

SHORT-TERM SOIL FERTILITY RESPONSES TO POULTRY MANURE, TRICHODERMA HARZIANUM AND MINERAL NPK UNDER WHEAT IN AN ALKALINE CALCAREOUS SOIL

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Abstract

Integrated nutrient management may improve crop production while rebuilding soil fertility in alkaline, low-organic-matter soils. A field experiment was conducted during winter 2022-2023 at Jamra Farm, Takht Bhai, District Mardan, Pakistan, to determine post-harvest soil responses to poultry manure (PM), Trichoderma harzianum and mineral NPK. Four amendment regimes (no amendment, PM at 10 t ha⁻¹, Trichoderma at 1.75 kg ha⁻¹, and PM + Trichoderma) were combined with 0, 50 and 100% of the recommended N-P₂O₅-K₂O dose (120-90-60 kg ha⁻¹) in a three-replicate split-plot arrangement. Post-harvest bulk density, pH, electrical conductivity (EC), soil organic matter (SOM), total soil N and AB-DTPA extractable P and K were analyzed. Split-plot ANOVA was performed in Python, and principal component analysis was used for descriptive multivariate interpretation. Amendment and NPK significantly influenced SOM, total N, available P and available K. PM + Trichoderma + 100% NPK produced 0.97% SOM, 1.09 g kg⁻¹ total N, 7.80 mg kg⁻¹ extractable P and 103.13 mg kg⁻¹ extractable K. Relative to the unamended zero-NPK control, these values were 68, 569, 159 and 68% higher, respectively. Soil pH remained statistically stable (7.71-7.79), while bulk density was lowest (1.20 g cm⁻³) in poultry-manure treatments receiving 50 or 100% NPK. Mean EC increased with integrated inputs but remained in a non-saline range; its variability warrants monitoring. The first two principal components explained 72.4% of total variation and separated nutrient-rich integrated treatments from unamended controls. The findings show that organic, microbial and mineral inputs can rapidly improve soil fertility, although multi-season monitoring is required to assess nutrient accumulation, salinity risk and persistence.

1. INTRODUCTION

Loss of soil organic matter and imbalance of nutrient is a major constraint on sustainable crop

production in intensive agriculture. Low organic carbon levels in alkaline and calcareous soils

hinder aggregate stability, water retention and biological activity, and also low phosphorus availability due to precipitation and adsorption reactions. Mineral fertilizers can address an immediate nutrient deficiency without directly replacing the carbon loss due to harvest and decay. It is necessary, then, to have a soil fertility strategy for this environment that will integrate easily accessible mineral nutrients, organic matter and beneficial biological inputs.

Poultry manure contains a good amount of N, P and K as well as organic carbon. It can reduce the bulk density, increase soil organic matter and enhance nutrient availability, although the effects have varied with soil type, application rate and mineral fertilizer application (Agbede et al., 2017; Adekiya et al., 2019, 2020). Long-term and meta-analysis studies reveal that, in general, manure application leads to an increase in soil organic carbon, available K, available P and total N, and that integrated organic-mineral manure application generally results in more balanced soil properties than either application alone (Bhatt et al., 2019; Zhao et al., 2024).

Trichoderma spp. can also enhance the soil and plant responses by colonizing the roots, decomposing the tissues, releasing nutrients, and altering the microbial activity. The field experiments have recently revealed that microbial fertilizers that include Trichoderma species can help improve soil quality and wheat production if they are used in a manner that involves adding carbon-rich amendments to the soil (Ma et al., 2025). The influence of Trichoderma on short-term post harvest fertility of alkaline calcareous soils is however not well documented.

The effect of poultry manure, Trichoderma harzianum and three levels of mineral NPK on bulk density, pH, electrical conductivity, soil organic matter, total N and AB-DTPA extractable P and K after wheat crop were investigated in the present study. We hypothesized that the effects of poultry manure and Trichoderma would be higher than soil organic matter and available nutrient levels; the effects of NPK would be greater, and due to the buffering capacity of the calcareous soil the soil pH would not change greatly.

