site, the findings should be considered preliminary. Further trials across multiple seasons and agroecological zones are necessary to validate these results and assess their broader applicability. Our results, combined with previous research highlight the strong potential of black soldier fly frass—especially when composted, as a sustainable and effective organic fertilizer for maize production in the southeastern Madagascar. Our findings show that composted BSFF notably improves maize growth, grain yield, and nitrogen use efficiency, making it a valuable resource for smallholder farmers seeking locally available nutrient sources. Given these benefits, integrating BSFF into local farming practices offers a sustainable strategy to improve soil health and crop productivity while promoting circular bioeconomy approaches that valorize organic waste. Additionally, our findings highlight the potential of BSFF in improving food security and livelihoods among vulnerable communities in Madagascar. Further research across diverse agricultural environments, including dose–response trials with BSFF, assessing long-term soil impacts, and evaluating farmer adoption barriers are recommended to fully maximize the agronomic and environmental benefits of BSFF. Future research should compare BSFF treatments with full, half, and one-third doses of regionally recommended chemical fertilizers, and incorporate detailed cost–benefit and marginal rate of return analyses to identify agronomically effective and economically viable nutrient management strategies for smallholder farming systems.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Author contributions

CS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. CO: Conceptualization, Investigation, Methodology, Writing – review & editing. SB: Conceptualization, Funding acquisition, Resources, Validation, Writing – review & editing. BF: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. CS and CO were supported by Innocent Foundation, Health In Harmony and Darwin Initiative grant 30-015.

Acknowledgments

The authors thank Sedera Ramaromanana, Eddy Ramaratsialonina and all the Health in Harmony staff for support with field trip and experiment, as well as all local community members we worked with. We also thank the two reviewers for their constructive feedback, which greatly improved the quality of this manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2025.1673188/full#supplementary-material

References

Andrianorosoa Ony, C., Solofondranohatra, C. L., Ramiadantsoa, T., Ravelomanana, A., Ramanampamonjy, R. N., Hugel, S., et al. (2024). Effect of cricket frass fertilizer on growth and pod production of green beans (*Phaseolus vulgaris* L.). *PLoS One* 19:e0303080. doi: 10.1371/journal.pone.0303080

Anyega, A. O., Korir, N. K., Beesigamukama, D., Changeh, G. J., Nkoba, K., Subramanian, S., et al. (2021). Black soldier fly-composted organic fertilizer enhances growth, yield, and nutrient quality of three key vegetable crops in sub-Saharan Africa. *Front. Plant Sci.* 12:680312. doi: 10.3389/fpls.2021.680312

Baligar, V. C., Fageria, N. K., and He, Z. L. (2001). Nutrient use efficiency in plants. *Commun. Soil Sci. Plant Anal.* 32, 921–950. doi: 10.1007/978-3-319-10635-9

Beesigamukama, D., Mochoge, B., Korir, N. K., Fiaboe, K. K., Nakimbugwe, D., Khamis, F. M., et al. (2020b). Exploring black soldier fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions. *Front. Plant Sci.* 11:574592. doi: 10.3389/fpls.2020.574592

Beesigamukama, D., Mochoge, B., Korir, N. K., Fiaboe, K. K., Nakimbugwe, D., Khamis, F. M., et al. (2021a). Low-cost technology for recycling agro-industrial waste into nutrient-rich organic fertilizer using black soldier fly. *Waste Manag.* 119, 183–194. doi: 10.1016/j.wasman.2020.09.043

Beesigamukama, D., Mochoge, B., Korir, N., Ghemoh, C. J., Subramanian, S., and Tanga, C. M. (2021b). In situ nitrogen mineralization and nutrient release by soil amended with black soldier fly frass fertilizer. *Sci. Rep.* 11:14799. doi: 10.1038/s41598-021-94269-3

Beesigamukama, D., Mochoge, B., Korir, N., Musyoka, M., Fiaboe, K. K. M., Nakimbugwe, D., et al. (2020a). Nitrogen fertilizer equivalence of black soldier fly frass fertilizer and synchrony of nitrogen mineralization for maize production. *Agronomy* 10:1395. doi: 10.3390/agronomy10091395

Bernai, M. P., Paredes, C., Sánchez-Monedero, M. A., and Cegarra, J. (1998). Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresour. Technol.* 63, 91–99. doi: 10.1016/S0960-8524(97)00084-9

