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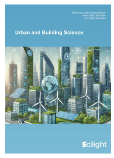

Article

Sustainable Agriculture through Black Soldier Fly Larvae Frass: Impacts on Soil Properties, Shallot Crop Productivity, and Cost Analysis

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Abstract: Sustainable agriculture faces challenges in enhancing soil health and crop productivity while minimizing costs. Applying organic amendments like Black Soldier Fly Larvae (BSFL) frass presents a potential solution, yet its comprehensive effects on soil properties and crop yield remain underexplored. This study aimed to evaluate the impact of BSFL frass on soil properties, shallot crop productivity, and associated cost analysis. A field experiment was conducted with six treatments, including varying rates of BSFL frass and Nitrogen-Phosphorus-Potassium (NPK) fertilizer. Soil samples were analyzed for pH, soil organic carbon (SOC), total nitrogen, and available phosphorus, while shallot yield was measured post-harvest. Results indicated that BSFL frass significantly improved soil pH and SOC levels, with the highest yield recorded in the treatment combining BSFL frass and NPK fertilizer. Treatment BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1} notably outperformed other treatments in both yield and profitability, suggesting that an optimal combination of organic and inorganic inputs can substantially enhance productivity and financial returns. These findings indicate that BSFL frass not only improves soil health and crop yield but also offers a cost-effective alternative to conventional fertilizers, promoting sustainable agricultural practices. Future research should focus on the long-term effects and scalability of BSFL frass application in diverse cropping systems.

Keywords: soil carbon sequestration; organic amendment; soil health; fertilizer efficiency; production cost

1. Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report mentioned carbon dioxide removals (CDR) as the technology to offset greenhouse gas emissions from hard-to-abate sectors [1]. CDR refers to anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. Among all CDRs, afforestation, reforestation, improved forest management, agroforestry, and soil carbon sequestration are currently the only widely practiced methods. Soil carbon sequestration (enhanced sinks) is a mechanism for soil carbon enrichment towards sustainable agriculture through organic nutrient amendment instead of chemical nutrients.

Sustainable agriculture has become a critical focus in recent years, as climate change, land degradation, and excessive use of chemical fertilizers pose challenges to worldwide food production. The excessive application of these fertilizers can lead to nutrient runoff, contaminating water bodies and groundwater and disrupting aquatic ecosystems [2]. Furthermore, long-term use of chemical fertilizers can deplete soil fertility, resulting in lower crop yields and a higher risk of disease and pests [3]. The continuous decline in crop yields forces farmers to spend more on purchasing chemicals to maintain their crop production levels. This cycle poses a threat not only to food security but also to the environment, causing problems such as water contamination and loss of biodiversity [4]. Substituting chemical fertilizers with organic fertilizers is an alternative solution to improve soil properties while providing nutrients to plants, thus supporting sustainable agricultural practices.

In Indonesia, shallot (*Allium cepa var. ascalonicum*) farming is a significant agricultural activity, providing essential income for local farmers and supporting the country's food supply security. The average productivity of shallots in Indonesia is reported to be around 9.69 tons per hectare, which is significantly lower than its potential yield of 11.10 tons per hectare [5]. However, relying on synthetic fertilizers to boost crop productivity has led to deteriorating soil health, nutrient depletion, and environmental pollution [6]. The excessive use of nitrogen, phosphorus, and potassium fertilizers can result in nutrient imbalances, soil acidification, and a decline in organic matter content [7]. This degradation reduces the soil's ability to retain moisture and nutrients, ultimately leading to lower crop yields.

The cost analysis of organic shallot cultivation is a multifaceted topic encompassing various economic, agronomic, and market-based considerations. Organic shallots cultivated without synthetic fertilizers and pesticides often yield lower quantities than their conventional counterparts. However, they command higher market prices, which can enhance profitability. Lasmini et al. indicated that applying organic fertilizers, such as bokashi compost, in conjunction with reduced inorganic fertilizers could enhance soil quality and improve shallot yields [8]. Additionally, the analysis of semi-organic shallot production in Bantul Regency reveals that integrating sustainable practices into the value chain can significantly impact profitability. Dewayanti et al. examined the constraints and assessed the sustainability performance of semi-organic shallots, suggesting that addressing these challenges could improve market access and farmer income [9].

Organic fertilizers, particularly those derived from biological processes, offer a promising solution to the challenges posed by chemical fertilizers. Integrating organic waste management with agricultural practices not only address waste disposal issues but also enhances soil fertility and increases crop yields. Black Soldier Fly (BSF) larvae (*Hermetia illucens*), known for their efficiency in converting organic waste into high-quality protein, produce a byproduct containing plant nutrients and beneficial microorganisms called frass [10]. Studies have indicated that BSFL frass can significantly improve soil chemical properties, enhance nutrient availability, and promote plant growth [6]. However, further investigation is necessary to determine the efficacy and optimal application rates of BSF larvae frass on specific crops like shallots. Most studies have focused on staple crops like maize and vegetables, leaving a lack of comprehensive data on the application of BSF frass in shallot cultivation. Furthermore, the interaction between BSF frass and local soil types, and their long-term effects on soil health and crop yield, requires further investigation.

This research aimed to investigate the effects of BSF larvae frass on soil properties, shallot productivity, and its cost analysis. By conducting field trials and analyzing the impact of varying application rates of BSFL frass, this study sought to provide empirical evidence on its potential as a sustainable organic fertilizer. Understanding the relationship between BSFL frass application and shallot productivity will contribute to the development of sustainable agricultural practices that benefit farmers in Indonesia [11].

2. Data and Methodology

2.1. Data

Data collection was carried out through both field measurements and laboratory analyses. Soil samples were collected before treatment application (baseline) and after harvest to assess changes in chemical properties. Plant growth data, including height and number of tillers, were recorded at 14, 28, and 42 days after planting (DAP), while yield data were collected at harvest from each plot.

The experimental data were statistically analyzed using a one-way Analysis of Variance (ANOVA) to evaluate the effects of treatments on soil properties, growth, and yield performance. A post-hoc analysis was conducted using the least significant difference (LSD) test to determine significant differences between treatments at a confidence level of 95% ($p < 0.05$). The data analysis was performed using Microsoft Excel, IBM SPSS 25, and R Studio with R version 4.4.1 (2024-06-14 ucrt)—"Race for Your Life", © 2024 The R Foundation for Statistical Computing. The experiment followed a Randomized Block Design (RBD) with six treatments (A–F), each replicated four times, where Treatment B (NPK 500 kg ha^{-1}) served as the control (see Section 2.2.3 for a detailed description of the experimental design). Benefit Cost Ratio (BCR) is calculated based on the revenue and cost deviations from this standard treatment. Specifically, the BCR for each treatment is measured by the formula:

$$BCRTi = \frac{RTi - RC}{CTi - CC}$$

where *RTi* is the total revenue from treatment *i* (yield multiplied by market price), *RC* is the revenue from the control treatment, *CTi* is the production cost of treatment *i*, and *CC* is the cost of the control treatment. Treatment B (NPK alone) serves as the baseline in this formula, with *BCR* defined as 1.0 by convention. A *BCR* above 1 indicates that the treatment is more cost-effective than the control, while a *BCR* less than 1 suggests lower cost efficiency.

2.2. Methodology

2.2.1. Time and Location

The researchers conducted a field experiment from March to July 2024 at the Faculty of Agriculture, Siliwangi University, Tasikmalaya Regency, West Java, Indonesia, at an altitude of 315 m above sea level with the highest average temperature of 32 °C and the lowest of 21.7 °C. The average humidity at the research location was 84% with an average rainfall of 160.64 mm/month. Soil analysis was carried out at the Soil Laboratory of Siliwangi University to assess the impact of treatments on soil properties. The experimental site and laboratory provided the controlled conditions and resources necessary for accurate and reliable data collection.

