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Harmonized tripartite Approach: Enhancing nutrient Accessibility, Uptake, and wheat productivity through *Trichoderma harzianum*, Compost, and phosphorus synergy

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ABSTRACT

Objectives: Microbes inoculated with organic and inorganic amendments influence the nutrient pool in soil. Herein, this study aimed to investigate the potential of a harmonized tripartite approach to improve nutrient accessibility, uptake, and wheat productivity in nutrient-deficient soil.

Methods: The tripartite components consisted of *Trichoderma harzianum* (TRI), compost (Comp), and inorganic phosphorus (P) sources, including rock phosphate (RP) and single super phosphate (SSP). Under field conditions, the experiment was conducted in a randomized complete block design with three replications. The main plot treatments consist of two compost application rates: 0 and 10 tons ha^{-1}. Subplot treatments included the application of TRI and inorganic phosphorus sources at the rates of 5 and 90 kg ha^{-1} for RP and SSP, respectively.

Results: The findings demonstrated that the harmonized tripartite treatments significantly regulated nutrient accessibility, uptake, and wheat productivity, with promising effects observed in combinations such as TRI + SSP + Comp and TRI + RP + Comp. TRI + RP + Comp positively influenced plant height, spike length, and biomass, while TRI + SSP + Comp led to increased grain yield (4325 ± 54 kg ha^{-1}) compared to control (2765 ± 33 kg ha^{-1}). Moreover, TRI + SSP + Comp significantly improved soil organic matter from 1.20 ± 0.03 % (control) to 2.28 ± 0.11 % and P concentration from 3.95 mg kg^{-1} to 13.60 ± 0.11 mg kg^{-1}. Notably, TRI + Comp treatment maximized the accessibility of micronutrients, including copper (Cu), zinc (Zn), and manganese (Mn), and showed the higher availability of iron (Fe) with a sole TRI application. Furthermore, TRI + RP + Comp significantly increased the uptake of P, Cu, Fe, Zn, and Mn by 510 %, 106 %, 111 %, 63 %, and 137 %, respectively. Multivariate and cluster analyses further confirmed the strong positive relationship among most variables, highlighting the efficacy of the harmonized treatments without any negative associations.

Conclusion: These findings accentuated the potential of a harmonized tripartite approach to significantly improve soil fertility, nutrient uptake, and productivity in wheat crops under nutrient-deficient soil.

Abbreviations: Cu, copper; Comp, compost; Fe, iron; GB, green biofertilizer; Mn, manganese; P, phosphorus; (PVT) LTD, Private Limited company; PCA, principal components analysis; RP, rock phosphate; SSP, single super phosphate; SOM, soil organic matter; TRI, Trichoderma harzianum; Zn, zinc.

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1. Introduction

Crop production is often limited due to the unavailability of essential macro and micronutrients in the soil (White and Brown, 2010). One essential macronutrient for plant growth and production is phosphorous (Taj et al., 2022). Nevertheless, despite the widespread use of P-based mineral fertilizers in contemporary agriculture, soil P deficiencies lead to significant agronomic issues (Qaswar et al., 2022). For instance, despite a large amount of P in soils, this nutrient significantly restricts plant growth because it is fixed as insoluble phosphates of iron, aluminum, or calcium, all of which are unavailable to plants (Mat Hassan et al., 2013). In soil, P fixation depends on soil pH and existing minerals (Mat Hassan et al., 2012). The availability of P is low in 43 % of worldwide soils. Consequently, a shortage of it can restrict growth parameters by impairing physiological processes like cell division, photosynthesis, and metabolism. P shortage in cereal crops results in stunted development and purplish leaves (Sanjotha et al., 2011). Soils are deficient in micronutrients like Fe, Mn, Cu, and Zn, which are crucial for plant physiological and metabolic processes. Numerous intensively used farm soils have micronutrient deficiencies, the depletion of these nutrients brought on by increased population growth and the demand for greater yields (Altomare and Tringovska, 2011). Micronutrients are vital for balanced plant nutrition, and their scarcities lead to severe reduction in production and the quality of agriculture products. Therefore, strategies are required to improve the bioavailability and uptake of these essential plant nutrients. As an alternative, a source of bio-fertilizer that contains a variety of microorganism species such as phosphate solubilizing bacteria, arbuscular mycorrhizal fungi, etc., can be utilized to solubilize macro and micronutrients and make them available to plants (Khan et al., 2022; Ul Haq et al., 2022).

In this regard, a saprophytic fungus called *T. harzianum* is frequently utilized as a biocontrol agent because of its effectiveness against a variety of economically significant soil-borne plant pathogens. Similarly, *T. harzianum* are a promising biofertilizer and a supplement to minimize the use of mineral fertilizers in crop production. Strains of *T. harzianum* are mostly applied as a seed-inoculation, soil application and foliar treatments as bio-fertilizer and bio-fungicide (Şesan et al., 2020). The positive effect of *T. harzianum* on the growth of numerous crop species has been found (Bononi et al., 2020), increased plant biomass and soil total P influenced plant developments by solubilization of insoluble micronutrients in soil (Jain et al., 2012) and is an effective biocontrol agent (Asghar and Kataoka, 2021). It has also been reported for the mitigation of salinity stress by enhancing the antioxidative defense system in *Brassica Juncea L* (Ahmad et al., 2015). The biological mechanisms of *T. harzianum* are essential for supplying plant nutrients through the mineralization and solubilization processes (Colla et al., 2015). A study conducted by Sharma and colleagues showed that fungi occupy bigger areas in soil than bacteria and they also produce a variety of organic acids that are essential for the solubilization of inorganic P (Sharma et al., 2011). Similarly, Yedidia et al. (2001) showed that Trichoderma-inoculated cucumber roots significantly increased the concentration of P, Fe, Mn, Cu, and Zn. Trichoderma. harzianum has been investigated as a biocontrol agent for vegetable crops, however, limited focus is being placed on its potential role as a biofertilizer to improve plant nutrition under cereal crops, particularly P and micronutrients (Cu, Fe, Zn, and Mn) in wheat under natural field conditions. Consequently, the following research objectives were developed after taking into account the significance of T. harzianum on the solubility of P and micronutrients: to explore the influence of the harmonized effect of T. harzianum, Comp, and inorganic sources of P on, i) morphological and yield-related traits of wheat, ii) the solubilization of soil P and micronutrient, and their accessibility in soil and uptake by the wheat plants under natural field conditions.

