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Depth-wise soil fertility and micronutrient dynamics under conservation agriculture practices in a maize-wheat system

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ABSTRACT

A field experiment was conducted at ICAR-CSSRI, Karnal, Haryana, India, to evaluate short-term changes in soil fertility and micronutrient availability under conservation agriculture practices in a maize-wheat system. Five treatments were compared in a randomized block design: conventional tillage with residue removal (CT), zero tillage with maize residue (ZT+M), zero tillage without maize residue (ZT-M), permanent bed with maize residue (PB+M) and permanent bed without maize residue (PB-M). Soil samples were collected after wheat harvest in 2023 and 2024 from 0-15 and 15-30 cm depths and analysed for pH, electrical conductivity, organic carbon, available phosphorus, available potassium, available sulphur and DTPA-extractable Zn, Fe, Cu and Mn. Soil pH remained near neutral to slightly alkaline and electrical conductivity remained low across all treatments, indicating no short-term salinity build-up. Organic carbon was consistently higher in the 0-15 cm layer than in the 15-30 cm layer; in 2024, the highest surface organic carbon was recorded under ZT+M (0.63%), followed by PB+M (0.59%) and ZT-M (0.56%). Available potassium and micronutrients varied more than pH and available phosphorus. Surface enrichment was evident for Zn and Fe in several treatments, while sulphur and Cu showed less consistent treatment responses. The results suggest that early conservation agriculture effects on soil fertility are expressed mainly through depth-wise redistribution and surface organic carbon enrichment rather than uniform increases in all nutrients. Continued monitoring is required before making strong long-term fertility claims.

Keywords: Conservation agriculture, Maize-wheat system, Micronutrients, Soil fertility, Zero tillage, Permanent bed

Introduction

The maize-wheat system is becoming an important cereal production option in the north-western Indo-Gangetic Plains because it can reduce some of the pressure associated with intensive rice-wheat production while maintaining cereal output. In this region, repeated tillage, residue removal, high input use and intensive irrigation have raised concerns about soil organic matter decline, nutrient imbalance and long-term soil health. Conservation agriculture has therefore been promoted as a management approach that combines reduced soil disturbance, crop residue retention and diversified cropping to improve resource use and soil functioning (Hobbs *et al.*, 2008; Kassam *et al.*, 2019) [1, 2].

Soil fertility responses to conservation agriculture are often slower and more complex than crop yield responses. Minimum tillage and residue retention can alter where crop residues decompose, where roots proliferate and how nutrients are distributed within the soil profile (Jat *et al.*, 2019; Choudhary *et al.*, 2018) [3, 4]. These effects may increase organic carbon near the surface, but they may also create nutrient stratification because fertilizers, residues and roots interact more strongly in the upper soil layer. For this reason, evaluating only the surface soil can miss important subsurface changes, especially in cereal systems where crop roots and nutrient uptake extend below 15 cm.

Micronutrients deserve separate attention in intensive cereal systems because their availability is strongly influenced by soil pH, organic matter, moisture and redox conditions. Zinc, iron, copper and manganese are required in small amounts, but deficiencies or imbalances can affect crop growth and grain quality. Available sulphur is also important because cereal intensification and the use of high-analysis fertilizers can reduce sulphur inputs relative to crop demand. Conservation agriculture may influence these nutrients through residue return and organic matter accumulation, but the direction and speed of change can vary with soil depth and management configuration.

Many studies on conservation agriculture in the Indo-Gangetic Plains focus on crop yield, profitability, greenhouse-gas indicators or soil organic carbon (Gathala *et al.*, 2013; Gora *et al.*, 2024) [5, 6]. These outcomes are important, but they do not fully describe the chemical fertility environment that supports crop production. There is still a practical need for field evidence on how zero tillage and permanent beds, with and

without residue retention, influence routine soil fertility parameters and DTPA-extractable micronutrients across soil depths. The present study was designed to address this need using post-wheat-harvest soil data from a maize-wheat conservation agriculture experiment at Karnal, Haryana.

