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Enhancing productivity and ecological resilience of dryland shallots through the integration of *Trichoderma harzianumand* organic mulch

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ABSTRACT

Agricultural production in dryland ecosystems is constrained by low soil fertility, erratic rainfall, and limited water availability. To address these challenges, the integration of *Trichoderma harzianum* with organic mulch was investigated as an eco-friendly strategy. The effects of *T. harzianum* and organic mulch on Rubaru local shallots (*Allium cepa* var. Aggregatum) cultivated in Sumenep, Indonesia, were evaluated. A factorial randomized block design with four replications was applied, consisting of two mulch types (bamboo litter and corn plant litter) and four *T. harzianum* dosages (0, 10, 20, and 30 g/plant). Significant improvements in plant height, leaf number, shoot formation, bulb number, bulb weight, and total yield were recorded under *T. harzianum* treatments, with the best response obtained at 30 g/plant. Productivity was further enhanced by bamboo litter mulch, compared to corn plant litter mulch. In addition, increasing doses of *T. harzianum* were associated with a reduction in downy mildew (*Peronospora*) incidence across observation periods, with the greatest reduction (45.4%) observed at 30 g/plant at 6 weeks after planting. By principal component analysis (PCA), 82.5% of total variation was explained, with growth and yield traits found to be positively correlated and negatively associated with disease incidence. This study confirmed that integrating *T. harzianum* with organic mulch is an effective, environmentally friendly strategy to enhance productivity, reduce disease incidence, and improve input efficiency in shallot cultivation under dryland conditions.

Keywords: biocontrol, dryland, organic mulch, shallot, sustainable intensification, *Trichoderma harzianum*.

INTRODUCTION

Dryland ecosystems are characterized by low soil fertility, erratic rainfall, and limited water availability, posing major challenges for sustainable agricultural development (FAO, 2019; Hall et al., 2020; Wang et al., 2023). Although marginal, drylands have the potential for food production, as they cover more than 40% of the world's land surface (Stavi et al., 2021). Moreover, food demand is increasing. Therefore, intensifying sustainable agriculture in drylands is an urgent need, especially through a holistic, innovative approach that improves resource-use efficiency while maintaining ecosystem health.

In the face of these challenges, eco-friendly cultivation practices appear to be a sustainable alternative to agricultural systems that rely on high inputs. This approach emphasizes reducing the use of synthetic chemicals, improving soil health, and harnessing soil biological activity to support plant growth naturally (Chowdhuri and Pal, 2025; Koskey et al., 2021; Ortiz and Sansinenea, 2022). One important approach in this practice is the use of beneficial microbes and integrated nutrient management to increase input productivity efficiently and sustainably (Bargaz et al., 2018; Shah and Wu, 2019).

One of the beneficial microorganisms that has demonstrated great promise as a biological agent in sustainable agriculture is the soil fungus *Trichoderma harzianum*. In both biotic and abiotic settings, this fungus is known for its diverse roles as a stress-mitigating agent, biofertilizer, and biocontrol agent (Hugar et al., 2025; Mukhopadhyay and Kumar, 2020; Nafady et al., 2022; Pacheco-Trejo et al., 2022; Xiao et al., 2023). To ensure steady operation, its presence in the rhizosphere needs to be maintained. Therefore, organic mulching, which improves the biophysical properties of soil and helps retain moisture, should be incorporated into its application. Stavi (2020) highlighted that in dryland agriculture, organic mulches like leaf litter are effective water-saving techniques. According to Jourgholami et al. (2021), mulching arid soils with crop residues improves their biophysical properties and reduces soil compaction.

There is increasing evidence supporting the positive effects of *Trichoderma* in mitigating various stressors across different crops. For instance, Saha et al. (2025) showed that the application of *Trichoderma* enhanced salinity tolerance in *Brassica juncea* and reduced the impact of salt stress in *Cucumis sativus* (Zhang et al., 2019). Other research reported that *Trichoderma* alleviated both salinity and disease severity caused by *Sclerotinia sclerotiorum* in *Phaseolus vulgaris* (Abdelrhim et al., 2024). Its co-application with organic fertilizers has also been shown to suppress the *Sclerotium rolfsii*-induced disease in potato (Chowdhury et al., 2023). In rice, *Trichoderma* improved seedling vigor by enhancing nutrient uptake and activating peroxidase enzymes involved in oxidative stress resistance (Swain et al., 2018). Beyond plant growth, *Trichoderma* exhibits potential in environmental remediation through the biodegradation of synthetic dyes (Hugar et al., 2025). As a biofertilizer, it has contributed to yield improvements in tomato and *Bupleurum chinense* (Khan et al., 2025; Liu et al., 2022; Molla et al., 2012). Despite the breadth of these findings, their application in local shallot (*Allium cepa* var. Agregatum) cultivation under dryland conditions – especially when integrated with organic mulch such as bamboo leaves or corn husks – remains underexplored. Therefore, further research is essential to bridge this gap and assess the potential synergistic effects of *Trichoderma harzianum* and organic mulch in increasing productivity in dryland shallot farming systems.

This study was conducted in Sumenep, a representative dryland agroecosystem located on Madura Island, East Java, Indonesia. The region is characterized by low annual rainfall, poor soil quality, limited irrigation infrastructure, and the predominance of traditional smallholder farming systems (Ramadhani et al., 2024). Shallots (*Allium cepa* var. *Aggregatum*) constitute the primary horticultural crop in this area, with the Rubaru variety recognized as a prominent local landrace originating from Sumenep (Dewi et al., 2024; Rachmawati et al., 2023). The Rubaru variety exhibits distinct morphological and biochemical traits (Wati et al., 2025), such as a strong characteristic aroma, adaptability to dryland conditions, and high consumer preference, although it typically produces relatively smaller bulbs. Previous research indicates that bulb size, bulb color, and leaf morphology significantly influence shallot productivity and environmental adaptation (Putri et al., 2020). Despite these favorable attributes, the productivity of Rubaru remains relatively low, primarily due to its susceptibility to soil-borne pathogens prevalent in Madura dryland systems. This vulnerability is exacerbated by low soil organic matter and high temperatures, which may further limit yield stability (Arifin and Saeri, 2019; Asih et al., 2022).

The results of this study are anticipated to guide the development of more efficient and sustainable farming methods suited to comparable agroecological zones, given the widespread occurrence of dryland conditions across Indonesia. In response to these challenges, this study aimed to evaluate the effects of *Trichoderma harzianum* application and the use of organic mulch on increasing productivity and growth performance of local shallot varieties in dryland agroecosystems. By integrating eco-friendly biological agents into existing traditional farming systems, this research sought to contribute meaningfully to the intensification of sustainable agriculture, particularly in the regions that are increasingly vulnerable to the impacts of climate change.

MATERIALS AND METHODS

Study site and experimental design

The study geographical location is located at coordinates south (S) 6°59'13.16", east (E) 113°45'54.65".The research was carried out using a factorial randomized complete block design (RCBD), which was repeated 4 (four) times. Factor I is the use of mulch, consisting of 2 levels, namely M1 = mulch from bamboo litter/leaves, M1 = mulch from corn plant litter. Factor II is the dose/dose of *Trichoderma harzianum*, consisting of 4 levels, namely T0 = no administration of *Trichoderma harzianum*, T1 = 10 g/plant (g/plant), T2 = 20 g/plant, and T3 = 30 g/plant.

Preparation of *Trichoderma harzianum biofertilizer*

Trichoderma harzianum was isolated from indigenous microorganisms using a rice-based medium placed in a single-node bamboo segment, which was subsequently buried in a bamboo plantation area for 3 weeks at Mandala valage, Sumenep district. The purified culture was used as an inoculum and propagated by suspending it in 1 L of water at 2%. A total of 10 kg of rice bran (obtained from rice milling) was prepared, mixed thoroughly with 1 L of water, steamed for 3 hours, and cooled to approximately 28 °C. The cooled substrate was then uniformly inoculated with 1 kg of *T. harzianum* culture, packed into plastic bags, and incubated in a shaded area protected from rain and direct sunlight. The biofertilizer was ready for application after 7 days, as indicated by a greenish coloration of the substrate. The population density of *T. Harzianum* reached 10^7 CFU/g.