2.2.2. Materials

The materials used in this study were BSF larvae frass from the manufacturer, shallot tubes with Pancasona varieties obtained from the Indonesian Instruments Standardization Testing Center for Vegetables, black silver plastic mulch, inorganic fertilizer (NPK 16-16-16), and dolomite. Some of the equipment used in the study included hoes, sprayers, portable digital scales, rulers, calipers, buckets, a thermo hygrometer, glassware (beaker glass, pipette, volumetric flask, burette, etc.), and laboratory analysis instruments.

2.2.3. Experimental Design

The experimental design used a Randomized Block Design (RBD) with a single factor to evaluate the effects of six different treatments on shallot growth and soil properties. The treatments included: (A) BSF Larvae 30 ton ha^{-1}, (B) NPK 16-16-16 500 kg ha^{-1}, (C) BSF Larvae 15 ton ha^{-1} + NPK 250 kg ha^{-1}, (D) BSFL 15 ton/ha + NPK 375 kg ha^{-1}, (E) BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}, and (F) BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}. Each treatment was replicated four times, resulting in a total of 36 research plots, with five biological replicates per plot to ensure data robustness and reliability.

2.2.4. Observed Parameters

The observed parameters included soil properties, plant performance, and cost and feasibility analyses. Soil samples were collected before (initial soil analysis) and after treatments (residual analysis). The soil parameters measured included soil organic carbon (SOC), pH, total nitrogen, and available P_2O_5. The SOC was measured using the Walkley-Black Method. This wet chemical technique was used to determine soil organic carbon by oxidizing the organic matter with a potassium dichromate solution in concentrated sulfuric acid and back-titrating the excess dichromate with ferrous sulfate. The soil pH was measured using a potentiometric method. Potentiometric pH analysis preparing a solution or suspension, then measuring the electrical potential difference between a pH-sensitive glass electrode and a stable reference electrode. The Kjeldahl method was used to measure the total nitrogen content in soil by treating the sample with sulfuric acid and a catalyst, which transformed nitrogen into ammonium sulfate. Next, ammonia was distilled by introducing a strong base, and then the collected ammonia was titrated in a boric acid solution using a standard acid to determine the total nitrogen content. Lastly, the Olsen method determined available phosphate in neutral to alkaline soils by extracting the phosphorus with a sodium bicarbonate solution, then measuring the resulting-colored complex with a spectrophotometer.

Shallot growth performance was evaluated by measuring plant height and tiller number at specified intervals during the growing period. Yield performance was assessed by measuring the tuber weight per hill, the number of tubers per hill, and the tuber weight per plot at harvest. The total farming cost for each treatment was obtained by calculating the costs of BSF larvae, NPK fertilizer, labor, and other relevant inputs. Feasibility analysis was conducted by estimating the cost-benefit ratio (CBR), net profit margin, and return on investment (ROI) for each treatment to determine its economic viability. The overall research framework of this study is presented in Figure

1. The framework illustrates the logical connection between the research objectives, methods, and key results, linking the effects of BSFL frass application with soil properties, shallot productivity, and cost efficiency.

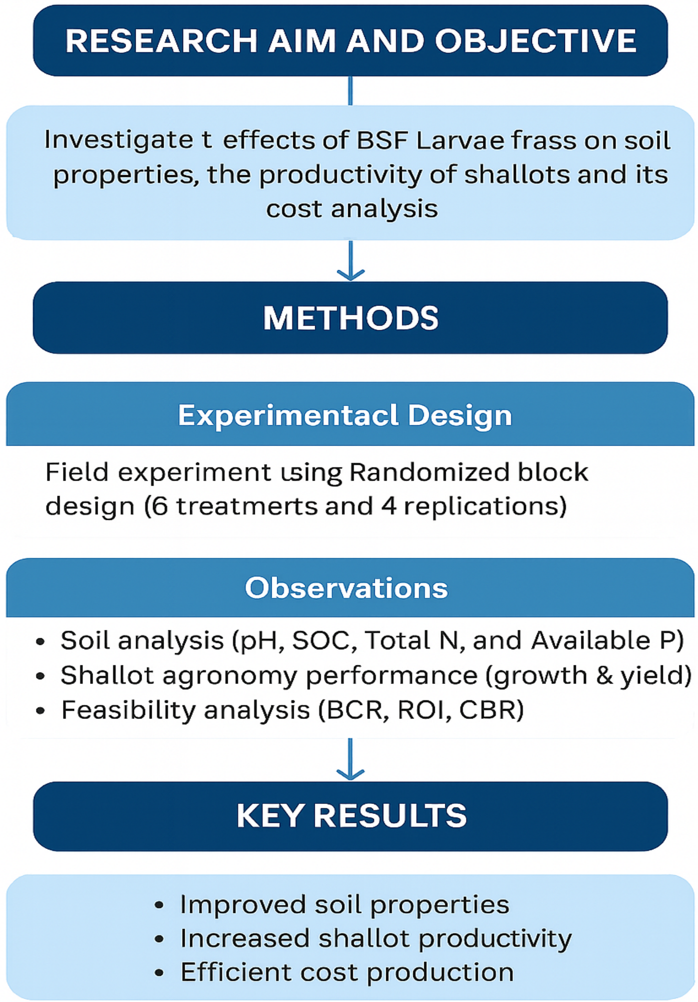

Figure 1. Research framework of this study.

3. Result and Discussion

3.1. Initial Soil Analysis

Results from the initial soil analysis (Table 1) revealed several key baseline properties critical for evaluating the impact of Black Soldier Fly Larvae (BSFL) frass on soil health and crop productivity. The pH level was neutral at 6.5, which is generally favorable for most crops, as it optimizes soil nutrient availability and microbial [12]. However, the soil organic carbon (SOC) content was low at 2.89%, and the carbon-to-nitrogen (C/N) ratio was also low at 6.72, indicating potential limitations in nutrient availability for optimal plant growth. The soil water content was 6.68%, and although total nitrogen (N) was at a medium level of 0.43%, the available phosphorus (P_2O_5) was also medium at 8.55 ppm. The presence of medium nitrogen and phosphorus levels indicates that while some nutrients are available, amendments may still be necessary to enhance overall soil fertility. These initial conditions suggest that the soil may benefit from amendments that could enhance its organic matter content and nutrient availability, making BSFL frass a potentially valuable addition.

Table 1. Soil analysis before treatment.

Parameter	Method	Unit	Result	Criteria
pH: H_2O	Potentiometric	-	6.50	Neutral
SOC	Walkley and Black	%	2.89	Low
C/N	-	%	6.72	Low
Water Content	Gravimetric	%	6.68	-
Total N	Kjeldahl	%	0.43	Medium
Available P_2O_5	Olsen–Spectrophotometry UV-Vis.	ppm	8.55	Medium

3.2. Residual Soil Analysis

A statistical test of residual soil analysis on several chemical properties is shown in Table 2. Analysis of residual soil properties after application of fertilizer treatments showed significant differences in the pH, SOC, Total N, and Available P_2O_5, respectively. The pH values ranged from 6.48 in Treatment B (NPK 16-16-16 500 kg ha^{-1}) to 6.94 in Treatment A (BSFL 30 ton ha^{-1}). The highest pH value observed in Treatment A indicates that applying Black Soldier Fly Larvae (BSFL) frass can increase soil alkalinity, which is beneficial for nutrient availability and microbial activity. Treatments C (BSFL 15 ton ha^{-1} + NPK 250 kg ha^{-1}) and D (BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}) showed intermediate pH values of 6.69 and 6.80, respectively, implying that BSFL frass combined with NPK fertilizers can produce a pH regime suitable for crop growth. In contrast, Treatment B, containing only NPK fertilizer, had the lowest pH value, indicating that synthetic fertilizers might cause soil acidification over time.