The objective of this paper was to evaluate the effects of five agro-nomic management practices on soil pH, electrical conductivity, organic carbon, available phosphorus, available potassium, available sulphur and DTPA-extractable Zn, Fe, Cu and Mn at two soil depths after wheat harvest. The analysis emphasizes observed treatment and depth-wise patterns and avoids long-term claims because the dataset represents the early phase of the experiment.

Materials and methods

Experimental site and treatment details

The experiment was conducted at ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, India, in the western Indo-Gangetic Plains. The region represents an irrigated cereal production environment where conservation agriculture is being evaluated as an alternative to repeated conventional tillage and residue removal. The experiment was maintained under a maize-wheat sequence during 2022-23 and 2023-24.

The experimental site has a subtropical semi-arid climate with very hot summers, cold winters and a warm humid monsoon period. Long-term weather records for Karnal indicate an average annual rainfall of about 748 mm, with nearly 80% received during June to September. Mean monthly maximum temperature ranges from about 17 °C in January to 40 °C during May-June, while mean monthly minimum temperature ranges from about 5.7 °C in January to 27 °C in July. Mean relative humidity generally remains between 60 and 90%, and mean annual pan evaporation is approximately 1495 mm. Daily weather data during the experimental years 2022-23 and 2023-24 were recorded at the agro-meteorological observatory located at CSSRI Karnal; these weather variables were used only to describe the site environment and were not treated as experimental factors in the present soil fertility analysis.

The trial was laid out in a randomized block design with three replications. Five treatments were evaluated: conventional tillage with residue removal (CT), zero tillage with maize residue retention (ZT+M), zero tillage without maize residue retention (ZT-M), permanent bed with maize residue retention (PB+M) and permanent bed without maize residue retention (PB-M). These treatments allowed comparison of tillage configuration and residue retention within the same field environment. Wheat and maize crop management followed the common experimental protocol used at the site.

Soil sampling and laboratory analysis

Soil samples were collected after wheat harvest in 2023 and 2024 from two depths, 0-15 cm and 15-30 cm. The depth-wise sampling was used because conservation agriculture can change the vertical

distribution of organic inputs and nutrients. In the CT treatment, the third plot could not be sampled at the time of soil collection because it was inaccessible; therefore, CT means are based on two field replicates, while the means for ZT+M, ZT-M, PB+M and PB-M are based on three field replicates.

Soil pH and electrical conductivity were determined using standard soil-water suspension methods. Organic carbon was determined using the Walkley-Black method (Walkley *et al.*, 1934) [7]. Available phosphorus was determined using routine soil testing procedures based on bicarbonate extraction principles (Olsen *et al.*, 1954) [8], and available potassium was determined following standard soil chemical analysis procedures (Jackson, 1973) [9]. Available sulphur and DTPA-extractable Zn, Fe, Cu and Mn were estimated in the soil testing laboratory using standard analytical protocols; the DTPA micronutrient extraction followed the approach of Lindsay *et al.* (1978) [10]. The same parameter set was used for both years and both soil depths, allowing comparison of treatment and depth-wise patterns after wheat harvest.

Statistical approach

Treatment means were compared within the same year, soil depth and parameter. In the tables, means followed by different lowercase letters differ significantly at $p < 0.05$. Columns without letters indicate non-significant treatment effects. Because CT soil data had two replicates while the conservation agriculture treatments had three replicates, the interpretation gives greater weight to consistent depth-wise and treatment-wise trends than to isolated numerical differences. This approach was used to keep the conclusions aligned with the strength of the data.

Results

Soil pH and electrical conductivity

Soil pH remained near neutral to slightly alkaline under all treatments and in both soil layers (Table 1). In 2023, surface pH ranged from 7.09 under ZT+M to 7.40 under PB-M, while subsurface pH ranged from 7.42 under PB-M to 7.58 under ZT-M. In 2024, surface pH ranged from 7.20 under CT to 7.32 under PB-M, and subsurface pH ranged from 7.45 under CT to 7.57 under ZT+M and ZT-M. Across both years, pH was generally higher in the 15-30 cm layer than in the 0-15 cm layer, indicating a depth effect rather than a strong treatment-specific shift.