Field experiment procedures

The dryland agricultural area was cleared of weeds and plowed twice using a hand tractor. The land was subsequently divided into 2 × 4 m experimental plots. Each plot was separated by drainage channels (30 cm wide and 30 cm deep). As a basic fertilizer, organic fertilizer, cow dung, is used with a dose of 15 tons per hectare (t/ha), and Mutiara brand nitrogen, phosphorus, potassium, NPK fertilizer with a dose of 250 kilograms per hectare (kg/ha). Follow-up fertilizer is given at the age of 21 days after planting (DAP) and 35 DAP using NPK compound fertilizer at a dose of 250 kg/ha. The research plot contained 200 shallot plants with a planting distance of 20 centimeters (20 × 20 cm). The seedlings were planted in the prepared plots. The *Trichoderma harzianum* treatment was applied at planting by placing it into the planting hole. Subsequently, dry bamboo leaves and chopped corn husks were applied uniformly as mulch on the soil surface of each plot. Mulch was applied at a thickness of approximately 2 cm to prevent interference with early shallot seedling growth. Each treatment plot was assigned 10 randomly selected sample plants for vegetative growth observation. Observation of the components of vegetative growth includes the number of leaves, plant height, and number of stems/seedlings. The vegetative growth observation interval was 1 week, from 2 to 7 weeks of age. During harvesting, observations were made of the product components, namely the number of bulbs per plant, the mass of the bulbs per plant, and the quality of the bulbs (shape, aroma, color, and skin). The yield component at harvest was determined on the entire crop of each experimental plot. The intensity of disease attacks was assessed as the percentage of affected leaves, scored on a scale of 0–9 based on Halterman et al., (2008), according to the percentage of infected leaf area, as follows: 0 = no visible symptoms; 1 = < 10% leaf area affected; 2 = 10–25% leaf area affected; 3 = 26–40% leaf area affected, with plants still predominantly green; 4 = 41–60% leaf area affected; 5 = 61–70% leaf area affected, with visible browning of plant tissues; 6 = 71–80% leaf area affected, including infection of basal and apical parts; 7 = 81–90% leaf area affected, with only the upper parts remaining green; 8 = > 90% leaf area affected, with minimal green tissue remaining; 9 = 100% leaf damage, with no green tissue remaining.

Statistical analysis

The data obtained from the observations were analyzed to determine the effect of the treatment on growth, the rate of attack by the main pest and disease organisms, the outcome, and the quality of the results. The data was analyzed using R Studio analysis of variance (ANOVA), followed by least significant difference (LSD) with p-value 0.05 to assess parameter alterations. Principal component analysis was performed to identify the significant factors influencing shallot production under eco-friendly cultivation with *Trichoderma harzianum.*

RESULTS AND DISCUSSION

Growth performance

Plant height

Analysis of variance (ANOVA) showed a significant interaction between *Trichoderma* dose and mulch type at plant height in the 4th week after planting ($p = 0.036$). In other weeks, including WAP 7, the interaction was not significant ($p > 0.05$). However, the results of Tukey's post hoc test did not indicate a significant difference among the treatment combinations. Figure 1.

The interactions obtained from the average plant height plot, with 95% confidence intervals, showed a different pattern between the two types of mulch (bamboo leaf litter and corn husk). In bamboo leaf litter mulching, the average line of plant height across *Trichoderma* doses showed a relatively parallel pattern from 2 to 7 weeks after planting (WAP), indicating that the effect of *Trichoderma* dose on plant height was relatively consistent, with little change over time. In contrast, in the corn husk mulch, a pattern of intersecting lines, especially around WAP 4, indicates an interaction between the *Trichoderma* dose and the mulch at that time. This cross-section indicates that the effect of *Trichoderma* dosage on plant height depends on the type of mulch, especially in week 4. This is consistent with the ANOVA results, which found significant interactions in WAP 4. On the graph, the label "stable patterns: parallel lines" is placed on the bamboo leaf litter panel to confirm that the plant's tall pattern between *Trichoderma* doses is relatively stable over time. On the corn husk litter panel, the label "pattern changes: lines cross" is accompanied by an arrow showing a line crossing on WAP 4. This thin arrow marks the point where notable interactions occur, indicating that the plant's response to *Trichoderma* dosage differs depending on the type of mulch in the week. In weeks other than WAP 4, the line pattern on the mulch corn husk litter was less likely to intersect, indicating the absence of a strong interaction between the dosage factor and the mulch.

Number of leaves

At the beginning of growth, to three weeks of age, the number of shallots was significantly affected by the application of *T. harzianum* and organic mulch ($p < 0.05$), but was not affected by the interaction between the two factors from 2 weeks to 7 weeks after planting. The development of the number of leaves until the shallots are 7 weeks old is only very noticeably affected ($p < 0.01$) by the dose of *Trichoderma*. Although the type of organic mulch does not have a noticeable effect on the number of leaves, there is a tendency for the number of leaves in corn husk mulch to be higher than that of bamboo leaf mulch. The increase in the number of leaves presented in Figure 2.

Number of shoots

The results of the variant analysis showed that the dose of *T. harzianum application* had a very significant effect on the number of shoots at the age of 2 WAP to 7 WAP ($p < 0.05$). Meanwhile,

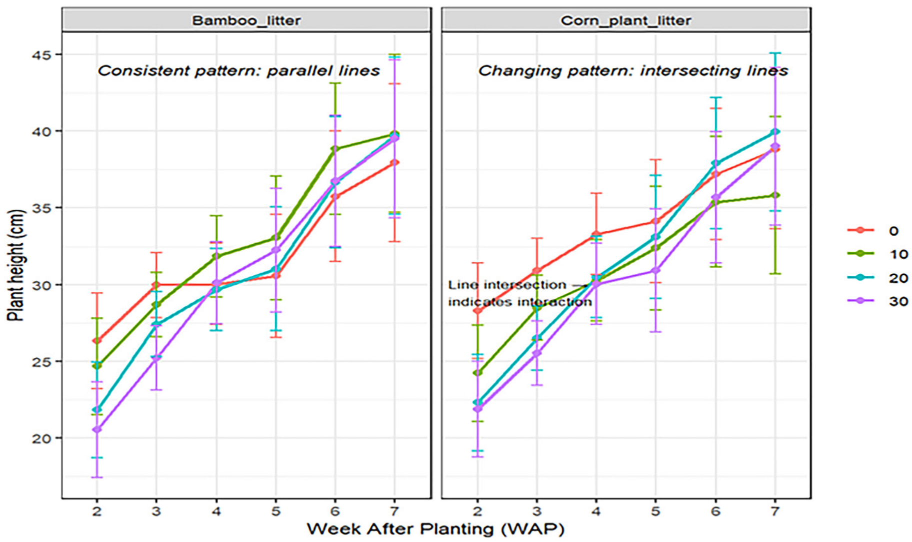
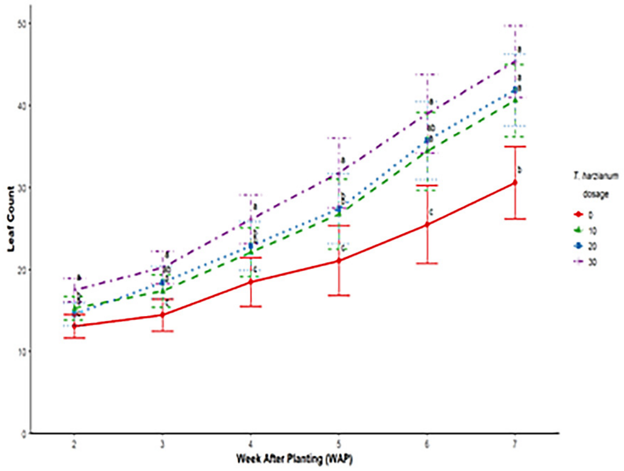