2. Materials and methods

2.1 Site, soil and amendment characteristics

The experiment was carried out in Jamra Farm, Takht Bhai, District Mardan, Khyber Pakhtunkhwa, Pakistan during winter 2022-2023. Before sowing, the silty-loam soil had a bulk density of 1.31 g cm⁻³, porosity of 45.66%, lime content of 8.91%, pH 7.70, EC 0.86 dS m⁻¹ and soil organic matter of 0.61%. Poultry manure contained 21.07% organic carbon, 2.76% N, 0.92% P and 2.05% K, with a C:N ratio of 7.63.

2.2 Experimental design

The four amendment regimes were factored with three different mineral NPK levels under a three-replicate randomized complete-block/split-plot design. No amendment, poultry manure (10 t ha⁻¹) and Trichoderma harzianum (1.75 kg ha⁻¹) were used as amendments. Mineral fertilizer levels were 0, 50 and 100% of the recommended 120-90-60 kg N-P₂O₅-K₂O ha⁻¹ dose. Gulzar-2019 cultivar was cultivated from 15th November 2022 to 14th May 2023. The agronomic management was uniform for all plots except for the treatments to be applied.

Table 1 Experimental treatment combinations.

Thesis code	Paper code	Amendment	NPK level	Rate
T1	C-0	No amendment	0 NPK	0-0-0
T3	C-50	No amendment	50% NPK	60-45-30 kg N-P ₂ O ₅ -K ₂ O ha ⁻¹
T2	C-100	No amendment	100% NPK	120-90-60 kg N-P ₂ O ₅ -K ₂ O ha ⁻¹

T4	PM-0	Poultry manure	0 NPK	0-0-0
T6	PM-50	Poultry manure	50% NPK	60-45-30 kg N- P2O5-K2O ha-1
T5	PM-100	Poultry manure	100% NPK	120-90-60 kg N- P2O5-K2O ha-1
T7	T-0	Trichoderma	0 NPK	0-0-0
T9	T-50	Trichoderma	50% NPK	60-45-30 kg N- P2O5-K2O ha-1
T8	T-100	Trichoderma	100% NPK	120-90-60 kg N- P2O5-K2O ha-1
T10	PMT-0	Poultry manure + Trichoderma	0 NPK	0-0-0
T12	PMT-50	Poultry manure + Trichoderma	50% NPK	60-45-30 kg N- P2O5-K2O ha-1
T11	PMT-100	Poultry manure + Trichoderma	100% NPK	120-90-60 kg N- P2O5-K2O ha-1

Note: Poultry manure was applied at 10 t ha⁻¹ and Trichoderma harzianum at 1.75 kg ha⁻¹.

2.3 Post-harvest soil analyses

The core method (Blake and Hartge, 1986) was used to measure soil bulk density after wheat harvest. Soil pH and EC were measured in a 1:5 soil: water mixture. The soil organic matter was calculated from the soil organic carbon by dichromate oxidation according to Nelson and Sommers (1996). Total soil N was determined by digestion and distillation. Soltanpour (1985) extracted available P and K from soil using ammonium bicarbonate-DTPA and measured them by spectrophotometer and flame photometer, respectively.

2.4 Statistical and multivariate analysis

The values were examined at the replicate level in python. Split plot analysis involved replications, amendment, replication x amendment, NPK, amendment x NPK. The residual was used for testing the interaction between NPK and amendment, while the subplot residual was used for testing NPK and amendment. Standard errors for means are reported and $p < 0.05$ was deemed to be significant. The multiple data for each plot (bulk density, pH, EC, SOM, total N, available P and available K) were individually standardized and then subjected to PCA for descriptive purposes to summarize the multivariate soil-fertility gradient.

3. Results

Table 2 Split-plot ANOVA results for the principal response variables.

Response	Amendment p	NPK p	Amendment x NPK p
Bulk density	0.008	0.008	0.017
Soil pH	0.509	0.077	0.629
Electrical conductivity	0.017	0.266	1.000

Soil organic matter	<0.001	<0.001	0.197
Total soil N	<0.001	<0.001	<0.001
AB-DTPA extractable P	<0.001	<0.001	<0.001
AB-DTPA extractable K	<0.001	<0.001	0.349

Note: Amendment was tested against the replication x amendment mean square; NPK and the interaction were tested against the subplot residual. Values below 0.05 are statistically significant.

