Effectiveness of Combined Shallot Skin Compost and NPK Fertilizer on Cayenne Pepper (*Capsicum frutescens*) Plants in Ultisol Soil

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ABSTRACT

The cultivation of cayenne pepper (Capsicum frutescens L.) is important due to its widespread use in the food and pharmaceutical industries, as well as in everyday cooking. This study aimed to evaluate the effectiveness of combining shallot skin compost and NPK fertilizer on the growth and yield of cayenne pepper plants grown in Ultisol soil. The experiment was conducted using a Completely Randomized Design (CRD) in a factorial arrangement, with two factors: shallot skin compost (0, 200, 400 g per polybag) and NPK fertilizer (0, 13, 25 g per polybag), each replicated three times. The observed parameters included plant height, stem diameter, number of branches, fruit count, and fruit weight. Data were analyzed using ANOVA followed by Duncan's Multiple Range Test (DMRT) at a 5% significance level. Results indicated that the application of 200 g of shallot skin compost and 25 g of NPK fertilizer per polybag significantly improved plant height, stem diameter, and overall fruit production. Furthermore, a significant interaction between shallot skin compost and NPK fertilizer was observed, particularly in terms of fruit yield and weight. This study suggests that combining organic and inorganic fertilizers can enhance the productivity of cayenne pepper plants in Ultisol soil, offering a sustainable approach to increasing crop yield. Further research is recommended to explore the long-term effects of these treatments on soil health and plant growth.

1. INTRODUCTION

Cayenne pepper (*Capsicum frutescens* L.) is an important crop widely cultivated for its diverse uses in the food, pharmaceutical, and culinary industries. Its high demand in Indonesia is driven by its rich nutrient profile, which includes essential vitamins (A, B, C), minerals (calcium, iron, phosphorus), and bioactive compounds like capsaicin, making it a staple ingredient in various dishes and food products (Batiha et al., 2020; Azlan et al., 2022). However, the fluctuating market prices of cayenne pepper are often a result of inconsistent production levels, highlighting the need for strategies to stabilize and increase yield (Mardiyati & Natsir, 2024).

One of the main challenges in cultivating cayenne pepper, particularly in Indonesia, is managing soil fertility, especially when growing in nutrient-deficient soils such as Ultisol. Ultisol soils, which are common in tropical regions, are characterized by high acidity, low organic matter content, and limited essential nutrients (Pane et al., 2023; Purnama et al., 2023a & 2023b; Lidar & Purnama, 2021). These properties often lead to suboptimal plant growth unless appropriate soil management practices are implemented. Enhancing soil fertility through effective fertilization strategies is therefore critical to improving the productivity of cayenne pepper, especially when cultivated in such challenging soil environments.

Fertilization is a fundamental aspect of improving plant growth and yield. Organic fertilizers, such as compost, have been shown to improve soil structure, water retention, and microbial activity, which are vital for plant development. Shallot skin compost, in particular, has been identified as a promising organic fertilizer due to its nutrient-rich composition, including potassium (K), phosphorus (P), and micronutrients such as manganese (Mn) and zinc (Zn), along with growth-promoting hormones like auxin and gibberellin (Widjaya & Suparti, 2023). Additionally, the use of shallot skin compost not only enhances plant growth but also addresses environmental concerns related to organic waste by converting it into valuable agricultural inputs (Hikmahwati et al., 2023).

Inorganic fertilizers, such as NPK, provide essential macronutrients that are crucial for plant health. Nitrogen (N) aids in vegetative growth, phosphorus (P) supports root development, and potassium (K) enhances disease resistance and fruit quality (Fang et al., 2023). NPK fertilizers are known for their effectiveness in boosting crop yields, especially when applied in the correct proportions, as they ensure a balanced nutrient supply throughout the plant's growth cycle.

Although there is substantial evidence supporting the benefits of organic and inorganic fertilizers when used independently, there is a lack of research on the combined application of shallot skin compost and NPK fertilizer, particularly in soils like Ultisol. Previous studies have demonstrated that integrating organic and inorganic fertilizers can have synergistic effects, leading to improved nutrient availability and better plant growth (Khairi et al., 2023). However, the specific effects of combining shallot skin compost with NPK fertilizer on cayenne pepper cultivation in Ultisol soil have not been thoroughly investigated. Given the nutrient deficiencies and poor structural properties of Ultisol, exploring effective fertilization strategies that combine both organic and inorganic inputs could lead to more sustainable and productive agricultural practices.

