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Research Article`

Integrating phosphate-solubilizing fungi and moderate phosphorus application for sustainable corn production

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ABSTRACT

Corn (Zea mays) is a vital staple crop and the second-largest agricultural commodity in Indonesia. However, productivity remains suboptimal, often due to nutrient imbalances, particularly in phosphate-rich soils where availability to plants is limited. This study aimed to assess the effects of reducing phosphate fertilizer by 50% in combination with bioagents Trichoderma harzianum, Metarhizium anisopliae, and arbuscular mycorrhizal fungi on key agronomic traits of corn. A randomized block design was employed to measure parameters including root volume, root-to-shoot ratio, leaf width, and seed sphericity. Results showed that applying 50% phosphate fertilizer alone yielded the highest root volume (70.00±18.19 mL) and root-to-shoot ratio (0.50±0.32), suggesting improved root development. In contrast, treatment with Metarhizium produced the widest leaves (10.14±0.30 cm) but showed the lowest values for root volume and root-to-shoot ratio. These findings highlight the potential of combining moderate phosphate input with beneficial bioagents to improve corn performance in marginal soils. The approach offers a cost-effective and environmentally sustainable alternative for managing nutrient imbalances. Further studies on long-term effects and economic feasibility are recommended to support wider adoption of these practices in sustainable agriculture.

Keywords: maize; Metharizium; nutrient management; sustainable agriculture; Trichoderma

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INTRODUCTION

Corn (*Zea mays*) is a staple crop and the second-largest agricultural commodity in Indonesia, with production reaching 16.53 million tons in 2022 (BPS, 2024; Nunilawati et al., 2024). Despite this achievement, a productivity gap persists between national and East Java yields, highlighting the potential for optimization (Hazmi & Suparwata, 2024). This disparity is rooted in nutrient management challenges, particularly in phosphate-dense soils such as those in Pontang Village, Jember. Excessive phosphate application in intensively cultivated fields has led to nutrient imbalances, impacting root architecture and overall plant health (Singh et al., 2023; Shukla et al., 2017; Solangi et al., 2023). Addressing these issues is critical to sustaining corn productivity and ensuring agricultural resilience in marginal lands. To overcome these constraints, biological interventions have gained attention.

Indonesia has a significant area of land with high phosphate content, yet much of it remains underutilized. Lands in West Java are known to have naturally high phosphate levels due to years of intensive fertilization (Susanto et al., 2020). It is estimated that more than 1.5 million hectares of agricultural land in Indonesia contain high levels of phosphate, but much of it is fixed in forms that are unavailable to plants. Therefore, approaches such as the use of phosphate-solubilizing fungi have become crucial strategies to sustainably optimize the potential of these lands (Asril et al., 2023).

Phosphate-solubilizing fungi (PSF) offer a promising solution to nutrient management challenges (Aberathna et al., 2023; Dhir, 2017; Wang et al., 2023). Fungi like *Trichoderma harzianum* and *Metarhizium anisopliae* not only enhance phosphate bioavailability but also function as biocontrol agents, improving plant vigor under stress conditions. Their dual roles as nutrient solubilizers and biological enhancers align with sustainable agriculture principles, offering a pathway to reduce dependency on synthetic fertilizers while maintaining high productivity (Dhir, 2017; Siqueira et al., 2020; Wang et al., 2023). In particular, moderate applications of phosphate fertilizers combined with PSF have shown potential to optimize root-shoot biomass allocation, seed uniformity, and physiological efficiency in crops like corn (Fitriatin et al., 2014; Gong et al., 2014; Kumar et al., 2020). This study explores the integration of PSF into site-specific nutrient management (SSNM) practices for sustainable corn cultivation. By evaluating the effects of *Trichoderma harzianum*, *Metharizium anisopliae*, and arbuscular Mycorrhizal fungi under varying phosphate levels, this research aimed to assess the effects of reducing phosphate fertilizer by 50% in combination with bioagents Trichoderma harzianum, Metarhizium anisopliae, and arbuscular mycorrhizal fungi on key agronomic traits of corn.

