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Seasonal variation in physicochemical properties of some agricultural soils in Lucknow district, Uttar Pradesh of India

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Abstract

Background The long-term food security of Indo-Gangetic Plain depends heavily on the resilience of alluvial soil, which face compounding pressures from intensive multi-cropping and seasonal climatic extremes. Soil is a fundamental natural resource that supports agricultural productivity and seasonal changes are among the most important factors influencing soil chemical characteristics. We hypothesize that soil physicochemical characteristics in the study area would exhibit significant seasonal variation. Hence, our objective was to study the seasonal variation in the soil physical and chemical properties of the major agricultural fields in the Lucknow district and to infer the principal components responsible for the specific soil characteristics of a particular crop field. The study will provide insights into soil characteristics across different crop fields and assist farmers, researchers, and policymakers in crop management, thereby improving crop yields.

Methods The district is divided into 8 blocks, of which 6 were selected for soil sampling during 2023–2025. Wheat, paddy, and mustard crop fields having major cover were selected for the study. Soil samples were collected from selected crop fields in each block, in replicate, on a seasonal basis, and brought to the laboratory for analysis following the standard methods.

Results The texture of soil was sandy clay loam, loam, and sandy clay with an average 45% of sand, 30% clay, and 25% silt. The available nitrogen content was high across all sites, ranging from 102.23 kg/ha to 396.08 kg/ha. Available potassium ranged from 125 to 300 kg/ha, and available phosphorus from 7.53 to 34.3 kg/ha. Seasonal variation was found to be significant in the sand ($F_{2,61}$, = 177.64, $p < 0.001$) and clay ($F_{2,61}$ = 68.22, $p < 0.001$).

Conclusion The study will help farmers, researchers, and policymakers in crop management to improve yield, and include new ways for sustainable agriculture. The findings will support evidence-based soil management strategies, enhance agricultural productivity, and contribute to the scientific understanding of soil chemical processes.

Keywords Agricultural crops, Land use, Soil properties, Uttar Pradesh, PCA

1 Introduction

Soil is one of the most crucial factors for plant and crop growth [1] and for sustaining the overall ecosystem. The physical and chemical characteristics of soil are closely connected affecting health and production, making it a dynamic system [2]. Its organic and mineral matter, water, air, and living things make up its natural frame. Its potentials, which may be roughly divided into physical and chemical traits, have an immense impact on its capacity to encourage plant growth and maintain ecological processes [3]. Soil texture, structure, porosity, density, and water-holding capacity are examples of physical characteristics that describe the composition and assembly of soil [4]. Aeration, drainage, water infiltration, and root dissemination are all impacted by these properties. The structure of the soil and its capacity to hold and release nutrients are associated with its chemical characteristics [5]. Significant chemical characteristics include salinity, nutrient availability, organic matter, cation exchange capacity, and pH [6, 7]. These features affect soil organism activity, plant nutrient intake, and nutrient cycling.

Soil's physical and chemical properties are the chief drivers of agricultural production, environmental sustainability, and the well-being of terrestrial ecosystems hence their implications cannot be overlooked [8]. Crop production, ecosystem health, and long-term environmental sustainability are all significantly impacted by the physical and chemical characteristics of soil [9, 10]. The way soil particles are organized into masses, peds, or the assembly of the soil, alters the impact of texture [11]. Irrespective of the underlying texture, well-aggregated soils with stable granular assemblies provide a network of macropores that improve water infiltration [12]. This enhanced structure makes it easier for roots to penetrate, giving plants access to supplementary soil elements [13]. Inadequately compressed or structured soils, which are characterized by a lack of accumulation and reduced pore space, limit air and water flow, hamper root development, and raise the possibility of soil erosion [14]. Soil assembly is directly reflected in bulk density, which is a measure of soil mass per unit volume [15]. A high bulk density suggests inadequate root growth and decreased absorbency, whereas a low bulk density specifies more permeable soil that is favourable for plant life. One factor that affects the accessibility of vital plant nutrients is the pH of the soil [16]. In the pH range of 6.0 to 7.5, which is slightly acidic to neutral, most macronutrients and micronutrients show satisfactory solubility and absorption by plants [17].