2. Materials and methods

2.1. Experimental setup

A field trial was carried out in the winter of 2016–2017 at the Agricultural Research Institute Swat in Khyber Pakhtunkhwa, Pakistan, located at an Altitude of 984 m, Latitude of 34.14 ^{o}N, and Longitude of 71.6 ^{o}E (Fig. S1). The trial was conducted using RCBD with split plot arrangement, and three replications. The Pirsabaq-2005 wheat variety was sown in late November 2016 on a 3 m x 4 m subplot with a seed rate of 120 kg ha^{-1}. The row-to-row distance was kept at 25 cm; while plot to plot distance was kept at 0.5 m. The experimental site had a wheat-maize and maize-alfalfa cropping history.

Compost (Comp) produced from poultry litter was distributed manually among the main plots, which had two levels of 0 and 10 tons ha^{-1}. *Trichoderma. harzianum Strain (GB)* was provided by Agro Services (PVT) LTD Swat and contains at least 1.0 x 10^{7} colony forming units per gram dry weight. According to the treatment plan, 5 kg ha^{-1} *T. harzianum* was first mixed with soil and then manually broadcasted among the subplots. Similarly, P sources, including SSP and RP, were manually broadcasted @ 90 kg ha^{-1} among the subplots. Urea was applied in a base dose, half at sowing and half at the tillering stage. Moreover, Swat city recorded temperatures between 18.57 and 38.96 °C, with an average temperature of 31.5 °C. Average rainfall and relative humidity were 910 mm and 95.87 %, respectively (Fig. S2).

2.2. Soil and plant analysis

One composite pre-sowing soil sample from the experimental site was collected using a zigzag manner and another after harvest the crop. Pre-sowing soil samples were representative of the soil at the experimental site, whereas post-harvest soil samples were representative of each experimental unit that received various treatments. After being air dried and grounded and passed through a 2-mm sieve, the pre- and post-soil samples were analyzed for the different selected parameters. The soil texture, includes relative proportion of silt, sand, and clay, was determined by Gee's Method (2002). Nelson and Sommers (1996) method was used to determine soil organic matter content. Soil pH and EC were determined by the methods of McLean (1983) and Rhoades and Corwin (1981) respectively. Soil total nitrogen was determined by the method of Bremner (1996). The concentration of P and micronutrients in soil was determined by following the procedure developed by Soltanpour and Schwab (1977). The P content was then determined by spectrophotometer after standardization while the micronutrients (Cu, Fe, Mn, and Zn) were determined by atomic absorption spectrophotometer (Optima 3000 +). After harvesting, the sample of plant parts were washed, dried, grounded, sieved, and stored in paper bags for future analysis. Plant parts were analyzed for P and micronutrient uptake by following the procedure of wet digestion as explained by Rashid and Ryan. (2004). The following formula was used to calculate the total uptake of P and micronutrients.

$$\text{Total Nutrient Uptake} = \text{concentration of Nutrtient in Plant} \times \text{biomass}$$

The pre-harvest soil was a silt loam composed of 16.6 % clay, 61.1 % silt, and 22.3 % sand. Prior to the experiment, topsoil (0–20 cm) had the chemical and nutrient composition as: total nitrogen 0.06 g kg^{-1}, organic matter content 1.21 g kg^{-1}, nitrate nitrogen 22.40 mg kg^{-1}, ammonium nitrogen 2.5 mg kg^{-1}, available P 3.92 mg kg^{-1}, K 149 mg kg^{-1}, pH 6.9. Micronutrient concentrations, Cu, Fe, Zn, and Mn were 0.39 mg kg^{-1}, 4.81 mg kg^{-1}, 1.79 mg kg^{-1}, and 3.02 mg kg^{-1}, respectively.

2.3. Morphological and yield-related traits

Ten plants were randomly selected from each subplot to estimate plant height. A tape measure was used to estimate the plant's height from the soil's surface to the tip of plant. The average was then calculated in centimeters. Similarly, with the help of a measuring ruler, the spikes of five randomly selected plants in each sub-plot were measured, and the average was computed. For biological yield (total dry matter accumulation of wheat), the middle two rows of each subplot were harvested. The plant bundles were sun-dried after harvesting, and they were then weighed by using balance. The biological yield was calculated and converted to kg ha^{-1} by using the following formula.

$$\mathrm{Total\,Mass\,at\,Maturity} = \left(\frac{\mathrm{Mass\,in\,Kg}}{\mathrm{row\,to\,row\,distance} \times \mathrm{row\,length} \times \mathrm{no\,of\,rows\,selected}}\right) \times 1000$$

The center two rows for the grain yield (kg ha^{-1}) were threshed, cleaned, and weighed. The following formula was used for the calculation of grain yield in kg ha^{-1}.

$$\mathrm{Grain\,Yield}\left(\mathrm{Kgha}^{-1}\right) = \left(\frac{\mathrm{Grain\,Yield\,in\,Kg}}{\mathrm{row\,to\,row\,distance} \times \mathrm{row\,lenght} \times \mathrm{No\,of\,rows\,selected}}\right) \times 1000$$

2.4. *Data analysis*

The data obtained on various soils and crop parameters were statistically analyzed using the two-factor analysis of variance (ANOVA) technique using Statistix 8.1 software and MS Excel. Tukey's HSD test was applied to estimate the differences among the treatments at a 5 % significance level. The figures were made by OriginPro 9.0. To identify the principal components that underlie changes in various treatments in this experiment, the principal component analysis (PCA) and Heatmap with Dendogram were conducted using the statistical package XLSTAT.