Electrical conductivity remained low under all treatments, suggesting that none of the management practices caused short-term salt accumulation after wheat harvest. In 2023, EC values were between 0.02 and 0.13 dS m⁻¹. In 2024, EC values were numerically higher in some treatments, but still remained low. Surface EC in 2024 was highest under ZT+M and CT, while PB+M recorded the lowest surface EC. These values indicate that the observed nutrient differences were not associated with a salinity problem in the experimental soil.

Organic carbon and available macronutrients

Table 1. Soil pH, electrical conductivity, organic carbon and available P and K after wheat harvest in 2023 and 2024.

Treatment	Depth (cm)	2023					2024				
		pH	EC	OC	Avail. P	Avail. K	pH	EC	OC	Avail. P	Avail. K
CT*	0-15	7.1	0	0.6	3.14	166.88	7.2	0.18a	0.54c	2.92	145.6
CT*	15-30	7.5	0	0.4	3	181.44a	7.5	0.16	0.35	3.36	183.69
ZT+M	0-15	7.1	0	0.7	2.9	144.85	7.3	0.19a	0.63a	2.72	165.76
ZT+M	15-30	7.5	0.1	0.5	2.96	129.51b	7.6	0.08	0.5	2.66	177.71
ZT-M	0-15	7.2	0	0.6	2.66	141.87	7.3	0.06b	0.56b	2.6	153.75
ZT-M	15-30	7.6	0.1	0.5	2.81	159.79a	7.6	0.19	0.43	2.9	164.27
PB+M	0-15	7.2	0	0.6	2.21	109.01	7.3	0.02b	0.59b	2.3	144.85
PB+M	15-30	7.5	0.1	0.4	3.8	126.93b	7.5	0.13	0.41	2.48	161.28
PB-M	0-15	7.4	0	0.7	3.05	144.85	7.3	0.08b	0.51c	2.69	167.77
PB-M	15-30	7.4	0.1	0.5	3.02	143.36b	7.5	0.12	0.43	3.14	137.39

Organic carbon showed a consistent depth-wise pattern. In both years, the 0-15 cm layer generally contained more organic carbon than the 15-30 cm layer. In 2023, surface organic carbon ranged from 0.57% under CT to 0.66% under ZT+M, while subsurface organic carbon ranged from 0.41% under PB+M to 0.51% under ZT+M. In 2024, significant differences were observed in surface organic carbon, with ZT+M recording the highest value (0.63%), followed by PB+M (0.59%) and ZT-M (0.56%). CT and PB-M recorded lower surface values in 2024. This pattern suggests early surface carbon enrichment under selected conservation agriculture treatments, especially where zero tillage was combined with residue retention.

Available phosphorus varied within a relatively narrow range compared with organic carbon and potassium. In 2023, surface available phosphorus ranged from 2.21 to 3.14 kg ha⁻¹, while subsurface values ranged from 2.81 to 3.80 kg ha⁻¹. In 2024, surface values ranged from 2.30 to 2.92 kg ha⁻¹ and subsurface values ranged from 2.48 to 3.36 kg ha⁻¹. These values did not show a stable treatment ranking across both years and depths, indicating that the short-term management effect on available phosphorus was weak in this dataset.

Available potassium showed greater variation than available phosphorus. In 2023, subsurface potassium differed significantly, with CT and ZT-M placed in the higher statistical group and ZT+M, PB+M and PB-M in the lower group. In 2024, surface potassium ranged from 144.85 kg ha⁻¹ under PB+M to 167.77 kg ha⁻¹ under PB-M, while subsurface potassium ranged from 137.39 kg ha⁻¹ under PB-M to 183.69 kg ha⁻¹ under CT. The potassium results therefore indicate treatment and depth-wise variability, but not a simple residue-retention response across years.

Available sulphur and DTPA-extractable micronutrients

Available sulphur varied widely among treatments and depths (Table 2). In 2023, the highest surface sulphur values were recorded under ZT+M (9.90 kg ha⁻¹) and PB+M (9.08 kg ha⁻¹), while ZT-M recorded the lowest surface value (3.44 kg ha⁻¹). In 2024, the highest sulphur value was observed in the 15-30 cm layer under ZT-M (10.56 kg ha⁻¹). These contrasting patterns show that sulphur availability did not respond uniformly to residue retention during the early phase of the experiment.