This research is significant for Lucknow district because of the intense rice-wheat and horticulture farming on changeable alluvial soils. Continuous cropping and nutrient imbalances threaten soil health and production. The link between soil quality and yield allows for site-specific management options, sustainable intensification, increased farmer income, and long-term agricultural resilience [18, 19]. Seasonal variations in the physical and chemical characteristics of soil are vital to soil fertility and crop production in the agriculturally rigorous plains of the study area [20]. Nutrient accessibility, structural stability, and crop expansion potential are all significantly affected by seasonal variations in soil properties [3]. A detailed seasonal evaluation of these soil characteristics is critical for long-term soil health management and sustainable agriculture, given the incessant changes in land-management techniques and climatic patterns [21]. Raj et al. [22] reported how Nitrogen (N), Phosphorus (P), and Potassium (K) (NPK), and vermicompost regimes affect soil bulk density, water retention, and organic carbon in maize fields of Eastern Uttar Pradesh.

Shankar and Prasad [23] from drought-prone soils in Hamirpur, Uttar Pradesh, show noteworthy correlations between moisture, water-holding capacity, and organic carbon, which impact resilience and fertility. In Lucknow, the rice-wheat-mustard cropping pattern dominates agricultural landscapes, putting constant stress on soil nutrients. Rice production in flooded fields modifies soil redox potential and influences nitrogen and phosphorus dynamics, whereas wheat requires balanced NPK and micronutrients for optimum grain growth [24, 25]. Mustard is especially vulnerable to sulphur and boron deficits, which are increasingly common in intensively farmed alluvial soils. Continuous fertilizer application without soil testing frequently results in nutritional imbalances, diminishing soil organic carbon, and lower nutrient utilization efficiency [26]. Previous studies on agricultural soils have primarily focused on soil fertility assessment at single time points or specific cropping seasons and there are few studies assessing seasonal variations in soil chemistry in the Lucknow district using analytical methods like Principal Component Analysis (PCA) and Linear Mixed Models (LMM) and there is also substantial knowledge gap about the seasonal dynamics of soil chemical characteristics and the primary causes of these changes in the agricultural fields. Our study hypothesized that season has a major impact on soil properties in agricultural land. The objective of the study was to assess the seasonal variability of soil physico-chemical characteristics and nutrients in cropping fields of study area to identify shortages, guide site-specific fertilizer management, and sustainable long-term production. The significance of this study lies in its contribution to understanding the seasonal dynamics of soil physico-chemical properties in agricultural fields of Lucknow district, Uttar Pradesh. By examining variations in soil fertility indicators across different seasons, the research provides valuable information for improving nutrient management and sustainable agricultural practices. Furthermore, the study will aid farmers, researchers, and policymakers in developing effective crop management strategies.

2 Materials and methods

2.1 Study area

Lucknow district lies between latitudes 26°30′ N and 27°10′ N and longitudes 80°30′ E and 81°13′ E and is the state capital (Fig. 1). From June to October, the southwest monsoon provides an average of 896 mm of annual rainfall; in January, the northeast monsoon occasionally brings frontal showers. Approximately 21% of the district population

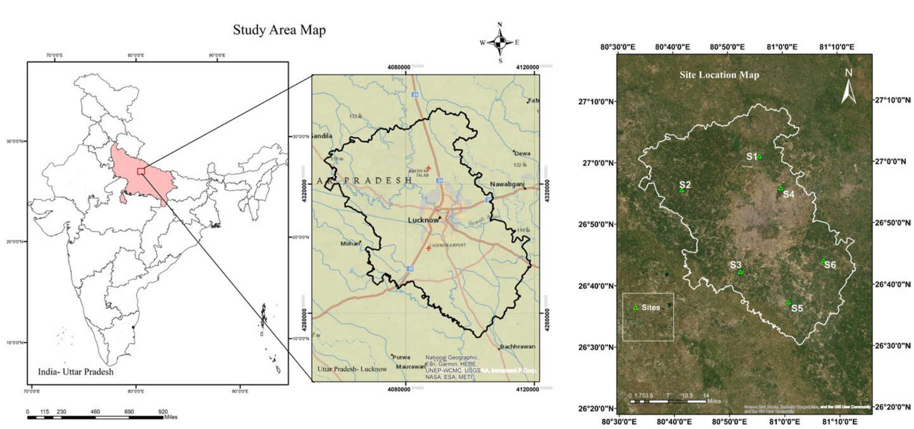

Fig. 1 Map of the study area

is engaged in agriculture, and the average land holding is about 0.8 ha. Mango, banana, guava, and papaya are fruit crops, and the main crops include wheat, rice, mustard, field peas, and sugarcane, while vegetable crops include potatoes, okra, eggplant, and peas. The district is divided into eight zones, i.e., Mohanlal Ganj, Gosaiganj, Sarojini Nagar, Chinhat, Kakori, Bakshi ka Talab, Malihabad, and Mall.

