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Impact of long-term nutrient management on soil physico-chemical properties across the soil depth of a Vertisol under soybean-wheat cropping

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ABSTRACT

Long-term nutrient management can influence soil chemical properties and carbon dynamics, with important implications for maintaining soil quality under continuous cropping. The present study evaluated the effects of long-term fertilizer and manure application on soil pH, electrical conductivity (EC) and soil organic carbon (SOC) across the soil profile of a Vertisol under a soybean-wheat cropping system during 2024-25 at the AICRP-LTFE, 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 and an unfertilized control, arranged in a randomized block design with three replications. Soil samples collected after wheat harvest from six depths (0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm) were analysed for pH, EC and SOC. Soil pH remained statistically unaffected by nutrient management, with values ranging from 7.50-7.68 at 0-15 cm to 7.60-7.78 at 75-90 cm, showing a slight increase with depth. Similarly, EC was not significantly influenced by treatments and ranged from 0.14-0.18 dS m⁻¹ in the surface layer to 0.17-0.22 dS m⁻¹ at 75-90 cm, indicating no appreciable salt accumulation. In contrast, SOC showed significant treatment variation and declined progressively with depth, ranging from 4.28-8.99 g kg⁻¹ at 0-15 cm to 2.01-3.34 g kg⁻¹ at 75-90 cm. The 100% NPK + FYM treatment consistently maintained the highest SOC, whereas 100% N and control recorded the lowest values. All those, SOC was more responsive to long-term nutrient management than pH and EC, highlighting the importance of integrating FYM with balanced mineral fertilization for sustaining soil carbon and soil quality under continuous soybean-wheat cultivation.

Keywords: Electrical conductivity, Long-term fertilizer experiment, Soybean-wheat cropping system, Soil organic carbon, Soil pH, Vertisol

Introduction

Soil fertility is a dynamic property governed by continuous interactions among nutrient inputs, crop removal, organic matter turnover and changes in soil chemical conditions. Under intensive and continuous cropping, long-term nutrient removal without adequate and balanced replenishment can progressively modify soil chemical properties and carbon dynamics, with implications for the sustainability of soil productivity. Therefore, evaluation of long-term nutrient management needs to extend beyond crop productivity to include changes in key soil properties that regulate nutrient cycling, retention and availability (Sharma *et al.*, 2022; Datta *et al.*, 2025) [2, 1]. Among these properties, soil pH, electrical conductivity (EC) and soil organic carbon (SOC) provide complementary information on soil reaction, soluble salt status and the condition of the soil organic matter pool.

Soil pH is a fundamental property governing nutrient solubility, adsorption-desorption reactions and the availability of essential plant nutrients. Its response to long-term fertilizer application depends on fertilizer source, application rate, nutrient balance, cropping history and the buffering capacity of the soil. These factors are particularly important in Vertisols, which constitute an important agricultural soil resource in the semi-arid and sub-humid regions of India. Their high clay content, smectite-dominated mineralogy, high cation exchange capacity and pronounced shrink-swell behavior influence nutrient retention, water movement and chemical reactions within the soil profile (Zhang *et al.*, 2022) [3]. Consequently, although Vertisols possess considerable buffering capacity, prolonged cultivation and contrasting fertilizer regimes may gradually modify their chemical environment, particularly where nutrient replenishment is inadequate or unbalanced (Peng *et al.*, 2015; Zhou *et al.*, 2020) [4, 5].

Electrical conductivity (EC) is an important indicator of the soluble salt status of soil and reflects the concentration of dissolved ionic constituents in the soil solution. Repeated application of mineral fertilizers introduces substantial quantities of nutrient ions and may influence soil EC depending on fertilizer rate, nutrient combination, crop uptake, rainfall, drainage and movement of soluble constituents through the profile. Conversely, organic amendments can modify the soluble nutrient environment through decomposition and

nutrient release. Thus, long-term monitoring of EC is important for determining whether continuous fertilizer and manure application results in appreciable accumulation of soluble salts or changes in the chemical environment of intensively cultivated soils. The response of EC may also vary with depth because of differences in ion movement, retention and redistribution within the soil profile.