This study aims to address the gap in existing research by evaluating the effectiveness of combining shallot skin compost and NPK fertilizer on the growth and yield of cayenne pepper plants grown in Ultisol soil. Specifically, it seeks to determine the individual and interactive effects of shallot skin compost and NPK fertilizer on key growth parameters such as plant height, stem diameter, and fruit yield. The findings from this study are expected to provide valuable insights into sustainable agricultural practices by integrating organic and inorganic fertilization strategies. By addressing the challenges of growing cayenne pepper in Ultisol soil, this research could help improve crop productivity, reduce dependency on chemical fertilizers, and promote the use of organic waste products like shallot skins, contributing to environmental sustainability.

2. MATERIAL AND METHODS

2.1. Study Location and Experimental Design

The experiment was conducted at the Agricultural Experiment Field of Universitas Lancang Kuning, Pekanbaru, Indonesia (0°34'37.2"N 101°25'29.9"E), located at an altitude of 16 meters above sea level, with flat topography and characterized by Ultisol soil. A Completely

Randomized Design (CRD) was used in a factorial arrangement, involving two main factors: shallot skin compost (B) and NPK fertilizer (N). The shallot skin compost was applied at three levels: B0 (0 g/polybag), B1 (200 g/polybag), and B2 (400 g/polybag). The NPK fertilizer was also applied at three levels: N0 (0 g/polybag), N1 (13 g/polybag), and N2 (25 g/polybag). This resulted in a total of 9 treatment combinations (B0_N0, B0_N1, B0_N2, B1_N0, B1_N1, B1_N2, B2_N0, B2_N1, and B2_N2), each replicated three times, yielding 27 experimental units. Each unit consisted of 4 plants, with 2 plants chosen as samples for data collection, resulting in a total of 108 plants, as shown in Figure 1.

Figure 1. **Experimental setup for cayenne pepper cultivation:** (a) preparation of planting media and arrangement of polybags based on the experimental design, (b) transplanting of cayenne pepper seedlings into the prepared polybags

2.2. Plant Materials and Growth Conditions

The plant material used was cayenne pepper seedlings of the 'Genie' variety, selected for uniform size and health after a germination period of 30 days. The seedlings were transplanted into polybags measuring 30 cm × 30 cm (see Figure 1), each containing a mixture of topsoil (Ultisol), compost (based on the treatment level), and other soil amendments where appropriate. Prior to planting, the soil was prepared by loosening and mixing thoroughly to ensure proper aeration and water retention (Sharma & Kumar, 2023).

2.3. Preparation of Shallot Skin Compost

The shallot skin compost was prepared by collecting shallot skins from local market in Rumbai, Pekanbaru, which were mixed with other organic waste (such as dried leaves and small plant debris) and fermented using an effective microorganism (EM) solution to accelerate decomposition (Jatra et al., 2021). The composting process lasted about four weeks, during which the mixture was turned regularly to ensure uniform decomposition. After curing, the compost was finely sieved to ensure a consistent texture before application. To assess its nutrient content, the compost was analyzed for key parameters such as pH, organic matter content, N, P, K, and the carbon-to-nitrogen (C/N) ratio.

2.4. NPK Fertilizer Application

NPK fertilizer (16:16:16) was applied at three doses, following the respective treatment levels. The fertilizer was administered in three stages: 15 days after transplanting (DAT), 30 DAT, and 45 DAT. During each application, the NPK was evenly distributed around the base of the plants, maintaining a distance of approximately 5 cm from the stem to prevent root damage.

2.5. Planting and Treatment Application

The experimental site, measuring 12 m × 4 m, was cleared of weeds and debris. Raised beds (plots) were prepared, with each plot measuring 80 cm × 80 cm and a height of 20 cm, with 50 cm spacing between plots. The cayenne pepper seedlings were transplanted into the polybags after they had developed 5-6 true leaves. Compost application was done one week before transplanting by incorporating the compost into the soil in each polybag based on the specified treatment dose.

2.6. Water Management and Maintenance

Regular irrigation was conducted twice daily (morning and evening) using a watering can to maintain optimal soil moisture. Manual weeding was performed as needed to keep the plots weed-free. Preventative pest and disease control measures were taken by applying insecticides (Curacron 500 EC, active ingredient: Profenofos) and fungicides (Nopatek, a bio-fungicide combination of *Trichoderma sp.* and *Gliocladium sp.*) at 30 DAT, followed by bi-weekly applications as required (Dauda et al., 2024). Pest and disease management ceased one week before the harvest to ensure residue safety.