3.1 Bulk density, pH and electrical conductivity

Bulk density was affected by amendment ($p = 0.008$), NPK ($p = 0.008$) and their interaction ($p = 0.017$). Poultry-manure treatments with either the 50 or 100% NPK had the lowest mean bulk density of 1.20 g cm⁻³. The average density of the PM + Trichoderma treatments ranged from 1.21 to 1.25 g cm⁻³ whereas the highest average density (1.30 g cm⁻³) was observed in the unamended 50% NPK treatment. All the treatment means after harvest were less than that of pre-sowing bulk density of 1.31 g cm⁻³.

The soil pH was in a narrow range of alkaline (7.71-7.79) and was not significantly influenced by

any of the amendments, NPK or interaction. The mean EC was raised from 1.00 dS m⁻¹ (no amendment) to 1.31 dS m⁻¹ (PM + Trichoderma). The amendment effect was significant ($p = 0.017$) and NPK and interaction were not. The PM + Trichoderma + 100 % NPK treatment gave the highest mean EC (1.39 dS m⁻¹) which is still below the levels generally reported to produce salinity injury in wheat. The results of the ECs should be taken with caution as one of the high replicates (1.90 dS m⁻¹) was included in the PMT-0 treatment.



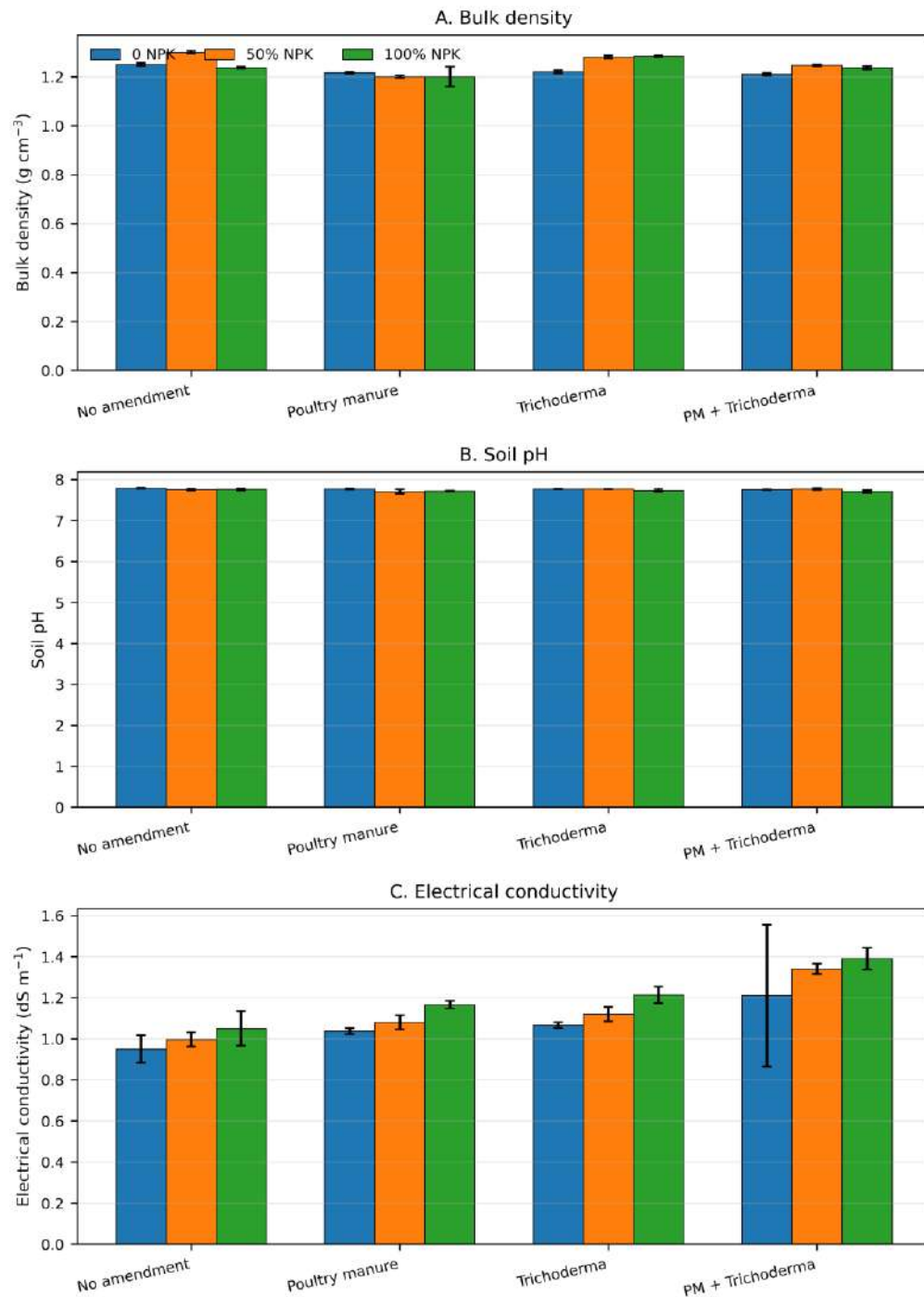


Figure 1 Effects of poultry manure, *Trichoderma harzianum* and NPK on post-harvest bulk density, pH and electrical conductivity. Bars show means $\pm$ standard error (n = 3).

Table 3 Post-harvest soil bulk density, pH and electrical conductivity.

Treatment	Bulk density (g cm ⁻³)	Soil pH (unitless)	Electrical conductivity (dS m ⁻¹)
C-0	1.250 ± 0.006	7.79 ± 0.01	0.95 ± 0.07
C-50	1.300 ± 0.006	7.76 ± 0.02	1.00 ± 0.03