MATERIALS AND METHODS

This study was conducted in Pontang Village, Ambulu District, Jember Regency, utilizing fields with high phosphate content. The land was the property of a farmer. The experiment was conducted during the rainy season from July 29th until November 24th, 2024. The experiment was performed using a randomized block design (RBD), with each block serving as a replicate (see Figure 1). Five treatments were performed, i.e., control, arbuscular Mycorrhiza, *Trichoderma harzianum*, *Metarhizium anisopliae*, and 50% phosphate fertilizer. The control group received no fungal treatment applications. Phosphate fertilizer was applied at approximately 100 kg ha^{-1}, representing a 50% reduction from the local recommendation of about 200 kg ha^{-1}, for all treatments except the control. The plot size used in this study was 4 m × 5 m per treatment replicate, with 20 plants observed per plot. Three replications were evaluated.

Soil preparation began with an analysis of both actual and potential phosphate content. Organic fertilizer 2,500 kg ha^{-1} and potassium fertilizer (KCl) at a dose of 150 kg ha^{-1} were applied as the base for land preparation. Corn seeds were sown in a single row with a planting distance of 30 cm x 30 cm. No urea (N source) was applied.

Fungal treatments, including arbuscular Mycorrhiza, *Trichoderma harzianum*, and *Metarhizium anisopliae*, were applied at four weeks of seedling age via soil drenching. Each isolate solution had a concentration of 10^8 CFU/mL.

The agronomic parameters were then observed, covering morphological, physiological, and productivity. The study assessed various agronomic parameters of corn, including plant height, number of leaves, leaf length, leaf width, stem diameter, chlorophyll content, ear length, ear diameter, root volume, ear weight (with husk), seed dimensions/weight (length), root length, fresh weight (shoot), dry weight of the plant, root-shoot ratio (AT), productivity (with husk), and productivity (without husk). Post-harvest soil analysis was carried out to assess changes in phosphate content due to the treatments.

Data were analyzed using analysis of variance (ANOVA) to identify significant differences among treatments. Data visualization was performed using the Python programming language and Google Colab, utilizing libraries (Matplotlib and Seaborn).

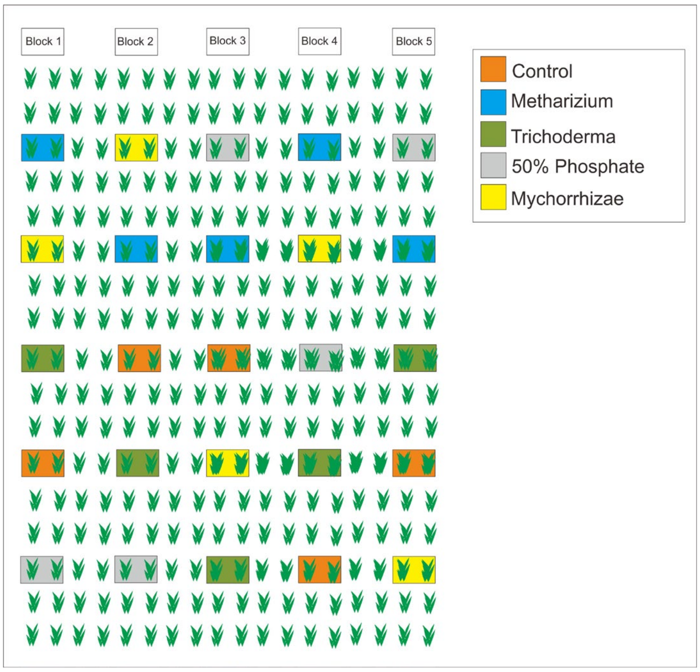


Figure 1. Layout of experiment using randomized block design.

RESULT AND DISCUSSION

The results of the ANOVA indicated that the treatments had a significant impact on several key parameters of plant growth and productivity (Table 1). Leaf width showed a significant effect from the Metarhizium treatment compared to the control (F = 3.29, p = 0.032), indicating measurable changes in leaf morphology. Root volume was one of the most significantly affected parameters (F = 6.16, p = 0.002), with the 50% Phosphate treatment showing a drastic increase compared to the control, Metarhizium, and Mycorrhizae groups. This parameter highlights the importance of phosphate in supporting an optimal root system for efficient nutrient and water absorption.