3. Results

3.1. *Effect on morphological and yield-related traits of wheat*

The statistical analysis of the data revealed that the harmonized TRI, Comp, and P sources predominantly improved wheat morphology and yield compared to single treatment application and control (Table 1). The harmonized TRI + RP + Comp predominantly improved plant height by 108.0 ± 0.61, followed by TRI + SSP + Comp (107.1 ± 0.83), compared to the control (99.8 ± 1.37). The same trend was also recorded for the spike length, as the harmonized TRI + RP + Comp predominantly improved spike length by 9.9 ± 01.5 followed by TRI + SSP + Comp (9.7 ± 0.10), compared to control (7.8 ± 0.15). In the case of grain yield, TRI + SSP + Comp significantly increased grain yield by 4325 ± 54, followed by TRI + RP + Comp (4296 ± 11), compared to control (2765 ± 33). TRI + RP + Comp significantly increased biomass by 9356 ± 222, followed by TRI + SSP + Comp (9092 ± 157), compared to control (7494 ± 141). TRI + RP + Comp performed better than TRI + SSP + Comp and other harmonized and single treatments.

3.2. *Effect on post-harvest SOM conent (%) and soil P concnetration (mg kg^{-1})*

The statistical analysis of the data revealed that the harmonized TRI, Comp, and P sources predominantly improved SOM and soil P concentration compared to single treatment application and control (Fig. 1). Soil organic matter content was significantly higher in the soil collected from TRI + SSP + Comp (2.28 ± 0.11 %), followed by TRI + Comp (2.16 ± 0.05 %), TRI + RP + Comp (2.12 ± 0.10 %) whereas less SOM content was found in the SSP (1.46 ± 0.05 %) and TRI (1.52 ± 0.06 %), compared to the control treatment (1.20 ± 0.03 %) (Fig. 1a). Tukey's HSD test revealed that there are significant differences among the treatments for the 9 groups, which can be observed in the figure, even though the treatments' effects on SOM are significant at $p < 0.05$.

The highest P concentration was found at TRI + SSP + Comp (13.60 ± 0.11 mg kg^{-1}), followed by SSP + Comp (12.43 ± 0.12 mg kg^{-1}), TRI + SSP (11.25 ± 0.12 mg kg^{-1}), TRI + RP + Comp (9.47 ± 0.26 mg kg^{-1}), while the lowest concentration was found at the TRI (6.15 mg kg^{-1}) and control (Fig. 1b). Tukey's HSD test showed that there are significant differences between the treatments for all 11 groups except TRI + SSP + Comp, even though the treatments' effects on soil P are significant at $p < 0.05$.

3.3. *Effect on post-harvest soil micronutrient concentration (mg kg^{-1})*

The data analysis showed that the harmonized treatments of TRI, Comp, and P sources significantly improved micronutrient concentration in soil for wheat crop growth compared to single treatment application and control (Fig. 2). It can be seen in Fig. 2a, that the highest Cu concentration was recorded at the treatment combination of TRI + Comp (0.720 ± 01 mg kg^{-1}), followed by TRI + SSP + Comp (0.660 ± 02 mg kg^{-1}), TRI + RP + Comp (0.630 ± 02 mg kg^{-1}), TRI + RP (0.590 ± 02 mg kg^{-1}) and TRI + SSP (0.580 ± 08 mg kg^{-1}), compared to the control (0.350 ± 01 mg kg^{-1}). The concentration of Fe was observed differently with the treatments compared to other micronutrients. The highest Fe concentration was found at sole TRI (7.690 ± 08 mg kg^{-1}) followed by TRI + Comp (6.610 ± 03 mg kg^{-1}), TRI + RP + Comp (7.360 ± 13 mg kg^{-1}), TRI + SSP + Comp (7.150 ± 06 mg kg^{-1}), TRI + RP (6.760 ± 05 mg kg^{-1}), and SSP + Comp (6.620 ± 35 mg kg^{-1}), respectively. Meanwhile, the lowest Fe concentration was found at RP (5.92 ± 0.24 mg kg^{-1}), compared to control (4.64 ± 0.06 mg kg^{-1}) (Fig. 2b). The maximum concentration of Zn was recorded at TRI + Comp (4.07 ± 0.16 mg kg^{-1}), followed by TRI + RP + Comp (3.61 ± 0.08 mg kg^{-1}), TRI (3.52 ± 0.05 mg kg^{-1}), TRI + RP (3.48 ± 0.06 mg

Table 1

Morphological and yield traits of wheat as influenced by single and combined application of treatments.

Treatments	Plant height (cm)	Spike length (cm)	Grain yield (kg ha^{-1})	Biological yield (kg ha^{-1})
Control	99.8 ± 1.37 fg	7.8 ± 0.15 h	2765 ± 33f	7494 ± 141f
TRI	103.9 ± 0.71 cde	8.7 ± 0.15f	3765 ± 46 d	8422 ± 72 cd
RP	102.0 ± 0.45 ef	8.1 ± 0.15 g	3648 ± 35 de	7765 ± 102 ef
SSP	102.9 ± 0.38 de	8.8 ± 0.10 ef	3569 ± 23 e	7721 ± 188 ef
TRI + SSP	106.8 ± 0.45 abc	9.2 ± 0.06 cd	4254 ± 56 ab	8591 ± 155 bcd
TRI + RP	105.7 ± 0.80 abcd	9.4 ± 0.06 bc	4165 ± 130b	8887 ± 71 abc
Comp	98.6 ± 0.80 g	8.1 ± 0.06 gh	2834 ± 28f	7418 ± 132f
TRI + Comp	104.2 ± 0.49 bcde	9.1 ± 0.15 cde	3920 ± 8c	8499 ± 90 cd
RP + Comp	103.5 ± 2.63 de	8.7 ± 0.10f	3633 ± 38 de	8180 ± 465 de
SSP + Comp	105.3 ± 0.64 abcd	8.9 ± 0.10 def	3569 ± 23 e	8250 ± 46 de
TRI + SSP + Comp	108.0 ± 0.61 a	9.7 ± 0.10 ab	4325 ± 54 a	9092 ± 157 ab
TRI + RP + Comp	107.1 ± 0.83 ab	9.9 ± 01.5 a	4296 ± 11 ab	9356 ± 222 a

Values are the means of three replicates and contain standard deviation of means (n = 3). In each column, values with different letters differ significantly from each other at $P < 0.05$.