C-100	1.237 ± 0.003	7.76 ± 0.03	1.05 ± 0.08
PM-0	1.217 ± 0.003	7.77 ± 0.02	1.04 ± 0.01
PM-50	1.200 ± 0.006	7.71 ± 0.05	1.08 ± 0.04
PM-100	1.200 ± 0.040	7.72 ± 0.01	1.17 ± 0.02
T-0	1.220 ± 0.006	7.77 ± 0.01	1.07 ± 0.01
T-50	1.280 ± 0.006	7.77 ± 0.00	1.12 ± 0.04
T-100	1.283 ± 0.003	7.73 ± 0.04	1.21 ± 0.04
PMT-0	1.210 ± 0.006	7.75 ± 0.01	1.21 ± 0.35
PMT-50	1.247 ± 0.003	7.77 ± 0.02	1.34 ± 0.03
PMT-100	1.237 ± 0.007	7.71 ± 0.03	1.39 ± 0.05

Note: Values are means ± standard error (n = 3). Treatment codes are defined in Table 1.

3.2 Soil organic matter and total nitrogen

The amendment application significantly ($p < 0.001$) increased the soil organic matter, and similarly the application of NPK significantly ($p < 0.001$) increased the soil organic matter, but the interaction of the two was not significant. The minimum was 0.58% for C-0, while the maximum was 0.97% for PMT-100. At average level of NPK applications, the SOM was 0.65% without amendment, 0.78% for poultry manure, 0.84% for Trichoderma and 0.92% for PM + Trichoderma. So, the overall amendment effect resulted in an overall increase in the SOM level at all fertilizer rates.

The effects of the amendments and NPK x amendment were significant for total soil N (all $p < 0.001$). Values ranged from 0.16 g kg⁻¹ under C-0 to 1.09 g kg⁻¹ under PMT-100. The high interaction was due to the very high NPK response in the amended plots and the very high NPK response in the unamended soil at 100% NPK. In both cases poultry manure and Trichoderma resulted in more N retained or accumulated,

compared to the unamended soil across treatments.