Table 1. Summary of ANOVA.

Parameters	F-value	P-value
Plant height	0.96	0.452
Number of leaves	0.12	0.974
Leaf length	0.93	0.468
Leaf width	3.29	0.032*
Stem diameter	0.53	0.718
Chlorophyll content	1.38	0.276
Ear length	1.25	0.321
Ear diameter	0.84	0.516
Root volume	6.16	0.002*
Ear weight (With husk)	2.39	0.085
Seed dimension/ Sphericity (Length)	3.46	0.027*
Root length	1.69	0.192
Fresh weight (Shoot)	1.52	0.235
Dry plant weight	0.46	0.767
Root-shoot ratio	4.96	0.006*
Productivity (With husk)	2.38	0.086
Productivity (Without husk)	1.78	0.172

Seed uniformity improved significantly under 50% phosphate treatment, which is particularly beneficial for hybrid maize (F = 3.46, p = 0.027). This is crucial for ensuring harvest quality, especially for hybrid corn varieties. The root-shoot ratio was also significantly affected by this treatment (F = 4.96, p = 0.006), reflecting the balance of biomass allocation between roots and shoots, which supports plant adaptation in environments with water or nutrient stress. Parameters such as plant height, number of leaves, chlorophyll content, and dry plant weight did not show significant differences among treatments, indicating that these variables may be less responsive to the treatments in this study. These results demonstrate that the 50% Phosphate treatment consistently had a positive effect on key parameters such as root volume, seed uniformity, and root-shoot ratio (Table 2).

Table 2. The summary of significant value treatments.

Treatments	Root volume (mL)	Leaf width (cm)	AT ratio
Control	32.50±7.34	9.18±0.48	0.14±0.05
50% Phosphate	70.00±18.19	9.32±0.29	0.50±0.32
Trichoderma	49.90±23.78	9.38±0.60	0.22±0.14
Mychorrhyzae	35.75±10.44	9.58±0.55	0.15±0.05
Metharizium	29.50±8.80	10.14±0.30	0.12±0.02

Note: AT ratio = Root to shoot ratio

In the context of corn cultivation, the moderate use of phosphate could be an effective agronomic strategy to enhance productivity, especially in marginal lands (Choudhary et al., 2014; Husnain et al., 2014; Kumar et al., 2020). Treatments based on biological agents like Metarhizium also showed potential in supporting leaf growth, which is relevant for enhancing photosynthesis (Behie & Bidochka, 2014; Siqueira et al., 2020). The combination of these treatments offers significant potential for strengthening harvests sustainably, while also supporting plant adaptation to environmental challenges.

Table 2 shows that the highest root volume was found in the 50% phosphate treatment (70.00±18.19 mL), followed by Trichoderma (49.90±23.78 mL), while the lowest was observed in the Metharizium treatment (29.50±8.80 mL). Leaf width appeared relatively consistent across treatments, with the highest value recorded in the Metharizium treatment (10.14±0.30 cm), slightly higher than the others. The highest AT ratio was also observed in the 50% phosphate treatment (0.50±0.32), indicating a significant increase compared to other treatments, while the lowest was in Metharizium (0.12±0.02). These results suggest that the application of 50% phosphate has the most positive impact on root development and AT ratio in plants.

The application of 50% phosphate significantly improved seed uniformity, which is a critical indicator of seed quality and market value, especially in hybrid maize production. Enhanced phosphate availability supports more consistent nutrient uptake during the grain-filling stage, resulting in uniform seed development (Choudhary et al., 2014). Moreover, leaf width is a key morphological trait influencing photosynthetic efficiency. While wider leaves generally provide a larger surface area for light interception, which can enhance photosynthesis, the relationship is not always linear. Excessively large leaves may lead to mutual shading or higher transpiration rates under certain conditions (Husnain et al., 2014). Therefore, moderate increases in leaf width, as observed in the Metarhizium treatment, can contribute positively to photosynthetic performance and overall plant productivity, particularly in resource-limited environments.