Soil organic carbon (SOC) is a major indicator of soil quality and is closely associated with soil structure, aggregation, nutrient retention and biological functioning. Long-term mineral fertilization can influence SOC indirectly by modifying crop productivity, root growth and residue returns, while organic amendments such as farmyard manure (FYM) provide an additional and direct source of carbon to the soil. The magnitude of SOC change depends on the quantity and quality of carbon inputs, nutrient balance, cropping intensity and the stabilization of organic matter within the soil matrix (Kumari *et al.*, 2024) [6]. Integration of mineral fertilizers with FYM can therefore enhance carbon inputs and contribute to the maintenance of soil organic matter over the long term (Patil *et al.*, 2022; Sahu *et al.*, 2026) [7, 8]. Long-term fertilizer experiments provide an appropriate framework for assessing these cumulative changes because nutrient-management effects are evaluated under a relatively consistent soil, climate and cropping history.

The soybean-wheat cropping system is an important production system in central India, particularly Madhya Pradesh, where continuous cultivation involves substantial nutrient demand and repeated removal of nutrients through harvested biomass. Long-term differences in fertilizer rate, nutrient combination and organic manure application can consequently create contrasting trajectories of soil chemical properties and carbon status (Meena *et al.*, 2023) [9]. Furthermore, pH, EC and SOC are not uniformly distributed within the soil profile. Surface soil generally receives greater inputs of crop residues and root-derived organic matter, whereas the distribution of soluble constituents and soil reaction may be influenced by downward movement, mineral interactions and changes in organic matter with depth. Hence, assessment across the soil profile is necessary to capture the cumulative effects of long-term nutrient management beyond the surface layer.

Long-term fertilizer experiments (LTFE) provide a unique opportunity to quantify the cumulative and residual effects of contrasting nutrient-management practices under relatively consistent soil, climate and cropping conditions over several decades (Dikr, 2023; Tiwari *et al.*, 2024) [10, 11]. The present investigation was therefore undertaken to evaluate the vertical distribution of soil pH, electrical conductivity and soil organic carbon in a Vertisol under a long-term soybean-wheat cropping system subjected to contrasting rates and combinations of mineral fertilizers, nutrient omission, Zn application, FYM integration and an unfertilized control. The study specifically aimed to characterize depth-wise changes in soil pH, EC and SOC and assess the long-term effects of contrasting nutrient-management practices on the chemical environment and carbon status of the soil profile.

Materials and methods

Experimental site and design

The investigation was carried out in 2024-25 using the ongoing Long-Term Fertilizer Experiment (LTFE) established at JNKVV, Jabalpur, Madhya Pradesh, India (23°21' N, 79°94' E; 393 m above mean sea level). The experiment began in 1972 and the soybean-wheat cropping sequence has been maintained since 1993-94. The experimental soil is a clayey Vertisol (*Typic Haplustert*) of the Kheri series, classified under the fine, montmorillonite, hyperthermic family.

The study comprised nine contrasting nutrient-management regimes: 50% NPK, 100% NPK, 150% NPK, 100% NPK + Zn, 100% NP, 100% N, 100% NPK + FYM, 100% NPK-S and an unfertilized control. Treatments were maintained in a randomized block design with three replications, with each experimental plot measuring 17 × 10.8 m. The recommended fertilizer rates were 20:80:20 kg N:P:K ha⁻¹ for soybean and 120:80:40 kg N:P:K ha⁻¹ for wheat. Farmyard manure was incorporated annually at 5 t ha⁻¹ in soybean, whereas the NPK +

Zn treatment received 20 kg ZnSO₄ ha⁻¹ in alternate wheat seasons until 1987. For the NPK-S treatment, we supplied phosphorus using DAP instead of SSP.

