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FROM CONVENTIONAL FERTILIZATION TO INTELLIGENT CULTIVATION: HARNESSING TRICHODERMA-BASED TRICHOCOMPOST TO SUPPORT SUSTAINABLE AGROINDUSTRY 4.0 IN MAIZE PRODUCTION

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ABSTRACT

Maize production in low-organic-matter soils requires cultivation technologies that can sustain yield while reducing dependence on inorganic fertilizers. Trichocompost enriched with local Trichoderma isolates offers a promising biological input to improve soil function, plant growth, and productivity. This study evaluated the effectiveness of trichocompost prepared with Trichoderma asperellum TZ11DI1 and Trichoderma reesei TZ31DU1 on maize growth, biomass, and yield components under reduced inorganic fertilizer application. The field experiment was conducted in Gorontalo Province, Indonesia, using a randomized complete block design with three treatments and three replications: full recommended inorganic fertilizer without trichocompost, 75% inorganic fertilizer combined with TZ11DI1 trichocompost, and 75% inorganic fertilizer combined with TZ31DU1 trichocompost. Growth, root development, biomass, and yield components were measured during vegetative growth and after harvest. The results showed that both trichocompost treatments improved plant height, number of leaves, root length, root biomass, shoot biomass, ear development, kernel weight, and 1000-kernel weight compared with the control. TZ11DI1 produced the best performance in most shoot and yield parameters, including plant height, leaf number, shoot biomass, ear weight, kernel weight, and 1000-kernel weight, whereas TZ31DU1 was more effective in increasing root length and root biomass. These findings indicate that local Trichoderma-based trichocompost can maintain and enhance maize productivity while reducing inorganic fertilizer use by 25%. This technology provides a practical and environmentally friendly strategy for sustainable maize cultivation and supports biological innovation in Agroindustry 4.0.

Key words: Maize, Productivity, Sustainability, Trichocompost, Trichoderma.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most strategic agricultural commodities that plays an essential role in supporting food security, livestock feed industries, and agroindustrial development in Indonesia. Increasing demand for maize driven by population growth and industrial expansion requires cultivation systems capable of maintaining high productivity while ensuring environmental sustainability. However, maize production systems in many developing countries remain heavily dependent on the intensive use of inorganic fertilizers. The continuous application of chemical fertilizers not only increases production costs but may also deteriorate soil quality by reducing soil organic matter content, disrupting soil microbial diversity, and decreasing nutrient-use efficiency (Kong *et al*., 2008).

The transition toward Agroindustry 4.0 demands the implementation of intelligent, efficient, and environmentally friendly cultivation practices. Agroindustry 4.0 emphasizes not only digital transformation but also the integration of biological innovations that enhance resource-use efficiency through the optimization of natural ecosystem functions. One promising approach is the utilization of functional organic fertilizers enriched with beneficial microorganisms that simultaneously improve soil health and crop productivity (Gouda *et al*., 2018).

Among beneficial microorganisms, species belonging to the genus Trichoderma have received considerable attention due to their multifunctional roles in sustainable agriculture. In addition to their well-known capacity as biological control agents against plant pathogens, Trichoderma spp. accelerate organic matter decomposition, enhance nutrient availability, stimulate plant growth through phytohormone production, improve plant tolerance to abiotic stress, and promote crop productivity (Zin & Badaluddin, 2020). The incorporation of Trichoderma into the composting process produces trichocompost, a functional organic fertilizer that serves not only as a source of organic matter but also as a carrier of beneficial microorganisms capable of establishing positive interactions with plants.

Previous studies have demonstrated the effectiveness of trichocompost in improving plant growth and yield. Asghar *et al*., 2024 reported that trichocompost application enhanced nutrient availability and crop performance under various field conditions. Furthermore, Trichoderma asperellum has been shown to produce indole-3-acetic acid (IAA), a phytohormone involved in cell division and elongation, thereby stimulating root development and vegetative growth (Zhao *et al*., 2015). Egamberdieva *et al*., (2017) also highlighted that beneficial microorganisms facilitate nutrient acquisition and plant development through phytohormone biosynthesis and plant growth-promoting activities.