Analysis of SOC content after applying various fertilizer treatments demonstrated significant differences. Applying BSFL frass significantly increased the SOC compared to NPK fertilizer treatment alone. Treatment A (BSF Larvae 30 ton ha^{-1}) showed the highest SOC of 4.95 ± 0.25% compared to treatments B (NPK 16-16-16 500 kg ha^{-1}), C (BSFL 15 ton ha^{-1} + NPK 250 kg ha^{-1}), and D (BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}), but was not significantly different from treatments E (BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}) and F (BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}). On the contrary, treatment B (NPK 16-16-16 500 kg ha^{-1}) showed the lowest organic carbon content compared to the other treatments.

The application of various fertilizer treatments showed a significant effect on the total N in the soil. Treatment C (BSFL 15 ton ha^{-1} + NPK 250 kg ha^{-1}) had the lowest total N compared to the other treatments. The difference in N content in treatment C is likely due to the low rate of NPK fertilizer applied. Meanwhile, applying BSFL frass fertilizer treatment at several levels did not show significant differences. This aligns with the findings by Gebremikael et. al. (2022), revealing that applying frass generally results in initial net N immobilization lasting 26–70 days after application [13]. Nitrogen is a highly mobile nutrient, making it easily lost from the soil. In addition to its plant uptake, nitrogen can be lost through fertilizers after leaching and evaporation [14]. Nitrification converts N-ammonium (NH_4) into N-nitrate (NO^{3-}), which is not absorbed by the surface of the soil colloids. Thus, it is easily leached. Increased soil pH (alkaline conditions) and high-temperature conditions also favor volatilization of ammonium nitrogen (NH_4^+), changing it to gaseous ammonia (NH_3) and causing nitrogen to be lost to the atmosphere [15].

Applying BSFL frass significantly improved soil chemical properties with sole NPK fertilization. The increase in soil pH and SOC following BSFL treatments can be attributed to the organic matter content and neutral pH of the frass. Organic matter enhances soil aggregation and buffering capacity, reducing acidification risks commonly observed under continuous mineral fertilizer use. These results are consistent with Gebremikael et al. (2022), who reported that frass applications improved nitrogen cycling and stimulated microbial activity, thereby supporting long-term soil fertility [13]. The higher available phosphorus levels in combined frass + NPK treatments also indicate that frass may promote microbial solubilization of P, a mechanism similarly observed by Beesigamukama et al. (2020) in maize systems [16].

Figure 2d shows that combining BSFL frass with NPK fertilizer increases phosphorus availability in the soil. Treatments A (BSFL 30 ton ha^{-1}) and B (NPK 16-16-16 500 kg ha^{-1}), which applied BSFL frass and NPK independently, showed lower phosphorus levels. On the other hand, combining BSFL frass and synthetic NPK produced higher available P_2O_5 with Treatment D (BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}) as the highest. This is consistent with the study by Gebremikael et al. (2022), which highlighted the role of organic amendments in improving soil structure and microbial activity, which can enhance phosphorus mobilization [13]. The authors found that combining organic fertilizers with mineral fertilizers led to a significant increase in the phosphorus availability, particularly in soil with low initial phosphorus levels [3].

Table 2. Residual soil chemical properties under different treatments (mean ± SE).

Symbol	Fertilizer Treatment	pH Value	SOC (%)	Total N (%)	Available P_2O_5 (ppm)
A	BSF Larvae 30 ton ha^{-1}	6.94 ± 0.14 ^{c}	4.95 ± 0.25 ^{c}	0.24 ± 0.02 ^{b}	14.14 ± 1.33 ^{a}
B	NPK 16-16-16 500 kg ha^{-1}	6.48 ± 0.11 ^{a}	2.48 ± 0.24 ^{a}	0.24 ± 0.02 ^{b}	16.07 ± 1.98 ^{a}
C	BSF Larvae 15 ton ha^{-1}+ NPK 250 kg ha^{-1}	6.69 ± 0.09 ^{ab}	3.08 ± 0.34 ^{b}	0.17 ± 0.00 ^{a}	43.13 ± 2.93 ^{b}
D	BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}	6.80 ± 0.05 ^{bc}	4.06 ± 0.36 ^{b}	0.26 ± 0.01 ^{b}	55.07 ± 4.73 ^{c}
E	BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}	6.80 ± 0.01 ^{bc}	4.45 ± 0.26 ^{bc}	0.27 ± 0.01 ^{b}	37.87 ± 4.81 ^{b}
F	BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}	6.61 ± 0.10 ^{ab}	4.54 ± 0.21 ^{bc}	0.26 ± 0.01 ^{b}	44.85 ± 2.28 ^{b}

Note: Values followed by different superscript letters in the same column differ significantly ($p < 0.05$) according to the LSD test.

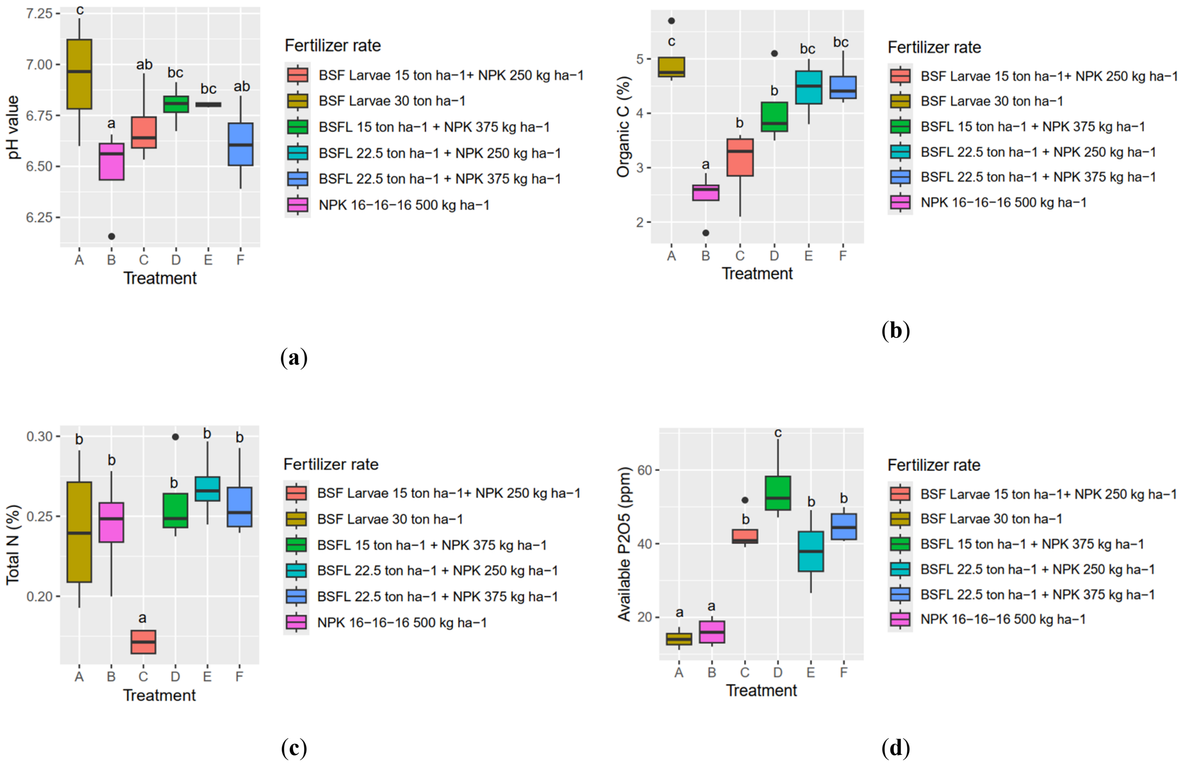

Figure 2. Analysis of Residual Soil Properties on different fertilizer rates; (**a**) pH value; (**b**) SOC; (**c**) Total Nitrogen; (**d**) Available P_2O_5.