Table 2. Available sulphur and DTPA-extractable micronutrients after wheat harvest in 2023 and 2024.

Treatment	Depth (cm)	2023					2024				
		S	Zn	Fe	Cu	Mn	S	Zn	Fe	Cu	Mn
CT*	0-15	7.2	6.4	13.4	1.14	15.35a	2.29	4	27.42a	1.72a	11.14
CT*	15-30	4.1	3	5.28	1.30a	8.96	2.84	1.81	8.00a	1.2	9.36
ZT+M	0-15	9.9	6.2	9.13	1.35	9.52a	4.29	4.71	9.41b	1.15b	8.32
ZT+M	15-30	6.3	3.6	4.09	1.01b	7.49	4.86	2.59	5.15b	1.03	4.75
ZT-M	0-15	3.4	5	8.76	1.15	10.01a	3.06	5.52	8.19b	1.19b	5.96
ZT-M	15-30	4.7	2.4	3.81	0.91b	8.03	10.6	2.93	5.23b	1.17	6.87
PB+M	0-15	9.1	3.8	9.89	1.2	6.55b	4.17	4.95	8.19b	1.09b	6.27
PB+M	15-30	5.6	2	6.87	1.12a	10.01	4.81	2.24	3.63b	1.01	4.95
PB-M	0-15	6.3	4.4	7.61	1.16	10.16a	3.08	5.04	8.17b	1.32b	9.8
PB-M	15-30	4.5	2.8	6.76	1.17a	9.81	3.01	1.97	4.11b	1.08	5.09

DTPA-extractable zinc generally showed higher values in the surface layer than in the subsurface layer. In 2023, surface Zn ranged from 3.83 mg kg⁻¹ under PB+M to 6.36 mg kg⁻¹ under CT, whereas subsurface Zn ranged from 1.99 mg kg⁻¹ under PB+M to 3.63 mg kg⁻¹ under ZT+M. In 2024, surface Zn ranged from 4.00 mg kg⁻¹ under CT to 5.52 mg kg⁻¹ under ZT-M, while subsurface values ranged from 1.81 mg kg⁻¹ under CT to 2.93 mg kg⁻¹ under ZT-M. This indicates clear depth stratification of Zn, with stronger availability in the surface layer.

DTPA-extractable iron also showed depth-wise variation. In 2023, surface Fe ranged from 7.61 mg kg⁻¹ under PB-M to 13.42 mg kg⁻¹ under CT, while subsurface Fe ranged from 3.81 mg kg⁻¹ under ZT-M to 6.87 mg kg⁻¹ under PB+M. In 2024, CT recorded a high surface Fe value of 27.42 mg kg⁻¹, while all conservation agriculture treatments had lower surface values between 8.17 and 9.41 mg kg⁻¹. Subsurface Fe in 2024 ranged from 3.63 to 8.00 mg kg⁻¹. Because the high CT value in 2024 was based on two replicates, it should be interpreted cautiously, but the overall pattern still supports stronger Fe availability in the surface layer than in the subsurface layer.

Copper and manganese showed less consistent responses than Zn and Fe. In 2023, Cu values ranged from 1.14 to 1.35 mg kg⁻¹ in the surface layer and from 0.91 to 1.30 mg kg⁻¹ in the subsurface layer. In 2024, surface Cu differed significantly, with CT recording the highest value (1.72 mg kg⁻¹), while conservation agriculture treatments ranged from 1.09 to 1.32 mg kg⁻¹. Manganese showed significant treatment differences in the surface layer in 2023, but the ranking was not repeated consistently in 2024. These results show that micronutrient responses were nutrient-specific rather than uniform across all elements.

The graphical summary uses the same bar-and-line format as the weather figure, but the panels are labelled by sampling year rather than phase. The sharp decline of the Fe line from CT to the conservation agriculture treatments in 2024 reflects the measured surface-soil Fe values: CT recorded 27.42 mg kg⁻¹, whereas the conservation agriculture treatments ranged from 8.17 to 9.41 mg kg⁻¹. Because CT soil means were based on two replicates, this contrast is interpreted cautiously and should be read together with Tables 1-3.