Bernal, M. P., Alburquerque, J. A., Barrena, R., Komilis, D., and Sánchez, A. (2017). Current approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits. *Adv. Agron.* 144, 143–233. doi: 10.1016/bs.agron.2017.03.002

Bernal, M. P., Alburquerque, J. A., and Moral, R. (2009). Composting of animal manures and chemical criteria for compost maturity assessment: a review. *Bioresour. Technol.* 100, 5444–5453. doi: 10.1016/j.biortech.2008.11.027

Bohm, K., Hatley, G. A., Robinson, B. H., and Gutiérrez-Ginés, M. J. (2023). Analysis of chemical and phytotoxic properties of frass derived from black soldier fly-based bioconversion of biosolids. *Sustainability* 15:11526. doi: 10.3390/su151511526

Chairiyah, R. R., Ramija, K. E., and Batubara, S. F. (2021). Liming of acid soil and the interaction with soil pH and corn productivity. *IOP Conf. Ser. Earth Environ. Sci.* 807:042071. doi: 10.1088/1755-1315/807/4/042071

Chen, B., Liu, E., Tian, Q., Yan, C., and Zhang, Y. (2014). Soil nitrogen dynamics and crop residues—a review. *Agron. Sustain. Dev.* 34, 429–442. doi: 10.1007/s13593-014-0207-8

Choi, S., and Hassanzadeh, N. (2019). BSFL frass: a novel biofertilizer for improving plant health while minimizing environmental impact. *Can. Sci. Fair J.* 2, 41–46. doi: 10.18192/csfj.v2i220194146

Coudron, C., Spranghers, T., Elliot, D., and Halstead, J. (2019). Lab scale and pilot scale experiments with mealworm and black soldier fly. Roeselare, Belgium: BioBoost – Insect Breeding.

CREAM (2013). Monographie Région Atsimo Atsinanana. Antananarivo, Madagascar: Centre de Recherches, d'Études, de l'Appui à l'Analyse Économique de Madagascar.

Emino, E. R., and Warman, P. R. (2004). Biological assay for compost quality. *Compost Sci. Util.* 12, 342–348. doi: 10.1080/1065657X.2004.10702203

Epstein, E. (1997). The science of composting. Boca Raton, FL, USA: CRC Press.

FAO (1980). A manual of rural composting; FAO/UNDP regional project RAS/75/004 field document no. 15. Rome, Italy: FAO.

FAO (2017). The state of food and agriculture. Leveraging food Systems for Inclusive Rural Transformation. Rome, Italy: FAO Publishing Group.

Fick, S. E., and Hijmans, R. J. (2017). WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37, 4302–4315. doi: 10.1002/joc.5086

FOFIFA/CENRADERU – Foibem-pirenena momba ny Fikarohana ampiharina amin'ny Fampandrosoana ny eny Ambanivohitra / Centre National de Recherche Appliquée au Développement Rural (2024). Fiches Techniques de Base Destinées aux Techniciens Agricoles. Antananarivo, Madagascar: FOFIFA.

Gachimbi, L. N., Van Keulen, H., Thuranira, E. G., Karuku, A. M., De Jager, A., Nguluu, S., et al. (2005). Nutrient balances at farm level in Machakos (Kenya), using a participatory nutrient monitoring (NUTMON) approach. *Land Use Policy* 22, 13–22. doi: 10.1016/j.landusepol.2003.07.002

Gärttling, D., Kirchner, S. M., and Schulz, H. (2020). Assessment of the N- and P-fertilization effect of black soldier fly (Diptera: Stratiomyidae) by-products on maize. *J. Insect Sci.* 20:8. doi: 10.1093/jisesa/ieaa089

Green, T. R., and Popa, R. (2012). Enhanced Ammonia content in compost leachate processed by black soldier fly larvae. *Appl. Biochem. Biotechnol.* 166, 1381–1387. doi: 10.1007/s12010-011-9530-6

Harvey, C. A., Rakotobe, Z. L., Rao, N. S., Dave, R., Razafimahatratra, H., Rabarijohn, R. H., et al. (2014). Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philos. Trans. R. Soc. B Biol. Sci.* 369:20130089. doi: 10.1098/rstb.2013.0089

Hénault-Ethier, L., Quinche, M., Reid, B., Hotte, N., Fortin, A., Normandin, É., et al. (2024). Opportunities and challenges in upcycling agri-food byproducts to generate insect manure (frass): a literature review. *Waste Manag.* 176, 169–191. doi: 10.1016/j.wasman.2023.12.033

Herrera, J. P., Rabezara, J. Y., Ravelomanantsoa, N. A. F., Metz, M., France, C., Owens, A., et al. (2021). Food insecurity related to agricultural practices and household characteristics in rural communities of Northeast Madagascar. *Food Secur.* 13, 1393–1405. doi: 10.1007/s12571-021-01179-3

ISTA (2020). International rules for seed testing. Bassersdorf, Switzerland: International Seed Testing Association.