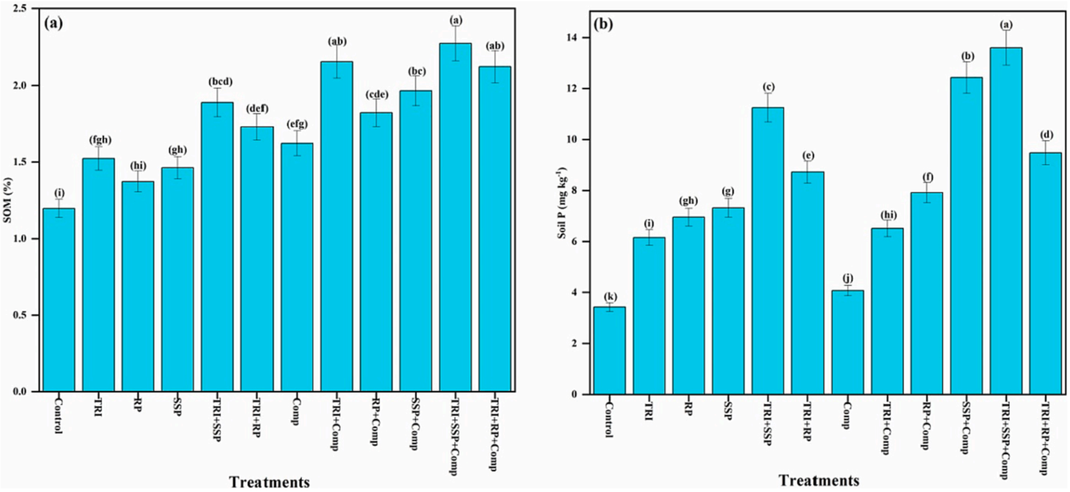

Fig. 1. The influence of treatments on soil a) organic matter (%), and b) phosphorus (mg kg^{-1}). Bars are the values of three replicates (means) and contain standard deviations of means ($n = 3$). In each panel, bars with different letters differ significantly from each other at 5 % significance level ($p < 0.05$).

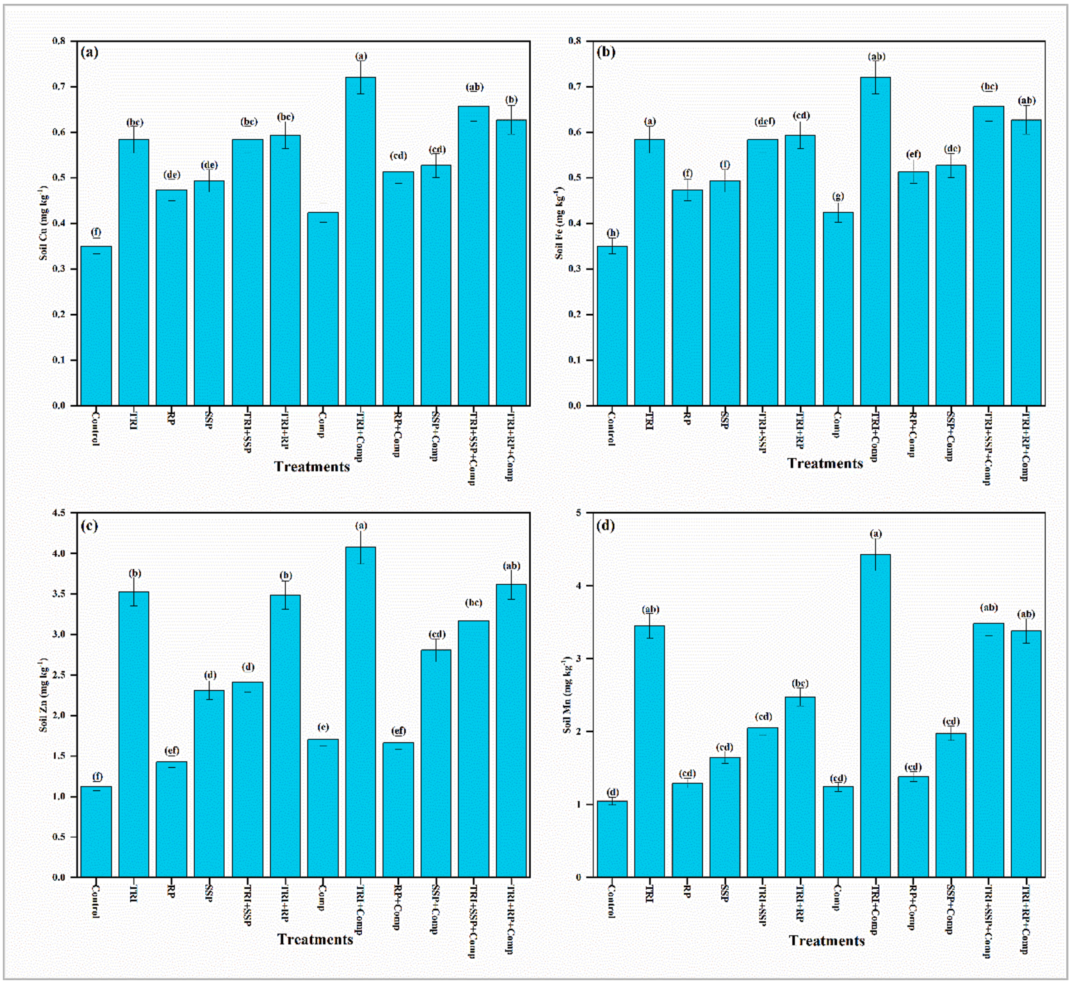

Fig. 2. The influence of treatments on soil a) Cu, b) Fe, c) Zn, and d) Mn in mg kg^{-1}. Bars are the values of three replicates (means) and contain standard deviations of means ($n = 3$). In each panel, bars with different letters differ significantly from each other at 5 % significance level ($p < 0.05$).