Figure 2 illustrates the distribution of treatment effects on the leaf width parameter. The results show that the control and *Metarhizium* treatments have statistically significant differences, indicating the impact of the microorganism treatments on the control group (see red asterisk). Treatments such as 50% phosphate, *Mycorrhizae*, and *Trichoderma* did not show significant differences, with distributions tending to be symmetrical and the range of mean differences mostly between -1.0 and 1.0. The greater variability in the 50% phosphate treatment indicates heterogeneity in response. In the context of maize, an increase in leaf width can contribute significantly to photosynthetic efficiency, which ultimately enhances plant productivity, especially in resource-limited soils.

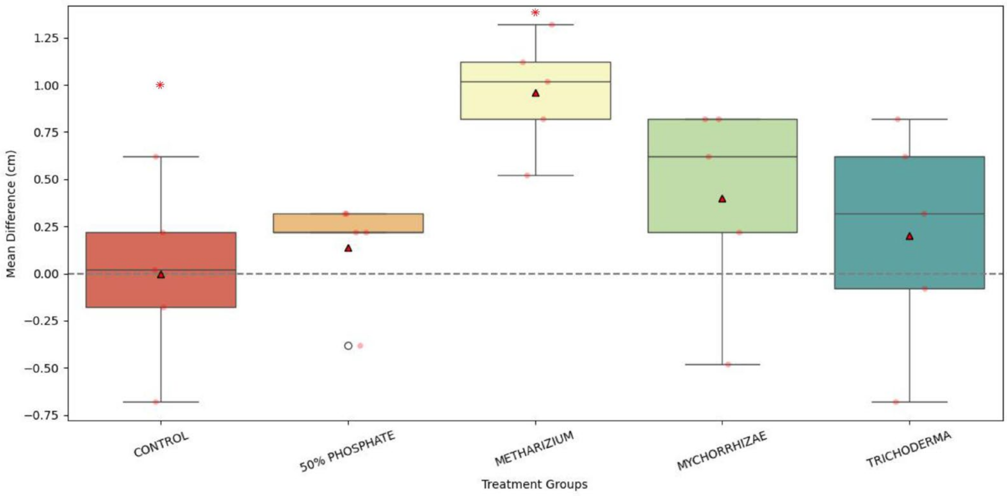


Figure 2. Effect of different treatments on leaf width: Mean difference across groups.

In the root volume parameter, the 50% phosphate treatment clearly showed a significant effect compared to the control and other treatments (Table 2). This reflects how phosphate availability can improve the plant root system, expanding the capacity for nutrient and water absorption (Zhang et al., 2016). A well-developed root system is crucial for maize, especially when it is cultivated in areas with low rainfall, to maintain stable yields (Wu et al., 2022). This finding underscores the importance of phosphorus nutrient management in optimizing root growth.

Seed dimension provides insights into the quality of the harvest, where the 50% phosphate treatment showed a significant difference compared to the control (Table 2). Meanwhile, the other treatments did not have a substantial impact on seed uniformity. In maize production, physically uniform seeds have higher market value, especially for hybrid varieties (Paulsen et al., 2019). Therefore, the use of moderate phosphate application becomes a strategic choice to improve the competitiveness of maize products (Cheptoek et al., 2021; Kassie et al., 2018).

The boxplot visualization for the root volume parameter highlights how treatments affect the development of the root system (Figure 3). The 50% phosphate treatment shows a significant impact compared to the control group and other treatments, including *Metarhizium* and *Mycorrhizae*, as indicated by the circle symbol (o). This suggests that moderate phosphate availability can significantly stimulate root growth. In contrast, the other treatment groups, such as the control, *Metarhizium*, *Mycorrhizae*, and *Trichoderma*, show relatively uniform results with no significant differences.

In the context of maize cultivation, these findings suggest that phosphate supplementation at the correct dose can enhance root development, which is crucial for more efficient water and nutrient absorption (Zhang et al., 2016). A well-developed root system is an essential factor for plant stability, especially in challenging environmental conditions such as drought or soils with low nutrient content (Koevoets et al., 2016; Wu et al., 2022). Therefore, the application of 50% phosphate can be an effective agronomic strategy to support maize production in various soil conditions.

