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Long-term Nutrient Management Influences the Vertical Distribution of DTPA-Extractable Micronutrients in a Vertisol under Soybean-Wheat Cropping System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Long-term nutrient management plays an important role in maintaining soil micronutrient fertility under continuous cropping. The present study evaluated the effect of long-term fertiliser and manure application on the vertical distribution of DTPA-extractable Zn, Cu, Mn and Fe in a Vertisol under a soybean-wheat cropping system during 2024-25 at the AICRP-LTFE experimental farm, JNKVV, Jabalpur, Madhya Pradesh, India. The long-term experiment was initiated in 1972 and comprised nine nutrient-management treatments, including graded NPK levels, nutrient omission treatments, NPK + Zn, NPK + FYM, sulphur-free NPK

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and an unfertilised control, and was arranged in a randomised block design with three replications. Soil samples were collected after wheat harvest from six depths (0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm) and analysed for DTPA-extractable micronutrients. All four micronutrients showed clear treatment- and depth-dependent variation, with concentrations generally declining with increasing soil depth. At 0-15 cm, DTPA-Zn, Cu, Mn and Fe ranged from 0.24-1.03, 0.90-1.83, 10.97-17.11 and 13.61-28.35 mg kg^{-1}, respectively, compared with 0.10-0.46, 0.46-0.84, 3.78-8.87 and 4.37-9.13 mg kg^{-1} at 75-90 cm. The 100% NPK + Zn treatment recorded the highest Zn concentration, whereas 100% NPK + FYM maintained the highest Cu, Mn and Fe concentrations across the soil profile. The 150% NPK treatment also maintained high Mn and Fe and was at par with NPK + FYM at 60-75 cm. In contrast, the control consistently recorded the lowest concentrations. The results demonstrate that balanced fertilisation, particularly when integrated with FYM, is effective in sustaining micronutrient fertility and improving the vertical distribution of extractable micronutrients in long-term soybean-wheat cultivation on Vertisol.

Keywords: Copper; Iron; vertisol; long-term fertiliser experiment; manganese; soybean-wheat cropping system; zinc.

1. Introduction

Soil fertility is a dynamic property governed by interactions among nutrient inputs, crop removal, organic matter turnover and nutrient transformations. Under intensive cropping, sustained nutrient removal without adequate and balanced replenishment can alter soil fertility and the availability of major nutrients and micronutrients. Therefore, long-term nutrient management must be evaluated not only in terms of crop productivity but also for its effects on soil nutrient pools that sustain productivity over time (Nayak *et al*., 2015; Sharma *et al*., 2022). These effects are particularly important in Vertisols, where clay mineralogy and associated physicochemical properties regulate nutrient retention, transformation and mobility.

Vertisols are important agricultural soils of the semi-arid and sub-humid regions of India and support intensive cropping systems because of their high clay content and nutrient-holding capacity. Their smectite-dominated mineralogy, high cation exchange capacity, shrink-swell behaviour and low hydraulic conductivity strongly influence nutrient movement and transformation within the profile (Coulombe *et al*., 1996; Dinka *et al*., 2013). Despite their inherent fertility, prolonged cultivation can cause nutrient imbalance and depletion, particularly under inadequate or disproportionate fertiliser inputs (Peng *et al*., 2015; Zhou *et al*., 2020). Interactions of nutrients with clay minerals, carbonates and other soil constituents further influence their solubility and plant availability.

The extensive adoption of mineral fertilisers has substantially increased crop productivity; however, continuous fertiliser application without balanced nutrient replenishment may alter soil chemical conditions and nutrient availability. Long-term fertiliser use has been associated with changes in soil organic carbon, nutrient balance and other fertility attributes, depending on fertiliser rate, nutrient combination and cropping history (Wacal *et al*., 2019; Sharma *et al*., 2022). In contrast, integrating mineral fertilisers with farmyard manure (FYM) can provide a sustained nutrient supply and modify soil organic matter, cation exchange properties and nutrient retention processes (Patial *et al*., 2022; Sahu *et al*., 2026). Thus, long-term experiments with contrasting fertiliser regimes are essential for understanding cumulative changes in soil fertility.

Recent long-term evidence from a subtropical Vertisol under a soybean-wheat system similarly indicates that integrated use of mineral fertilisers and FYM can improve soil quality relative to nutrient management based on mineral inputs alone (Bangre et al., 2024). Long-term field evidence from a pearl millet-wheat system also shows that combining organic manures with mineral fertilisers can enhance soil organic carbon and microbiological properties, supporting the role of integrated inputs in maintaining soil fertility (Kumari et al., 2024). Within a long-term Vertisol experiment, integrated nutrient management with NPK and FYM was also associated with improved soil organic carbon and available nutrient status across the sampled surface layers (Pradhan et al., 2024).

The soybean-wheat cropping system is important in central India, particularly Madhya Pradesh. Continuous cultivation of this high-input sequence involves substantial nutrient removal and may accelerate soil fertility deterioration when nutrient replenishment is inadequate or unbalanced (Behera *et al*., 2007; Debnath *et al*., 2020, 2022). In this context, micronutrients such as zinc (Zn), copper (Cu), manganese (Mn) and iron (Fe) warrant particular attention. These nutrients are essential for enzyme activity, redox processes, photosynthesis and other physiological functions. Their plant-available pools are strongly influenced by soil reaction, organic matter, clay content, carbonate status and fertiliser management. Micronutrient responses are also sensitive to fertiliser source and method of application; field evidence for Zn management has shown corresponding changes in the content and uptake of Zn, Cu, Fe and Mn (Sardar et al., 2024).

Importantly, micronutrient availability varies with soil depth. Besides surface fertiliser and manure inputs, vertical distribution is influenced by downward movement, adsorption and fixation, organic matter accumulation, root activity and nutrient recycling. Consequently, surface-soil assessments may not adequately represent the nutrient status of the entire profile. Despite the importance of Vertisols under soybean-wheat cultivation, information on the depth-wise response of available Zn, Cu, Mn and Fe to long-term contrasting fertiliser and manure regimes remains limited.