The analysis of Black Soldier Fly larvae (BSFL) frass demonstrated its potential as a high-quality organic fertilizer, with significant implications for sustainable agriculture. Table 3 shows the chemical properties of BSF larvae Frass used in this experiment. The frass was found to have an organic carbon (C) content of 15%, as measured by the Walkley-Black method. This high organic C content enhances the frass's ability to improve soil organic matter when applied as a fertilizer, thereby supporting soil structure and fertility.

The carbon-to-nitrogen (C/N) ratio was recorded at 3.75, indicating a nutrient-rich composition with potential for rapid nitrogen release. This low C/N ratio is beneficial as it suggests that the frass can decompose quickly, releasing nitrogen essential for crop growth without immobilizing soil nitrogen, which is a common challenge with high-carbon materials [15–17]. This field experiment validated the capacity of frass to minimize the leaching of nutrients from mineral fertilizers [18,19]. Conversely, the comparable influence of frass on both biomass and nutrient absorption in relation to NPK indicates that frass served as a nutrient source and may be utilized as a partial or complete replacement for mineral fertilizers [13]. Frass has a neutral pH of 6.0, making it suitable for most agricultural soils and can prevent the risks associated with soil acidification, which is often a concern with synthetic fertilizers. This pH level is optimal for nutrient availability, particularly phosphorus, which is critical for crop energy transfer and root development. The frass showed a water content of 10.8%, lower than the minimum requirement of organic fertilizer from the Minister of Agriculture of the Republic of Indonesia, with the minimum value at 15% [20].

In terms of macronutrients, the total nitrogen (N) content was impressively high at 4.1%, as measured using the Kjeldahl method. This level is exceptional compared to typical nitrogen levels in organic amendments, which are usually much lower. This aligns with findings by Gebremikael et al. (2022), which highlighted that BSFL frass contributes positively to soil fertility and plant growth due to its high nutrient content [13]. High nitrogen content supports rapid plant growth and reduces the need for additional nitrogenous fertilizers [21]. Phosphorus (P) content was also high at 3.0%, as determined by $HClO_4$ + HNO_3 digestion and UV-VIS spectrophotometry. This is considerably higher than most organic amendments and can significantly enhance root development and crop yield [22]. Lastly, the potassium (K) content measured at 0.8% through Atomic Absorption Spectroscopy is advantageous for crop osmoregulation and stress tolerance. This level is adequate to support plant growth, especially in potassium-deficient soils [23].

Table 3. Chemical analysis of BSF Larvae Frass.

No.	Parameter	Unit	Result	Method
1	Organic–C	%	15	Walkley and Black
2	C/N Ratio	-	3.75	-
3	pH H_2O	-	6	Potentiometric–pH meter
4	Water Content	%	10.8	Gravimetric
5			Macronutrients:	
	Total N	%	4.1	Kjeldhal
	Total P	%	3.0	$HClO_4$ + HNO_3-Spectrophotometry UV-VIS
	Total K	%	0.8	$HClO_4$ + HNO_3–Atomic Absorption Spectroscopy

3.3. Growth Performance

3.3.1. Response to Plant Height

The study evaluated the effect of various fertilizer treatments on shallot plant height at different growth stages (14, 28, and 42 days after planting). As presented in Table 4, the results indicated significant differences in plant height among treatments, demonstrating that BSFL frass is a future non-polluting alternative to fertilization. The highest improved plant height of 18.50 ± 0.44 cm at 14 DAP was achieved through combining BSFL at 22.5 ton ha^{-1} with NPK 250 kg ha^{-1} (Treatment E). This was considerably higher than the treatment with NPK alone (Treatment B), where plant height was the least (16.19 ± 0.45 cm). At 28 DAP, Treatment E continued to outperform the other treatments, achieving a growth height of 30.00 ± 0.54 cm, significantly exceeding the NPK-alone treatment, which recorded a height of 24.19 ± 0.97 cm. At 42 days after planting (DAP), Treatment E maintained its lead with a plant height of 38.75 ± 0.49 cm, which was significantly taller than all other treatments. The consistent performance of this treatment across various growth stages suggests the potential of BSFL frass as a viable substitute for inorganic fertilizers. This indicates that nutrient and organic matter content in BSFL frass would be superior to induce early plant growth than synthetic fertilizers alone.

The combination of BSFL and NPK appears to provide well-balanced nutrient availability, facilitating improved growth. Based on a study by Beesigamukama et al. (2020), maize treated with BSFL frass exhibited the tallest plants and the highest chlorophyll concentrations compared to those treated with commercial organic fertilizer and mineral fertilizers [16]. Moreover, the synergistic effects of combining organic and inorganic fertilizers have been documented, indicating that such mixtures can enhance nutrient availability and plant uptake [17]. The literature supports the notion that applying frass can improve plant growth and soil health, providing a slow release of macro- and micronutrients, thereby minimizing nutrient runoff [18]. Additionally, the high waste degradation efficiency of BSFL, which ranges from 65–78%, further underscores the sustainability of using BSFL frass in agricultural practices [19].

Table 4. Effect of different fertilizer rates on the plant height of shallot at 14–42 DAP.

Symbol	Fertilizer Treatment	Plant Height (cm)		
		14 DAP	**28 DAP**	**42 DAP**
A	BSF Larvae 30 ton ha^{-1}	18.16 ± 0.71 ^{b}	27.25 ± 0.78 ^{b}	34.75 ± 0.78 ^{b}
B	NPK 16-16-16 500 kg ha^{-1}	16.19 ± 0.45 ^{a}	24.19 ± 0.97 ^{a}	30.56 ± 1.89 ^{a}
C	BSF Larvae 15 ton ha^{-1}+ NPK 250 kg ha^{-1}	17.03 ± 0.55 ^{ab}	28.25 ± 0.68 ^{bc}	34.69 ± 0.63 ^{b}
D	BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}	15.38 ± 1.14 ^{a}	27.88 ± 1.36 ^{bc}	36.56 ± 0.89 ^{bc}
E	BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}	18.50 ± 0.44 ^{b}	30.00 ± 0.54 ^{c}	38.75 ± 0.49 ^{c}
F	BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}	16.97 ± 0.72 ^{ab}	28.94 ± 0.98 ^{bc}	35.31 ± 1.21 ^{b}

Note: Values followed by different superscript letters in the same column differ significantly ($p < 0.05$) according to the LSD test.

The findings generally indicate that BSFL frass, especially in combination with NPK, has the potential to promote shallot growth significantly and serve as a sustainable and effective alternative to conventional fertilizers. The research validates the efficacy of insect-based fertilizers for sustainable agriculture systems through soil health and crop yield improvement. It is recommended that more studies be conducted on the long-term effect of BSFL frass on soil characteristics and its economic feasibility in commercial agricultural applications.

3.3.2. Number of Tillers

The number of tillers in shallots was assessed on the 14th, 28th, and 42nd days after planting, affected by different fertilizer treatments (Table 5). BSFL frass treatments alone, specifically the Treatment A-30 ton ha^{-1} and Treatment E combined with 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}, produced significantly higher tillers of 4.56 ± 0.41 and 4.56 ± 0.43, respectively, compared to the sole application of Treatment B, which gave 3.88 ± 0.33 at 14 DAP. It also indicates that organic matter in BSFL frass has the potential to improve early tiller development, possibly due to improved soil structure and nutrient availability. By 28 DAP, Treatment C (BSFL 15 ton ha^{-1} + NPK 250 kg ha^{-1}) had the largest number of tillers (7.88 ± 0.55) and was significantly higher than Treatment D (NPK only), which exhibited 6.25 ± 0.23 tillers. The results revealed that Treatment C was still leading with 8.750 ± 0.729 tillers, while Treatment F followed closely, having 8.625 ± 0.505 tillers at 42 DAP (BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}).