3.3 AB-DTPA extractable phosphorus and potassium

Amendment, NPK and NPK × amendment (all $p < 0.001$) were significant factors in the available P. PMT-100 produced 7.80 mg P kg⁻¹, compared with 3.01 mg kg⁻¹ under C-0. The application of full NPK gradually increased in response from unamended treatment to poultry manure, Trichoderma and PM + Trichoderma, which suggests that the amendments influenced the soil's ability to retain or mobilize extractable P.

The interaction between amendment and NPK was not significant, whereas the NPK and amendment had an increasing effect on Available K ($p < 0.001$). Mean K ranged from 61.40 mg kg⁻¹ under C-0 to 103.13 mg kg⁻¹ under PMT-100. The average of NPK levels showed that extractable K in PM + Trichoderma was 98.27 mg kg⁻¹ while in the unamended soil it was 64.78 mg kg⁻¹.

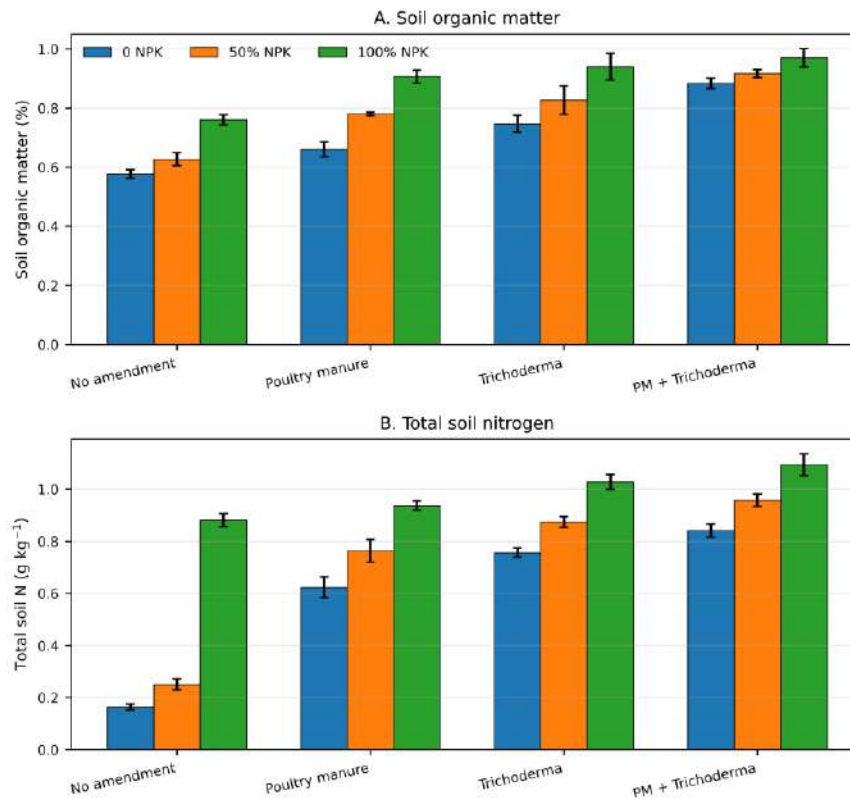


Figure 2 Post-harvest soil organic matter and total N under the amendment and NPK treatments. Bars show means $\pm$ standard error (n = 3).