Long-term fertiliser experiments (LTFEs) provide a unique opportunity to determine cumulative nutrient-management effects under a common soil, climate and cropping system over several decades (Hemalatha *et al*., 2013; Pathariya *et al*., 2022). Therefore, this investigation evaluated the vertical distribution of DTPA-extractable Zn, Cu, Mn and Fe under a long-term soybean-wheat cropping system on a Vertisol subjected to different rates and combinations of mineral fertilisers, nutrient omission, Zn application, FYM integration and an unfertilised control. The study aimed to elucidate the depth-wise response of available micronutrients to long-term nutrient management and identify practices capable of sustaining micronutrient availability throughout the soil profile.

2. Materials and Methods

2.1 Experimental Site and Design

The study was conducted during 2024-25 in the Long-Term Fertilizer Experiment (LTFE) at JNKVV, Jabalpur, Madhya Pradesh, India (23°21′ N, 79°94′ E; 393 m above mean sea level). The experiment began in 1972 and has followed a soybean-wheat sequence since 1993-94. The soil is a clayey Vertisol (*Typic Haplustert*), Kheri series, belonging to the fine, montmorillonitic, hyperthermic family.

Nine long-term nutrient-management treatments were evaluated in a randomised block design with three replications: 50% NPK, 100% NPK, 150% NPK, 100% NPK + Zn, 100% NP, 100% N, 100% NPK + FYM, 100% NPK-S and control. The plot size was 17 × 10.8 m. Recommended N:P:K doses were 20:80:20 kg ha^{-1} for soybean and 120:80:40 kg ha^{-1} for wheat. FYM was applied at 5 t ha^{-1} $year^{-1}$ to soybean, while $ZnSO_4$ was applied at 20 kg ha^{-1} in alternate years to wheat in the NPK + Zn treatment until 1987. In the NPK-S treatment, P was supplied through DAP instead of SSP.

2.2 Soil Sampling and Analysis

After wheat harvest in 2024-25, we collected soil samples from three replications at six depths (0-15, 15-30, 30-45, 45-60, 60-75, and 75-90 cm) using a screw auger. We collected representative samples from several locations within each plot. Samples were air-dried, freed from visible roots and residues, gently crushed and passed through a 2-mm sieve before chemical analysis.

DTPA-extractable Zn, Fe, Cu and Mn were determined following Lindsay and Norvell (1978). Briefly, 12.5 g of soil was extracted with 25 mL of DTPA solution containing 0.005 *M* DTPA, 0.01 *M* $CaCl_2$ and 0.1 *M* triethanolamine (pH 7.3), shaken for 2 h and filtered through Whatman No. 42 filter paper. Micronutrient concentrations in the extract were determined by atomic absorption spectrophotometry and expressed as mg kg^{-1} soil.

2.3 Statistical Analysis

Data were subjected to analysis of variance appropriate for the randomised block design, and treatment means were compared using the critical difference (CD) at the 5% probability level when treatment effects were significant.

3. Results and Discussion

3.1 DTPA-extractable Micronutrients

Long-term nutrient management substantially modified the concentration and vertical distribution of DTPA-extractable Zn, Cu, Mn and Fe in the Vertisol under the soybean-wheat cropping system. Across all treatments, the four micronutrients showed a distinct vertical stratification, with concentrations generally decreasing progressively from the surface (0-15 cm) towards the deepest layer (75-90 cm). However, the magnitude of this decline varied considerably with nutrient-management history, indicating that long-term fertiliser and manure inputs influenced not only the size of the available micronutrient pools but also their persistence within the soil profile.

At 0-15 cm, DTPA-extractable Zn, Cu, Mn and Fe varied from 0.24-1.03, 0.90-1.83, 10.97-17.11 and 13.61-28.35 mg kg^{-1}, respectively. At 75-90 cm, their corresponding ranges declined to 0.10-0.46, 0.46-0.84, 3.78-8.87 and 4.37-9.13 mg kg^{-1}. The consistently greater concentrations in the surface soil can be attributed to the greater contribution of fertiliser-derived nutrients, crop-residue return, root turnover and rhizosphere activity in the upper soil layer. In contrast, the subsurface layers receive relatively limited fresh organic inputs and root-derived carbon, which may restrict biological cycling and enhance the proportion of micronutrients retained by soil minerals. Singh *et al*. (2023) reported similar depth-dependent decreases in DTPA-extractable micronutrients under long-term nutrient-management practices.

3.2 DTPA-extractable Zinc

DTPA-extractable Zn exhibited a clear treatment-dependent and depth-dependent response. Surface-soil Zn ranged from 0.24 to 1.03 mg kg^{-1}, while the corresponding range at 75-90 cm was 0.10-0.46 mg kg^{-1} (Table 1 and Fig 1(a)). Among the nutrient-management treatments, 100% NPK + Zn consistently maintained the highest DTPA-extractable Zn throughout the soil profile, with the concentration declining from 1.03 mg kg^{-1} at 0-15 cm to 0.46 mg kg^{-1} at 75-90 cm. The persistence of the higher Zn pool under this treatment is primarily linked to the long-term history of Zn fertilisation, which provided an external source of Zn to offset removal by the intensively cultivated soybean-wheat sequence. The greater Zn concentration at depth relative to most other treatments also indicates some redistribution of Zn within the profile over the long experimental period. Enhanced DTPA-Zn under sustained and higher fertiliser inputs has similarly been reported by Rathod *et al.* (2025) and Ghosh *et al.* (2001).

The 100% NPK + FYM treatment maintained the second-highest Zn concentrations, decreasing from 0.71 mg kg^{-1} in the surface layer to 0.30 mg kg^{-1} in the deepest layer. Although FYM did not produce Zn concentrations equivalent to the specific Zn-fertilised treatment, its consistently superior Zn status compared with the remaining treatments demonstrates the contribution of organic amendments to Zn availability. Repeated FYM addition supplies organic substrates that can interact with Zn through complexation and chelation, thereby modifying its retention and extractability. Decomposition of organic residues may also stimulate microbial activity and nutrient turnover, facilitating the transformation of less available Zn pools into more extractable forms. Similar increases in DTPA-Zn under long-term integrated nutrient management have been reported by Meena *et al.* (2019), Meena *et al.* (2023) and Puniya *et al.* (2019).