Table 3. Statistical summary of treatment effects based on verified mean-separation letters in the original soil tables.

Parameter	Year	Depth	Treatment effect	Highest / notable group
EC	2024	0-15 cm	Significant	CT and ZT+M higher group; ZT-M, PB+M and PB-M lower group
Organic carbon	2024	0-15 cm	Significant	ZT+M highest group; PB+M and ZT-M intermediate; CT and PB-M lower
Available K	2023	15-30 cm	Significant	CT and ZT-M higher group; ZT+M, PB+M and PB-M lower

Parameter	Year	Depth	Treatment effect	Highest / notable group
Mn	2023	0-15 cm	Significant	CT, ZT+M, ZT-M and PB-M higher group; PB+M lower
Cu	2023	15-30 cm	Significant	CT, PB+M and PB-M higher group; ZT+M and ZT-M lower
Fe	2024	0-15 cm	Significant	CT higher group; all conservation agriculture treatments lower group
Cu	2024	0-15 cm	Significant	CT higher group; all conservation agriculture treatments lower group
Most other parameter x year x depth combinations	2023-2024	0-15 and 15-30 cm	Non-significant	No verified treatment separation letters reported

Note for Tables 1-3: In Table 1, EC is expressed as dS m^{-1} , OC as %, and available P and K as kg ha^{-1} . In Table 2, S is expressed as kg ha^{-1} and Zn, Fe, Cu and Mn as mg kg^{-1} . CT* means are based on two field replicates because the third CT plot was inaccessible during soil sampling; all other treatment means are based on three field replicates. Within the same year, depth and parameter, different lowercase

letters indicate significant differences at $p < 0.05$. Columns without letters indicate non-significant treatment effects. Table 3 summarizes only the significant/non-significant treatment separations already indicated by lowercase letters in the verified source tables; raw replicate values are required for a full ANOVA table with F values and standard errors.

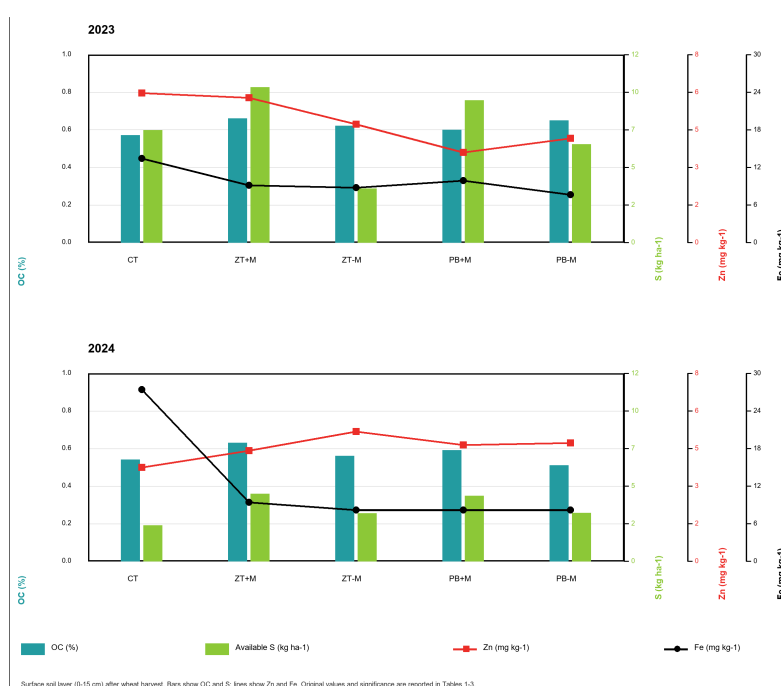


Figure 1. Surface soil fertility and micronutrient status under conservation agriculture practices after wheat harvest in 2023 and 2024. Bars show organic carbon and available sulphur, while lines show DTPA-extractable Zn and Fe in the 0-15 cm soil layer. The high Fe value under CT in 2024 is shown as measured and should be interpreted with the replication limitation noted in Tables 1-3.