Figure 1. Changes in plant height over time

(a)



(b)

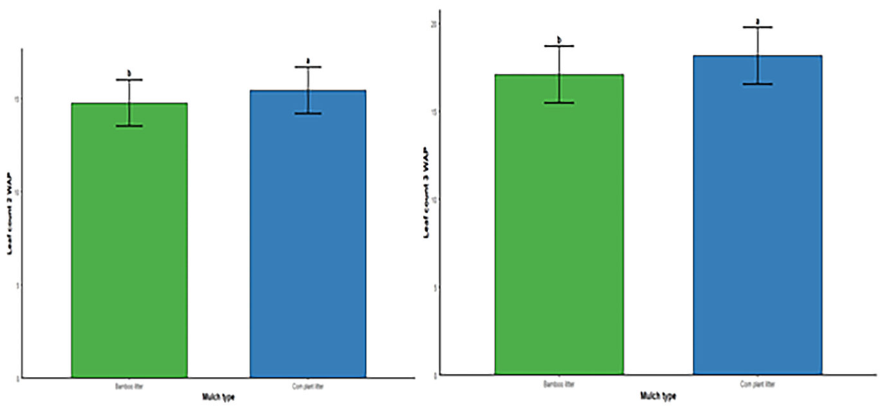


Figure 2. (a) Effect of T. harzianum doses on leaf count from 2 to 7 weeks after planting (WAP), (b) leaf count influenced by T. harzianum and organic mulch

the type of organic mulch only has a real effect on the number of shoots at 6 and 7 WAP. The interaction between the two treatments was not significant across the entire observation period. All doses of the *T. harzianum* treatment resulted in significantly more shoots than controls. The 30 g/plant dose produced the highest number of shoots and was significantly different from the other doses. The development of the number of shoots affected by the dose of *T. harzianum* is presented in Figure 3.

Yield components

Number and weight per bulb, and the number of bulbs per plant, were significantly affected by *T. harzianum application* at various doses ($p < 0.01$). However, using organic mulch does not significantly affect the number of bulbs.

Similarly, the interaction between the *T. harzianum* dose and the type of organic mulch did not significantly affect this variable. The number of bulbs per plant increases along with *T. harzianum* dose (Figure 4). The number of bulbs increased by 55% compared to the control (without *T. harzianum* application). A significant effect of *T. harzianum* application is also observed on average bulb weight. The treatment with 30 g/plant resulted in the highest tuber weight, with the difference from other dosage treatments very noticeable. Although the treatments at 10 g and 20 g/plant did not differ significantly from the controls, there was a tendency for average bulb weight to increase with increasing *T. harzianum* dose (Figure 5a). Bamboo mulch gives the highest number of bulbs compared to corn mulch (Figure 5b).

The increase in the yield component of local shallots, Rubaru, in response to the application of *T. harzianum* shows that this biological agent plays an important role in supporting the growth and yield of this variety of crops on dry land. The

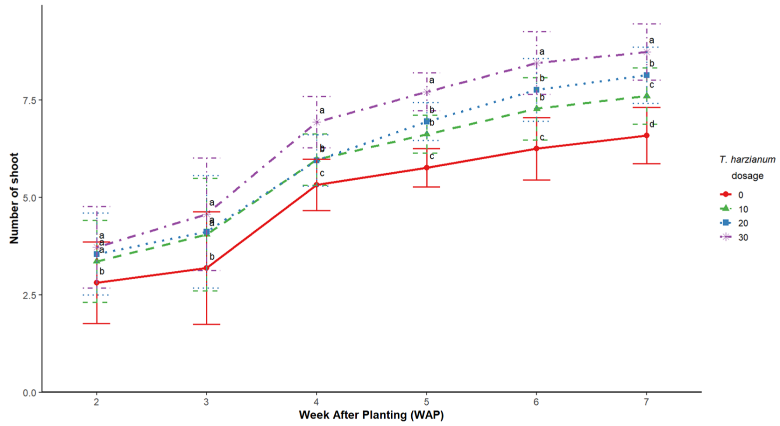


Figure 3. Number of shoots 2–7 WAP

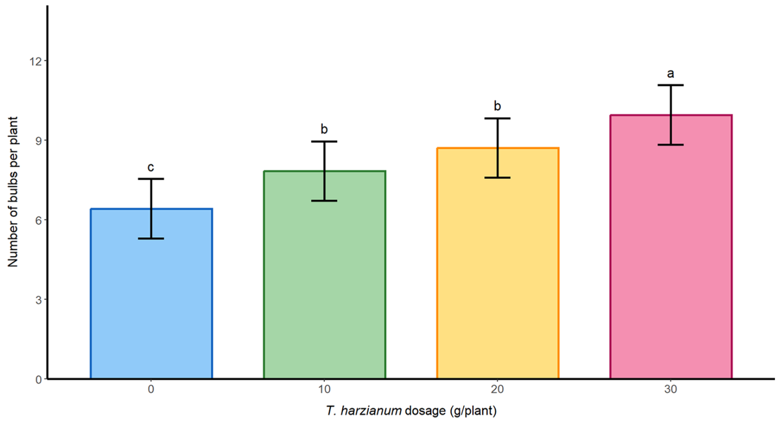


Figure 4. Number of bulbs per plant

best agronomic response was observed with a dose of 30 g/plant, which markedly improved all yield components compared to the control. These results suggest that *T. harzianum* can stimulate plant growth through various interrelated biological mechanisms, such as being able to increase the availability and uptake of essential nutrients, e.g., nitrogen, phosphorus, and potassium, through enzymatic activity and phosphate dissolution (Ali et al., 2022; Alwadai et al., 2024; Bononi et al., 2020; Islam et al., 2023; Liu et al., 2022). This activity accelerates cell division, increasing the number of bulbs. In addition, *T. harzianum* produces secondary metabolites, including indole-3-acetic acid, a growth hormone (Bader et al., 2020; Tyśkiewicz et al., 2022), which play a role in regulating tissue differentiation and the formation of underground organs such as bulbs. This fungus can act as a biocontrol agent, producing antibacterial and antifungal compounds to support plant health and increase crop yields (Aamir et al., 2023; Abdelrhim et al., 2024; Hugar et al., 2025). The increase in tuber weight at the highest doses suggests that *T. harzianum* not only increases the quantity but also the quality of the results. This is in line with the findings of Visconti et al. (2020), who reported that the application of Trichoderma-based biostimulant increases the accumulation of total and marketable biomass in horticultural crops. *Trichoderma* also helps improve plant defenses against abiotic and biotic stress (Pacheco-Trejo et al., 2022). This is reinforced by Khoshmanzar et al. (2020) and Rawal et al. (2022), who stated that *Trichoderma* helps cope with the stress of water scarcity. This effect becomes especially relevant for the adaptation of dryland agriculture to abiotic stress, such as water deficit and low nutrient availability in marginal soils (Boorboori and Zhang, 2022).