The 150% NPK, 100% NPK, 100% NPK-S and 100% NP treatments recorded intermediate Zn concentrations of 0.57, 0.54, 0.53 and 0.52 mg kg^{-1}, respectively, in the 0-15 cm layer. Their relatively higher Zn availability than the 50% NPK, 100% N, and control treatments may partly reflect greater crop growth and biomass production under comparatively adequate nutrient supply. Greater root development and residue production can increase Zn recycling through root turnover and decomposition of plant residues. Thus, even where Zn was not directly supplied, adequate macronutrient availability may have indirectly supported the maintenance of the available Zn pool, a finding similar to those reported by Rathod *et al.* (2025) and Kumar *et al.* (2025).

The lowest Zn concentration was consistently observed under the control, declining from 0.24 mg kg^{-1} at 0-15 cm to 0.10 mg kg^{-1} at 75-90 cm. The low Zn status under the control reflects the cumulative effect of continuous crop removal without external nutrient replenishment. The relatively low concentrations under 50% NPK and 100% N similarly indicate that reduced nutrient inputs may limit crop biomass and, consequently, the return of Zn through plant residues and root turnover. The strong contrast between Zn-fertilised and unfertilised treatments demonstrates the importance of long-term nutrient replenishment in preventing depletion of available Zn under intensive cropping.

The progressive decline in Zn with depth was evident even in the most favourable treatments. Under 100% NPK + Zn (1.03 to 0.46 mg kg^{-1}), Zn decreased by more than half between the surface and deepest layers. A pronounced reduction was also observed under the FYM and control treatments, closely agreeing with the depth-wise decline reported by Singh *et al.* (2023).

3.3 DTPA-extractable Copper

DTPA-extractable Cu displayed a pattern broadly similar to Zn, with a pronounced decrease down the soil profile. Copper concentration ranged from 0.90 to 1.83 mg kg^{-1} at 0-15 cm and from 0.46 to 0.84 mg kg^{-1} at 75-90 cm (Table 1 and Fig 1(b)). However, unlike Zn, where direct Zn fertilisation produced the highest values, the highest Cu availability was consistently observed under 100% NPK + FYM. Cu under this treatment decreased from 1.83 mg kg^{-1} at 0-15 cm to 0.84 mg kg^{-1} at 75-90 cm, indicating that FYM substantially enhanced the size of the extractable Cu pool throughout the profile.

The strong response of Cu to FYM can be explained by the close association of Cu with soil organic matter. Organic ligands generated during decomposition can form Cu-organic complexes and influence its retention, solubility and extractability. Continuous FYM application may therefore maintain a dynamic pool of Cu that is more readily extractable than under mineral fertilisation alone. In addition, enhanced microbial activity associated with organic matter decomposition may promote Cu transformation and recycling. Similar enhancement of DTPA-Cu under integrated fertiliser-FYM management has been reported by Singh *et al.* (2009), Meena *et al.* (2023), and Singh *et al.* (2019), whereas de Santiago *et al.* (2008) emphasised the role of organic ligands in enhancing micronutrient availability.

The 150% NPK treatment maintained the second-highest Cu availability, with concentrations declining from 1.55 to 0.79 mg kg^{-1} from 0-15 to 75-90 cm. The higher Cu availability under increased fertiliser application may be associated with greater crop productivity, root proliferation and residue return, thereby enhancing Cu recycling in the rhizosphere, as reported by Rathod *et al.* (2025). The 100% NPK + Zn, 100% NPK, 100% NPK-S and 50% NPK treatments recorded surface concentrations of 1.28, 1.19, 1.14 and 1.09 mg kg^{-1}, respectively. Thus, balanced nutrient supply maintained a substantially larger Cu pool than treatments receiving only N or no fertiliser.

The lowest Cu concentrations were recorded under 100% N and control, with surface values of 0.94 and 0.90 mg kg^{-1}, respectively, decreasing to 0.52 and 0.46 mg kg^{-1} at 75-90 cm. These lower concentrations suggest that continuous crop removal, without adequate nutrient replenishment, gradually reduced the replenishable Cu pool. The absence of FYM under these treatments may have further limited organic matter-mediated Cu complexation and recycling. The consistent depth-wise decline, together with the strong response to FYM, indicates that Cu availability was particularly responsive to the soil's long-term organic matter regime.

3.4 DTPA-extractable Manganese

DTPA-extractable Mn showed a strong vertical gradient, ranging from 10.97-17.11 mg kg^{-1} at 0-15 cm and decreasing to 3.78-8.87 mg kg^{-1} at 75-90 cm. The highest Mn concentration throughout the profile was recorded under 100% NPK + FYM, where it declined from 17.11 to 8.87 mg kg^{-1} with depth (Table 2 and Fig 2(a)). Maintaining a relatively large Mn pool under FYM suggests that long-term organic matter addition enhanced the processes responsible for Mn recycling and extractability. FYM decomposition can provide carbon substrates for microbial activity and organic ligands that modify Mn transformations and its interaction with soil constituents.

The 150% NPK treatment also maintained high Mn availability, with concentrations declining from 15.85 to 8.34 mg kg^{-1} across the profile. A particularly important observation was that at 60-75 cm, Mn under 150% NPK (10.98 mg kg^{-1}) was statistically at par with 100% NPK + FYM (11.12 mg kg^{-1}). This indicates that higher mineral nutrient supply maintained Mn availability comparable to integrated nutrient management at this depth. Enhanced crop growth, root development and residue return under 150% NPK may have increased the internal recycling of Mn within the soil-plant system.