Soil sampling

After wheat harvest in 2024-25, we collected profile soil samples separately from each treatment and replication at six depths: 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm. Within each experimental plot, we collected soil from multiple representative points using a screw auger to account for spatial variability. Samples corresponding to individual treatment × replication × depth combinations were maintained separately for subsequent laboratory analysis. The samples were then air-dried, manually cleared of visible roots and plant residues, gently disaggregated and passed through a 2-mm sieve before determining soil physicochemical properties.

Analysis of soil physico-chemical properties

The soil samples were analysed for soil pH, electrical conductivity (EC) and soil organic carbon (SOC) using standard laboratory procedures.

Soil pH

Soil pH was determined in a 1:2.5 soil-water suspension following Piper (1966) [12]. Ten grams of air-dried soil was mixed with 25 mL of distilled water and stirred thoroughly. After equilibration, the pH of the suspension was measured using a calibrated digital pH meter after standardization with buffer solutions of known pH.

Electrical conductivity

Electrical conductivity was determined in the 1:2.5 soil-water extract following Jackson (1973) [13]. The soil-water suspension was allowed to stand overnight and the electrical conductivity of the clear supernatant was measured using a conductivity meter. The EC values were expressed as dS m⁻¹ at 25 °C.

Soil organic carbon

Soil organic carbon was determined by the Walkley *et al.* (1934) [14] chromic acid wet oxidation method. Briefly, 1 g of air-dried soil was taken in a 500-mL conical flask and a blank was run simultaneously. Ten millilitres of 1 N potassium dichromate (K₂Cr₂O₇) solution was added, followed by 20 ml concentrated sulphuric acid (H₂SO₄). The contents were mixed carefully and allowed to stand for 30 min for oxidation of organic carbon. Subsequently, 200 ml distilled water, 10 ml orthophosphoric acid and 1 ml diphenylamine indicator were added. The excess dichromate was titrated against 0.5 N ferrous ammonium sulphate (FAS) until the colour changed from blue to green. Soil organic carbon was calculated from the difference between sample and blank titration readings and expressed as g kg⁻¹ soil.

Statistical analysis

The data for pH, EC and SOC were subjected to analysis of variance (ANOVA) appropriate for the randomized block design. Treatment means were compared using the critical difference (CD) at the 5% probability level when the treatment effect was significant.

Results and discussion

Soil pH

Long-term nutrient management did not significantly affect soil pH at any of the sampling depths, indicating that soil reaction remained relatively stable despite more than five decades of contrasting fertilizer and manure application. Across the treatments, soil pH ranged from 7.50-7.68 at 0-15 cm and increased slightly with depth to 7.60-7.78 at 75-90 cm (Fig 1). The 100% NPK + FYM treatment generally recorded the lowest pH, whereas the control maintained the highest values throughout the profile. The relatively lower pH under FYM may be associated with the decomposition of organic materials and the formation of organic acids; however, the magnitude of this change was insufficient to produce a statistically significant treatment effect.

The limited response of soil pH to long-term nutrient management is characteristic of the strong buffering capacity of Vertisols. Their high clay content and carbonate-bearing nature can effectively moderate changes in soil reaction arising from repeated fertilizer inputs. Similar stability of soil pH under long-term nutrient management in black soils was reported by Dwivedi *et al.* (2015) [15], while Dubey *et al.* (2015) [16] observed non-significant variation in pH across depths following prolonged fertilizer application in Vertisol. Bairwa *et al.* (2020) [17] attributed the stability of soil reaction to the clay-rich nature and Tiwari *et al.* (2024) [11] likewise reported statistically unchanged soil pH under continuous fertilization and manuring.

The slight increase in pH with depth, together with the absence of significant treatment effects, suggests that the inherent buffering properties of this Vertisol were sufficient to minimize cumulative changes in soil reaction under the long-term nutrient regimes. In contrast to SOC, which showed clear treatment-related differences, pH remained within a relatively narrow range throughout the 0-90 cm profile, indicating greater resistance of soil reaction to long-term nutrient-management changes.