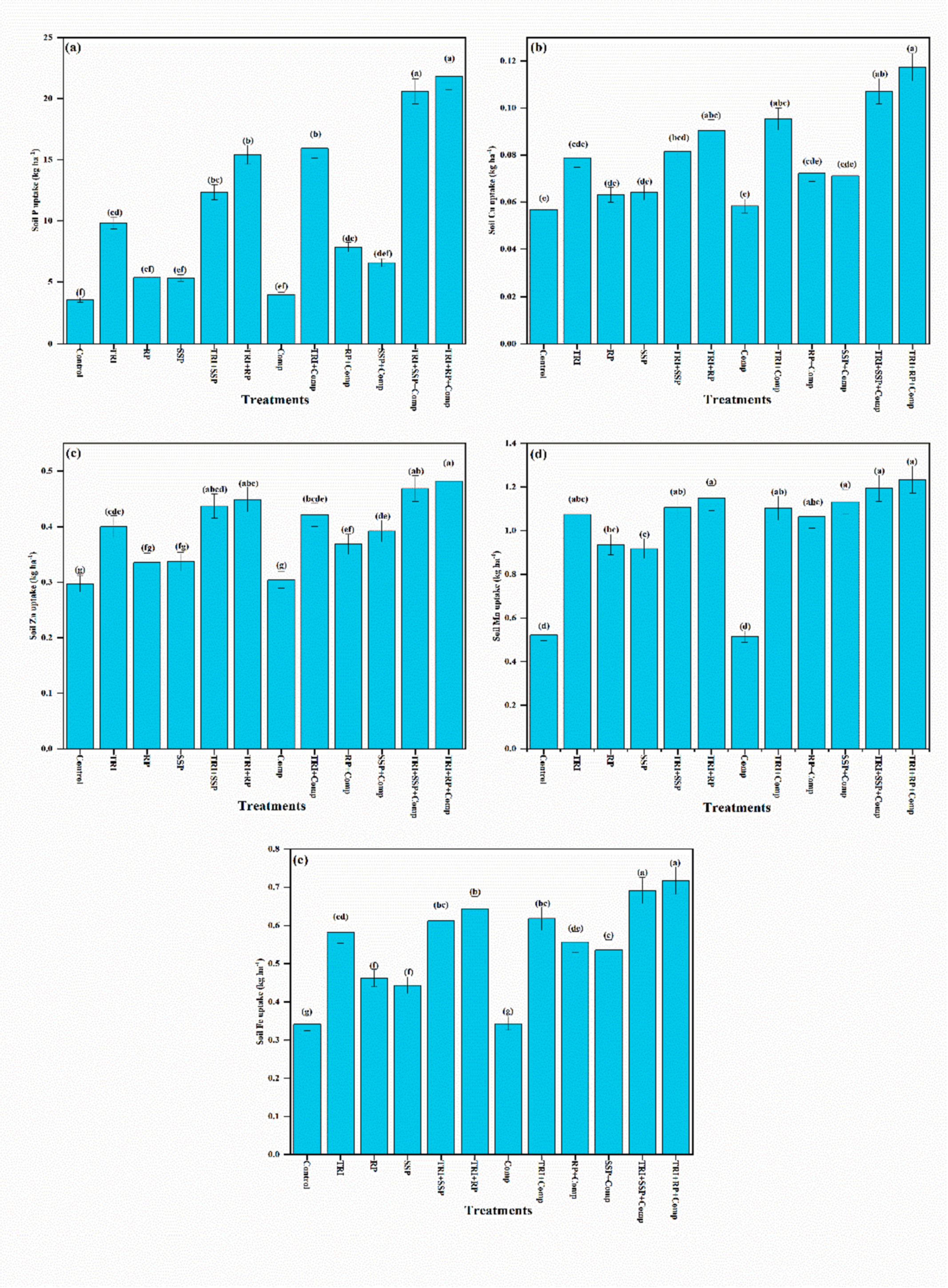

Fig. 3. The influence of treatments on the uptake of soil a) P, b) Cu, c) Zn, d) Mn, and e) Fe in kg ha^{-1}. Bars are the values of three replicates (means) and contain standard deviations of means (n = 3). In each panel, bars with different letters differ significantly from each other at 5 % significance level ($p < 0.05$).

kg^{-1}) and TRI + SSP + Comp (3.17 ± 0.05 mg kg^{-1}), whereas, minimum concentration was recorded at the plot with RP (1.42 ± 0.11 mg kg^{-1}), compared to control (1.12 ± 0.07) (Fig. 2c). TRI + Comp had the highest concentration of soil Mn (4.430 ± 08 mg kg^{-1}) compared to TRI + SSP + Comp (3.490 ± 25), TRI (3.450 ± 19), TRI + RP + Comp (3.380 ± 46), and TRI + RP (2.480 ± 04 mg kg^{-1}) (Fig. 2d).

3.4. Effect on soil P and micronutrients uptake by wheat plants

The harmonized treatments showed a significant ($P < 0.05$) effect on soil P and micronutrient uptake by wheat plants (Fig. 3). When compared to other doses and the control, the P uptake by wheat plants was significantly ($P < 0.05$) higher with the treatment combinations TRI + RP + Comp (510 %) and TRI + SSP + Comp (474 %). Other treatments, either alone or in combination, resulted in the following trends in P uptake by wheat plants: TRI + Comp (345 %), TRI + RP (330 %), TRI + SSP (244 %), RP (49 %), and SSP (48 %) (Fig. 3a). The TRI + RP + Comp treatment combination significantly increased Cu, Fe, Zn, and Mn uptake by 106 %, 111 %, 63 %, and 137 %, respectively. TRI + SSP + Comp increased Cu, Fe, Zn, and Mn uptake by 88 %, 104 %, 58 %, and

Table 2
Pearson's correlation among the studied variables/traits.