Table 1. Vertical changes in DTPA-extractable zinc and copper as influenced by long-term addition of fertilizer and manure

Treatments	DTPA-Extractable Zinc (mg kg^{-1})						DTPA-Extractable copper (mg kg^{-1})					
	Soil Depth (cm)						Soil Depth (cm)					
	0-15	**15-30**	**30-45**	**45-60**	**60-75**	**75-90**	**0-15**	**15-30**	**30-45**	**45-60**	**60-75**	**75-90**
50% NPK	0.42	0.35	0.31	0.23	0.19	0.16	1.09	1.00	0.95	0.82	0.71	0.56
100% NPK	0.54	0.48	0.41	0.31	0.27	0.23	1.28	1.19	1.09	0.96	0.84	0.71
150% NPK	0.57	0.51	0.43	0.32	0.28	0.24	1.55	1.38	1.23	1.05	0.91	0.79
100% NPK + Zn	1.03	0.93	0.79	0.59	0.53	0.46	1.30	1.22	1.14	0.98	0.86	0.74
100% NP	0.52	0.44	0.39	0.29	0.25	0.22	1.14	1.04	0.99	0.85	0.75	0.60
100% N	0.28	0.23	0.20	0.14	0.12	0.11	0.94	0.85	0.81	0.66	0.58	0.52
100% NPK + FYM	0.71	0.62	0.52	0.41	0.34	0.30	1.83	1.57	1.45	1.23	1.14	0.84
100% NPK (- S)	0.53	0.46	0.40	0.31	0.26	0.22	1.19	1.09	1.02	0.89	0.75	0.64
Control	0.24	0.21	0.18	0.13	0.12	0.10	0.90	0.81	0.78	0.64	0.54	0.46
SEm (±)	**0.034**	**0.031**	**0.028**	**0.018**	**0.016**	**0.012**	**0.043**	**0.042**	**0.039**	**0.036**	**0.035**	**0.032**
CD (*p*=0.05)	**0.102**	**0.093**	**0.083**	**0.054**	**0.048**	**0.036**	**0.129**	**0.126**	**0.117**	**0.107**	**0.104**	**0.097**

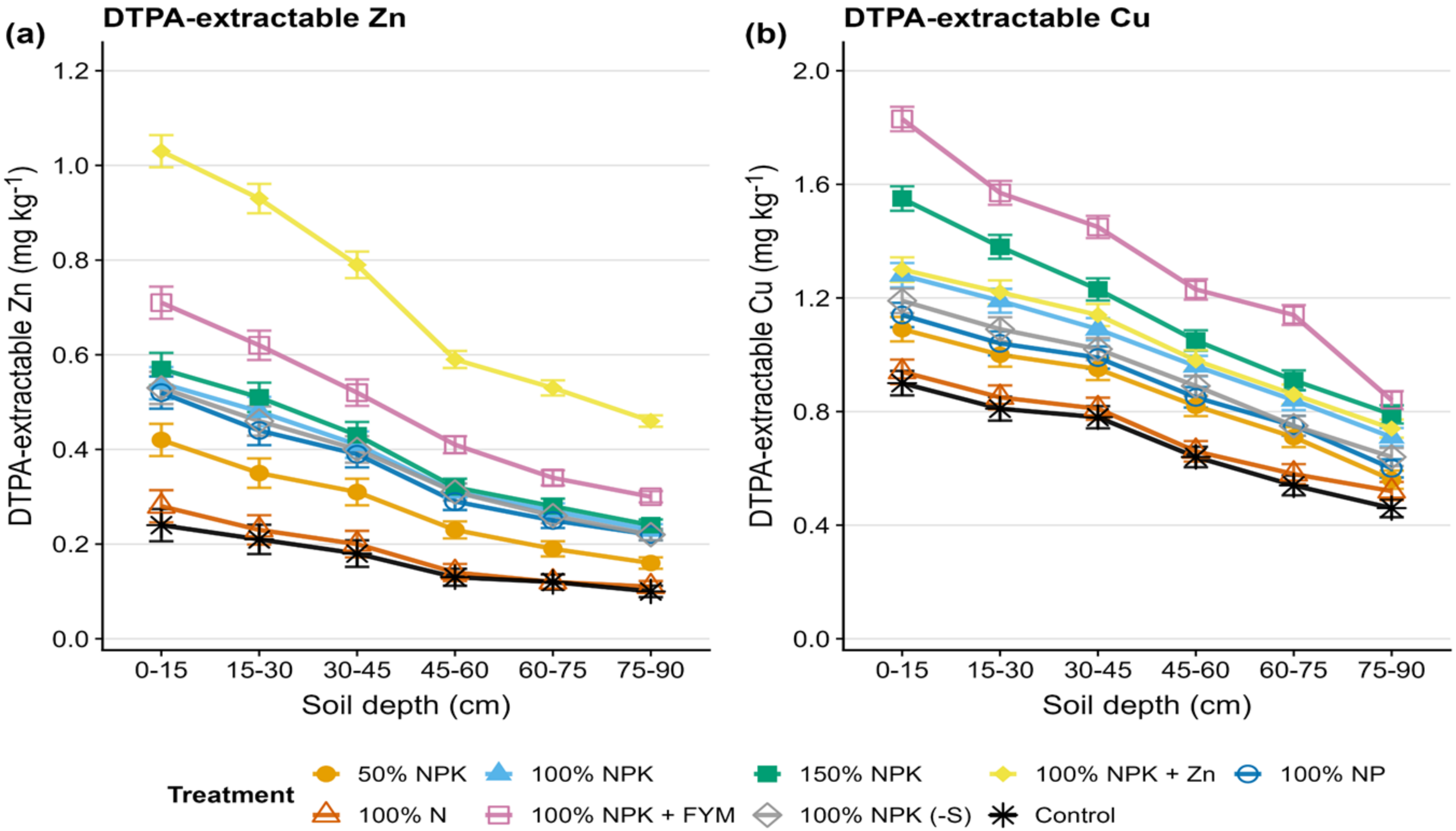

Fig. 1. Vertical changes in DTPA-extractable zinc and copper as influenced by long-term addition of fertilizer and manure