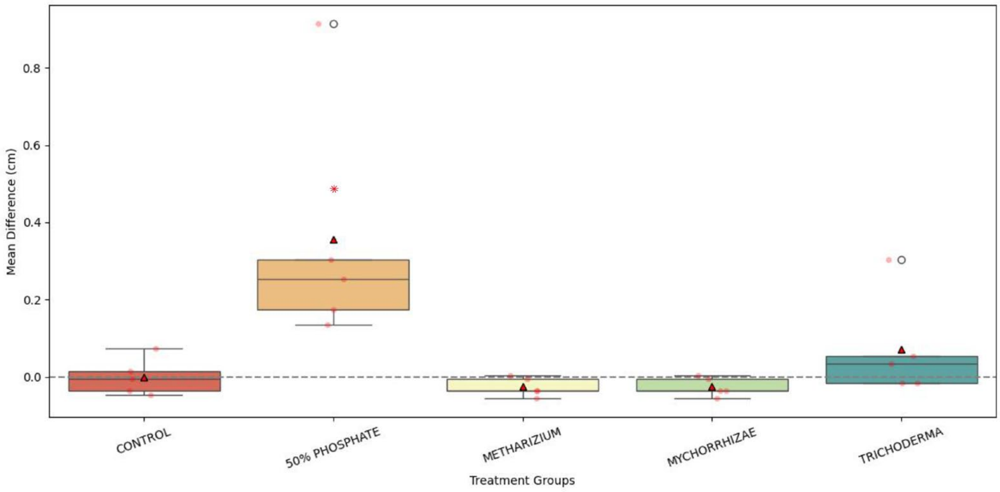


Figure 3. Effect of different treatments on root-shoot ratio: Mean difference across groups.

Figure 4 visualizes the seed uniformity parameter, showing that the 50% phosphate treatment has a significant effect compared to the control group, as indicated by the red asterisk symbol (*). This finding suggests that moderate phosphate dosing can substantially affect seed uniformity, improving the physical quality of the seeds compared to the control condition. In contrast, other treatments, such as *Metarhizium*, *Mycorrhizae*, and *Trichoderma*, showed no significant differences compared to the control, with the mean difference values tending to overlap within the confidence interval.

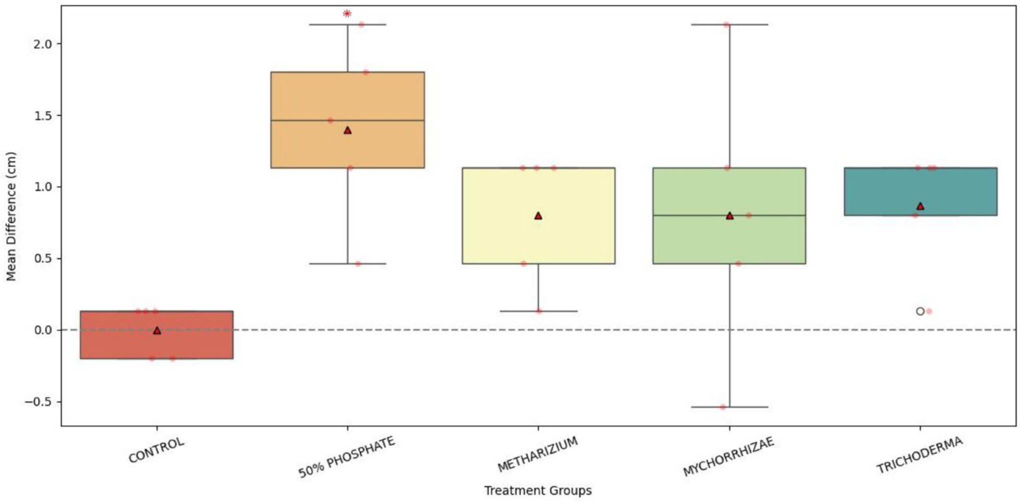


Figure 4. Effect of different treatments on seed sphericity: Mean difference across groups.

In the context of maize cultivation, seed uniformity has significant implications for market competitiveness, particularly for hybrid varieties that require high physical quality (Paulsen et al., 2019). Uniform maize seeds not only facilitate mechanical planting processes but also enhance economic value (Kandasamy et al., 2020; Paulsen et al., 2019). These data suggest that moderate phosphate supplementation can be a strategic approach to significantly improve maize seed quality, while other treatments are less effective in producing similar results.