Variables	P uptake	Cu uptake	Zn uptake	Fe uptake	Mn uptake	Soil P	Soil Cu	Soil Zn	Soil Fe	Soil Mn	SOM	Plant height	Spike length	Grain yield	Biol. yield
P uptake	1														
Cu uptake	0.99*	1													
Zn uptake	0.94*	0.94*	1												
Fe uptake	0.92*	0.92*	0.98*	1											
Mn uptake	0.74*	0.77*	0.88*	0.93*	1										
Soil P	0.56*	0.57*	0.72*	0.70*	0.77*	1									
Soil Cu	0.85*	0.85*	0.88*	0.90*	0.84*	0.56*	1								
Soil Zn	0.78*	0.80*	0.81*	0.79*	0.73*	0.40*	0.90*	1							
Soil Fe	0.75*	0.78*	0.81*	0.86*	0.86*	0.49*	0.92*	0.92*	1						
Soil Mn	0.80*	0.82*	0.76*	0.77*	0.65*	0.32*	0.91*	0.93*	0.90*	1					
SOM	0.80*	0.81*	0.81*	0.79*	0.71*	0.72*	0.82*	0.67*	0.69*	0.69*	1				
Plant height	0.83*	0.83*	0.94*	0.94*	0.93*	0.87*	0.80*	0.68*	0.74*	0.62*	0.76*	1			
Spike length	0.83*	0.83*	0.94*	0.94*	0.93*	0.87*	0.80*	0.688*	0.74*	0.62*	0.76*	1	1		
Grain yield	0.85*	0.84*	0.93*	0.95*	0.93*	0.74*	0.86*	0.70*	0.78*	0.66*	0.70*	0.94*	0.94*	1	
Biol. yield	0.95*	0.96*	0.99*	0.98*	0.86*	0.69*	0.83*	0.78*	0.79*	0.74*	0.78*	0.92*	0.92*	0.91*	1

2-tailed of significance is used. *Correlation is significant at 0.05 level ($P < 0.05$).

128 %, respectively (Fig. 3b-e).

3.5. Multivaraite and cluster analysis for the studied varaibles

To investigate the association between the studied variables under the harmonized effect of TRI, Comp and inorganic sources of P a multivariate analysis such as Pearson's correlation, principal components analysis (PCA) and Heatmap with Dendogram was performed. The correlation between the studied variables as affected by the single or combined treatments is presented in Table 2. As can be seen, Pearson's correlation analysis indicated that all the investigated variables showed a strong positive association except for soil P and micronutrients, which exhibit weak but positive association. There was no evidence of a negative association, demonstrating the efficacy of the treatments on soil fertility and wheat productivity. Similarly, the results obtained from PCA revealed that soil P and micronutrient uptake, and wheat productivity attributes were more closely associated with TRI + RP + Comp and TRI + SSP + Comp. These results further proved that the uptake of P, and micronutrient by wheat plants was highly correlated with the availability of P and micronutrients in the soil, as well as the concentration of soil organic matter (SOM). The first principal component (PC1) and PC2 explained 82.7 % and 8.56 % of the total variation,

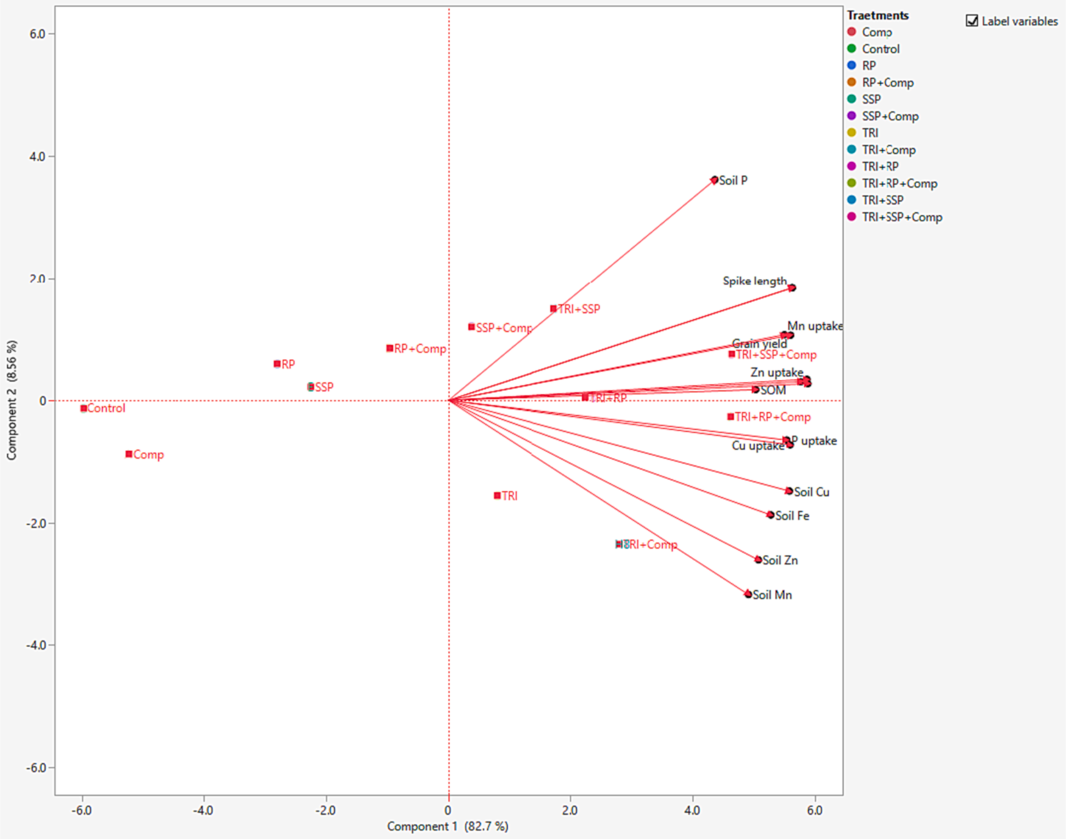

Fig. 4. Biplot with a 95% Confidence Ellipse for the principal component analysis of the variables under investigation.