Table 2. Vertical changes in DTPA-extractable manganese and iron as influenced by long-term addition of fertilizer and manure

Treatments	DTPA-Extractable Manganese (mg kg^{-1})						DTPA-Extractable Iron (mg kg^{-1})					
	Soil Depth (cm)						Soil Depth (cm)					
	0-15	**15-30**	**30-45**	**45-60**	**60-75**	**75-90**	**0-15**	**15-30**	**30-45**	**45-60**	**60-75**	**75-90**
50% NPK	12.65	10.45	9.31	7.98	6.77	5.37	17.08	13.42	10.76	8.31	6.43	4.92
100% NPK	14.51	12.61	11.83	10.65	9.40	7.14	20.70	15.83	13.17	10.51	9.35	7.20
150% NPK	15.85	14.08	12.68	11.98	10.98	8.34	26.60	17.87	15.63	12.32	11.03	9.01
100% NPK + Zn	14.95	13.27	12.03	10.98	9.65	7.59	21.74	16.15	13.79	11.02	9.75	7.58
100% NP	13.20	11.76	9.74	8.89	7.41	6.24	19.75	14.49	11.99	9.65	7.68	5.57
100% N	11.35	9.89	8.01	7.38	6.02	4.58	15.31	11.84	9.38	7.48	5.14	4.65
100% NPK + FYM	17.11	14.74	12.85	12.12	11.12	8.87	28.35	19.65	17.31	12.86	11.67	9.13
100% NPK (- S)	13.92	12.53	11.35	10.11	8.96	6.81	20.30	14.89	12.52	10.13	8.97	6.71
Control	10.97	8.65	6.94	6.47	5.36	3.78	13.61	10.30	8.76	6.96	4.89	4.37
SEm (±)	**0.429**	**0.256**	**0.253**	**0.309**	**0.241**	**0.296**	**0.571**	**0.505**	**0.543**	**0.448**	**0.415**	**0.377**
CD (p=0.05)	**1.286**	**0.767**	**0.758**	**0.925**	**0.722**	**0.886**	**1.713**	**1.513**	**1.628**	**1.343**	**1.243**	**1.132**

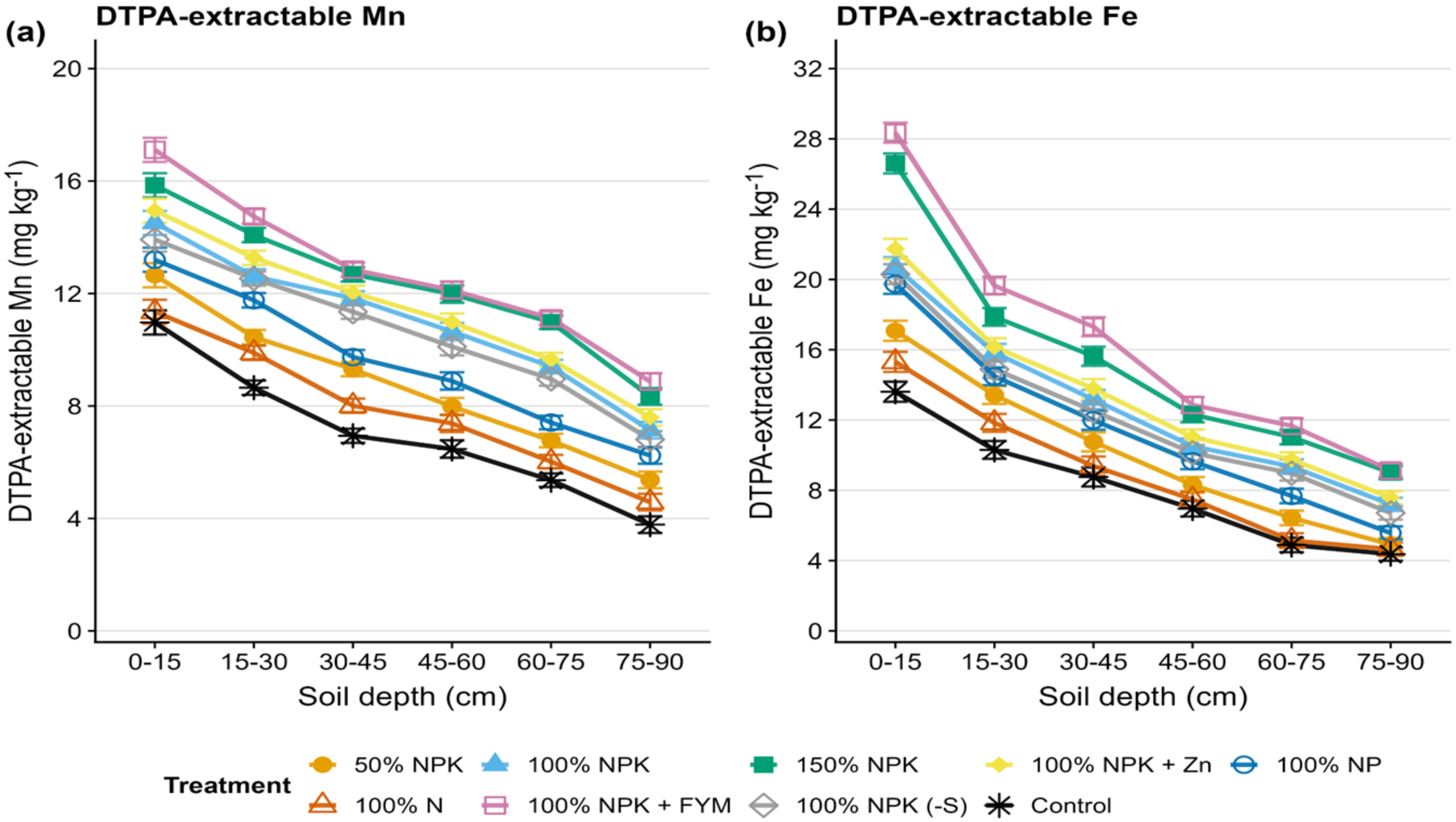

Fig. 2. Vertical changes in DTPA-extractable manganese and iron as influenced by long-term addition of fertilizer and manure

The 100% NPK + Zn, 100% NPK and 100% NPK-S treatments maintained relatively high Mn concentrations, recording 14.95, 14.51 and 13.92 mg kg^{-1}, respectively, at 0-15 cm. The relatively high Mn status under these treatments suggests that balanced macronutrient supply can indirectly support micronutrient cycling by sustaining crop growth and root activity. In contrast, surface Mn concentrations under 100% NP, 50% NPK and 100% N were lower at 13.20, 12.65 and 11.35 mg kg^{-1}, respectively.