Lalander, C. H., Fidjeland, J., Diener, S., Eriksson, S., and Vinnerås, B. (2015). High waste-to-biomass conversion and efficient *Salmonella spp.* reduction using black soldier fly for waste recycling. *Agron. Sustain. Dev.* 35, 261–271. doi: 10.1007/s13593-014-0235-4

Liu, T., Awasthi, M. K., Awasthi, S. K., Duan, Y., and Zhang, Z. (2020). Effects of black soldier fly larvae (Diptera: Stratiomyidae) on food waste and sewage sludge composting. *J. Environ. Manag.* 256:109967. doi: 10.1016/j.jenvman.2019.109967

Lopes, I. G., de Souza, L. F., da Cruz, M. C. P., and Vidotti, R. M. (2019). Composting as a strategy to recycle aquatic animal waste: case study of a research Centre in São Paulo State, Brazil. *Waste Manag. Res.* 37, 590–600. doi: 10.1177/0734242X19830170

Lopes, I. G., Wiklicky, V., Vinnerås, B., Yong, J. W. H., and Lalander, C. (2024). Recirculating frass from food waste bioconversion using black soldier fly larvae: impacts on process efficiency and product quality. *J. Environ. Manag.* 366:121869. doi: 10.1016/j.jenvman.2024.121869

Lopes, I. G., Yong, J. W., and Lalander, C. (2022). Frass derived from black soldier fly larvae treatment of biodegradable wastes: a critical review and future perspectives. *Waste Manag.* 142, 65–76. doi: 10.1016/j.wasman.2022.02.007

Luo, Y., Liang, J., Zeng, G., Chen, M., Mo, D., Li, G., et al. (2018). Seed germination test for toxicity evaluation of compost: its roles, problems and prospects. *Waste Manag.* 71, 109–114. doi: 10.1016/j.wasman.2017.09.023

Menino, R., Felizes, F., Castelo-Branco, M. A., Fareleira, P., Moreira, O., Nunes, R., et al. (2021). Agricultural value of black soldier fly larvae frass as organic fertilizer on ryegrass. *Heliyon* 7:e05855. doi: 10.1016/j.heliyon.2020.e05855

Monneveux, P., Zaidi, P. H., and Sanchez, C. (2005). Population density and low nitrogen affects yield-associated traits in tropical maize. *Crop Sci.* 45, 535–545. doi: 10.2135/cropsci2005.0535

Muchena, F. N., Onduru, D. D., Gachini, G. N., and de Jager, A. (2005). Turning the tides of soil degradation in Africa: capturing the reality and exploring opportunities. *Land Use Policy* 22, 23–31. doi: 10.1016/j.landusepol.2003.07.001

R Core Team (2020). R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Raj, D., and Antil, R. S. (2011). Evaluation of maturity and stability parameters of composts prepared from agro-industrial wastes. *Bioresour. Technol.* 102, 2868–2873. doi: 10.1016/j.biortech.2010.10.077

Ramírez, W. A., Domene, X., Andrés, P., and Alcañiz, J. M. (2008). Phytotoxic effects of sewage sludge extracts on the germination of three plant species. *Ecotoxicology* 17, 834–844. doi: 10.1007/s10646-008-0246-5

Randrianarison, N., Nischalke, S., and Andriamazaoro, H. (2020). The role of biodiversity and natural resource management in food security in South-Eastern Madagascar. *Acta Hortic.* 1267, 267–273. doi: 10.17660/ActaHortic.2020.1267.40

Rehan, I., Lopes, I. G., Murta, D., Lidon, F., Fareleira, P., Esteves, C., et al. (2024). Agronomic potential of *Hermetia illucens* frass in the cultivation of ryegrass in distinct soils. *J. Insects Food Feed* 11, 803–818. doi: 10.1163/23524588-00001242

Riquier (1972). Mémento de l'Agronome. *2nd* Edn. Paris, France: Ministère de la Coopération.