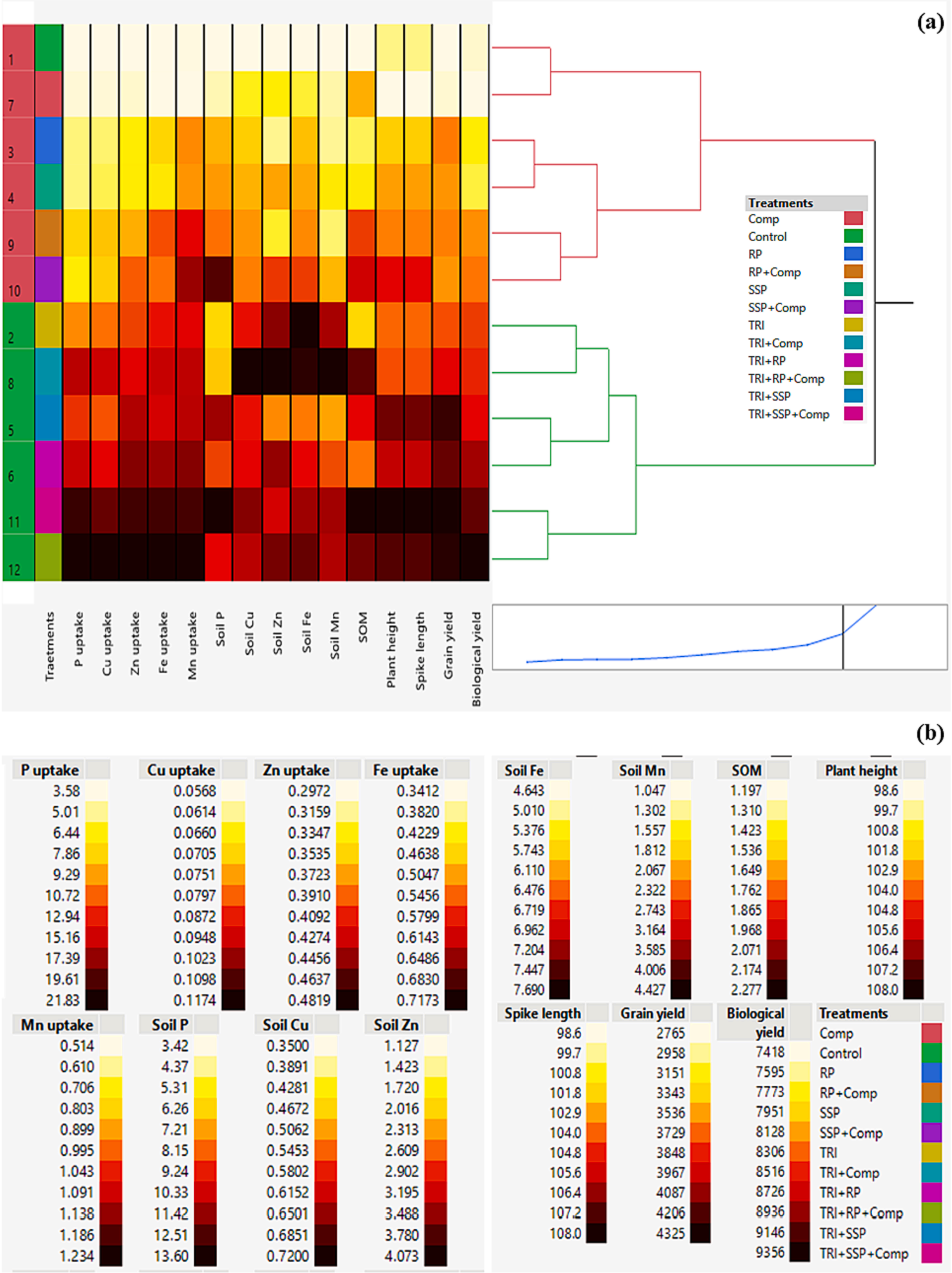

Fig. 5. Heatmap with Dendo-gram for the studied variables under single or combined TRI, Comp and inorganic P sources application.

respectively (Fig. 4). Additionally, a Heatmap coupled with Dendogram was analyzed, and the colors scale revealed that the effects of the harmonized treatments were more pronounced towards TRI + RP + Comp and TRI + SSP + Comp (darker to darker red). The Dendogram displayed two separate data clusters or groups. The course of treatment where the TRI, Comp, and inorganic sources of P fertilizers were harmonized or administered in combination, as illustrated in the green tree cluster, made the apparent differentiation. The single treatments were clustered or grouped separately in a red tree (Fig. 5). Overall, the multivariate and cluster analysis of the data showed that the harmonized treatments significantly increased SOM, soil P, and micronutrient concentration, which subsequently regulate P and micronutrient uptake, resulting in improved soil fertility, wheat growth, and production.