The control treatment recorded the lowest Mn concentration, decreasing from 10.97 mg kg^{-1} in the surface layer to 3.78 mg kg^{-1} at 75-90 cm. The magnitude of depletion in the unfertilised soil suggests that continuous crop removal without replenishment progressively reduced the available Mn pool. The substantially lower Mn concentrations in deeper soil further indicate that the absence of organic inputs and reduced root activity limited Mn replenishment at depth. These findings support observations by Meena *et al.* (2023), Wei *et al.* (2006) and Zhang *et al.* (2022) on the beneficial effects of balanced and integrated nutrient management on micronutrient availability.

3.5 DTPA-extractable Iron

DTPA-extractable Fe exhibited the largest concentration range among the four micronutrients and followed the same overall depth-dependent pattern. Surface Fe concentrations ranged from 13.61 to 28.35 mg kg^{-1}, while at 75-90 cm they declined to 4.37-9.13 mg kg^{-1} (Table 2 and Fig 2(b)). The highest Fe availability was consistently recorded under 100% NPK + FYM, declining from 28.35 to 9.13 mg kg^{-1} across the profile. This treatment effect indicates a strong association between sustained organic matter addition and maintenance of the extractable Fe pool.

The higher Fe concentration under FYM may result from the formation of soluble Fe-organic complexes and the supply of organic ligands during decomposition. Such interactions can modify Fe retention and reduce its conversion into less extractable forms. Enhanced microbial activity and greater rhizosphere activity under repeated FYM application may further contribute to Fe cycling. Consistent enhancement of DTPA-Fe under integrated fertiliser-FYM management has been reported by Meena *et al.* (2019), Rathod *et al.* (2025), Singh *et al.* (2019) and Singh *et al.* (2023).

The 150% NPK treatment maintained the second-highest Fe concentration, declining from 26.60 to 9.01 mg kg^{-1} with depth. Similar to Mn, Fe under 150% NPK (11.03 mg kg^{-1}) was statistically at par with 100% NPK + FYM (11.67 mg kg^{-1}) at 60-75 cm. This observation is particularly relevant because it demonstrates that the positive effect of increased fertiliser input was not restricted to surface soil but extended into the subsurface profile. Greater crop biomass, root proliferation and residue return under higher nutrient availability may have contributed to enhanced Fe recycling.

At 0-15 cm, 100% NPK + Zn, 100% NPK and 100% NPK-S recorded 21.74, 20.70 and 20.30 mg kg^{-1} Fe, respectively. The corresponding concentrations under 50% NPK, 100% NP and 100% N were 17.08, 19.75 and 15.31 mg kg^{-1}. These differences demonstrate that balanced nutrient supply generally maintained a greater extractable Fe pool than nutrient omission or reduced-input treatments.

The control had the lowest Fe availability, declining from 13.61 mg kg^{-1} at 0-15 cm to 4.37 mg kg^{-1} at 75-90 cm. The low Fe status under the unfertilised treatment can be related to continuous crop removal, reduced biomass and residue return, and limited organic matter-mediated mobilisation. Singh *et al.* (2023) similarly reported the lowest micronutrient availability under control conditions compared with integrated nutrient management, emphasising the role of sustained organic and mineral nutrient inputs in maintaining micronutrient availability.

Comparing the four micronutrients revealed an element-specific response to long-term nutrient management. Direct Zn fertilisation produced the strongest response for Zn, with 100% NPK + Zn consistently maintaining the highest DTPA-Zn throughout the 0-90 cm profile. In contrast, FYM integration produced the most consistent improvement in Cu, Mn and Fe, with 100% NPK + FYM recording the highest values across the profile. The higher concentrations of Cu, Mn and Fe under FYM-integrated management indicate a favourable effect of long-term FYM addition on their extractable availability. The 150% NPK treatment also maintained comparatively high concentrations of Cu, Mn and Fe and was statistically comparable with NPK + FYM for Mn and Fe at 60-75 cm. Conversely, the consistently lower values under 50% NPK, 100% N and particularly the control indicate that inadequate or absent nutrient addition was associated with lower available micronutrient concentrations.

The pronounced decline in all four micronutrients with depth was also important from a soil-fertility perspective. Surface enrichment was most evident under treatments receiving adequate fertiliser and organic inputs, whereas deeper layers generally showed progressively lower concentrations, a pattern similar to that reported by Singh *et al.* (2023) and Kumar *et al.* (2025). Thus, the long-term nutrient-management legacy was expressed not only through differences among treatments but also through differences in the vertical distribution of available micronutrients. These results show that assessing micronutrient fertility based solely on surface soil may not fully capture the effects of long-term nutrient management across the soil profile.