Despite these findings, most previous studies have focused primarily on the use of trichocompost as a general organic amendment or biofertilizer. Limited information is available regarding the use of trichocompost derived from local Trichoderma isolates as an intelligent cultivation strategy to reduce dependency on inorganic fertilizers, particularly in soils with low organic matter content. Moreover, evidence concerning the ability of trichocompost to sustain maize productivity under reduced inorganic fertilizer inputs remains scarce, especially under the agroecological conditions of Gorontalo Province, Indonesia.

Therefore, this study introduces a novel approach by utilizing trichocompost developed from local isolates of Trichoderma asperellum TZ11DI1 and Trichoderma reesei TZ31DU1 as an intelligent cultivation technology supporting the transition from conventional fertilization toward sustainable Agroindustry 4.0. This approach integrates multiple biological functions, including organic matter decomposition, plant growth stimulation, and enhancement of nutrient-use efficiency, into a single practical technology applicable at the farm level.

The objectives of this study were to evaluate the effectiveness of trichocompost based on T. asperellum TZ11DI1 and T. reesei TZ31DU1 in improving maize growth and yield under low-organic-matter soil conditions and to assess its potential to reduce inorganic fertilizer application without compromising crop productivity. The findings of this study are expected to provide scientific evidence supporting the development of efficient, environmentally sound, and sustainable maize cultivation practices as part of the implementation of Agroindustry 4.0.

MATERIALS AND METHODS

Study site and experimental period

The field experiment was conducted in Huluduotamo Village, Suwawa District, Bone Bolango Regency, Gorontalo Province, Indonesia, from October 2023 to January 2024. The experimental site was selected based on its low soil organic matter.

Preparation of trichocompost

Trichocompost was prepared using maize straw as the primary substrate and local isolates of Trichoderma asperellum TZ11DI1 and Trichoderma reesei TZ31DU1 as decomposing agents.

Experimental design

The experiment was arranged in a Randomized Complete Block Design (RCBD) consisting of three treatments and three replications. The treatments were as follows: K0: 100% recommended dose of inorganic fertilizer without trichocompost application; K1: 75% recommended dose of inorganic fertilizer combined with 5 t ha^{-1} trichocompost prepared using T. asperellum TZ11DI1; K2: 75% recommended dose of inorganic fertilizer combined with 5 t ha^{-1} trichocompost prepared using T. reesei TZ31DU1. Each experimental plot measured 7 m × 15 m. Within each plot, five sampling subplots measuring 1 m × 3 m were established diagonally for plant observations.

Treatment application and crop establishment

Trichocompost was incorporated into the soil two weeks before planting at a rate of 5 t ha^{-1}, equivalent to 52.5 kg per plot. The compost was evenly distributed and thoroughly mixed with the soil. Control plots did not receive trichocompost application.

Maize seeds were planted manually using a dibbling method at a spacing of 75 cm × 40 cm with two seeds per planting hole. Gap filling was conducted at 7–10 days after planting to maintain uniform plant populations. The recommended inorganic fertilizer rates for the experimental site, according to the Indonesian Ministry of Agriculture Regulation No. 13 of 2022, consisted of : Urea: 350 kg ha^{-1}; SP-36: 125 kg ha^{-1}; KCl: 50 kg ha^{-1}.

The control treatment received the full recommended fertilizer dose, whereas trichocompost treatments received 75% of the recommended inorganic fertilizer rates.

Routine crop maintenance practices, including irrigation and weed control, were performed throughout the growing season.

Growth and yield measurements

Plant growth observations were conducted on all plants within the sampling plots. Growth parameters included : Plant height (cm); Number of leaves (leaves plant^{-1}). Measurements were performed weekly from one week after planting until the end of the vegetative stage. Plant height was measured from the stem base to the tip of the longest leaf using a measuring tape, while the number of fully expanded leaves was recorded. Biomass and yiield parameters were assessed after harvest and included: Root length (cm); Root fresh weight (g); Root dry weight (g); Shoot fresh weight (g); Shoot dry weight (g);

Number of ears per plot; Ear weight (g); Ear length (cm); Ear diameter (cm); Number of kernel rows per ear; Number of kernels per row; Grain weight per plot (g); One-thousand kernel weight (g). parameter pproduksi

Statistical analysis

Data were subjected to analysis of variance (ANOVA) at the 5% significance level. When significant treatment effects were detected, means were separated using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level.