Total yield per hectare

The results of the analysis showed that the yield of fresh shallot bulbs per hectare was strongly affected by the *T. harzianum* application dose (p <

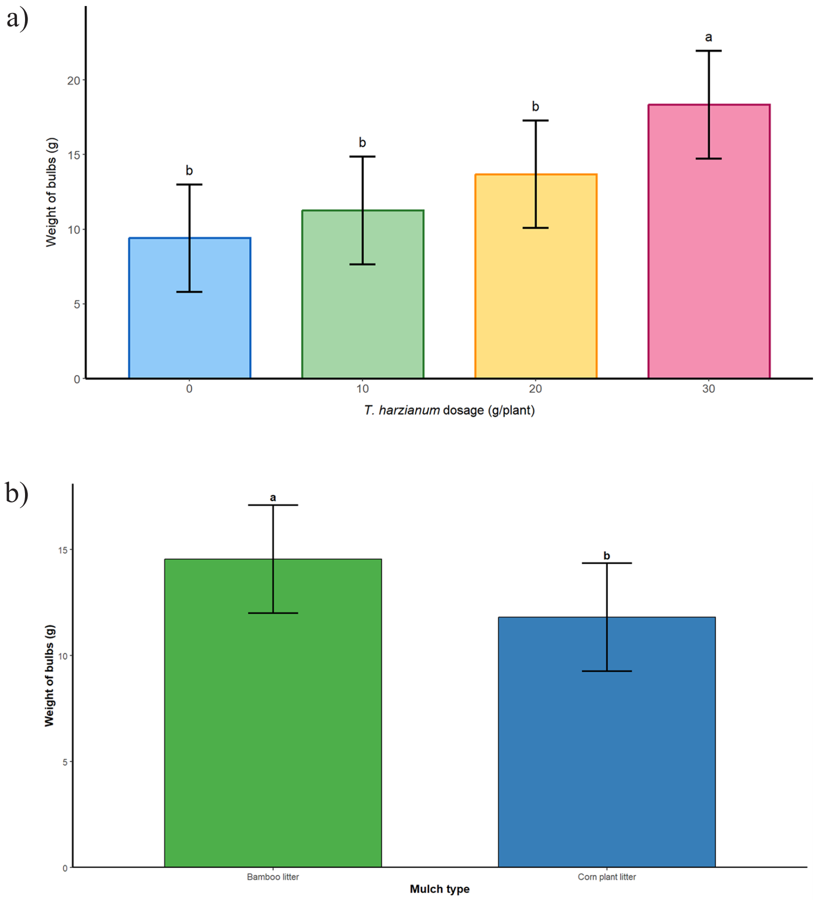


Figure 5. a)Weight of bulbs influenced by T. harzianum dosage, b) Weight of bulbs influenced by type of mulch

0.01) and by the type of organic mulch ($p < 0.05$). However, the interaction between the two statistically showed no significant effect ($p < 0.05$). The application *of T. harzianum* increased fresh tuber yield by 13.24% to 28.87% compared to controls. Applying *T. harzianum* 30 g/plant showed the highest tuber yield per hectare, followed by a dose of 10 g/plant. Statistically, the two treatments are not significantly different. Meanwhile, a dose of 20 g/plant resulted in lower yield than 10 g or 30 g/plant, indicating a non-linear response to increasing dose. Organic mulch types showed a noticeably different effect on bulb yield per hectare ($p < 0.05$). Using bamboo leaf litter resulted in higher yield than dried corn husks, with a 23.20% difference. These results are illustrated in Figure 6.

A yield response that is not entirely linear with increasing doses of *T. harzianum* (e.g., productivity at 20 g/plant is lower than at 10 g) is not strictly dose-dependent and may involve complex interactions within the rhizophere. Previous studies have shown that *Trichoderma* spp. can promote plant growth through multiple mechanisms, including nutrient solubilization, phytohormone production, and enhanced root development, but these effects are often dependent on the applied dose and environmental conditions (Alwadai et al., 2024; Asad et al., 2023; Thangaraj, 2025; Tyśkiewicz et al., 2022; Yao et al., 2023). The reduced performance at the intermediate dose may be associated with increased microbial competition or imbalance in the rhizophere microbiome, which can influence nutrient availability and plant-microbe interaction (Assainar et al., 2018; Qiu et al., 2019). Microbial competition for root exudates and the production of secondary metabolites such as antibiotics and siderophores can further shape microbial community structure and affect plant performance (Chepsergon and Moleleki, 2023). This mechanism may account for the significantly lower yield observed at the intermediate dose (20 g/plant), suggesting that excessive or imbalanced microbial activity at this level may have reduced the effectiveness of plant growth promotion.

In addition, spatial variability in soil properties under field conditions may contribute to the inconsistent response across application rates. The effectiveness of microbial inoculants is highly

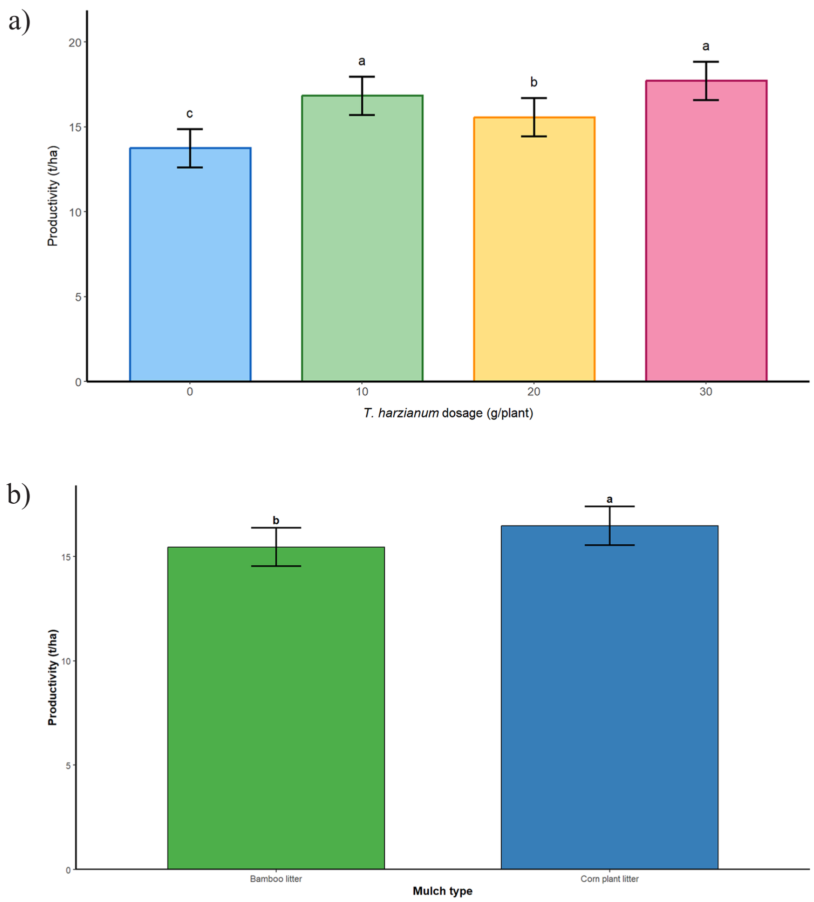


Figure 6. a) Productivity influenced by T. harzianum, b) Productivity influenced by type of mulch

dependent on site-specific factors such as nutrient availability, soil moisture, and organic matter content, leading to variable outcomes even under similar treatment (Fiorentino et al., 2018; Francioli et al., 2025). Therefore, the efficiency and effectiveness of the dosage are important factors to consider when applying this biological agent.

The results of this study are consistent with several previous reports showing the positive role of Trichoderma in increasing the yield of horticultural crops, including shallots (Nafady et al., 2022; Xiao et al., 2023). However, the effectiveness of the application is also highly dependent on local agroecosystem conditions, soil type, and the cultivation method used. The local variety of Rubaru used in this study comes from Sumenep Regency, Madura, and is known for its sharp, distinctive aroma, which is highly preferred by consumers, especially for fried onion products. However, this variety has restrictions on bulb size, which tends to be small, so its yield is lower than that of the national superior varieties. Consequently, the strategy for improving outcomes with bioinoculants, such as *T. harzianum,* is highly pertinent to the development of this local variety. The increase in tuber quantity and average weight in this study indicates that the use of *T. harzianum* may help address the size limitations of the Rubaru variety without altering its distinctive aroma and flavor characteristics. In addition, the success of applying *T. harzianum* to increase the productivity of Rubaru shallots further strengthens the argument that local varieties have considerable potential to be developed sustainably through agroecological approaches. This approach is consistent with the principles of conserving local genetic resources and raising the added value of regional products, as stated by Raggi et al. (2024) The Allium genera that have economic value require preservation for the sake of global food security. By increasing environmentally friendly, sustainable productivity, local farmers can not only achieve higher yields but also conserve the identity of varieties that are integral to the culinary culture of the Madurese people.