4. Conclusion

Long-term nutrient management markedly influenced the amount and vertical distribution of DTPA-extractable Zn, Cu, Mn and Fe in the Vertisol under soybean-wheat cultivation. Concentrations of all four micronutrients declined with soil depth, indicating pronounced surface enrichment and lower availability in deeper layers. The 100% NPK + Zn treatment maintained the highest Zn concentration throughout the profile, whereas 100% NPK + FYM consistently maintained the highest Cu, Mn and Fe concentrations. The 150% NPK treatment also sustained comparatively high Mn and Fe concentrations and was statistically at par with NPK + FYM for these micronutrients at 60-75 cm. In contrast, the unfertilised control consistently recorded the lowest micronutrient concentrations, reflecting the long-term effect of nutrient removal without external replenishment. These findings show that nutrient-management history affects not only surface micronutrient availability but also its distribution through the 0-90 cm soil profile. Balanced mineral fertilisation, together with FYM integration where applicable, therefore provides a practical basis for sustaining extractable micronutrient pools under long-term soybean-wheat cropping in this Vertisol.

5. Limitations

The study represents one long-term experimental site, one Vertisol and a soybean-wheat cropping system, so the observed depth-wise micronutrient patterns should be interpreted within these site and management conditions. Micronutrient status was assessed using DTPA-extractable Zn, Cu, Mn and Fe after wheat harvest; therefore, the findings specifically describe extractable pools at the sampling time rather than all soil micronutrient fractions or their seasonal dynamics.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Bangre, J., Sinha, N. K., Mohanty, M., Jayaraman, S., Sahoo, R. N., Dwivedi, A. K., Singh, D., Mishra, A., Kumar, S., Wanjari, R., Jha, P., Kumar, D., Mishra, R., Mandloi, S., Singh, U. K., Chaudhary, R., Reddy, K. S., Prabhakar, M., Singh, V. K., & Rao, C. S. (2024). Long-term impact of inorganic fertilizers and farmyard manure on soil quality and productivity in subtropical Vertisols under a soybean-wheat cropping system. *Land Degradation & Development, 35*(14), 4257-4270. https://doi.org/10.1002/ldr.5220

Behera, U. K., Sharma, A. R., & Pandey, H. N. (2007). Sustaining productivity of wheat-soybean cropping system through integrated nutrient management practices on the Vertisols of Central India. *Plant and Soil, 297*, 185-199. https://doi.org/10.1007/s11104-007-9332-3

Coulombe, C. E., Wilding, L. P., & Dixon, J. B. (1996). Overview of Vertisols: Characteristics and impacts on society. In D. L. Sparks (Ed.), *Advances in agronomy* (Vol. 57, pp. 289-375). Academic Press. https://doi.org/10.1016/S0065-2113(08)60927-X

de Santiago, A., Quintero, J. M., & Delgado, A. (2008). Long-term effects of tillage on the availability of iron, copper, manganese, and zinc in a Spanish Vertisol. *Soil and Tillage Research, 98*(2), 200-207. https://doi.org/10.1016/j.still.2008.01.002

Debnath, S., Narayan, R., Kumar, A., Kishor, A., & Singh, D. B. (2020). Are horticulture-based land uses benign for fertility and health of soils in mid to high hills of the north-western Himalayan region? *Soil Science and Plant Nutrition, 66*(3), 489-498. https://doi.org/10.1080/00380768.2020.1753110

Debnath, S., Purakayastha, T. J., Kishor, A., Kumar, A., & Bhowmik, A. (2022). Temperate fruit farming in fragile lands of the Northwestern Himalayan region: Implications for subsoil nutrient availability, nutrient stock and soil quality. *Land Degradation & Development, 33*(17), 3484-3496. https://doi.org/10.1002/ldr.4402

Dinka, T. M., Morgan, C. L. S., McInnes, K. J., Kishne, A. S., & Harmel, R. D. (2013). Shrink-swell behavior of soil across a Vertisol catena. *Journal of Hydrology, 476*, 352-359. https://doi.org/10.1016/j.jhydrol.2012.11.002

Ghosh, B. N., Prakas, V., & Singh, R. D. (2001). Micronutrient status in soybean (*Glycine max*)-wheat (*Triticum aestivum*) cropping system in Kumaon region of Uttaranchal. *The Indian Journal of Agricultural Sciences, 71*(3), 149-152. https://epubs.icar.org.in/index.php/IJAgS/article/view/39664

Hemalatha, S., Radhika, K., Maragatham, S., & Praveena Katharine, S. (2013). Influence of long term fertilization on soil fertility: A review. *Research & Reviews: Journal of Agriculture and Allied Sciences, 2*(3), 30-36. https://www.rroij.com/open-access/influence-of-long-term-fertilization-on-soil-fertility--a-review.php?aid=33805

Kumar, A., Saini, K. S., Sharma, S., Yadav, M., Singh, G., Devi, K., & Kumawat, K. C. (2025). Evaluating soil physico-chemical properties and nutrient availability through intensified conservation agriculture-based cropping systems. *Frontiers in Agronomy, 7*, 1612792. https://doi.org/10.3389/fagro.2025.1612792

Kumari, M., Sheoran, S., Prakash, D., Yadav, D. B., Yadav, P. K., Jat, M. K., Ankit, & Apurva. (2024). Long-term application of organic manures and chemical fertilizers improve the organic carbon and microbiological properties of soil under pearl millet-wheat cropping system in North-Western India. *Heliyon, 10*(3), e25333. https://doi.org/10.1016/j.heliyon.2024.e25333

Lindsay, W. L., & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal, 42*(3), 421-428. https://doi.org/10.2136/sssaj1978.03615995004200030009x

Meena, B. P., Biswas, A. K., Singh, M., Chaudhary, R. S., Singh, A. B., Das, H., & Patra, A. K. (2019). Long-term sustaining crop productivity and soil health in maize-chickpea system through integrated nutrient management practices in Vertisols of central India. *Field Crops Research, 232*, 62-76. https://doi.org/10.1016/j.fcr.2018.12.012

Meena, S. N., Sharma, S. K., Singh, P., Ram, A., Meena, B. P., Jain, D., Singh, D., Debnath, S., Yadav, S., Dhakad, U., Verma, P., Meena, J. K., & Nandan, S. (2023). Tillage-based nutrient management practices for sustaining productivity and soil health in the soybean-wheat cropping system in Vertisols of the Indian semi-arid tropics. *Frontiers in Sustainable Food Systems, 7*, 1234344. https://doi.org/10.3389/fsufs.2023.1234344