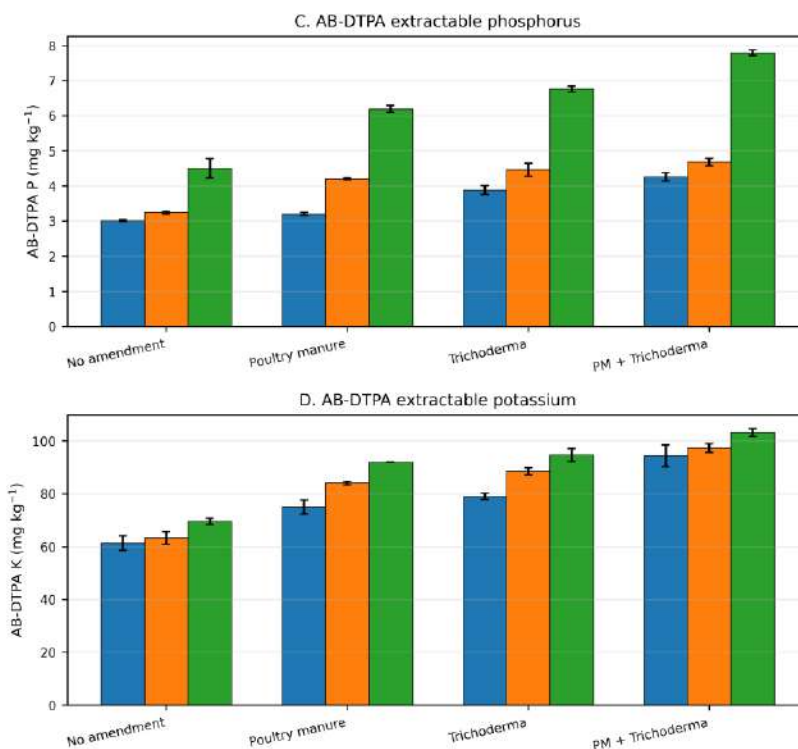


Figure 3 Post-harvest AB-DTPA extractable P and K under the amendment and NPK treatments. Bars show means $\pm$ standard error (n = 3).

Table 4 Post-harvest soil organic matter, total N and AB-DTPA extractable P and K.

Treatment	Soil organic matter (%)	Total soil N (g kg ⁻¹)	AB-DTPA extractable P (mg kg ⁻¹)	AB-DTPA extractable K (mg kg ⁻¹)
C-0	0.577 $\pm$ 0.015	0.163 $\pm$ 0.012	3.01 $\pm$ 0.02	61.40 $\pm$ 2.75
C-50	0.627 $\pm$ 0.022	0.250 $\pm$ 0.021	3.24 $\pm$ 0.04	63.33 $\pm$ 2.40
C-100	0.760 $\pm$ 0.017	0.880 $\pm$ 0.025	4.50 $\pm$ 0.28	69.60 $\pm$ 1.17
PM-0	0.660 $\pm$ 0.025	0.623 $\pm$ 0.041	3.20 $\pm$ 0.05	75.00 $\pm$ 2.65
PM-50	0.780 $\pm$ 0.006	0.763 $\pm$ 0.043	4.20 $\pm$ 0.02	84.00 $\pm$ 0.64
PM-100	0.907 $\pm$ 0.022	0.937 $\pm$ 0.018	6.19 $\pm$ 0.10	91.97 $\pm$ 0.03
T-0	0.747 $\pm$ 0.028	0.757 $\pm$ 0.018	3.88 $\pm$ 0.12	79.00 $\pm$ 1.15
T-50	0.827 $\pm$ 0.048	0.873 $\pm$ 0.020	4.46 $\pm$ 0.18	88.43 $\pm$ 1.37
T-100	0.940 $\pm$ 0.045	1.027 $\pm$ 0.028	6.76 $\pm$ 0.08	94.67 $\pm$ 2.40
PMT-0	0.883 $\pm$ 0.018	0.840 $\pm$ 0.025	4.26 $\pm$ 0.12	94.33 $\pm$ 4.18

PMT-50	0.917 ± 0.013	0.957 ± 0.024	4.68 ± 0.11	97.33 ± 1.67
PMT-100	0.970 ± 0.031	1.093 ± 0.042	7.80 ± 0.08	103.13 ± 1.49

Note: Values are means ± standard error (n = 3). Treatment codes are defined in Table 1.

3.4 Principal component analysis

The first two principal components accounted for 72.4% of the total standardized variation (PC1 = 57.5% and PC2 = 14.9%). PC1 was a soil-fertility gradient, with positive loadings for SOM, total N, available P, available K and EC, and negative loadings for pH and bulk density. The highest

positive PC1 score was obtained for PMT-100 while the unamended 0 and 50% NPK treatments had very negative scores. PC2 was dominated by bulk density and separated treatments had relatively high compaction compared with those in which manure lowered bulk density.