2.2 Soil analysis

Soil samples were collected randomly from the two depths i.e., 0–15 cm and 15–30 cm, with the help of soil corer (5.5 cm inner diameter) from the selected sites (S). There were six S1 to S6 agricultural sites selected in different locations of the district from different blocks (Fig. 1). The major crops grown at these sites at the time of sampling were vegetable crops, wheat, rice, mustard, green chilli, sugarcane, and potato. The crop fields selected for the study were wheat, paddy, and mustard. Sampling was done for three different seasons (monsoon, pre-monsoon, post-monsoon) for two years (2023‒2025). The samples were collected in April‒May for pre-monsoon, June and July for the monsoon season, and October‒November for post-monsoon. Wheat, paddy, and mustard fields are selected in Lucknow because they constitute the dominant cropping system that underpins regional food security and farmer income. These crops are cultivated sequentially throughout the year, resulting in continuous nutrient extraction and intensive soil use. A soil composite was prepared by mixing randomly collected soil subsamples from each site within their respective soil depth. Soil temperature was measured using a soil thermometer. A part of the fresh soil sample was used to determine the pH, moisture content, and conductivity, and another part was air-dried for the estimation of other soil parameters. The air-dried soil samples were sieved through 0.5 mm mesh, which was used for the analysis of soil organic carbon, available nitrogen, available phosphorus, and available potassium. Soil moisture content (SMC) was determined by the gravimetric method. The bulk density was estimated from the core samples as per the method described by Blake [27]. Soil water holding capacity and soil texture were determined following the method outlined by Piper [28, 29]. The soil pH value was estimated in 1:2.5 fresh soil: water (w/v) suspensions by the electrometric method with a digital pH meter. Walkley and Black's rapid titration method was used for organic carbon (SOC) estimation [30] Soil organic matter was estimated through multiplication of the SOC concentration by the factor 1.724 [31]. Soil available nitrogen was determined following [32] with the help of the Kelplus nitrogen analyser. Available phosphorus was assessed using the Bray and Kurtz No. 1 procedure [33]. Available potassium was determined from the soil with the help of a flame photometer following [32].

2.3 Data analysis

The strength and direction of linear correlations between the observed soil properties were listed using Pearson's correlation coefficient (r). It focused on identifying soil characteristics that showed strong correlations and determining how they may affect crop productivity. Principal Component Analysis (PCA) was used to reduce multicollinearity among soil metrics and identify the major soil factors responsible for the overall variability in the research region. PCA is a multivariate statistical method that reduces a set of correlated variables to a smaller number of uncorrelated components called principal components (PCs), each of which represents a particular percentage of the dataset's overall. Linear Mixed Models (LMM) were used to evaluate the effects of season, soil depth, and their interaction on soil properties while accounting for repeated observations and variability among sampling locations through random effects. Assumptions of the linear mixed model were tested. Residual normality was assessed using Q-Q plot, while homogeneity of variance was tested using residual-versus-fitted plots. Multicollinearity was assessed using Generalized Variance Inflation and the temporal autocorrelation was tested using Durban-Watson test. The values of potassium were log transformed to improve normality and variance homogeneity. The software used for analysis is R4.4.3 version and Google Colab.