RESULTS AND DISCUSSION

Effect of trichocompost on maize growth

Plant growth during the vegetative stage was assessed through weekly measurements of plant height and leaf number. These parameters are widely used as indicators of crop vigor and the effectiveness of nutrient utilization during early growth. The effects of trichocompost application on maize growth are presented in Table 1.

Table 1. Plant growth observations

No	Treatment	Week					
		I	II	III	IV	V	VI
		Plant height (cm)					
1	Control	0.522a	4.647a	16.346a	21.892a	32.243a	48.136a
2	TZ11DI1	2.127b	12.128b	24.175b	32.055b	52.725c	64.058b
3	TZ31DU1	1.721ab	10.664b	22.322b	30.315b	44.574b	62.599b
	HSD 5%	1.29	2.89	3.31	5.04	7.26	12.55
No	Perlakuan	**Number of leaves**					
1	Control	0.103a	1.589a	3.400a	5.164a	5.989a	7.087a
2	TZ11DI1	0.594b	2.935b	4.189b	5.519a	6.877b	9.445c
3	TZ31DU1	0.540b	2.590b	4.123b	5.589a	6.615b	8.075b
	HSD 5%	0.11	0.47	0.33	0.51	0.52	0.77

Plant height increased progressively throughout the six-week observation period in all treatments; however, plants inoculated with TZ11DI1 and TZ31DU1 exhibited significantly greater growth than the control. At week I, TZ11DI1 produced the highest plant height (2.127 cm), followed by TZ31DU1 (1.721 cm), while the control showed the lowest value (0.522 cm). From week II onward, both bacterial treatments consistently outperformed the control. The greatest differences were observed at week V, where TZ11DI1 reached 52.725 cm, significantly higher than TZ31DU1 (44.574 cm) and the control (32.243 cm). At the end of the experiment (week VI), TZ11DI1 and TZ31DU1 achieved plant heights of 64.058 cm and 62.599 cm, respectively, compared with only 48.136 cm in the control. These results indicate that both bacterial isolates enhanced plant growth, with TZ11DI1 showing the strongest stimulatory effect.

A similar trend was observed for the number of leaves. During the early growth stages (weeks I–III), both TZ11DI1 and TZ31DU1 significantly increased leaf production compared with the control. Although no significant differences among treatments were detected at week IV, the positive effect of bacterial inoculation became evident again at weeks V and VI. At the final observation, TZ11DI1 produced the highest number of leaves (9.445 leaves plant^{-1}), followed by TZ31DU1 (8.075 leaves plant^{-1}), whereas the control produced only 7.087 leaves plant^{-1}. The statistical grouping showed that all treatments differed significantly at week VI, indicating that bacterial inoculation substantially promoted vegetative development, particularly leaf formation, during the later growth stages.

The higher plant height and number of leaves in TZ11DI1- and TZ31DU1-treated plants indicate that these isolates may act as plant growth-promoting fungi. The improvement in vegetative growth compared with the control may be related to the ability of Trichoderma spp. to enhance nutrient availability, stimulate root development, produce growth-promoting metabolites, and improve plant physiological performance (Contreras-Cornejo *et al*., 2016; Woo *et al*., 2023). These mechanisms can support better nutrient uptake and shoot development, which explains the consistently higher plant height observed in both Trichoderma treatments.

The TZ11DI1 treatment showed the strongest growth-promoting effect, particularly at weeks V and VI. This response may be associated with the ability of Trichoderma to influence plant hormonal regulation, especially auxin-related responses that promote root growth, cell elongation, and vegetative development (Hermosa *et al*., 2022; Woo *et al*., 2023). Therefore, the superior plant height recorded under TZ11DI1 suggests that this isolate may have greater potential to stimulate plant growth than TZ31DU1.

The increase in leaf number under TZ11DI1 and TZ31DU1 is also important because leaves are the main photosynthetic organs supporting plant biomass accumulation. Trichoderma spp. can improve plant growth by enhancing nutrient absorption, increasing root vigor, and supporting photosynthetic efficiency through improved plant health and physiological status (Mendoza-Mendoza *et al*., 2018; Woo *et al*., 2023). This supports the result that plants treated with TZ11DI1 produced the highest number of leaves at week VI, followed by TZ31DU1, while the control produced the lowest leaf number.