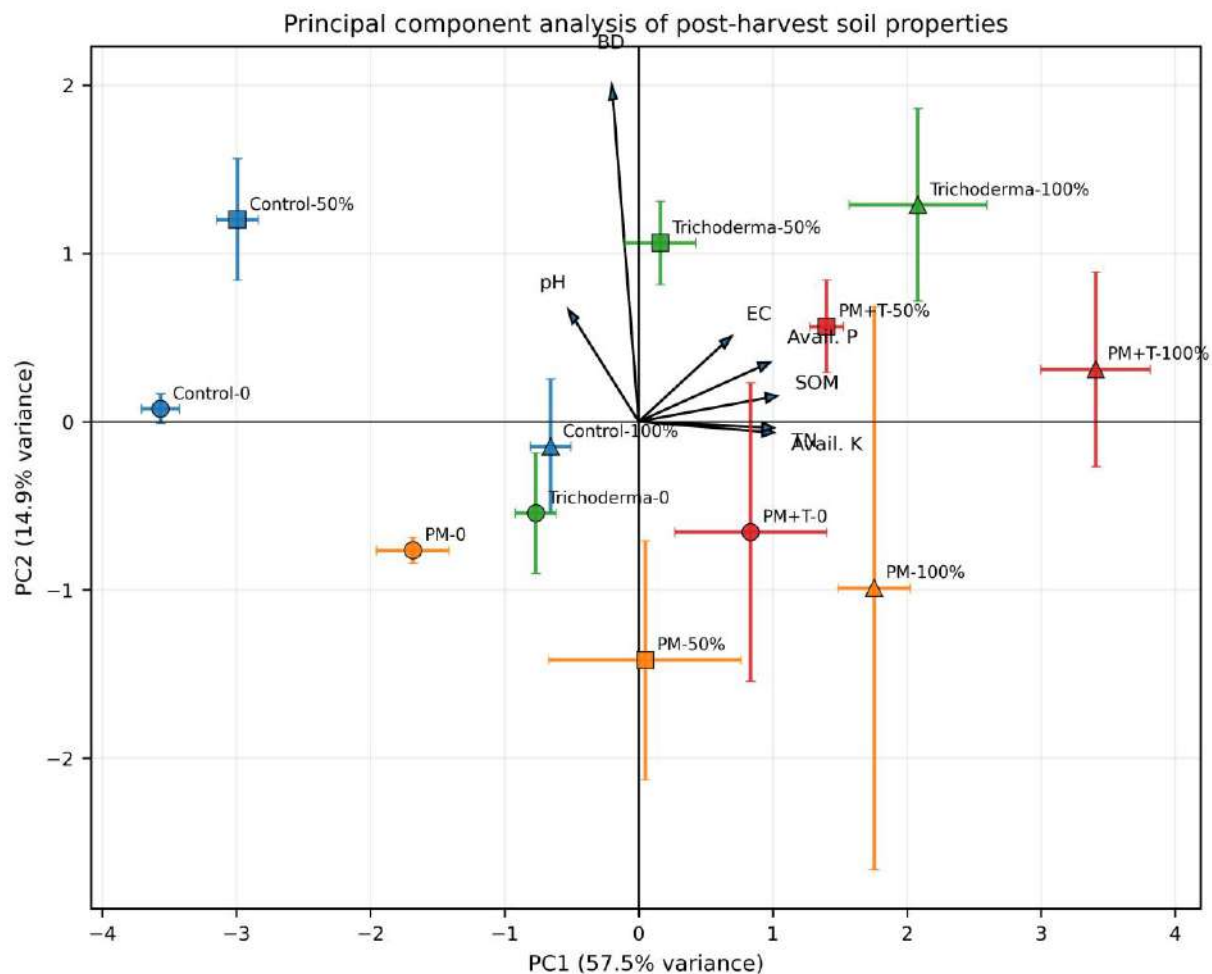


Figure 4 PCA biplot of post-harvest soil properties. Points are treatment means with standard-deviation error bars across three replications. Circles, squares and triangles denote 0, 50 and 100% NPK, respectively. BD = bulk density; EC = electrical conductivity; SOM = soil organic matter; TN = total N.