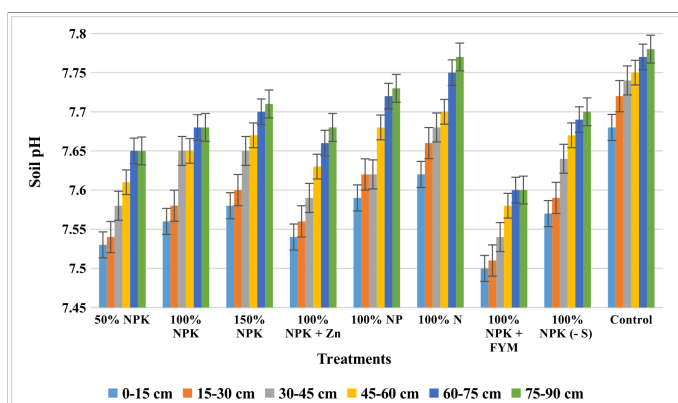


Figure 1. Impact of Long-term Nutrient Management on Soil pH across the Soil depth

Electrical conductivity

Electrical conductivity (EC) was not significantly influenced by long-term nutrient management at any soil depth, indicating that prolonged fertilizer and manure application did not result in appreciable accumulation of soluble salts in the soil profile. At 0-15 cm, EC ranged from 0.14-0.18 dS m⁻¹, while at 75-90 cm it increased slightly to 0.17-0.22 dS m⁻¹ (Fig 2). Among the treatments, 150% NPK generally recorded the highest EC, whereas 50% NPK recorded the lowest values.

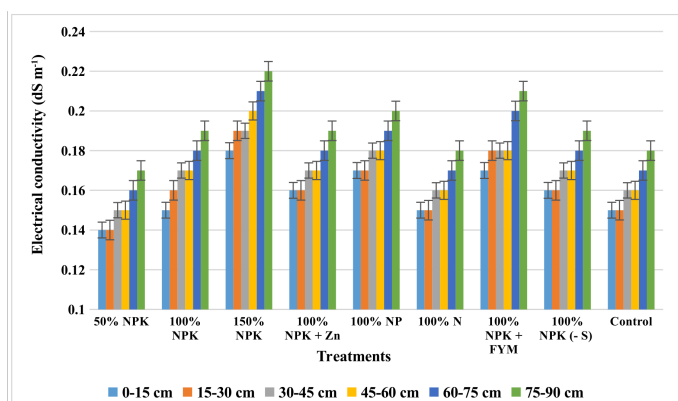


Figure 2. Impact of Long-term Nutrient Management on Electrical conductivity (dS m⁻¹) across the Soil depth

The relatively higher EC observed under 150% NPK is consistent with the greater quantity of fertilizer-derived ions introduced into the soil under this treatment. Singh *et al.* (2015) [18] similarly reported relatively higher EC under long-term 150% NPK, 100% NPK and

100% NPK + Zn treatments. Nevertheless, the absence of significant treatment differences in the present study indicates that the additional soluble ions associated with higher fertilizer inputs did not accumulate to a level sufficient to substantially modify the electrical conductivity of the soil.

A slight increase in EC with depth was observed across the soil profile. This pattern may reflect redistribution and downward movement of soluble constituents within the profile. Since individual soluble ions were not quantified in the present investigation, the depth-wise increase in EC cannot be attributed to any specific ionic component. Importantly, the consistently low EC values indicate that the soil remained under a low-salinity condition despite long-term nutrient application. Suman *et al.* (2018) [19] reported similarly marginal changes in EC under long-term inorganic fertilization, while Birla *et al.* (2015) [20] highlighted the potential role of FYM in regulating soil chemical conditions. Pradhan *et al.* (2024) [21] and Tiwari *et al.* (2024) [11] also reported low EC and limited salt accumulation under long-term nutrient-management practices.