Such persistence of the treatments through these growth stages demonstrates the potential of BSFL frass for enhancing shallot productivity, especially in conjunction with NPK. This would further mean that organic and inorganic fertilizers acting synergistically provide better nutrient balances to keep the tillers growing well. This is in agreement with the findings of Gebremikael et al. (2022), who observed that insect-based fertilizers can enhance plant growth by improving nutrient cycling and soil health [13]. Overall, the results showed that BSFL frass, especially in combination with NPK, can effectively increase tillering in shallots. Using BSFL frass as an alternative to conventional fertilizers in agriculture is highly sustainable and efficient.

Table 5. Effect of different fertilizer rates on the number of tillers of shallot at 14–42 DAP.

Symbol	Fertilizer Treatment	Number of Tillers		
		14 DAP	**28 DAP**	**42 DAP**
A	BSF Larvae 30 ton ha^{-1}	4.56 ± 0.41 ^{b}	6.81 ± 0.58 ^{abc}	8.250 ± 0.736 ^{ab}
B	NPK 16-16-16 500 kg ha^{-1}	3.88 ± 0.33 ^{ab}	6.25 ± 0.23 ^{ab}	7.500 ± 0.661 ^{ab}
C	BSF Larvae 15 ton ha^{-1}+ NPK 250 kg ha^{-1}	4.44 ± 0.41 ^{b}	7.88 ± 0.55 ^{c}	8.750 ± 0.729 ^{b}
D	BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}	3.50 ± 0.44 ^{a}	5.75 ± 0.44 ^{a}	6.563 ± 0.400 ^{a}
E	BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}	4.56 ± 0.43 ^{b}	7.75 ± 0.40 ^{c}	8.563 ± 0.572 ^{b}
F	BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}	4.38 ± 0.46 ^{ab}	7.25 ± 0.47 ^{bc}	8.625 ± 0.505 ^{b}

Note: Values followed by different superscript letters in the same column differ significantly ($p < 0.05$) according to the LSD test.

3.4. Yield Performance

3.4.1. Weight of Tuber per Hill

The results depicted in Figure 3 highlight the efficacy of Black Soldier Fly Larvae (BSFL) frass as a viable alternative to synthetic NPK fertilizers in enhancing the weight of shallot tubers per hill. Applying high-rate BSFL frass (30 ton ha^{-1}) yielded results comparable to conventional NPK fertilization (500 kg ha^{-1}), indicating that BSFL frass can effectively substitute synthetic fertilizers. This finding aligns with previous studies demonstrating the nutrient-rich profile of BSFL frass, which contains a significant quantity of nitrogen, phosphorus, potassium, and essential micronutrients for crop production [16,21]. The nutrient quality of BSFL frass has been shown to support the growth of various crops, including shallots, suggesting its potential as a sustainable fertilizer option.

Moreover, the combination of BSFL frass with reduced amounts of NPK fertilizer, particularly in Treatment E (BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}), resulted in the highest tuber weight. This synergistic effect indicates that integrating organic and synthetic fertilizers can enhance crop productivity beyond what either treatment could achieve alone. The interaction between BSFL frass and NPK fertilizers may promote nutrient availability and uptake, resulting in better plant growth [19,22]. Studies have shown that the microbial communities associated with BSFL residues can further enhance nutrient cycling in the soil, thereby improving plant performance under various conditions [23]. Apart from serving as a fertilizer that supplies nutrients to plants, BSF fertilizer also functions as a soil amendment, improving the soil's chemical, physical, and biological properties. Consequently, its application significantly enhances plant productivity.

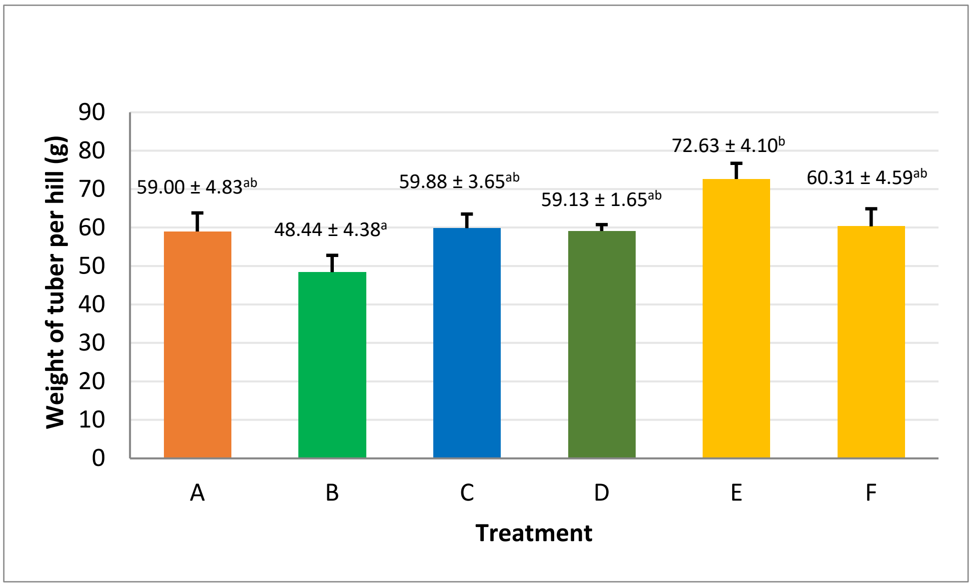

Figure 3. Effect of different fertilizer rates on the weight of the tuber per hill. Notes: (**A**) BSF Larvae 30 ton ha^{-1}, (**B**) NPK 16-16-16 500 kg ha^{-1}, (**C**) BSF Larvae 15 ton ha^{-1} + NPK 250 kg ha^{-1}, (**D**) BSFL 15 ton/ha + NPK 375 kg ha^{-1}, (**E**) BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}, and (**F**) BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}.

The implications of these findings are significant for sustainable agriculture, particularly in regions where soil nutrient depletion is a concern. The use of BSFL frass not only provides a nutrient source but also contributes to soil health by enhancing microbial diversity and activity [24]. Furthermore, the potential for BSFL frass to reduce reliance on synthetic fertilizers aligns with the goals of circular agriculture, promoting environmentally friendly practices [25,26]. As such, the results underscore the importance of exploring alternative fertilization strategies that leverage organic waste products like BSFL frass to improve crop yields sustainably.

3.4.2. Number of Tubers per Hill

The analysis showed significant differences among various fertilizer treatments in the number of tubers per hill in shallots (Figure 4). The average number of tubers per hill for each treatment was as follows: Treatment A (BSFL 30 ton ha^{-1}) produced 9.38 ± 1.10 tubers, Treatment B (NPK 16-16-16 500 kg ha^{-1}) yielded 8.19 ± 0.74 tubers, Treatment C (BSFL 15 ton ha^{-1} + NPK 250 kg ha^{-1}) resulted in 9.69 ± 0.70 tubers, Treatment D (BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}) had the lowest count at 7.56 ± 0.59 tubers, while Treatments E (BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}) and F (BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}) produced 9.94 ± 0.63 and 9.63 ± 0.73 tubers, respectively. The results indicate that applying BSFL frass, particularly in combination with NPK, can significantly enhance tuber production in shallots.