Discussion

The soil reaction and electrical conductivity results indicate that the early phase of conservation agriculture did not create adverse chemical conditions at the experimental site. Soil pH stayed within a narrow near-neutral to slightly alkaline range, and EC values remained low in both years. This matters because pH and salinity can strongly influence nutrient solubility, root activity and micronutrient availability. Since these two parameters remained broadly stable, the observed differences in organic carbon, potassium, sulphur and micronutrients are more likely associated with management, depth and inherent spatial variation than with major pH or salinity shifts.

The most consistent result was the higher organic carbon concentration in the surface layer. This is agronomically meaningful because reduced tillage and surface residue retention are expected to place more organic inputs in the upper soil layer. The highest surface organic carbon value in 2024 under ZT+M supports this interpretation, but the result should be described as an early surface enrichment signal rather than long-term soil carbon sequestration. The experiment

covered only two crop cycles, and stronger carbon conclusions require longer monitoring and complete soil sampling across all plots. Available phosphorus did not show a strong or stable treatment response. This may be because phosphorus availability in calcareous or alkaline soils is regulated by several processes, including fixation reactions, fertilizer placement, soil moisture and organic matter interactions. In the present dataset, available phosphorus values varied within a narrow range and did not identify a single superior conservation agriculture practice. Therefore, the evidence does not support a strong claim that short-term conservation agriculture increased available phosphorus at this site.

Available potassium showed clearer numerical variation than phosphorus, but the direction of response changed with year and depth. Higher subsurface K under CT and ZT-M in 2023 and variable values in 2024 suggest that potassium distribution was not controlled by residue retention alone. Potassium can be influenced by crop uptake, residue return, mineral weathering and movement within the soil profile. The present results therefore indicate the need for continued nutrient balance monitoring rather than a simple treatment ranking.

The micronutrient results highlight the importance of depth-wise sampling. Zinc and iron were generally more available in the surface layer than in the 15-30 cm layer, indicating stratification of these nutrients. This pattern is consistent with the concentration of organic matter and root activity near the soil surface. Organic matter can influence micronutrient complexation and availability, while reduced soil mixing can maintain stronger surface gradients. For practical soil testing, this means that sampling depth should remain consistent when comparing conservation agriculture and conventional tillage treatments.

Sulphur, copper and manganese showed less consistent treatment responses. In 2023, residue-retained treatments had relatively high surface sulphur values, but this pattern was not repeated clearly in 2024. Copper values were relatively narrow in range, except for the higher CT value in 2024. Manganese showed significant differences in selected cases but no stable treatment ranking. These results are important because they prevent over-generalization: conservation agriculture did not uniformly improve every measured nutrient within the short study period.

The main limitation of the soil dataset is the unequal replication for CT, where only two soil samples were available because one plot could not be sampled. This reduces the strength of treatment comparisons involving CT, especially for variables that showed large numerical differences. Another limitation is that the study represents early changes after two cropping cycles. The paper therefore emphasizes observed soil fertility patterns and depth-wise distribution rather than claiming permanent improvement in soil health. Future work should continue the same depth-wise monitoring, include complete replication and relate nutrient changes to crop uptake and grain nutrient concentration.

Conclusion

The study showed that short-term conservation agriculture practices maintained low electrical conductivity and near-neutral to slightly alkaline soil pH in a maize-wheat system at Karnal. The clearest fertility response was depth-wise stratification, especially higher organic carbon in the 0-15 cm layer than in the 15-30 cm layer. In 2024, ZT+M recorded the highest surface organic carbon among the treatments, suggesting early surface enrichment under zero tillage with residue retention. Available phosphorus remained relatively stable, while available potassium showed variable treatment and depth-wise patterns. Zinc and iron were generally more available in the surface soil than in the subsurface soil, whereas sulphur, copper and manganese did not show consistent treatment responses across years and depths. Overall, the results indicate that early conservation agriculture effects on soil fertility are expressed mainly through surface enrichment and nutrient redistribution rather than uniform increases in all measured nutrients. Longer-term, fully replicated monitoring is needed before making stronger conclusions about sustained soil fertility improvement.

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Conflict of interest

The authors declare no conflict of interest.

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