Nayak, T., Bajpai, R. K., & Sharma, P. (2015). Forms of soil phosphorus and depth wise distribution under organic and inorganic nutrient management in a Vertisol planted rice. *An Asian Journal of Soil Science, 10*(1), 47-54. https://doi.org/10.15740/HAS/AJSS/10.1/47-54

Pathariya, P., Dwivedi, B. S., Dwivedi, A. K., Thakur, R. K., Singh, M., & Sarvade, S. (2022). Potassium balance under soybean-wheat cropping system in a 44 year old long-term fertilizer experiment on a Vertisol. *Communications in Soil Science and Plant Analysis, 53*(2), 214-226. https://doi.org/10.1080/00103624.2021.1984516

Patial, D., Sankhyan, N. K., Sharma, R. P., Dev, P., & Anjali. (2022). Assessing soil physical and chemical properties under long term fertilization after forty-eight years in North-Western Himalayas. *Communications in Soil Science and Plant Analysis, 53*(17), 2257-2270. https://doi.org/10.1080/00103624.2022.2071436

Peng, X., Horn, R., & Hallett, P. D. (2015). Soil structure and its functions in ecosystems: Phase matter & scale matter. *Soil and Tillage Research, 146*, 1-3. https://doi.org/10.1016/j.still.2014.10.017

Pradhan, C., Ghosh, A. K., Dixit, B. K., Bhadani, S. K., & Pradhan, S. N. (2024). Impact of integrated nutrient management on soil properties under long-term fertilizer experiment in Vertisol. *International Journal of Environment and Climate Change, 14*(1), 513-521. https://doi.org/10.9734/ijecc/2024/v14i13864

Puniya, R., Pandey, P. C., Bisht, P. S., Singh, D. K., & Singh, A. P. (2019). Effect of long-term nutrient management practices on soil micronutrient concentrations and uptake under a rice-wheat cropping system. *The Journal of Agricultural Science, 157*(3), 226-234. https://doi.org/10.1017/S0021859619000509

Rathod, S. R., Jadhao, S. D., Bhoyar, S. M., Gabhane, V. V., Sonune, B. A., Wakchaure, S. D., & Pandao, M. R. (2025). Impact of long-term manuring and fertilization on micronutrient status under sorghum-wheat cropping sequence in Vertisols. *International Journal of Plant & Soil Science, 37*(4), 293-298. https://doi.org/10.9734/ijpss/2025/v37i45410

Sahu, P., Srivastava, L. K., Bachkaiya, V., & Panda, A. (2026). Long-term nutrient inputs and soil quality dynamics in Vertisol-dominated rice-wheat systems. *International Journal of Advanced Biochemistry Research, 10*(Special Issue 2), 559-565. https://doi.org/10.33545/26174693.2026.v10.i2Sg.7671

Sardar, S., Shahi, U. P., Ahluvalia, A. K., Kumar, R., Arya, R., & Singh, S. (2024). Effect of different zinc sources and application methods on content and uptake of micronutrients of Basmati rice. *Journal of Global Agriculture and Ecology, 16*(3), 41-52. https://doi.org/10.56557/jogae/2024/v16i38795

Sharma, T., Arya, V. M., Sharma, V., Sharma, J., Gulshan, T., Bera, A., & Laskar, Y. A. (2022). Integrated nutrient management: A long-term approach towards sustainability. *International Journal of Plant & Soil Science, 34*(20), 433-446. https://doi.org/10.9734/ijpss/2022/v34i2031171

Singh, A. K., Sarkar, A. K., Kumar, A., & Singh, B. P. (2009). Effect of long-term use of mineral fertilizers, lime and farmyard manure on the crop yield, available plant nutrient and heavy metal status in an acidic loam soil. *Journal of the Indian Society of Soil Science, 57*(3), 362-365.

Singh, M., Wanjari, R. H., Lakaria, B. L., Shirale, A., Kumar, U., & Jamra, S. (2019). Response of crops to applied potassium and estimation of critical limits in Vertisols. *Indian Journal of Fertilisers, 15*(7), 748-753.

Singh, V., Rai, H. K., Jain, P., Dwivedi, B. S., Upadhyay, A. K., Agrawal, S. B., Behera, S. K., & Singh, R. B. (2023). Effect of inorganic and integrated long-term nutrient management on DTPA-extractable micronutrients in a Vertisol under soybean-wheat cropping system across the soil depth. *International Journal of Environment and Climate Change, 13*(7), 471-478. https://doi.org/10.9734/IJECC/2023/v13i71899

Wacal, C., Ogata, N., Basalirwa, D., Sasagawa, D., Ishigaki, T., Handa, T., Kato, M., Tenywa, M. M., Masunaga, T., Yamamoto, S., & Nishihara, E. (2019). Imbalanced soil chemical properties and mineral nutrition in relation to growth and yield decline of sesame on different continuously cropped upland fields converted paddy. *Agronomy, 9*(4), 184. https://doi.org/10.3390/agronomy9040184

Wei, X., Hao, M., Shao, M., & Gale, W. J. (2006). Changes in soil properties and the availability of soil micronutrients after 18 years of cropping and fertilization. *Soil and Tillage Research, 91*(1-2), 120-130. https://doi.org/10.1016/j.still.2005.11.009

Zhang, Y., Wu, L., Zhang, X., Deng, A., Abdulkareem, R., Wang, D., Zheng, C., & Zhang, W. (2022). Effect of long-term organic amendment application on the vertical distribution of nutrients in a Vertisol. *Agronomy, 12*(5), 1162. https://doi.org/10.3390/agronomy12051162

Zhou, H., Chen, C., Wang, D., Arthur, E., Zhang, Z., Guo, Z., Peng, X., & Mooney, S. J. (2020). Effect of long-term organic amendments on the full-range soil water retention characteristics of a Vertisol. *Soil and Tillage Research, 202*, 104663. https://doi.org/10.1016/j.still.2020.104663

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