Another interesting finding is the increase in partial input productivity (PIP) of the use of NPK fertilizer. In this study, the application of *T. harzianum* only used half the standard dose of basic and follow-up NPK fertilizers, while controls (without *T. Harzianum*) were given NPK fertilizer using full standard doses. The results showed that although the fertilizer dose was lowered by 50% in the application treatment of *T. Harzianum*, the mean value of PIP increased from 36.35 kg/ha of NPK to 47.01 to 51.43 kg/ha of NPK 9 Table 2), demonstrating the efficiency of the input in real terms. Mobilization of beneficial microbes, such as *T. Harzianum*, in the provision of macronutrients and their absorption by plants (Awad-Allah et al., 2022; Bononi et al., 2020), as well as its interaction with NPK mineral fertilizer, improves the efficiency of fertilizer use. This is in line with Bibi et al., (2024), who reported that synergistic strategies between the use of beneficial microorganisms, organic, and inorganic fertilizers can reduce dependence on chemical fertilizers. The implications for cost-effectiveness and environmental sustainability.

Postharvest quality

In this study, shallot quality was assessed using the total soluble solids (TSS) variable. Based on the results of the variety analysis, there was no notable impact of *T. harzianum* application, the type of organic mulch, nor the interaction of the two on the total value of dissolved solids (TSS) and the fresh aroma score of Rubaru local shallots ($p > 0.05$). However, there is a tendency for TSS values and aroma to increase at higher doses of *T. harzianum*, but these differences do not reach statistical significance (Figure 7).

Plant diseases

From the beginning of growth to the 65-day harvest period, only three local shallot plants were affected by Fusarium in the control plot. However, all plots experience the *Downy mildew* (*Peronospora destructor* (Berk.) Casp) *attacks,* with symptoms of chlorotic lesions on leaves, followed by the appearance of grayish-purple sporulation, leading to leaf tip drying, necrosis, and eventual plant decline under favorable environmental conditions, starting at 2 weeks after planting. The application of *T. harzianum* had a significant effect on the *Peronospora destructor* (Berk.) Casp attack at age 2 WAP ($p < 0.05$) and a very pronounced effect at ages 4 and 6 WAP (p

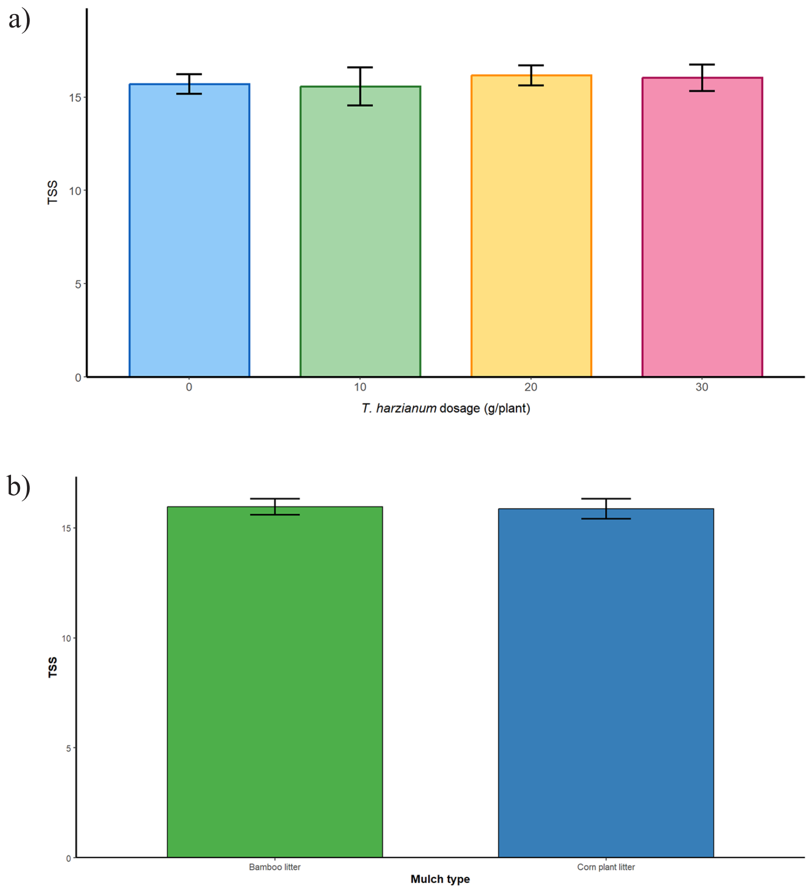


Figure 7. a) TSS of Shallot influenced by *T. harzianum*, b) TSS of Shallot influenced by type of mulch

< 0.01). The type of organic mulch and the interaction between the application of *T. harzianum* x organic mulch did not show any noticeable effect. Increasing the dose of *T. harzianum* further reduces disease severity, as shown in Table 1.

Principal component analysis (PCA)

PCA was performed on shallot growth and yield variables. The results of PCA show that the first two main components (PC1 and PC2) explain 82.5% of the total variation, with contributions of 70.74% (PC1) and 11.80% (PC2), respectively. This means that most of the information from the measured variables is well described by these two main components, as shown in Figure 8.

The PCA in Figure 8 shows that the organic mulch treatment combined with *T. harzianum* application significantly affects plant growth, yield, and disease incidence. PCA explains more than 82% of the total variance, with Dim1 accounting for 70.7%, providing a representative picture of the variables. Growth variables, such as the number of leaves, the number of stems, plant height, and tuber weight, are positively correlated with each other and are positively associated with Dim1. Conversely, the disease incidence variable shows a negative correlation between growth rate and disease intensity. The treatments with high doses of *T. harzianum* (20–30 g/plant) combined with corn or bamboo waste mulch were strongly associated with growth and yield variables. In turn, the treatments without *T. harzianum* applications tended to be associated with higher disease incidence. The mechanisms by which *T. harzianum* improves plant health include growth promotion, effects on soil physical and chemical properties, and alterations in rhizosphere microbial community structure. This aligns with studies by Contreras-Cornejo et al. (2024), which state that *Trichoderma* spp. plays a dual role as a biocontrol agent and biofertilizer. Its mechanisms involve the production of metabolites such as IAA and VOCs, increased nutrient uptake, efficient root colonization, and induction of plant resistance. With these capacities, *Trichoderma* is an important candidate for environmentally friendly and climate-adaptive agricultural technologies. In addition, the combination of organic mulch with biostimulants such as *Trichoderma* has also been shown to significantly increase the soil microbial population, as shown by Tripathi and Shukla (2024). The combination of biostimulants (Azotobacter + Phosphate-Solubilizing Bacteria (PSB) + *Trichoderma*) with dry leaf organic mulch has proven to be the most effective in boosting the soil microbial population in strawberries, thereby increasing the growth potential and plant resistance. The use of PCA in agronomy remains an important tool for extracting information patterns from complex data. This emphasizes that PCA is a highly effective statistical tool for analyzing complex agronomic data, particularly in the on-farm research settings characterized by high variability. In the context of our research, PCA serves a similar function, simplifying many growth variables (plant height, number of leaves, number of stems), yield (tuber weight), and disease incidence into easily understood primary components (Osawaru et al., 2015). The integration of *Trichoderma harzianum* with organic mulch has been proven to be an environmentally friendly strategy for enhancing productivity while reducing disease incidence in horticultural crops.