The absence of significant differences in leaf number at week IV suggests that the effect of Trichoderma inoculation may vary depending on plant growth stage. However, the reappearance of significant differences at weeks V and VI indicates that the beneficial effect became more evident over time. This may be related to the establishment of Trichoderma in the rhizosphere and its interaction with plant roots, because successful growth promotion depends on fungal colonization ability, production of bioactive compounds, and compatibility with the host plant (Hermosa *et al*., 2022; Woo *et al*., 2023). Thus, TZ11DI1 can be considered the most promising Trichoderma isolate for enhancing vegetative growth based on plant height and leaf number.

Effect of Trichocompost on Root Development and Plant Biomass

Root development and biomass accumulation are important indicators of plant performance because they reflect nutrient uptake capacity and photosynthetic productivity. To determine the influence of trichocompost on belowground and aboveground growth, root and shoot characteristics were measured at harvest. The results are presented in Table 2.

Table 2. Root Growth and Biomass of Maize Plants

No	Parameter	Treatment			HSD 5%
		Control	TZ11DI1	TZ31DU1	
1	Root lenght (cm)	21.50a	25.82b	26.47b	3.53
2	Root fresh weigh (g)	19.27a	26.88b	33.96c	7.07
3	Root dry weigh (g)	14.86a	20.64b	27.33c	5.7
4	Shoot fresh weigh (g)	82.93a	138.00b	133.80b	31.89
5	Shoot dried weigh (g)	34.43a	56.85b	54.33b	9.87

Note: Values followed by the same lowercase letter within the same row are not significantly different according to the HSD test at the 5% significance level ($p \leq 0.05$).

Trichocompost application significantly improved root growth and biomass accumulation in maize plants compared with the control. Root length increased from 21.50 cm in the control to 25.82 cm in TZ11DI1 and 26.47 cm in TZ31DU1. Based on the HSD test at the 5% level, both trichocompost treatments were significantly higher than the control, while TZ11DI1 and TZ31DU1 were not significantly different from each other. A clearer treatment effect was observed in root biomass. Root fresh weight was lowest in the control treatment (19.27 g), increased to 26.88 g under TZ11DI1, and reached the highest value under TZ31DU1 (33.96 g). The same pattern was found for root dry weight, where TZ31DU1 produced the highest value (27.33 g), followed by TZ11DI1 (20.64 g), and the control (14.86 g). The different letter notations indicate that all treatments differed significantly for root fresh and dry weight, suggesting that TZ31DU1 was the most effective treatment in increasing root biomass.

Shoot biomass also increased significantly following trichocompost application. Shoot fresh weight in the control was 82.93 g, while TZ11DI1 and TZ31DU1 produced substantially higher values of 138.00 g and 133.80 g, respectively. Similarly, shoot dry weight increased from 34.43 g in the control to 56.85 g in TZ11DI1 and 54.33 g in TZ31DU1. Both trichocompost treatments were significantly different from the control but were not significantly different from each other. These results indicate that trichocompost application enhanced both belowground and aboveground growth of maize plants. TZ31DU1 was more effective in promoting root biomass, whereas TZ11DI1 tended to produce the highest shoot biomass.

The significant increase in root length and root biomass under TZ11DI1 and TZ31DU1 indicates that trichocompost supported better root development in maize plants. This improvement may be associated with the ability of Trichoderma spp. to colonize the rhizosphere and interact with plant roots, thereby improving nutrient mobilization, root growth, and plant physiological performance. Trichoderma spp. are widely recognized as plant-beneficial fungi that can promote healthy plant growth and reduce dependence on chemical inputs (Martinez *et al*., 2023). In addition, the co-application of Trichoderma with organic compost has been reported to stimulate nitrogen mineralization, increase soil phosphatase activity, and improve plant growth, indicating that organic amendments may enhance the effectiveness of Trichoderma as a bioorganic fertilizer (Asghar & Kataoka, 2021). This supports the present result, where trichocompost-treated plants showed longer roots and greater root biomass than untreated plants.

The greater root fresh and dry weights recorded under TZ31DU1 suggest that this treatment was particularly effective in stimulating root biomass accumulation. A well-developed root system allows plants to explore a larger soil volume and absorb water and nutrients more efficiently. Vinci *et al*. (2018) reported that the combination of Trichoderma harzianum and compost enhanced maize growth, phosphorus uptake, and metabolites related to improved photosynthetic activity, showing that Trichoderma–compost interaction can support both nutrient acquisition and plant metabolic performance. Therefore, the higher root biomass observed in TZ31DU1 may reflect improved root activity and nutrient uptake capacity, which are important for sustaining maize growth.