Thus, the EC response indicates that even prolonged application of contrasting fertilizer regimes, including the higher 150% NPK level, did not produce significant salt accumulation within the 0-90 cm soil profile. This suggests that the balance among fertilizer inputs, crop uptake and movement of soluble constituents was sufficient to maintain a low-salinity soil environment under the soybean-wheat cropping system.

Soil organic carbon

In contrast to pH and EC, soil organic carbon (SOC) showed a significant response to long-term nutrient management and declined progressively with increasing soil depth. Across treatments, SOC ranged from 4.28-8.99 g kg⁻¹ at 0-15 cm, decreasing to 2.01-3.34 g kg⁻¹ at 75-90 cm (Fig 3). The higher SOC concentration in surface soil reflects the greater contribution of crop residues, root-derived carbon and other organic inputs to the upper soil layer. With increasing depth, these carbon inputs and associated biological processes generally decrease, resulting in lower SOC concentrations. Similar depth-wise declines under long-term nutrient management have been reported by Inwati *et al.* (2022) [22] and Thakur *et al.* (2011) [23].

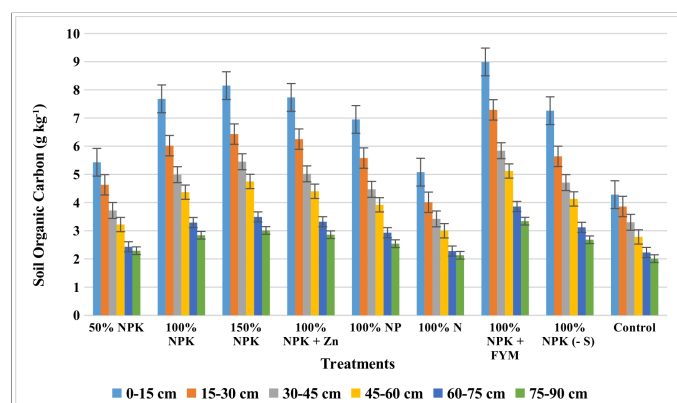


Figure 3. Impact of Long-term Nutrient Management on Soil Organic Carbon (g kg⁻¹) across the Soil depth

The 100% NPK + FYM treatment consistently recorded the highest SOC throughout the profile, with values of 8.99, 7.29, 5.84, 5.12, 3.86 and 3.34 g kg⁻¹ at 0-15, 15-30, 30-45, 45-60, 60-75 and 75-90 cm, respectively. The sustained superiority of this treatment highlights the importance of continuous organic inputs for maintaining soil carbon under intensive cropping. Annual FYM application directly contributes organic substrates to the soil, while balanced fertilization can promote crop growth and consequently increase carbon return through roots and crop residues. Swarup *et al.* (2000) [24] similarly reported an increase in SOC from 5.7 to 9.6 g kg⁻¹ under 100% NPK + FYM. Comparable enhancement of SOC under integrated nutrient management has been reported by Patel *et al.* (2018) [25],

Khandagle *et al.* (2019b) [26], Bairwa *et al.* (2021) [27], Verma *et al.* (2022) [28], Datta *et al.* (2025) [1] and Khandare *et al.* (2026) [29].

The 150% NPK treatment also maintained relatively high SOC, recording 8.15, 6.43, 5.45, 4.75, 3.49 and 3.01 g kg⁻¹ across the six depths and remaining statistically comparable with 100% NPK + FYM at most depths. In the absence of an external organic amendment, the higher SOC under 150% NPK may be related to sustained crop productivity and greater biomass, root and residue inputs resulting from greater nutrient availability. Thus, mineral fertilization can contribute indirectly to SOC maintenance by increasing plant-derived carbon inputs. Similar responses were reported by Kushwaha *et al.* (2017) [30], while Nagwanshi *et al.* (2023) [31] observed an increase in SOC from 5.62 g kg⁻¹ under sub-optimal fertilization to 8.51 g kg⁻¹ under super-optimal fertilization.