Treatments A, C, E, and F showed comparable effectiveness, suggesting that the nutrient profile of BSFL frass may provide a beneficial supplement to conventional fertilizers. Treatment E, which combined BSFL at 22.5 ton ha^{-1} with NPK at 250 kg ha^{-1}, yielded the highest number of tubers, suggesting that the synergistic effects of organic and inorganic fertilizers can optimize nutrient availability and uptake, leading to improved crop yields [21]. Moreover, the results align with the research of Lasmini et al. (2018), which emphasized that the rate of fertilizers plays a crucial role in determining the number of shallot bulbs produced [8]. Higher nutrient concentrations typically correlate with increased tuber production, as observed in the BSFL frass treatments. The lower yield in treatment D, despite the higher NPK application, suggests that there may be an optimal balance between organic and inorganic nutrients that maximizes tuber production without causing nutrient imbalances or toxicity.

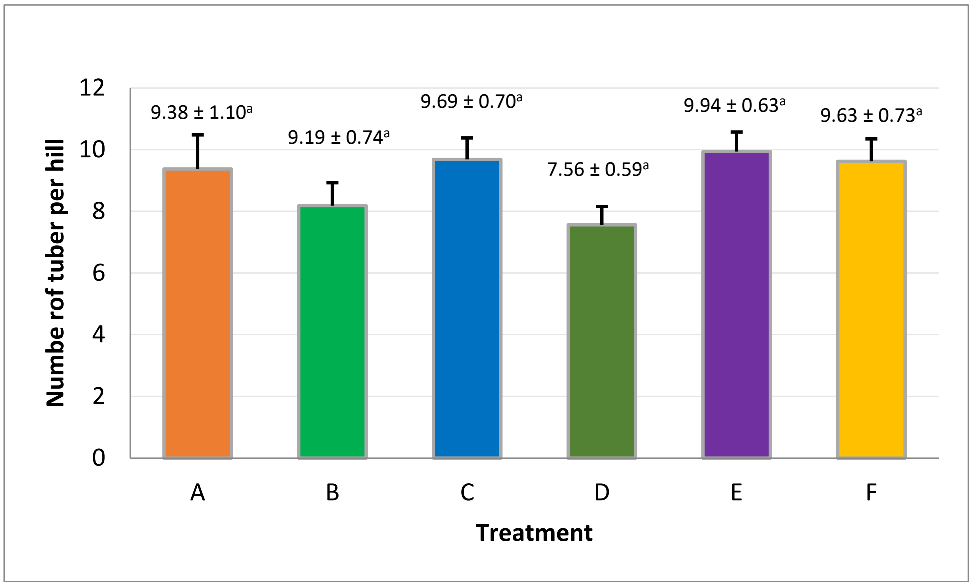

Figure 4. Effect of different fertilizer rates on the number of tubers per hill. Notes: (**A**) BSF Larvae 30 ton ha^{-1}, (**B**) NPK 16-16-16 500 kg ha^{-1}, (**C**) BSF Larvae 15 ton ha^{-1} + NPK 250 kg ha^{-1}, (**D**) BSFL 15 ton/ha + NPK 375 kg ha^{-1}, (**E**) BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}, and (**F**) BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}.

3.4.3. Weight of Tuber per Plot

The investigation on the impact of different fertilizer treatments on the weight of tubers per plot in shallots revealed distinct variations among the treatments. The recorded weights were as follows: Treatment A (BSFL 30 ton ha^{-1}) resulted in 1.765 ± 0.145 kg, Treatment B (NPK 16-16-16 500 kg ha^{-1}) had the lowest yield at 1.450 ± 0.130 kg, Treatment C (BSFL 15 ton ha^{-1} + NPK 250 kg ha^{-1}) produced 1.798 ± 0.112 kg, Treatment D (BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}) yielded 1.775 ± 0.047 kg, Treatment E (BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}) achieved the highest weight at 2.178 ± 0.125 kg, and Treatment F (BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}) produced 1.810 ± 0.139 kg (Figure 5).

The data indicated that combining BSFL frass with NPK fertilizer significantly enhanced tuber weight, particularly in Treatment E, which outperformed all other treatments. This suggests that the nutrient-rich profile of BSFL frass may play a crucial role in promoting tuber growth and overall plant health. The findings are consistent with previous studies that emphasized the advantages of organic fertilizers in improving crop yield and quality [27,28]. Conversely, the lower weight observed in Treatment B highlights the limitations of relying solely on synthetic fertilizers, which may not provide the necessary nutrients for optimal tuber development. The results also indicate that while Treatments A, C, D, and F produced comparable weights, they did not achieve the same level of success as Treatment E. This underscores the importance of finding the right balance between organic and inorganic fertilizers to maximize crop productivity.

In summary, the results affirm that incorporating BSFL frass, particularly in conjunction with NPK, can significantly enhance the weight of tubers per plot in shallots. This supports the notion of integrating insect-based fertilizers into sustainable agricultural practices, which can lead to improved crop yields and better soil health

[29,30]. Future studies should focus on the long-term implications of using BSFL frass on soil properties and examine its economic feasibility for widespread agricultural use.

The results of this study highlight the significant role of Black Soldier Fly Larvae (BSFL) frass in enhancing tuber weight in shallots. Treatment E, which combined BSFL at 22.5 ton ha^{-1} with NPK fertilizer, yielded the highest tuber weight at 2.178 ± 0.125 kg. This suggests that the synergistic effect of organic and inorganic nutrients can improve plant performance. The nutrient composition of BSFL frass, rich in nitrogen, phosphorus, and potassium, likely contributes to enhanced tuber development, as supported by previous research indicating that organic amendments can improve nutrient availability and soil structure [31–33]. In contrast, Treatment B, which relied solely on synthetic NPK, resulted in the lowest tuber weight, indicating that a balanced approach incorporating organic matter may be more effective for sustainable crop production.

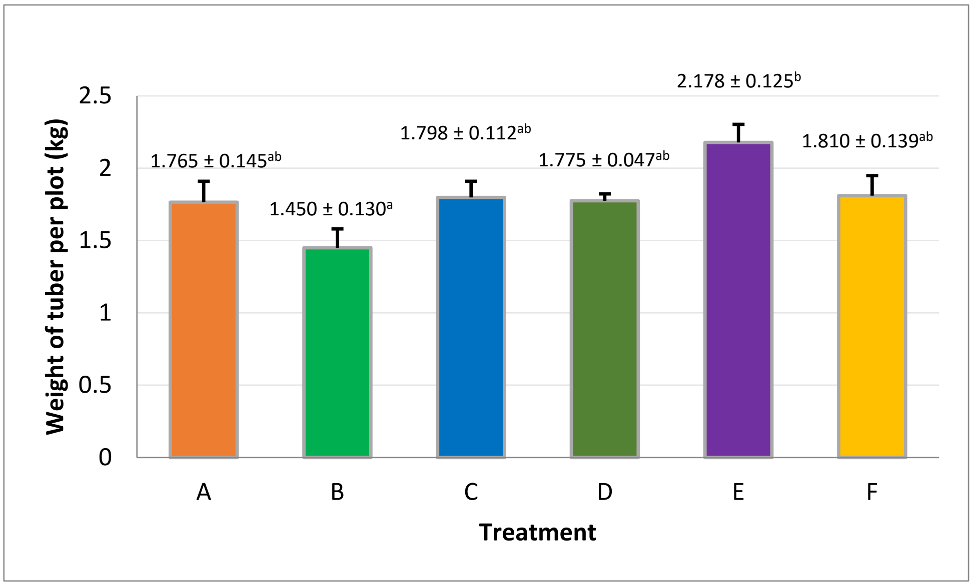

Figure 5. Effect of different fertilizer rates on the weight of the tuber per plot. Notes: (**A**) BSF Larvae 30 ton ha^{-1}, (**B**) NPK 16-16-16 500 kg ha^{-1}, (**C**) BSF Larvae 15 ton ha^{-1} + NPK 250 kg ha^{-1}, (**D**) BSFL 15 ton/ha + NPK 375 kg ha^{-1}, (**E**) BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}, and (**F**) BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}.