The increase in shoot fresh and dry weights under both trichocompost treatments indicates that improved root development was followed by better aboveground biomass production. Shoot dry weight is an important indicator of assimilate accumulation because it reflects the net result of photosynthesis and nutrient use efficiency. The higher shoot biomass in TZ11DI1 and TZ31DU1 may be explained by improved nutrient availability from compost decomposition and the growth-promoting effect of Trichoderma. Previous research showed that Trichoderma-based formulations can enhance plant development through root colonization, nutrient solubilization, stress tolerance, and plant growth modulation (Martinez *et al*., 2023). In maize, Trichoderma harzianum combined with reduced phosphorus fertilization has also been reported to improve growth parameters such as shoot and root dry weight, root volume, and plant nutrient content (de Lima Gonilha *et al*., 2024).

Although both trichocompost treatments improved maize growth, their effects differed between root and shoot parameters. TZ31DU1 produced the highest root fresh and dry weights, whereas TZ11DI1 produced the highest shoot fresh and dry weights. This difference suggests that each Trichoderma isolate may have a different functional capacity in promoting plant growth. Isolate-specific effects are common in Trichoderma because growth promotion depends on fungal colonization ability, compatibility with the host plant, production of bioactive metabolites, and interaction with organic substrates. The present findings therefore indicate that TZ31DU1 is more effective in promoting root biomass, while TZ11DI1 is slightly more favorable for shoot biomass accumulation. Overall, trichocompost application improved maize root development and biomass production, demonstrating its potential as a sustainable input for supporting vegetative growth.

Effect of trichocompost on yield components of maiz

Yield components were evaluated to determine the extent to which trichocompost application influenced reproductive development and grain production in maize. Parameters related to ear development and grain yield were measured at harvest, and the results are summarized in Table 3.

Table 3. Effect of *Trichoderma* Isolates on Yield Components of Maize

No	Parameter	Treatment			HSD 5%
		Control	TZ11DI1	TZ31DU1	
1	Number of ears per plot	20.93^{a}	27.53^{b}	24.40^{ab}	3.48
2	Ear weight (g)	47.34^{a}	115.53^{b}	104.66^{b}	17.61
3	Ear length (cm)	8.15^{a}	12.93^{b}	11.86^{b}	1.51
4	Ear diameter (cm)	2.05^{a}	3.35^{b}	3.26^{b}	0.37
5	Number of rows per ear	7.74^{a}	11.37^{b}	10.65^{b}	1.57
6	Number of kernels per row	11.68^{a}	21.61^{b}	20.52^{b}	2.45
7	Kernel weight (g)	440.66^{a}	1,077.00^{b}	949.33^{b}	177.05
8	1000-kernel weight (g)	187.66^{a}	226.66^{b}	218.33^{b}	22.66

Note: Values followed by the same lowercase letter within the same row are not significantly different according to the HSD test at the 5% significance level ($p \leq 0.05$).

The application of Trichoderma isolates significantly improved most yield components of maize compared with the control. The number of ears per plot increased from 20.93 in the control to 27.53 in TZ11DI1 and 24.40 in TZ31DU1. Based on the HSD test at the 5% level, TZ11DI1 was significantly different from the control, while TZ31DU1 was statistically intermediate. Ear weight also increased markedly under Trichoderma treatments, with TZ11DI1 producing the highest ear weight (115.53 g), followed by TZ31DU1 (104.66 g), both of which were significantly higher than the control (47.34 g). Similar trends were observed for ear length and ear diameter, where TZ11DI1 and TZ31DU1 significantly increased ear size compared with the control, but did not differ significantly from each other.

Yield-related kernel traits also responded positively to Trichoderma application. The number of rows per ear increased from 7.74 in the control to 11.37 in TZ11DI1 and 10.65 in TZ31DU1, while the number of kernels per row increased from 11.68 in the control to 21.61 and 20.52 under TZ11DI1 and TZ31DU1, respectively. Kernel weight showed the largest increase, with TZ11DI1 producing 1,077.00 g and TZ31DU1 producing 949.33 g, compared with only 440.66 g in the control. The 1000-kernel weight also increased significantly from 187.66 g in the control to 226.66 g in TZ11DI1 and 218.33 g in TZ31DU1. Overall, TZ11DI1 produced the highest values for all yield components, although in most parameters it was not significantly different from TZ31DU1.