The balanced 100% NPK and 100% NPK + Zn treatments also maintained comparatively high SOC, particularly in the surface layer, where concentrations were 7.68 and 7.73 g kg⁻¹, respectively. Their relatively higher SOC compared with nutrient-omission treatments may reflect sustained crop growth and greater return of plant-derived organic matter. Adequate nutrient availability can support biomass production and consequently increase carbon inputs through crop residues and roots. These observations are consistent with the broader findings of Raghuwanshi *et al.* (2016) [32], Panwar *et al.* (2019) [33] and Patidar *et al.* (2021) [34] regarding the role of balanced fertilization in maintaining soil organic matter and nutrient cycling.

In comparison, 100% NP and 100% NPK-S recorded lower SOC, with surface-layer values of 6.95 and 7.26 g kg⁻¹, respectively, declining to 2.54 and 2.68 g kg⁻¹ at 75-90 cm. The lower SOC under these treatments may be associated with long-term nutrient imbalance and reduced crop-derived carbon inputs. In the NPK-S treatment, sulphur omission may have restricted efficient nutrient utilization and biomass production, thereby reducing the return of carbon through roots and residues. These results emphasize that long-term maintenance of SOC under continuous cropping depends not only on the quantity of fertilizer applied but also on the balance among essential nutrients.

The lowest SOC concentrations throughout the profile were observed under 100% N and the control. At 0-15 cm, SOC was 5.08 g kg⁻¹ under 100% N and 4.28 g kg⁻¹ under control, declining to 2.13 and 2.01 g kg⁻¹, respectively, at 75-90 cm. The lower SOC under N-only fertilization indicates that nitrogen supply alone was insufficient to maintain the carbon status achieved under balanced nutrient management. Nutrient imbalance may restrict crop productivity and biomass return, thereby reducing replenishment of soil organic matter. The unfertilized control represents the greatest degree of nutrient depletion because crops were continuously cultivated without external nutrient replenishment. The resulting low SOC reflects the cumulative effect of continuous nutrient removal combined with limited external carbon inputs. Similar reductions in SOC under N-only and unfertilized treatments were reported by Kumari *et al.* (2013) [35], Suman *et al.* (2017) [36], Choudhury *et al.* (2018) [37] and Bairwa *et al.* (2020) [17].

The three properties exhibited contrasting sensitivity to long-term nutrient management. Soil pH and EC remained comparatively stable, whereas SOC showed a strong response to long-term nutrient-management history. The persistent superiority of 100% NPK + FYM in maintaining SOC demonstrates the value of combining organic and mineral nutrient sources under continuous soybean-wheat cultivation. Conversely, the narrow ranges of pH and EC across treatments indicate that the inherent buffering capacity and chemical characteristics of the Vertisol moderated substantial changes in soil reaction and soluble salt status. From an LTFE perspective, these results demonstrate that SOC provides a more sensitive indicator of long-term changes in soil quality than pH and EC under the conditions of the present experiment. The treatment contrasts observed after several decades further highlight the importance of sustained organic inputs and balanced fertilization for maintaining the functional quality of Vertisol under intensive cropping.

Conclusion

Soil pH and electrical conductivity remained relatively stable across the long-term nutrient-management treatments, whereas soil organic carbon showed a pronounced response to nutrient-management history and soil depth. Soil pH remained within 7.50-7.78, while EC remained low at 0.14-0.22 dS m⁻¹, indicating strong buffering and no appreciable salt accumulation in the Vertisol profile. In contrast, SOC declined progressively with depth, ranging from 4.28-8.99 g kg⁻¹ at 0-15 cm to 2.01-3.34 g kg⁻¹ at 75-90 cm. The 100% NPK + FYM treatment consistently maintained the highest SOC, whereas 100% N and control recorded the lowest values. Overall, the findings demonstrate that SOC was more responsive to long-term nutrient management than pH and EC, with NPK + FYM supporting better maintenance of soil carbon and soil quality under soybean-wheat cultivation.

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