2.7. Data Collection

Data collection focused on key growth and yield parameters, including plant height, stem diameter, number of branches, number of fruits per plant, and total fruit weight, following the standard methods outlined by Gomez and Gomez (1984).

2.8. Soil and Compost Analysis

Soil samples were taken before the experiment to analyze the physical and chemical properties of Ultisol soil, including pH, organic matter content, nitrogen (N), phosphorus (P), potassium (K), and micronutrients (Mn, Zn, Fe). Post-experiment soil samples were collected from the best-performing treatment plot to assess changes in soil nutrient status and evaluate the residual effects of the treatment. Soil samples were air-dried, sieved (2 mm mesh), and analyzed using standard soil analysis methods, including Kjeldahl digestion for nitrogen and atomic absorption spectrophotometry (AAS) for potassium and micronutrients (Oladimeji et al., 2024).

2.9. Experimental Analysis

The data obtained from the growth and yield parameters were statistically analyzed using Analysis of Variance (ANOVA) to determine the effects of the treatments. When a significant effect was observed ($p \leq 0.05$), Duncan's Multiple Range Test (DMRT) was applied to compare the means among treatments (Lestari et al., 2024). The statistical software package SPSS (Version 25.0) was used for all analyses.

3. RESULTS AND DISCUSSION

3.1. Effect of Treatments on Soil Properties

The application of shallot skin compost and NPK fertilizer had a significant impact on improving various soil properties, as reflected in the changes observed between the initial and final soil analysis (Table 1). Initially, the Ultisol soil was highly acidic, with a pH of 4.9, which is a common characteristic of this soil type known for limiting nutrient availability and hindering plant growth. After the application of treatments, the soil pH increased to 5.2, showing a slight but important shift towards a more neutral condition. This improvement can be attributed to the buffering capacity of the organic compost, which helps to mitigate soil acidity and enhance nutrient availability. A more balanced pH environment is particularly beneficial for the availability of essential nutrients such as phosphorus and micronutrients, which tend to be less accessible in acidic conditions (Michael, 2021).

Table 1. Soil nutrient analysis before and after experiment

Parameter	Initial Soil Condition (Before)	Final Soil Condition (After)
pH	4.9	5.2
Organic Matter (%)	1.5	2.8
Nitrogen (N) (%)	0.09	0.15
Phosphorus (P) (mg/kg)	5.5	10.2
Potassium (K) (mg/kg)	45.0	85.0
Manganese (Mn) (mg/kg)	12.0	18.0
Zinc (Zn) (mg/kg)	4.5	6.3
Iron (Fe) (mg/kg)	150.0	165.0

The organic matter content of the soil also increased significantly, from 1.5% to 2.8%. This boost is directly linked to the incorporation of shallot skin compost, which was rich in organic materials. Higher levels of organic matter improve soil structure, water retention, and microbial activity, all of which are crucial for sustaining healthy plant growth. The initial soil analysis before the experiment showed that the soil had a low organic matter content of 1.5%, which increased to 2.8% after treatment, indicating an improvement in soil fertility. This increase can be attributed to the application of shallot skin compost, which provided organic matter that enhanced soil structure and microbial activity, as also reported by Ho et al. (2022). Additionally, the soil pH increased from 4.9 to 5.2, suggesting a reduction in soil acidity, which improves nutrient availability and plant uptake. These changes demonstrate the positive impact of integrating organic amendments with NPK fertilization in improving soil conditions throughout the experiment (Table 1).

Further analysis showed that the treatments led to substantial improvements in soil macronutrient levels. The nitrogen content increased from 0.09% to 0.15%, a change that can be linked to the combined contributions of the compost and NPK fertilizer. Nitrogen is essential for promoting vegetative growth, and the observed increase suggests that the treatments effectively addressed the nitrogen deficiency common in Ultisol soils (Lestari et al., 2024). Phosphorus levels also improved, rising from 5.5 mg/kg to 10.2 mg/kg. Phosphorus is crucial for root development and energy transfer in plants, and its enhanced availability indicates that the combined use of organic and inorganic phosphorus sources was effective. The increase in potassium from 45.0 mg/kg to 85.0 mg/kg further supports plant resilience, water regulation, and enzyme activation, essential for healthy development. These findings are consistent with previous studies demonstrating the benefits of integrating organic and inorganic fertilizers to improve soil nutrient profiles (Khairi et al., 2023).