The value of this approach was confirmed through PCA, which positioned the findings within the context of recent literature on the roles of bioagents, organic amendments, and statistical analysis

Table 2. Partial input productivity value due to reduction of NPK fertilizer dose

Doses of *T. harzianum* (g/plant)	Yield (t/ha)	PIP NPK (kg/ha)
0	13.75	36.35
10	16.83	51.32
20	15.57	47.01
30	17.72	51.43

Table 1. Peronospora attack at 2,4, and 6 WAP influenced by *T. harzianum*

T. harzianum dosage	*Peronospora* attack		
	2 WAP	4 WAP	6 WAP
0	1.5 ± 0.327 a	42.5 ± 12.13 a	52.25 ± 4.31 a
10	0.875 ± 0.295 a	19.875 ± 3.55 b	46.25 ± 3.43 a
20	0.125 ± 0.125 b	18.25 ± 2.02 b	35.63 ± 2.53 b
30	0 b	6.5 ± 0.82 c	28.5 ± 2.74 b

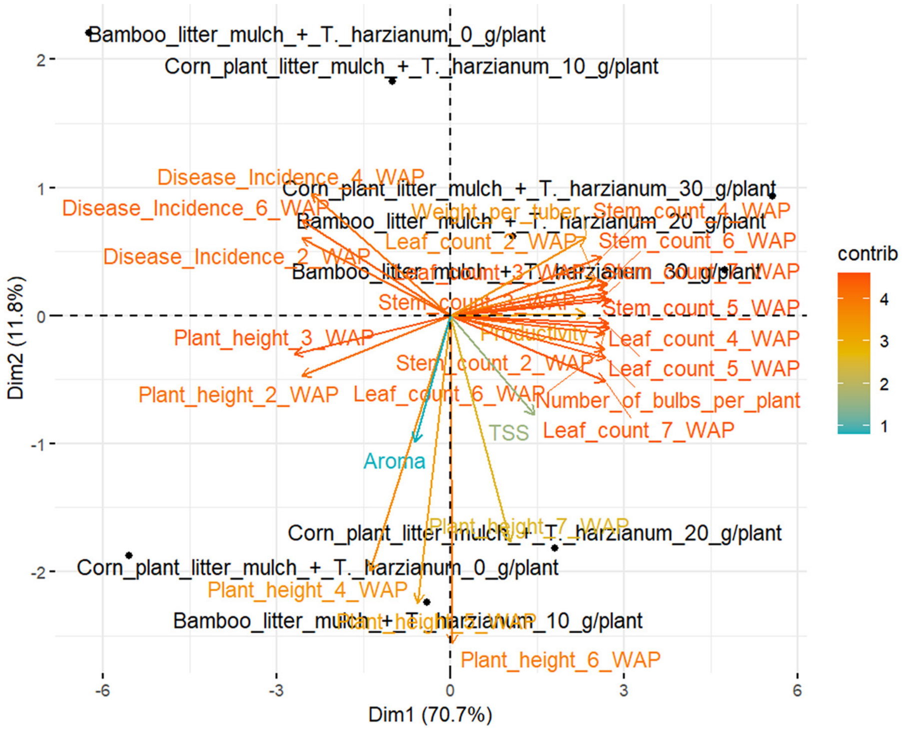


Figure 8. Dominant variables on PC1 and PC2

in sustainable agriculture. The positive response to *T. harzianum* application in local shallots suggests that these microorganisms may strengthen local genetic potential by improving the plant's physiological efficiency. This is consistent with the eco-friendly agricultural strategies, which promote the utilization of local genetic resources through environmentally friendly approaches. Furthermore, the results also have considerable implications for the conservation and breeding of local shallots. The interaction between endophytic or rhizosphere microbes, such as *Trichoderma*, and local genotypes can create opportunities to select the accessions with a high response to bioinoculants, thereby facilitating the development of high-yielding, adaptive varieties in arid lands.

CONCLUSIONS

This study demonstrated that the *Trichoderma harzianum* application significantly enhances the growth, yield, and disease resistance of Rubaru shallots in dryland agroecosystems. Among the tested doses, 30 g/plant consistently produced the best results across growth and yield parameters, indicating it is the optimal application rate. The use of organic mulch further improved plant performance, with bamboo leaf mulch showing greater effectiveness than corn husk mulch in enhancing soil moisture retention and increasing bulb yield.

Importantly, the integration of *T. harzianum* with organic mulching improved nutrient-use efficiency, as evidenced by maintained yield even under a 50% reduction in NPK fertilizer. These findings suggest that combining bioinoculants with locally available organic inputs can serve as a practical strategy to reduce chemical fertilizer dependency while maintaining yield. This approach has strong potential to support sustainable intensification and climate-resilient agriculture in dryland agroecosystems.

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REFERENCES

1. Aamir, M., Shanmugam, V., Dubey, M. K., Husain, F. M., Adil, M., Ansari, W. A., Rai, A., Sah, P. (2023). Transcriptomic characterization of *Trichoderma harzianum* T34 primed tomato plants: assessment of biocontrol agent induced host specific gene expression and plant growth promotion. *BMC Plant Biology*, *23*(1), 1–38. https://doi.org/10.1186/s12870-023-04502-6