4. Discussion

4.1 Rapid improvement in soil organic matter and nutrient status

The improvement in SOM following one wheat season indicates the role of poultry manure in improving SOM and the possible role of *Trichoderma* in carbon turnover and rhizosphere processes. Organic carbon was directly added to the poultry manure treatments, and higher growth of crops in fertilized treatments may have led to more root-derived carbon. The microbial inoculant was associated with increased SOM gains as indicated by the consistent amendment ranking (PM + *Trichoderma* > *Trichoderma* > poultry manure > no amendment) but the experiment did not measure the fungal colonization or microbial biomass and therefore cannot directly establish the mechanism.

The significant rise in total N, available P and available K are consistent with the findings of other researchers that organic materials increase nutrient pools through nutrient addition, decrease nutrient losses and alter biological transformations (Bhogal et al., 2018; Zhao et al., 2024). Poultry manure had significant amounts of N, P and K and mineral fertilizer provided readily available nutrients. The mixture thus contained a slow acting organic and a rapid mineral source. The significant amendment x NPK interaction for extractable P and the general evidence for microbial-fertilizer effects on soil quality (Ma et al., 2025) might indicate that *Trichoderma* has improved decomposition and nutrient solubilization, especially P.

4.2 Physical properties, pH buffering and salinity considerations

The bulk density decreased with poultry manure, especially at 50 and 100% NPK. The reduction in bulk density may be due to the increase in aggregation and pore space, and the decrease in the percentage of dense mineral material per unit soil volume, as a result of organic inputs (Agbede et al., 2017; Adekiya et al., 2019). The interaction suggests that the physical response was not consistent for all NPK levels, as was the case for *Trichoderma* with no poultry manure which did not always decrease bulk density.

The pH of the soil did not change appreciably since the soil was originally calcareous and highly buffered. This stability is agronomically useful in that nutrient pools increased without a large shift in reaction. In contrast, EC increased with the inputs of integrated systems, which are associated with soluble ions from manure and fertilizers. Treatment means were within a non-saline range, but salts may build up from repeated manure and fertilizer applications if nutrient inputs are greater than nutrient removal or drainage. Monitoring of EC should therefore be carried out in longer-term trials, particularly as one replicate of PMT-0 was significantly higher than the others.

4.3 Multivariate interpretation and management implications

A clear fertility gradient was summarized by the PCA, which showed that treatments with poultry manure, *Trichoderma* and full NPK had higher SOM, N, P and K, while unamended treatments had lower fertility. The advantage of PMT-100 was not limited to one nutrient, as it is at the positive extreme of PC1. The same axis, however, also contained EC, which showed a management trade-off between nutrient enrichment and salt accumulation. A practical nutrient-management program should therefore take into account the soil test results and adjust manure and mineral fertilizer rates accordingly; rather than applying all inputs at fixed high rates every season.

The results are short-term and location specific. Soil properties were measured post one crop and do not indicate persistence, carbon sequestration or long-term nutrient balance. Also, microbial biomass, enzyme activity, aggregate stability, mineral N forms, and greenhouse-gas emissions and nutrient leaching were not measured in the experiment. Future studies should include yield, economic return and environmental indicators and be conducted on the same plots over multiple seasons with full NPK and reduced NPK plus poultry manure and *Trichoderma*.

5. Conclusions

After one wheat season, poultry manure, *Trichoderma harzianum* and balanced mineral

NPK significantly enhanced post-harvest fertility in an alkaline calcareous soil. PM + Trichoderma + 100% NPK produced the highest SOM (0.97%), total N (1.09 g kg⁻¹), AB-DTPA P (7.80 mg kg⁻¹) and AB-DTPA K (103.13 mg kg⁻¹). Poultry manure also decreased the bulk density and pH was not affected. The integrated inputs did not affect EC, which remained at the treatment-mean level and was not saline, thus highlighting the importance of ongoing salinity monitoring. The use of integrated organic, microbial and mineral nutrient management is promising to restore soil fertility, but requires long-term optimization of rates to balance productivity, nutrient build up and environmental risk.

Declarations

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Conflict of interest: The authors declare no conflict of interest.

Ethics approval: Not applicable.

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