Table 2 provides a detailed analysis of the shallot skin compost used in this study. The compost was found to contain essential macronutrients, including nitrogen (1.8%), phosphorus (950 mg/kg), and potassium (1,200 mg/kg). These levels are significant because they provide a slow-release source of essential nutrients that can complement the fast-acting nature of NPK fertilizers. The relatively high potassium content in the compost is particularly beneficial for enhancing plant water regulation, stress tolerance, and overall productivity. The phosphorus content supports root development, which is crucial during the early stages of plant growth, while nitrogen aids in vegetative development, promoting healthier and more vigorous plants.

Table 2. Nutrient content analysis of shallot skin compost

Parameter	Value
pH	6.8
Organic Matter (%)	32.5
Nitrogen (N) (%)	1.8
Phosphorus (P) (mg/kg)	950.0
Potassium (K) (mg/kg)	1,200.0
C/N Ratio	18.0

The treatments also positively affected the availability of key micronutrients, which are critical for various plant physiological processes. Manganese levels rose from 12.0 mg/kg to 18.0 mg/kg, and zinc levels increased from 4.5 mg/kg to 6.3 mg/kg. Both of these micronutrients are essential for enzyme function and the overall health of the plants. The iron content showed a modest increase, from 150.0 mg/kg to 165.0 mg/kg, maintaining sufficient levels to support chlorophyll synthesis and plant metabolism. These improvements indicate that the compost was effective not only in supplying macronutrients but also in enhancing the availability of micronutrients, which are vital for comprehensive plant health (Dhaliwal et al., 2024).

The shallot skin compost played a critical role in these improvements. Its nutrient-rich composition ensured a steady supply of essential elements, while its high organic matter content facilitated better soil structure and moisture retention. Additionally, the use of shallot skin compost helps to recycle agricultural waste, promoting sustainable agricultural practices.

By integrating organic and inorganic inputs, the study demonstrates how a balanced approach to fertilization can improve soil health, reduce chemical dependency, and enhance overall crop productivity (Purnama et al., 2025). This combination of shallot skin compost and NPK fertilizer resulted in a synergistic effect, enhancing soil properties and creating conditions that are conducive to better crop productivity. This approach addresses the inherent limitations of Ultisol soils by offering a sustainable solution for enhancing the growth and yield of cayenne pepper plants.

3.2. Effect of Treatments on Plant Growth Parameters

Statistical analysis revealed significant differences among treatments in plant height, stem diameter, and the number of branches, as presented in Table 3. The statistical results confirmed that treatments incorporating shallot skin compost and NPK fertilizer significantly improved plant growth parameters, with distinct differences observed between treatments, as indicated by DMRT analysis at a 5% level.

Table 3. Effect of shallot skin compost and NPK fertilizer on plant growth parameters of cayenne pepper

Treatment (Compost + NPK)	Plant Height (cm)	Stem Diameter (cm)	Number of Branches (per plant)
B0_N0 (0 g + 0 g)	62.31 ± 1.25^{a}	0.90 ± 0.10^{a}	19.33 ± 0.76^{a}
B0_N1 (0 g + 13 g NPK)	68.63 ± 6.15^{b}	1.10 ± 0.10^{b}	23.33 ± 1.44^{b}
B0_N2 (0 g + 25 g NPK)	74.22 ± 7.01^{bc}	1.07 ± 0.12^{ab}	25.00 ± 0.87^{b}
B1_N0 (200 g + 0 g NPK)	68.40 ± 8.83^{b}	1.07 ± 0.06^{ab}	26.67 ± 0.29^{cd}
B1_N1 (200 g + 13 g NPK)	79.64 ± 10.91^{c}	1.17 ± 0.06^{c}	27.83 ± 0.82^{d}
B1_N2 (200 g + 25 g NPK)	77.82 ± 0.93^{bc}	1.17 ± 0.06^{c}	28.50 ± 0.82^{d}
B2_N0 (400 g + 0 g NPK)	72.72 ± 10.32^{bc}	1.00 ± 0.00^{a}	25.00 ± 1.00^{b}
B2_N1 (400 g + 13 g NPK)	74.31 ± 3.94^{bc}	1.07 ± 0.12^{ab}	29.50 ± 0.87^{e}
B2_N2 (400 g + 25 g NPK)	77.73 ± 5.26^{bc}	1.13 ± 0.06^{c}	29.17 ± 1.53^{e}

Notes: Values followed by the same lowercase letter (a – e) in the same column are not significantly different based on DMRT at a 5% level.