The improvement in maize yield components under TZ11DI1 and TZ31DU1 indicates that Trichoderma isolates positively influenced reproductive growth and yield formation. The increases in ear weight, ear length, ear diameter, number of rows per ear, number of kernels per row, kernel weight, and 1000-kernel weight suggest that Trichoderma application enhanced the plant's capacity to support cob development and grain filling. Trichoderma spp. are known as plant-beneficial fungi that can function as biostimulants and biofertilizers by improving nutrient availability, root activity, plant physiological performance, and tolerance to stress (Woo *et al*., 2023). These mechanisms likely contributed to the higher yield components observed in the treated plants compared with the uninoculated control.

The increase in ear size and kernel formation may be associated with improved nutrient uptake and better assimilate allocation during the reproductive stage. In maize, adequate nutrient availability, especially phosphorus, is essential for energy transfer, flowering, cob formation, and grain filling. De Oliveira *et al*. (2024) reported that Trichoderma harzianum increased root length, root surface area, plant phosphorus content, and total dry matter in maize, indicating that Trichoderma can improve nutrient-use efficiency. Therefore, the higher ear weight, number of kernels per row, and kernel weight in TZ11DI1 and TZ31DU1 treatments may be linked to improved nutrient acquisition and more efficient translocation of assimilates to developing grains.

The significantly higher kernel weight and 1000-kernel weight in Trichoderma-treated plants indicate better grain filling than in the control. This result is consistent with Estévez-Geffriaud *et al*. (2020), who found that seed treatment with Trichoderma asperellum T34 improved maize kernel number, kernel dry weight, and kernel nutrient parameters. Improved grain filling may result from enhanced photosynthetic performance, better water-use efficiency, and stronger physiological activity during the reproductive phase. Thus, the higher kernel weight recorded in TZ11DI1 and TZ31DU1 suggests that these isolates supported both yield formation and grain development.

Although both isolates improved yield components, TZ11DI1 generally produced the highest values across all parameters, particularly number of ears per plot, ear weight, kernel weight, and 1000-kernel weight. This suggests that TZ11DI1 may have stronger growth-promoting potential than TZ31DU1 in supporting reproductive development of maize. However, the statistical results show that TZ11DI1 and TZ31DU1 were not significantly different in most yield parameters, indicating that both isolates were effective. Similar findings have been reported in field studies where microbial fertilizers containing Trichoderma harzianum improved maize yield and soil nutrient status through enhanced biological activity and nutrient availability (Zhang *et al*., 2025). Therefore, the present results demonstrate that Trichoderma isolates, particularly TZ11DI1, have strong potential as biological inputs for improving maize yield components in a more sustainable production system.

Overall, the results indicate that trichocompost functions not only as an organic nutrient source but also as an intelligent biological input capable of improving resource-use efficiency and maintaining crop productivity. The integration of Trichoderma-based trichocompost into maize production systems therefore represents a practical strategy to support the transition from conventional fertilization practices toward innovation-driven and sustainable Agroindustry 4.0.

CONCLUSION

1. The application of Trichoderma-based trichocompost improved maize growth and productivity compared with the conventional fertilization practice using the full recommended rate of inorganic fertilizers without trichocompost.
2. Trichocompost prepared using Trichoderma asperellum TZ11DI1 exhibited the best performance in enhancing most growth and yield parameters, particularly grain yield, producing 1,077.00 g grain weight per plot and demonstrating its potential as an effective biological input for sustainable maize production.
3. Trichocompost based on Trichoderma reesei TZ31DU1 was more effective in promoting root development, as indicated by greater root length and root biomass, suggesting its important role in improving nutrient and water acquisition.
4. The integration of trichocompost with a 25% reduction in inorganic fertilizer application maintained and even enhanced maize productivity, indicating that this technology can increase nutrient-use efficiency while reducing dependence on chemical fertilizers.
5. The utilization of local Trichoderma-based trichocompost represents a promising intelligent cultivation strategy to support the transition from conventional agricultural practices toward sustainable Agroindustry 4.0 through the integration of biological innovation, resource-use efficiency, and environmentally friendly crop production systems.

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