2. Abdelrhim, A. S., Hemeda, N. F., Mwaheb, M. A., Omar, M. O. A., Dawood, M. F. A. (2024). The role of *Trichoderma koningii* and *Trichoderma harzianum* in mitigating the combined stresses motivated by Sclerotiniasclerotiorum and salinity in common bean (*Phaseolusvulgaris*). *Plant Stress*, *11*(August 2023), 100370. https://doi.org/10.1016/j.stress.2024.100370
3. Ali, S., Khan, M. J., Anjum, M. M., Khan, G. R., Ali, N. (2022). *Trichoderma harzianum*modulates phosphate and micronutrient solubilization in the Rhizosphere. *Gesunde Pflanzen*, *74*(4), 853–862. https://doi.org/10.1007/s10343-022-00643-0
4. Alwadai, A. S., Al Wahibi, M. S., Alsayed, M. F., Alshaikh, N. A., Perveen, K., Elsayim, R. (2024). Molecular characterization of plant growth-promoting Trichoderma from Saudi Arabia. *Scientific Reports*, *14*(1), 1–20. https://doi.org/10.1038/s41598-024-73762-5
5. Arifin, Z., Saeri, M. (2019). Water management and mulch on shalot in dry land. *Journal of Horticulture*, *29*.
6. Asad, R., Khan, A., Najeeb, S., Chen, J., Zhang, J., Hou, J., Liu, T., Wang, R. (2023). Insights into the molecular mechanism of Trichoderma stimulating plant growth and immunity against phytopathogens. *Physiologia Plantarum*, *175*(November), 1–18. https://doi.org/10.1111/ppl.14133
7. Asih, D. N. S., Soekarno, B. P. W., Yuliani, T. S., Surono, S. (2022). The study of relationship between weather and soil factors to the fusarium basal rot disease severity. *Journal of Horticulture*, *32*(1), 67–74.
8. Assainar, S. K., Abbott, L. K., Mickan, B. S., Whiteley, A. S., Siddique, K. H. M., Solaiman, Z. M. (2018). Response of wheat to a multiple species microbial inoculant compared to fertilizer application. *Frontiers in Plant Science*, *9*(November), 1–10. https://doi.org/10.3389/fpls.2018.01601
9. Awad-Allah, E. F. A., Shams, A. H. M., Helaly, A. A., Ragheb, E. I. M. (2022). Effective applications of trichoderma spp. as biofertilizers and biocontrol agents mitigate tomato fusarium wilt disease. *Agriculture (Switzerland)*, *12*(11). https://doi.org/10.3390/agriculture12111950
10. Bader, A. N., Salerno, G. L., Covacevich, F., Consolo, V. F. (2020). Native *Trichoderma harzianum* strains from Argentina produce indole-3 acetic acid and phosphorus solubilization, promote growth and control wilt disease on tomato (*Solanum lycopersicum* L.). *Journal of King Saud University - Science*, *32*(1), 867–873. https://doi.org/10.1016/j.jksus.2019.04.002
11. Bargaz, A., Lyamlouli, K., Chtouki, M., Zeroual, Y., Dhiba, D. (2018). Soil microbial resources for improving fertilizers efficiency in an integrated plant nutrient management system. *Frontiers in Microbiology*, *9*(July). https://doi.org/10.3389/fmicb.2018.01606
12. Bibi, H., Ur Rahim, H., Anwar Khan, A., Haris, M., Iqbal, M., Ali, R., El-Sheikh, M. A., Kaushik, P. (2024). Harmonized tripartite approach: Enhancing nutrient accessibility, uptake, and wheat productivity through *Trichoderma harzianum*, compost, and phosphorus synergy. *Journal of King Saud University - Science*, *36*(3), 103106. https://doi.org/10.1016/j.jksus.2024.103106
13. Bononi, L., Chiaramonte, J. B., Pansa, C. C., Moitinho, M. A., Melo, I. S. (2020). Phosphorus-solubilizing *Trichoderma* spp. from amazon soils improve soybean plant growth. *Scientific Reports*, *10*(1), 1–13. https://doi.org/10.1038/s41598-020-59793-8
14. Boorboori, M. R., Zhang, H. (2022). Arbuscular mycorrhizal fungi are an influential factor in improving the phytoremediation of arsenic, cadmium, lead, and chromium. *J. Fungi*, *8*(2), 176. https://doi.org/https://doi.org/10.3390/jof8020176
15. Chepsergon, J., Moleleki, L. N. (2023). Rhizosphere bacterial interactions and impact on plant health. *Current Opinion in Microbiology*, *73*, 102297. https://doi.org/10.1016/j.mib.2023.102297
16. Chowdhuri, I., Pal, S. C. (2025). Challenges and potential pathways towards sustainable agriculture crop production: A systematic review to achieve sustainable development goals (SDGs). *Soil and Tillage Research*, *248*(January). https://doi.org/10.1016/j.still.2024.106442
17. Chowdhury, M. R., Ahmed, S. F., Khalid, B., Bony, Z. F., Asha, J. F., Bhuiyan, M. K. A. (2023). Biocontrol efficiency of microencapsulated *Trichoderma harzianum* coupled with organic additives against potato stem rot caused by Sclerotium rolfsii. *Plant Stress*, *9*(February), 100181. https://doi.org/10.1016/j.stress.2023.100181
18. Contreras-Cornejo, H. A., Schmoll, M., Esquivel-Ayala, B. A., González-Esquivel, C. E., Rocha-Ramírez, V., Larsen, J. (2024). Mechanisms for plant growth promotion activated by Trichoderma in natural and managed terrestrial ecosystems. *Microbiological Research*, *281*(January). https://doi.org/10.1016/j.micres.2024.127621
19. Dewi, T., Yustika, R. D., Arianti, F. D. (2024). Enhancement of Production and Food Security Through Sustainable Shallot Cultivation. *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/1364/1/012052
20. FAO. (2019). The State of the World's Biodiversity for Food and Agriculture. In *The State of the World's Biodiversity for Food and Agriculture*. https://doi.org/10.4060/ca3129en
21. Fiorentino, N., Ventorino, V., Woo, S. L., Pepe, O., Rosa, A. De, Gioia, L., Romano, I., Lombardi, N., Napolitano, M., Colla, G., Rouphael, Y., Elia, A. (2018). Trichoderma -Based biostimulants modulate rhizosphere microbial populations and improve

n uptake efficiency, yield, and nutritional quality of leafy vegetables. *Frontiers in Plant Science*, *9*(June), 1–15. https://doi.org/10.3389/fpls.2018.00743

22. Francioli, D., Kampouris, I. D., Nagel, T. K., Babin, D., Sommermann, L., Behr, J. H., Chowdhury, S. P., Zrenner, R., Moradtalab, N., Schloter, M., Geistlinger, J., Ludewig, U., Neumann, G., Smalla, K., Grosch, R. (2025). Microbial inoculants modulate the rhizosphere microbiome, alleviate plant stress responses, and enhance maize growth at field scale. *Genome Biology*. https://doi.org/10.1186/s13059-025-03621-7
23. Hall, D. J. M., Davies, S. L., Bell, R. W., Edwards, T. J. (2020). Soil management systems to overcome multiple constraints for dryland crops on deep sands in a water limited environment on the south coast of western australia. *Agronomy*, *10*(12), 1–21. https://doi.org/10.3390/agronomy10121881
24. Halterman, D. A., States, U., Agricultural, A., Pathology, P., Kramer, L. C., Wielgus, S., Jiang, J. (2008). Performance of transgenic potato containing the late blight resistance gene RB. *Plant Disease*, *92*(3), 339–343.
25. Hugar, A., Rudrappa, M., Nayaka, S. (2025). *Trichoderma harzianum* AKH-5: A novel fungal isolate with antimicrobial efficacy for phytopathogen management and environmental remediation. *Microbial Pathogenesis*, *204*(February), 107606. https://doi.org/10.1016/j.micpath.2025.107606
26. Islam, S. S., Billah, A. T. M. M., Hasan, A. K., Karim, R., Khomphet, T. (2023). Evaluating the impact of Trichoderma biofertilizer and planting dates on mustard yield performance using the InfoCrop growth model. *PLoS ONE*, *18*(5 MAY), 1–15. https://doi.org/10.1371/journal.pone.0285482
27. Jourgholami, M., Khoramizadeh, A., Lo Monaco, A., Venanzi, R., Latterini, F., Tavankar, F., Picchio, R. (2021). Evaluation of leaf litter mulching and incorporation on skid trails for the recovery of soil physico-chemical and biological properties of mixed broadleaved forests. *Land*, *10*(6), 1–15. https://doi.org/10.3390/land10060625
28. Khan, R. A. A., Siddique, M. I., Li, P., Ahmad, M. (2025). Mitigating zinc oxide nanotoxicity in tomato plants: Role of Trichoderma-modulated rhizosphere microbiomes and soil glomalin content. *Plant Stress*, *17*(April), 100919. https://doi.org/10.1016/j.stress.2025.100919
29. Khoshmanzar, E., Aliasgharzad, N., Neyshabouri, M. R., Khoshru, B., Arzanlou, M., Asgari Lajayer, B. (2020). Effects of Trichoderma isolates on tomato growth and inducing its tolerance to water-deficit stress. *International Journal of Environmental Science and Technology*, *17*(2), 869–878. https://doi.org/10.1007/s13762-019-02405-4
30. Koskey, G., Mburu, S. W., Awino, R., Njeru, E. M., Maingi, J. M. (2021). Potential use of beneficial microorganisms for soil amelioration, phytopathogen biocontrol, and sustainable crop production in smallholder agroecosystems. *Frontiers in Sustainable Food Systems*, *5*(April), 1–20. https://doi.org/10.3389/fsufs.2021.606308
31. Liu, L., Xu, Y., Cao, H., Fan, Y., Du, K., Bu, X., Gao, D. (2022). Effects of *Trichoderma harzianum* biofertilizer on growth, yield, and quality of Bupleurum chinense. *Plant Direct*, *6*(11), 1–13. https://doi.org/10.1002/pld3.461
32. Molla, A. H., Manjurul Haque, M., Amdadul Haque, M., Ilias, G. N. M. (2012). Trichoderma-enriched biofertilizer enhances production and nutritional quality of tomato (*Lycopersicon esculentum* Mill.) and minimizes NPK fertilizer use. *Agricultural Research*, *1*(3), 265–272. https://doi.org/10.1007/s40003-012-0025-7
33. Mukhopadhyay, R., Kumar, D. (2020). Trichoderma: A beneficial antifungal agent and insights into its mechanism of biocontrol potential. *Egyptian Journal of Biological Pest Control*, *30*(1). https://doi.org/10.1186/s41938-020-00333-x
34. Nafady, N. A., Sultan, R., El-Zawahry, A. M., Mostafa, Y. S., Alamri, S., Mostafa, R. G., Hashem, M., Hassan, E. A. (2022). Effective and promising strategy in management of tomato root-knot nematodes by *Trichoderma harzianum* and arbuscular mycorrhizae. *Agronomy*, *12*(2). https://doi.org/10.3390/agronomy12020315
35. Ortiz, A., Sansinenea, E. (2022). The role of beneficial microorganisms in soil quality and plant health. *Sustainability (Switzerland)*, *14*(9). https://doi.org/10.3390/su14095358
36. Osawaru, M., Ogwu, M. C., Imarhiagbe, O. (2015). Principal component analysis (PCA) as an ideal tool for analysing on-farm research data Okra germplasm collection from Southern Nigeria and their characterization View project Exploring common leafy vegetable germplasms in Nigeria for food security and su. *Biological and Environmental Sciences Journal for the Tropics*, *15*(1), 514–522. https://www.researchgate.net/publication/286620136
37. Pacheco-Trejo, J., Aquino-Torres, E., Reyes-Santamaría, M. I., Islas-Pelcastre, M., Pérez-Ríos, S. R., Madariaga-Navarrete, A., Saucedo-García, M. (2022). Plant defensive responses triggered by *Trichoderma* spp. as tools to face stressful conditions. *Horticulturae*, *8*(12). https://doi.org/10.3390/horticulturae8121181
38. Putri, F., Aziz, S. A., Andarwulan, N., Melati, M., Java, W., Java, W., Java, W. (2020). Growth performance of green shallots from five different varieties in Indonesia. *Plant Archives*, *20*(Spesial Issue), 813–818.
39. Qiu, Z., Egidi, E., Liu, H., Kaur, S., Singh, B. K. (2019). New frontiers in agriculture productivity: Optimised microbial inoculants and in situ