The B1_N1 treatment (200 g compost + 13 g NPK) produced the tallest plants (79.6 ± 10.91 cm), which was significantly higher than the control group (B0_N0: 62.3 ± 1.25 cm). This result aligns with findings by Khairi et al. (2023) and Jatra et al. (2021), who reported that integrating organic compost with chemical fertilizers significantly enhanced plant growth by improving nutrient availability and soil structure. The data suggest that a moderate combination of compost and NPK effectively enhances plant height, possibly due to the balanced supply of macronutrients like nitrogen and organic matter that improves soil structure and nutrient uptake. The standard deviation values indicate variability, with the B1_N1 treatment showing the most significant height increase, marked by statistical differences from the control.

The treatments also had a positive effect on stem diameter, with the highest averages recorded in the B1_N1 and B1_N2 treatments (1.17 cm). Thicker stems suggest improved structural integrity and more efficient nutrient transport, which are essential for supporting better growth and higher yields. In contrast, the control treatment (B0_N0) had the lowest average stem diameter (0.90 ± 0.10 cm), indicating that the absence of compost and NPK limited stem development. A similar trend was reported by Wu et al. (2020), who found that organic amendments combined with chemical fertilizers led to thicker stems in tomato plants due to enhanced nutrient absorption and water retention in the soil. The significant differences in stem diameter among the treatments suggest that shallot skin compost, when combined with NPK, facilitates more robust growth by improving soil properties and providing a consistent supply of essential nutrients.

Branching, another key determinant of potential fruit production, was also enhanced by the combined treatments. The B2_N1 treatment (400 g compost + 13 g NPK) resulted in the highest number of branches, averaging 29.5 ± 0.87 per plant, followed closely by B2_N2 (400 g compost + 25 g NPK) at 29.17 ± 1.53 branches. These results highlight the positive effects of higher doses of compost, which likely enhanced soil organic matter content, water retention, and micronutrient availability, leading to more branching and potentially higher yields. The control group (B0_N0) had the fewest branches, with an average of 19.33 ± 0.76, reinforcing the need for both organic and inorganic inputs to optimize plant growth. These findings are consistent with those of Rahman et al. (2012), who observed that the addition of compost improved soil health and increased the number of branches in chili plants by providing essential micronutrients and improving soil aeration.

The findings clearly demonstrate that integrating shallot skin compost with NPK fertilizer is more effective at promoting plant growth than using either input alone. The compost improves soil structure and microbial activity, facilitating better nutrient uptake, while the NPK fertilizer provides an immediate boost of essential macronutrients, particularly nitrogen, phosphorus, and potassium. This synergy is evident in the B1_N1 treatment, which showed marked improvements across all parameters. The results align with previous studies, such as those by Abbasi & Yousra (2012), which suggest that the combination of organic compost and inorganic fertilizers can create synergistic effects, improving overall plant health and productivity. By reducing reliance on chemical fertilizers and repurposing organic waste like shallot skins, this integrated approach also promotes more sustainable agricultural practices.

3.3. Effect of Treatments on Yield

The application of shallot skin compost combined with NPK fertilizer significantly influenced the yield parameters of cayenne pepper plants, as evident in the data presented in Table 4. Treatments that included moderate to high levels of compost (200-400 g) and NPK (13-25 g) tended to yield a higher number of fruits per plant, as well as heavier fruits. The treatment B1_N2 (200 g compost + 25 g NPK) yielded the highest number of fruits (81.3 ± 9.86) and significantly increased fruit weight (67.2 ± 3.90 g). The high nutrient availability and improved soil structure due to compost can lead to better nutrient absorption, which is critical during the flowering and fruit-setting stages (Arya et al., 2024). However, excessive compost application, as in the B2_N2 treatment (400 g compost + 25 g NPK), may not have resulted in the highest growth and yield due to potential nutrient imbalances, competition for nitrogen immobilization, or excessive organic matter affecting root respiration and nutrient uptake (Reimer et al., 2023). Studies have shown that integrating organic matter, such as compost, enhances soil water retention, aeration, and microbial activity, all of which contribute to higher fruit yields (Cataldo et al., 2021). However, excessive organic amendments can sometimes alter soil nutrient dynamics, leading to suboptimal plant responses depending on crop species and soil conditions (Shrestha et al., 2020). These results suggest that a moderate compost application (200 g per plant) with 13–25 g of NPK provides the most balanced nutrient availability and uptake efficiency, leading to optimal growth and yield outcomes.