Risman, R. D. S., Nonkhonman, C., and Sungthongwises, K. (2025). Integrating vermicompost, black soldier fly, and inorganic fertilizers enhances corn growth and yield. *Heliyon* 11:e41314. doi: 10.1016/j.heliyon.2024.e41314

Rouf, S. T., Prasad, K., and Kumar, P. (2016). Maize – a potential source of human nutrition and health: a review. *Cogent Food Agric.* 2:1166995. doi: 10.1080/23311932.2016.1166995

Schipanski, M. E., MacDonald, G. K., Rosenzweig, S., Chappell, M. J., Bennett, E. M., Kerr, R. B., et al. (2016). Realizing resilient food systems. *Bioscience* 66, 600–610. doi: 10.1093/biosci/biw052

Setti, L., Francia, E., Pulvirenti, A., Gigliano, S., Zaccardelli, M., Pane, C., et al. (2019). Use of black soldier fly (*Hermetia illucens* (L.), diptera: stratiomyidae) larvae processing residue in peat-based growing media. *Waste Manag.* 95, 278–288. doi: 10.1016/j.wasman.2019.06.017

Solofondranohatra, C. L., Ramiadantsoa, T., Hugel, S., and Fisher, B. L. (2025). Black soldier fly frass fertilizer outperforms traditional fertilizers in terms of plant growth in restoration in Madagascar. *Sustainability* 17:7152. doi: 10.3390/su17157152

Song, S., Ee, A. W. L., Tan, J. K. N., Cheong, J. C., Chiam, Z., Arora, S., et al. (2021). Upcycling food waste using black soldier fly larvae: effects of further composting on frass quality, fertilizing effect and its global warming potential. *J. Clean. Prod.* 288:125664. doi: 10.1016/j.jclepro.2020.125664

Stoop, W. A., Uphoff, N., and Kassam, A. (2002). A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. *Agric. Syst.* 71, 249–274. doi: 10.1016/S0308-521X(01)00070-1

Tanga, C. M., Beesigamukama, D., Kassie, M., Egonyu, P. J., Ghemoh, C. J., Nkoba, K., et al. (2022). Performance of black soldier fly frass fertiliser on maize (*Zea mays* L.) growth, yield, nutritional quality, and economic returns. *J. Insects Food Feed* 8, 185–196. doi: 10.3920/jiff2021.0012

Temple, W. D., Radley, R., Baker-French, J., and Richardson, F. (2013). Use of Enterra natural fertilizer (black soldier fly larvae digestate) as a soil amendment. Langley City, Canada: Enterra Feed Corporation.

Tetteh, F. M., Ennim, S. A., Issaka, R. N., Buri, M., Ahiabor, B. A. K., and Fening, J. O. (2018). "Fertilizer recommendation for maize and cassava within the breadbasket zone of Ghana" In: Bationo, A., Ngaradoum, D., Youl, S., Lompo, F., Fening, J. (eds) Improving the profitability, sustainability and efficiency of nutrients through site specific fertilizer recommendations in West Africa agro-ecosystems. Springer, Cham. vol. 2, 161–184. doi: 10.1007/978-3-319-58792-9_10

Tully, K., Sullivan, C., Weil, R., and Sanchez, P. (2015). The state of soil degradation in sub-Saharan Africa: baselines, trajectories, and solutions. *Sustainability* 7, 6523–6552. doi: 10.3390/su7066523

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., et al. (2014). Sustainable intensification and the African smallholder farmer. *Curr. Opin. Environ. Sustain.* 8, 15–22. doi: 10.1016/j.cosust.2014.06.001

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., et al. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *Soil* 1, 491–508. doi: 10.5194/soil-1-491-2015

Wang, X., Ma, Y., Cao, Y., Wang, Q., Wu, N., and Xu, X. (2025). Fertilizing effects of black soldier fly larval frass composts sourced from pig and chicken manure on soil microbial community and maize seedling growth. *J. Soil Sci. Plant Nutr.* 25, 27–39. doi: 10.1007/s42729-024-02075-3

Yéton, B. G. A., Aliou, S., Noël, O., Lucien, A. G., Mouinou, I. A., Attuquaye, C. V., et al. (2019). Decomposition and nutrient release pattern of agro-processing by-products biodegraded by fly larvae in Acrisols. *Arch. Agron. Soil Sci.* 65, 1610–1621. doi: 10.1080/03650340.2019.1572118