The 50% phosphate treatment has a significant impact on the root-to-shoot ratio, as evidenced by a statistically meaningful difference compared to the control, *Metarhizium*, and *Mycorrhizae* groups, marked by the red asterisk symbol (*) (Figure 5). This effect suggests that moderate phosphate supplementation plays a key role in improving the balance of biomass allocation between the roots and shoots. In contrast, other treatment groups, such as the control, *Metarhizium*, *Mycorrhizae*, and *Trichoderma*, did not show significant differences from each other, with overlapping confidence intervals, indicating relatively similar effects.

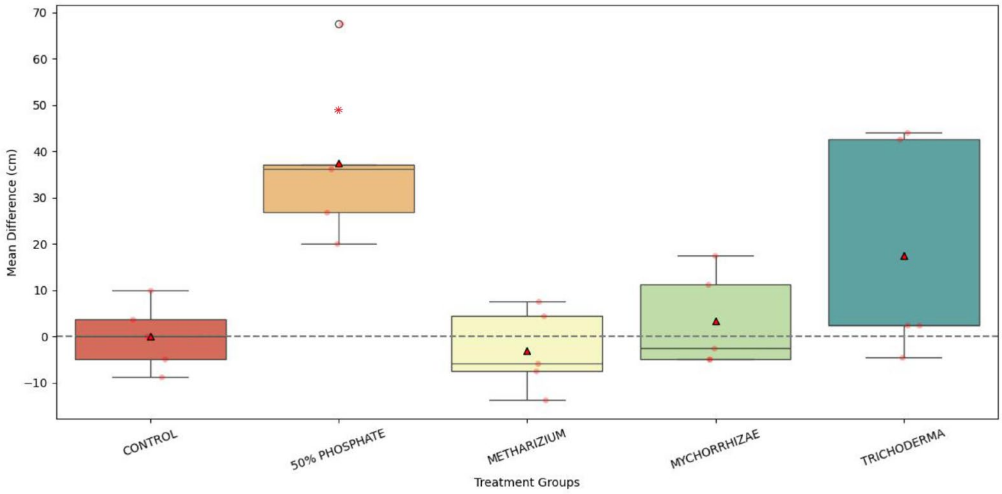


Figure 5. Effect of different treatments on root volume: Mean difference across groups.

In maize cultivation, an optimal root-to-shoot ratio is crucial for growth stability, particularly on lands with limited water availability. A better ratio enables plants to efficiently support water and nutrient uptake without compromising shoot development, which is essential for photosynthesis (Yousuf et al., 2022). These findings suggest that moderate phosphate can be an effective agronomic intervention to enhance maize plant adaptation to challenging environments, while also supporting higher productivity.

This bubble chart provides a detailed depiction of how various treatments affect four key parameters: leaf width, root volume, seed sphericity, and root-shoot ratio (Figure 6). The root volume parameter clearly shows that the 50% Phosphate treatment has a significant impact compared to other groups, with a noticeable average difference and larger bubble sizes. A similar trend is observed in the root-shoot ratio, where 50% Phosphate shows a marked effect compared to the Control, *Metarhizium*, and *Mycorrhizae* groups, indicating the treatment's ability to optimize biomass distribution between the roots and shoots.

Significant differences in the seed sphericity and leaf width parameters are particularly evident between the 50% phosphate and control groups (Figure 6). The larger bubble sizes for these parameters suggest that 50% Phosphate positively contributes to seed homogeneity and leaf growth (Emara & Abdelaal, 2017; Rashmi & Prakash, 2023). Some treatments did not lead to significant changes, as indicated by smaller bubbles near the zero line. This visualization offers a strong quantitative and visual understanding of how treatments impact various agronomic aspects. In the context of maize, these data provide valuable insights for selecting treatment strategies that can enhance crop yields and plant adaptation under diverse environmental conditions.