The positive effects of combining organic compost with NPK fertilizer are consistent with previous findings. For example, Fageria (2012) demonstrated that organic matter improves soil health by enhancing nutrient availability and facilitating better root growth, which translates into higher crop yields. Moreover, the nitrogen in NPK fertilizer is crucial for vegetative growth, while phosphorus and potassium are vital during the reproductive stage, aiding in fruit formation and size. While the control treatments (B0_N0) produced the lowest yields (34.1 fruits, 31.9 g weight), adding shallot skin compost significantly enhanced productivity even without NPK. However, the combination of both compost and NPK provided the highest yield, showcasing the synergistic benefits of integrated nutrient management.

Table 4. Effect of shallot skin compost and NPK fertilizer on yield parameters of cayenne pepper

Treatment (Compost + NPK)	**Number of Fruits (Mean ± SD)**	**Weight of Fruits (Mean ± SD, g)**
B0_N0 (0 g + 0 g)	34.1 ± 5.68[a]	31.9 ± 3.82[a]
B0_N1 (0 g + 13 g NPK)	55.8 ± 8.33[b]	46.9 ± 5.56[b]
B0_N2 (0 g + 25 g NPK)	65.4 ± 1.56[c]	57.1 ± 3.00[c]
B1_N0 (200 g + 0 g NPK)	50.1 ± 8.24[b]	43.6 ± 7.04[ab]
B1_N1 (200 g + 13 g NPK)	77.7 ± 7.82[d]	66.7 ± 5.61[d]
B1_N2 (200 g + 25 g NPK)	81.3 ± 9.86[d]	67.2 ± 3.90[d]
B2_N0 (400 g + 0 g NPK)	55.3 ± 7.98[b]	47.1 ± 4.65[b]
B2_N1 (400 g + 13 g NPK)	53.8 ± 11.56[b]	49.7 ± 8.58[b]
B2_N2 (400 g + 25 g NPK)	75.8 ± 7.33[d]	64.7 ± 4.25[d]

Notes: Values followed by the same lowercase letter in the same column are not significantly different based on DMRT at a 5% level.

These findings underscore the importance of integrating organic and inorganic nutrient sources to maximize crop productivity. The synergistic effects observed between shallot skin compost and NPK fertilizer demonstrate that this combined approach can address the limitations of relying solely on chemical fertilizers, such as nutrient leaching and soil degradation. By enriching the soil with organic matter, the compost improves its structure, moisture retention, and microbial activity, creating a more conducive environment for plant growth. Meanwhile, the targeted application of NPK fertilizer ensures that essential macronutrients are available during critical stages of development, enhancing both the quantity and quality of the yield. This study confirms that the strategic integration of compost and NPK is not only effective in increasing crop output but also contributes to more sustainable and resilient agricultural practices, supporting the long-term health of the soil ecosystem.

4. CONCLUSION

This study demonstrated that the combined application of shallot skin compost and NPK fertilizer significantly enhanced the growth and yield of cayenne pepper plants. The B1_N2 treatment (200 g compost + 25 g NPK) produced the best results, improving plant height, stem diameter, number of branches, and fruit production. The synergistic effect of organic compost and inorganic fertilizer contributed to better nutrient availability, soil structure, and moisture retention, leading to optimal plant growth and productivity. However, this study had certain limitations. Soil analysis was conducted only on the best-performing treatment due to budget constraints, which may not fully represent residual effects across all treatments. Additionally, the experiment was limited to a single growing season, restricting the assessment of long-term soil health and sustainability. Environmental factors such as soil variation and weather conditions were not extensively analyzed, which may influence the generalizability of the findings. Future research should focus on long-term effects across different crops and soil types, optimizing the balance between compost and NPK application to maximize efficiency while minimizing costs. Further studies should also explore the potential of alternative organic amendments to enhance soil fertility and plant productivity sustainably.

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