Plant growth and yield responses further illustrate the benefits of integrating frass with inorganic fertilizers. Treatments combining BSFL frass with reduced NPK (particularly Treatment E) consistently outperformed either input alone in terms of plant height, tiller number, and tuber yield. These complementary nutrient release patterns can explain that: BSFL frass supplies organic matter and nutrients gradually, improving root growth, soil water retention, and microbial activity, while NPK provides immediate nutrient availability. This synergy supports continuous nutrient supply throughout the crop cycle, minimizes leaching losses, and enhances overall nutrient use efficiency. Similar synergistic effects were reported by Tanga et al. (2022), who found that integrating frass with mineral fertilizers improved maize yield and profitability [25].

3.5. Cost Analysis and Feasibility Study

3.5.1. Cost Production

This study assessed the economic viability of using Black Soldier Fly Larvae (BSFL) frass as an alternative or supplementary fertilizer in sustainable agriculture by evaluating the impacts on the cost of shallot crop production. Comparison of Fertilizer Cost Components between BSF Larvae Frass and NPK 16-16-16 Applications at Various Treatment Levels was shown in Table 6. The production cost analysis revealed that the total variable cost for cultivation activities, excluding fertilizer inputs, amounted to IDR 56,250,000 (USD 3,383). This cost consisted of material expenses, including seeds, pesticides, and plastic mulch, and labor-related activities such as land preparation, planting, irrigation, and harvesting. As presented in Table 7, material costs contributed approximately IDR 31,500,000 (USD 1,894), while labor costs accounted for IDR 24,750,000 (USD 1,488), indicating that material inputs were the dominant component of overall production expenditures.

Six treatments varying in combinations and quantities of BSFL frass and NPK 16-16-16 fertilizer were analyzed for total production costs (Table 8). Treatment A, utilizing 30 tons per hectare of BSFL alone, incurred the highest fertilizer cost of IDR 45,000,000 (USD 2707), leading to a total production cost of IDR 116,250,000 (USD 6991). Conversely, Treatment B, which used only 500 kg of NPK per hectare, demonstrated a significantly lower fertilizer cost of IDR 10,000,000 (USD 602) and a total production cost of IDR 81,250,000 (USD 4886). Mixed treatments (C, D, E, F) combining BSFL frass with varying amounts of NPK resulted in intermediate costs, aligning the total production costs between IDR 98,750,000 (USD 5938) and IDR 112,500,000 (USD 6764).

Table 6. Comparison of Fertilizer Cost Components between BSF Larvae Frass and NPK 16-16-16 Applications at Various Treatment Levels.

Symbol	Fertilizer Treatment	BSF Larvae Frass	NPK 16-16-16	Amount
A	BSF Larvae 30 ton ha^{-1}	IDR 45,000,000 (USD 2707)	IDR 0 (USD 0)	IDR 45,000,000 (USD 2707)
B	NPK 16-16-16 500 kg ha^{-1}	IDR 0 (USD 0)	IDR 10,000,000 (USD 602)	IDR 10,000,000 (USD 602)
C	BSF Larvae 15 ton ha^{-1} + NPK 250 kg ha^{-1}	IDR 27,500,000 (USD 1654)	IDR 5,000,000 (USD 301)	IDR 32,500,000 (USD 1955)
D	BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}	IDR 30,000,000 (USD 1804)	IDR 7,500,000 (USD 451)	IDR 37,500,000 (USD 2255)
E	BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}	IDR 38,750,000 (USD 2331)	IDR 5,000,000 (USD 301)	IDR 43,750,000 (USD 2632)
F	BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}	IDR 41,250,000 (USD 2480)	IDR 7,500,000 (USD 451)	IDR 48,750,000 (USD 2931)

Notes: BSF Larvae Frass fertilizer price = IDR 1500 (USD 0.09) kg^{-1}. NPK Mutiara 16-16-16 = IDR 20,000 (USD 1.20) kg^{-1}.

Table 7. Analysis of Production Costs by Material and Labor Components without Inclusion of Fertilizer Inputs.

Variable Cost	Unit	Qty	Cost/Unit	Amount
Material cost				IDR 31,500,000.00 (USD 1894)
1.Seed	kg	800	IDR 25,000 (USD 1.50)	IDR 20,000,000 (USD 1203)
2.Pesticide	sett	1	IDR 4,000,000 (USD 241)	IDR 4,000,000 (USD 241)
3.Plastic Mulch	roll	10	IDR 750,000 (USD 45)	IDR 7,500,000 (USD 451)
Activity	duration (days)	Number of workers	Cost/day/worker	Amount
Labor cost				IDR 24,750,000 (USD 1488)
1. Land preparation	15	10	IDR 75,000 (USD 4.51)	IDR 11,250,000 (USD 677)
2. Fertilizer application	1	10	IDR 75,000 (USD 4.51)	IDR 750,000 (USD 45)
3. Planting	5	10	IDR 75,000 (USD 4.51)	IDR 3,750,000 (USD 226)
4. Re-planting	1	6	IDR 75,000 (USD 4.51)	IDR 450,000 (USD 27)
5. Sanitation	2	10	IDR 75,000 (USD 4.51)	IDR 1,500,000 (USD 90)
6. Pesticide application	6	4	IDR 75,000 (USD 4.51)	IDR 1,800,000 (USD 108)
7. Irrigation	4	5	IDR 75,000 (USD 4.51)	IDR 1,500,000 (USD 90)
8. Harvesting	5	10	IDR 75,000 (USD 4.51)	IDR 3,750,000 (USD 226)
Total Production Cost (without fertilizer)				IDR 56,250,000.00 (USD 3383)

Table 8. Total production cost for each treatment.

Symbol	Fertilizer Treatment	Production Cost		
		Fertilizer	Materials and Labor	Total
A	BSF Larvae 30 ton ha^{-1}	IDR 45,000,000 (USD 2707)	IDR 71,250,000 (USD 4284)	IDR 116,250,000 (USD 6991)
B	NPK 16-16-16 500 kg ha^{-1}	IDR 10,000,000 (USD 602)	IDR 71,250,000 (USD 4284)	IDR 81,250,000 (USD 4886)
C	BSF Larvae 15 ton ha^{-1}+ NPK 250 kg ha^{-1}	IDR 27,500,000 (USD 1654)	IDR 71,250,000 (USD 4284)	IDR 98,750,000 (USD 5938)
D	BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}	IDR 30,000,000 (USD 1804)	IDR 71,250,000 (USD 4284)	IDR 101,250,000 (USD 6088)
E	BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}	IDR 38,750,000 (USD 2331)	IDR 71,250,000 (USD 4284)	IDR 110,000,000 (USD 6616)
F	BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}	IDR 41,250,000 (USD 2480)	IDR 71,250,000 (USD 4284)	IDR 112,500,000 (USD 6764)

3.5.2. Cost Analysis and Feasibility

The profitability of different fertilizer treatments involving Black Soldier Fly Larvae (BSFL) frass and NPK 16-16-16 was evaluated to ascertain their economic impact on shallot production. The yield, revenue, and net benefit were calculated for each treatment, presenting significant insights into the economic viability of using BSFL in sustainable agriculture, as shown in Table 9. Treatment A, using only BSFL frass at 30 tons per hectare, yielded 10,296 kg/ha, generating a revenue of IDR 205,916,667 (USD 12,387) with a production cost of IDR 116,250,000 (USD 6991), resulting in a net profit of IDR 89,666,667 (USD 5396). Treatment B, with conventional NPK fertilizer at 500 kg/ha, produced a lower yield of 8458 kg/ha but substantially lower cost, leading to a profit of IDR 87,916,667 (USD 5289). Notably, mixed treatments exhibited varying degrees of economic efficiency.

Table 9. Economic analysis of shallot production: yield, revenue, production cost, profit, and benefit–cost ratio (BCR) for treatments A–F.