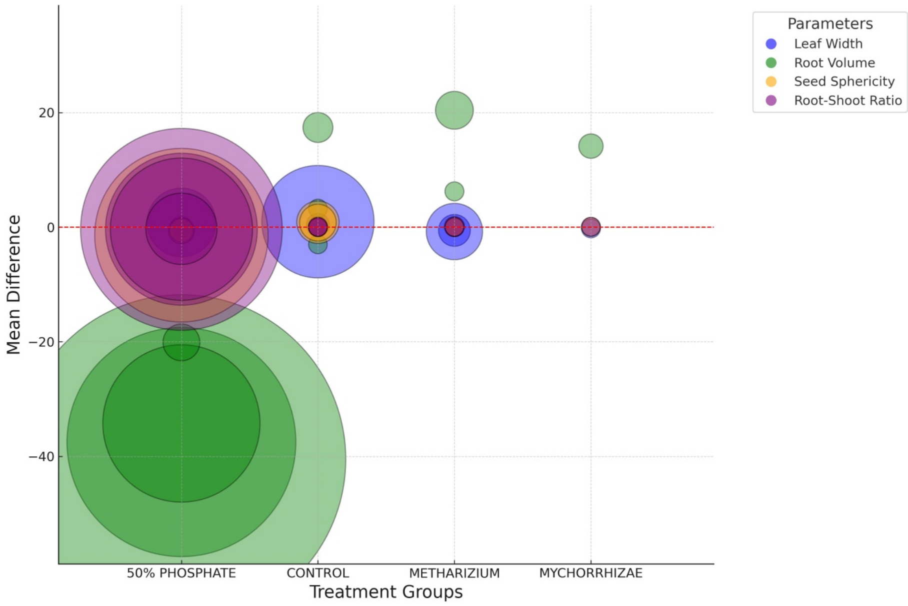


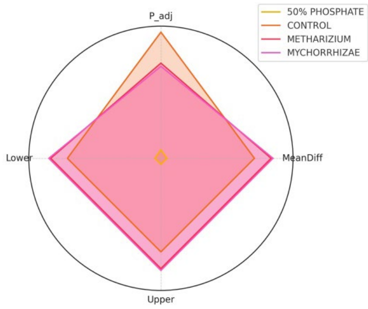
Figure 6. Comparative analysis of treatment effects on multiple parameters: Mean difference visualized via bubble chart.

Radar chart results show that Trichoderma and Metarhizium treatments had higher values in leaf width and root-shoot ratio (Figure 7). In the control group, leaf growth appears more limited, reflecting a lack of nutritional support or beneficial microorganisms. In contrast, treatments such as Metarhizium and Trichoderma demonstrate their ability to expand leaf width, significantly contributing to photosynthetic efficiency (Batista et al., 2022; Cano et al., 2019). The application of these biotic agents shows great potential in enhancing the plant's capacity to capture and utilize sunlight more efficiently (Cano et al., 2019; Liu et al., 2021). This is particularly crucial for maize plants to ensure that productivity remains optimal, especially in areas with limited light intensity.

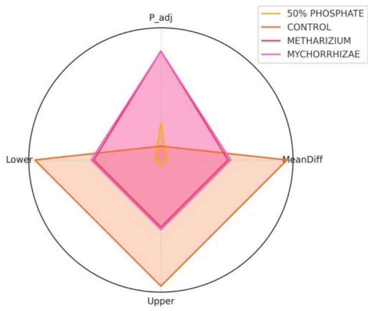
Phosphates in moderate doses, like those in the 50% phosphate treatment, significantly boost root development compared to the control group. Larger root volumes significantly enhance the plant's capacity to absorb water and nutrients (Li et al., 2016). This finding is particularly relevant for maize, especially in areas with low rainfall, where efficient water uptake is key to successful harvests. This treatment highlights that small changes in nutrient management can have a significant impact on plant adaptation to challenging environmental conditions.

Seed quality also stands out, as reflected in the seed sphericity parameter. The Metarhizium treatment results in more uniform seeds, indicating improved harvest quality. This is a major advantage for hybrid maize, which requires high seed uniformity for both market value and planting efficiency. Additionally, the root-shoot ratio provides insight into biomass balance in the plant. Treatments like 50% Phosphate and Metarhizium help maintain this balance, strengthening the root system while supporting shoot growth stability. This balance is crucial for the plant's adaptation to drought conditions and erosion-prone soils (Koevoets et al., 2016; Yousuf et al., 2022).