4. Discussion

The present study found a significant positive effect of *T. harzianum* co-application with mineral phosphate fertilizer and compost on soil P, micronutrient concentrations, availability, uptake by the wheat crop, yield, and growth parameters of the wheat crop over control through a variety of processes and mechanisms. Greater vegetative and reproductive growth responses of several crops, such as soybean (Arif et al., 2020), and wheat (Velmourougane et al., 2019), were also noticed by the application of *T. harzianum* and other bio-fertilizers. Previous studies have shown that *T. harzianum* improved plant growth development by root colonization and root system architecture (Chacón et al., 2007), recycling unavailable nutrients into available form (Colla et al., 2015), and releasing secondary metabolites in the rhizosphere (Mbarki et al., 2017). Mineral phosphate fertilizer and compost directly supplement nutrients in the soil as well as surges bioavailability, whereas *T. harzianum* has been reported to increase nutrient uptake and assimilation in plants (Asghar and Kataoka, 2021). Therefore, the co-application with *T. harzianum* might have synergistically facilitated improved wheat growth parameters i.e., biomass, plant height, and spike length, which might have been the reason for the higher grain yield under the current research. The positive effect of *T. harzianum* in the presence of phosphorus sources has also been reported (García López et al., 2015). The present findings are in agreement with findings Vinci et al. (2018), that the combined application of compost and *T. harzianum* was positive in terms of plant growth as compost act as a substrate for microorganisms, thus reducing the competition between plant and microorganisms for nutrients. Kaur and coworkers have reported improvement in wheat crop yield when RP was supplemented along with bio-fertilizer compared to the control (Kaur and Reddy, 2014).

The combined use of *T. harzianum* with phosphate fertilizer sources and compost enhanced nutrient uptake as compared to the sole application. Mostly soil nutrients are present in complex forms which are inaccessible to plant uptake. Microbes, including beneficial fungi and bacteria in the soil rhizosphere, have the ability to change soil pH (Asghar and Kataoka, 2021) as well as secrete various enzymes, which can help to solubilize the insoluble nutrients and lead to increased absorption by the plants (Halifu et al., 2019). Moreover, the enlargement in size by the intact of *T. harzianum* make the roots access to more soil-available P and other micronutrients, which have a positive impact during competition between plant and microorganisms, when nutrients are scarce (Yedidia et al., 2001). García-López and coworkers showed the positive contribution of *T. harzianum* to P uptake by plants due to the hydrolysis of non-readily available organic P forms (García-López et al., 2018).

The *T. harzianum* application alone or in combination with phosphorus sources increased the uptake of phosphorus as other experiments found higher availability at 69 % in moderately resistant and 96 % vulnerable varieties of sugarcane (Singh et al., 2010). Yedidia and workers reported 90 and 30 % P and Fe concentration increased in plant inoculated with *T. harzianum* (Yedidia et al., 2001). Colla and colleagues showed that *T. harzianum* can improve iron solubility and therefore, uptake and translocation by the plant (Colla et al., 2015). The results indicated that *T. harzianum* enhances Fe uptake due to the ability of *T. harzianum* that release siderophores (Segarra et al., 2010), which have been found to increase Fe supply to the plants (Dimkpa et al., 2009). The results are in contrast with the findings of De Santiago et al. (2009) who reported the adverse effect of *T. harzianum* on the Cu, Mn, and Zn nutrition of the wheat appeared to be related to restricted availability of these nutrients and thus the possible competition for nutrients between plants and microorganisms. But, consistent with previous studies, *T. harzianum* has the ability to increase Cu, Mn, and Zn concentration in the root and shoot of the plant (Yedidia et al., 2001).

It is evident from the results that various treatments had the inherent potential for improving soil properties especially related to SOM, available P, and micronutrients. Compost application enhanced SOM, which raised soil fertility in all treatments. Co-application of *T. harzianum* with SSP treatment recorded the highest SOM. In contrast, Kaur and colleagues found a high content of SOM when RP amended with *T. harzianum* (Kaur and Reddy, 2014). The changes in soil organic carbon contents are directly associated with the changes in microbial biomass and biological activity in soil (Nakhro and Dkhar, 2010). Maximum available P was observed in treatments supplemented with SSP alone or with *T. harzianum*. Our results showed that the combined application of organic and synthetic fertilizers improved phosphorus concentration in soil. Similar results were also reported by Poblete-Grant et al. (2019).

The findings confirmed that the application of *T. harzianum* with compost increased the micronutrient concentration as compared to the co-application of *T. harzianum* with mineral phosphate fertilizer. This might be due to the application of phosphatic fertilizers to the soil suppressing the micronutrients concentration in the soil. Other studies reported that applying different *T. harzianum* has a positive influence on the availability of micronutrients in soil to plants (de Santiago et al., 2013).

5. Conclusions

The study demonstrates the significant positive impact of the harmonized tripartite approach, involving *T. harzianum*, compost, and inorganic phosphorus sources, on regulating nutrient accessibility, uptake, and enhancing wheat productivity in nutrient-deficient soil. Notably, the combinations of TRI + SSP + Comp and TRI + RP + Comp exhibited the most pronounced effects, showcasing their potential as effective strategies for sustainable crop production. The findings also highlight the promising role of *T. harzianum* combined with compost as an alternative means to regulate nutrient availability to the plant demands, thereby reducing the excessive reliance on inorganic phosphorus fertilizers. This reduction in chemical fertilizer usage has significant implications for cost-effectiveness and environmental sustainability in agriculture systems. However, we acknowledge the need for long-term research under field conditions to validate and further assess the performance and stability of these harmonized treatments. This will help to provide more comprehensive insights into their efficacy, reliability, and adaptability in different agroecosystems.

Overall, our research contributes to the understanding of sustainable agricultural practices, emphasizing the potential of synergistic approaches that utilize beneficial microorganisms and organic amendments alongside inorganic nutrient sources. By promoting nutrient efficiency and reducing environmental impacts, the harmonized tripartite approach holds promise for fostering sustainable crop production, ultimately supporting food security and the well-being of farmers and consumers. Further studies and implementation of these findings on a larger scale will be essential to fully realize the benefits of this approach for the agriculture industry and the environment.

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CRediT authorship contribution statement

Hamida Bibi: Conceptualization, Methodology, Supervision. **Hafeez Ur Rahim:** Conceptualization, Supervision, Visualization, Writing – original draft. **Adnan Anwar Khan:** Visualization. **Muhammad Haris:** Data curation. **Mudassar Iqbal:** Writing – review & editing. **Roshan Ali:** Conceptualization, Methodology, Resources. **Mohamed A. El-Sheikh:** Funding acquisition. **Prashant Kaushik:** Funding acquisition, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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