Symbol	Fertilizer Treatment	Yield (kg ha^{-1})	Revenue (R)	Cost (C)	Profit (B)	R/C	B/C	BCR
A	BSF Larvae 30 ton ha^{-1}	10,296	IDR 205,916,667 (USD 12,387)	IDR 116,250,000 (USD 6991)	IDR 89,666,667 (USD 5396)	1.77	0.77	1.05
B	NPK 16-16-16 500 kg ha^{-1}	8458	IDR 169,166,667 (USD 10,175)	IDR 81,250,000 (USD 4886)	IDR 87,916,667 (USD 5289)	2.08	1.08	-
C	BSF Larvae 15 ton ha^{-1}+ NPK 250 kg ha^{-1}	10,485	IDR 209,708,333 (USD 12,609)	IDR 98,750,000 (USD 5939)	IDR 110,958,333 (USD 6676)	2.12	1.12	2.32
D	BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1}	10,354	IDR 207,083,333 (USD 12,454)	IDR 101,250,000 (USD 6089)	IDR 105,833,333 (USD 6365)	2.05	1.05	1.90
E	BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}	12,702	IDR 254,041,667 (USD 15,274)	IDR 110,000,000 (USD 6616)	IDR 144,041,667 (USD 8663)	2.31	1.31	2.95
F	BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1}	10,558	IDR 211,166,667 (USD 12,699)	IDR 112,500,000 (USD 6764)	IDR 98,666,667 (USD 5935)	1.88	0.88	1.34

Treatment with BSFL 15 tons/ha + NPK 250 kg/ha yielded to 10,485 kg/ha, the highest among mixed treatments, generating a revenue of IDR 209,708,333 (USD 12,609) and a net profit of IDR 110,958,333 (USD 6676). Treatment D, with a similar configuration but increased NPK, produced slightly less (10,354 kg/ha) but achieved a significant benefit, amounting to IDR 105,833,333 (USD 6365). Treatment E, incorporating a higher rate of BSFL (22.5 tons/ha) along with 250 kg of NPK, led to the highest yield (12,702 kg/ha) and revenue (IDR 254,041,667/ USD 15,274), culminating in the highest net profit of IDR 144,041,667 (USD 8663). Finally, Treatment F, which also used 22.5 ton/ha of BSFL but with increased NPK, resulted in a yield of 10,558 kg/ha and a benefit of IDR 98,666,667 (USD 5935).

Treatment with BSFL 30 ton ha^{-1} yielded a moderate BCR of 1.05. Despite achieving a reasonable yield of 10,296 kg/ha and generating substantial revenue, the high input cost of using a large amount of BSFL results in just above break-even profitability. This suggests that while high-volume organic inputs benefit soil health and long-term agricultural sustainability, it is necessary to carefully evaluate the financial returns of their upfront costs. In this study, Treatment B, which involved the application of NPK 16-16-16 at a rate of 500 kg per hectare, was designated as the standard treatment against which all other treatments were compared. This standardization is essential for assessing the economic viability and effectiveness of alternative fertilization treatments compared to a commonly used baseline. Given that Treatment B serves as the benchmark, it inherently assumes a BCR of 1.0. This is because the Benefit Cost Ratio (BCR) is calculated based on the revenue and cost deviations from this standard treatment. However, Treatment NPK 16-16-16 500 kg ha^{-1} showed impressive cost efficiency. The lower yield did not prevent it from achieving nearly as high a net benefit as Treatment A due to significantly lower costs. This treatment illustrates the ongoing relevance of traditional chemical fertilizers for immediate cost savings and ease of use, though it may have potential long-term environmental costs.

A combination of BSFL 15 ton ha^{-1} and NPK 250 kg ha^{-1} appeared to be the most economical, with a BCR of 2.32. This indicates a robust return on investment, balancing cost with a high yield. This treatment demonstrates how integrating moderate amounts of BSFL with reduced synthetic fertilizer can optimize production costs and enhance profitability, aligning with sustainable agriculture principles that advocate for reduced chemical input. Treatment with BSFL 15 ton ha^{-1} + NPK 375 kg ha^{-1} and BSFL 22.5 ton ha^{-1} + NPK 375 kg ha^{-1} showed BCRs of 1.90 and 1.34, respectively, providing valuable insights into the diminishing returns when increasing both organic and inorganic fertilizer inputs beyond optimal levels. These treatments highlight the importance of finding the right mix to maximize financial and agricultural outputs without excessive expenditure.

Treatment E (BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1}) provided the highest yield and an impressive BCR of 2.95. This optimal combination of a higher volume of BSFL with a moderate amount of NPK showcases the potential for organic inputs not only to match but to exceed the effectiveness of traditional fertilizers in certain configurations. This treatment stands as a testament to the potential for sustainable practices to lead in both ecological and economic fronts.

The economic analysis underscores the significant potential of BSFL frass when combined with synthetic fertilizers. The economic advantage of Treatment BBSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1} reflects not only higher yield but also optimized input use. Applying BSFL frass at moderate rates reduces the need for costly synthetic fertilizers while maintaining or increasing productivity. The increased yield and revenue from treatments with BSFL, particularly when combined with lower amounts of NPK, align with findings from Sharma et al. (2017), who observed improved soil fertility and plant growth due to the synergistic effects of organic and inorganic fertilizers [7]. Moreover, economic analyses, such as those by Fuhrmann et al. (2018), have shown that integrating organic and inorganic fertilizers can sometimes offer a practical compromise, combining the immediate effectiveness of chemical fertilizers with the long-term sustainability benefits of organic amendments [28]. Although BSFL-only treatments improved soil health, their higher costs lowered economic efficiency, suggesting that balanced combinations offer the most sustainable solution.

This study contributes to the ongoing debate in sustainable agriculture regarding the cost-effectiveness of integrating novel organic products like BSFL frass. The results suggest that while pure BSFL treatments may not always be the most cost-effective, combining them with traditional fertilizers offers a promising pathway for enhancing soil health, reducing environmental impact, and increasing economic returns. Further research should focus on long-term impacts, including soil health improvements and potential reductions in chemical usage, which could further justify the higher initial costs of organic fertilizers.

4. Conclusions

The results of this study demonstrate that applying Black Soldier Fly Larvae (BSFL) frass, particularly when combined with NPK fertilizer, significantly improved soil chemical properties, including pH, soil organic carbon, total nitrogen, and available phosphorus. The combined treatment of BSFL 22.5 ton ha^{-1} + NPK 250 kg ha^{-1} produced the highest shallot yield and profitability, indicating that moderate integration of organic and inorganic fertilizers can optimize both agronomic performance and economic efficiency.

These findings confirm that BSFL frass is an effective organic amendment that enhances soil fertility, supports nutrient cycling, and promotes higher shallot productivity while reducing dependence on synthetic fertilizers. Economically, this integrated approach reduced production costs and increased the benefit–cost ratio, demonstrating strong potential for adoption in smallholder farming systems.

Overall, the study highlights the dual environmental and economic benefits of BSFL frass application, contributing to sustainable agricultural practices and circular bioeconomy initiatives in Indonesia. Future studies should investigate long-term impacts on soil, scalability across different soil types and crops, and the development of standardized formulations to optimize the use of BSFL-based fertilizer in broader agroecosystems.

Author Contributions

J.J. contributed to the conceptualization, methodology, supervision, and writing—review and editing of the manuscript. I.P. was responsible for data curation, formal analysis, investigation, and writing—original draft preparation. B.S. contributed to validation, provision of resources, visualization, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable. This study did not involve humans or animals.

Informed Consent Statement

Not applicable. This study did not involve humans.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Due to institutional policies and ongoing related research, the data are not publicly available. All authors commit to retaining the data for at least 10 years after publication in accordance with good scientific practice.

Conflicts of Interest

All authors states that there is no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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