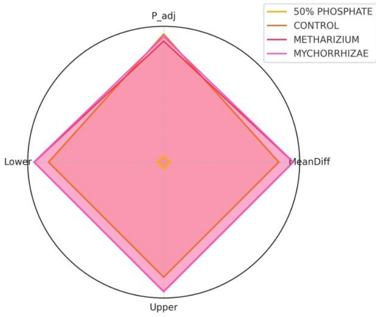
These findings suggest that the use of moderate phosphate and biotic agents not only enhances growth but also provides adaptive solutions to modern agronomic challenges. This approach could be a powerful strategy for maize cultivation, enhancing productivity on suboptimal land while promoting the sustainability of agricultural systems. By leveraging these technologies, farmers can achieve better harvests and a more resilient farming system.



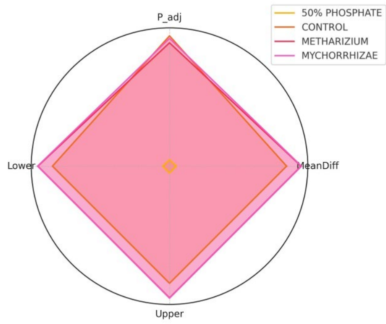
Root volume



Seed sphericity



Root-shoot ratio



Leaf width

Figure 7. Comparative radar analysis of agronomic parameters under different treatments: Root volume, seed sphericity, root-shoot ratio, and leaf width.

Figure 8 illustrates the effects of different treatments on corn ear quality. Trichoderma and 50% phosphate treatments produced the most optimal ears, large, uniform, and undamaged, reflecting the effectiveness of moderate phosphate application in supporting root systems and nutrient availability (Zhang et al., 2016). Metarhizium also resulted in more intact ears than the control, demonstrating its potential in enhancing resistance to biotic stress. In contrast, mycorrhizal and control treatments yielded smaller, less uniform ears, emphasizing the need for balanced phosphate and biotic inputs to improve yield quality.

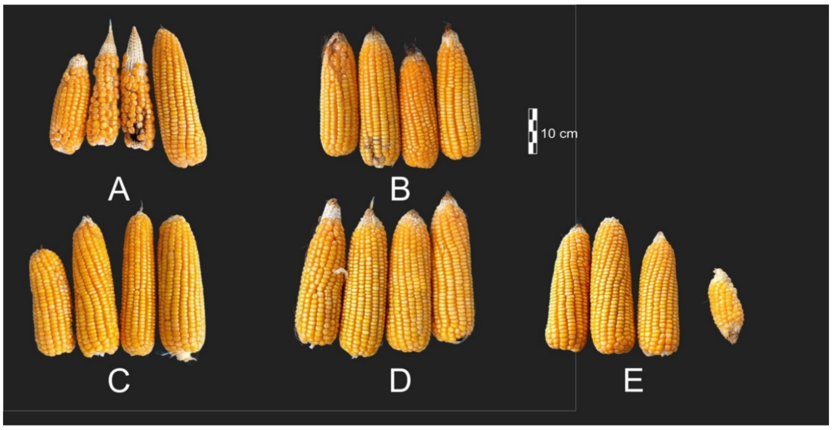


Figure 8. Visual comparison of corn ear quality under different treatments: Control (E), 50% phosphate (D), and fungi applications (A = Mychorizhae, B = Metharizium, C = Trichoderma).

CONCLUSION

This study demonstrates that 50% phosphate supplementation significantly improves key agronomic traits in maize, particularly root volume, root-shoot ratio, and seed sphericity, indicating enhanced nutrient uptake and biomass allocation. Fungi of *Metarhizium anisopliae* and *Trichoderma harzianum* contributed to improved leaf width and seed uniformity, supporting photosynthetic performance and grain quality. The integration of moderate phosphate with biological treatments offers a sustainable strategy for increasing productivity in phosphate-dense and marginal soils. Further multi-location and seasonal studies are recommended to validate these findings and support broader agricultural applications.

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