microbiome engineering. *Biotechnology Advances*, *37*(6), 107371. https://doi.org/10.1016/j.biotechadv.2019.03.010

40. Rachmawati, D., Aisyawati, L., Latifah, E., Sandrakirana, R., Baswarsiati, B. (2023). The potential and characteristics of genetic resources of 7 national superior of shallots varieties in Indonesia. *International Conference on Agricultural Sustainability*. https://doi.org/10.1088/1755-1315/1246/1/012022
41. Raggi, L., Zucchini, C., Sayde, E., Gigante, D., Negri, V. (2024). Priority areas for the establishment of genetic reserves to actively protect key crop wild relative species in Italy. *Global Ecology and Conservation*, *50*(November 2023), e02836. https://doi.org/10.1016/j.gecco.2024.e02836
42. Ramadhani, F., Surmaini, E., Dariah, A., Apriyana, Y., Estiningtyas, W., Susanti, E., Yustika, R. D., Sarvina, Y., Fanggidae, Y. R., Nurjaya, N. (2024). Multisource spatiotemporal analysis of cropping patterns on dry upland: A case study in Rubaru Subdistrict, Sumenep Regency. *Egyptian Journal of Remote Sensing and Space Science*, *27*(2), 403–415. https://doi.org/10.1016/j.ejrs.2024.04.008
43. Rawal, R., Scheerens, J. C., Fenstemaker, S. M., Francis, D. M., Miller, S. A., Benitez, M. S. (2022). Novel trichoderma isolates alleviate water deficit stress in susceptible tomato genotypes. *Frontiers in Plant Science*, *13*(May), 1–16. https://doi.org/10.3389/fpls.2022.869090
44. Saha, K. C., Uddin, M. K., Shaha, P. K., Hossain Chowdhury, M. A., Hassan, L., Saha, B. K. (2025). Application of *Trichoderma harzianum* enhances salt tolerance and yield of Indian mustard through increasing antioxidant enzyme activity. *Heliyon*, *11*(1), e41114. https://doi.org/10.1016/j.heliyon.2024.e41114
45. Shah, F., Wu, W. (2019). Soil and crop management strategies to ensure higher crop productivity within sustainable environments. *Sustainability*, *11*(5), 1485. https://doi.org/10.3390/su11051485
46. Stavi, I., Paschalidou, A., Kyriazopoulos, A. P., Halbac-cotoara-zamfir, R. (2021). Multidimensional food security nexus in drylands under the. *Land*, 1–14.
47. Swain, H., Adak, T., Mukherjee, A. K., Mukherjee, P. K., Bhattacharyya, P., Behera, S., Bagchi, T. B., Patro, R., Shasmita, Khandual, A., Bag, M. K., Dangar, T. K., Lenka, S., Jena, M. (2018). Novel Trichoderma strains. isolated from tree barks as potential biocontrol agents and biofertilizers for direct seeded rice. *Microbiological Research*, *214*(April), 83–90. https://doi.org/10.1016/j.micres.2018.05.015
48. Thangaraj, P. (2025). Biological control of *Trichoderma* spp.: Mechanisms of action against phytopathogens, insect pests, and its multifaceted roles in agro - ecosystems. *Environment Conservation Journal*, *26*(1), 302–314.
49. Tripathi, A. V. K., Shukla, P. (2024). Influence of biostimulants and organic mulch on soil microbial population in strawberry (F. × ananassa Dutch.). *Biochemical and Cellular Archives*, *24*(2). https://doi.org/10.51470/bca.2024.24.2.2551
50. Tyśkiewicz, R., Nowak, A., Ozimek, E., Jaroszuk-ściseł, J. (2022). Trichoderma: estado actual de su aplicación en la agricultura para el biocontrol de hongos fitopatógenos y la estimulación del crecimiento vegetal. *Revista Internacional de Ciencias Moleculares*, *23*(4), 2329.
51. Visconti, D., Fiorentino, N., Cozzolino, E., Woo, S. L., Fagnano, M., Rouphael, Y. (2020). Can Trichoderma-based biostimulants optimize N use efficiency and stimulate growth of leafy vegetables in greenhouse intensive cropping systems? *Agronomy*, *10*(1), 1–16. https://doi.org/10.3390/agronomy10010121
52. Wang, S., Fu, B., Wei, F., PiaoShilong, Maestre, F. T., Wang, L., Jiao, W., Liu, Y., Li, Y., Li, C., Zhao, W. (2023). Drylands contribute disproportionately to observed global productivity increases. *Science Bulletin*, *68*(2), 224–232. https://doi.org/https://doi.org/10.1016/j.scib.2023.01.014
53. Wati, H. D., Waluyo, B., Ekawati, I., Fajarianingtyas, D. A. (2025). Variation in morphological traits of Rubaru local shallot from Sumenep, Madura Island, and its potential for future agricultural innovation. *International Journal of Agricultural Technology*, *21*(5), 2083–2096.
54. Xiao, Z., Zhao, Q., Li, W., Gao, L., Liu, G. (2023). Strain improvement of *Trichoderma harzianum*for enhanced biocontrol capacity: Strategies and prospects. *Frontiers in Microbiology*, *14*(April), 1–16. https://doi.org/10.3389/fmicb.2023.1146210
55. Yao, X., Guo, H., Zhang, K., Zhao, M., Ruan, J., Chen, J. (2023). Trichoderma and its role in biological control of plant fungal and nematode disease. *Frontiers in Microbiology*, *May*, 1–15. https://doi.org/10.3389/fmicb.2023.1160551
56. Zhang, F., Wang, Y., Liu, C., Chen, F., Ge, H., Tian, F., Yang, T., Ma, K., Zhang, Y. (2019). *Trichoderma harzianum*mitigates salt stress in cucumber via multiple responses. *Ecotoxicology and Environmental Safety*, *170*(May 2018), 436–445. https://doi.org/10.1016/j.ecoenv.2018.11.084