3 Results

During the pre-monsoon period, a mixture of sandy clay loam, clay loam, and loam was found, signifying a higher overall sand and clay content. Whereas clay loam and loam textures were predominant during the monsoon season, during the post-monsoon season, the majority of soil samples showed sandy clay loam and sandy clay textures. It can be inferred that the samples have a high content of sand and clay. The soil pH ranged from 6.5 to 8.12, indicating neutral to alkaline conditions, while the average soil organic carbon was 2.5%. The bulk density ranged from 0.29 to 1.90 g/cm^3. The 15–30 cm depth consistently retained more moisture during the monsoon; Site S5 had the highest SMC, possibly due to its favourable texture, whereas S4 and S6 had the lowest. Due to mineralization, available nitrogen usually increases after the monsoon, with surface soils exhibiting greater nitrogen levels. It was highest at Site S5 (396.08 kg/ha) during the post-monsoon (0–15 cm) and lowest at Site S6 during the pre-monsoon (15–30 cm). While there are variations across seasons, the post- monsoon season generally shows slightly higher available potassium levels compared to pre-monsoon and monsoon seasons across most sites and depths. With higher availability in surface layers and seasonal improvement after the monsoon, phosphorus was highest at Site S5 and lowest at Site S1. Potassium levels in topsoil were somewhat higher and exhibited an increasing trend from S1 to S5, with post-monsoon levels often greater than those of previous.

3.1 Correlation analysis

The correlation matrix highlights the functional links that control soil fertility and physical behaviour by revealing noteworthy relationships among soil parameters (Table 1). Soil organic carbon is negatively associated with clay content ($r = -0.728$) and strongly positively correlated with sand content ($r=0.764$). Soil organic matter exhibits a similar pattern to that of SOC. Water Holding Capacity had very modest relationships with most variables; nitrogen ($r=0.263$) and phosphorus ($r=0.463$) show a positive relationship with soil moisture content. Potassium and phosphorus show a significant positive correlation ($r=0.729$). The predicted antagonistic behaviour of texture components is demonstrated by the negative correlations between sand and clay ($r = -0.935$) and between sand and silt ($r = -0.128$). Acidification tendencies in finer sediments may be seen in the negative correlation between silt and pH ($r = -0.433$).

3.2 Principal component analysis

To analyse the main gradients influencing soil variability, principal component analysis (PCA) was used. Out of the thirteen components, the first five explained 79.3% of

Table 1 Correlation matrix for the selected variables

Parameters	pH	BD	SOC	SOM	WHC	SMC	*N*	*P*	K	Sand	Silt	Clay
pH	1											
BD (g /cm^3)	-0.008	1										
SOC (%)	-0.17	0.165	1									
SOM	-0.17	0.164	1	1								
WHC (%)	0.069	0.129	0.051	0.051	1							
SMC	0.101	0.114	-0.345	-0.345	0.073	1						
N (kg/ha)	-0.161	-0.034	0.059	0.059	0.263	0.124	1					
P(kg/ha)	-0.191	0.204	0.011	0.011	0.22	0.463	0.519	1				
K(kg/ha)	0.055	0.268	0.097	0.097	0.144	0.681	0.434	0.729	1			
Sand (%)	0.013	-0.051	0.764	0.764	0.024	-0.288	0.161	0.058	0.17	1		
Silt (%)	-0.433	0.022	0.239	0.239	-0.405	-0.147	0.008	0.014	-0.128	0.262	1	
Clay (%)	0.148	0.034	-0.728	-0.728	0.128	0.295	-0.138	-0.054	-0.095	-0.935	-0.587	1

the variation.Among these, the first three component that is, PC1 (29.6%), PC2 (20.7%), and PC3 (11.9%) accounted for the largest proportion of the variation and represented the principal gradients in soil properties. The PCA biplot based on PC1 and PC2 are presented in Fig. 2. PC4 (8.8%) and PC5 (8.3%) contributed additional variation. The remaining components individually accounted for less than 5% of the total variance and had eigenvalues below 1. With significant positive loadings for sand (%), silt (%), soil organic carbon (SOC), and soil organic matter (SOM), and a negative loading for clay (%), PC1 demonstrated a vigorous soil texture-organic matter gradient (Fig. 3a and b). This axis distinguished clay-dominated soils from sandy, organic-rich soils. PC2 separated nutrient-rich, wet soils from comparatively nutrient-poor soils by capturing a nutrient-moisture gradient that was marked by high negative loadings for total nitrogen (N), phosphorus (P), potassium (K), soil moisture content (SMC), and water-holding capacity (WHC). A secondary chemical-physical gradient was shown by the correlation between PC3 and soil pH, WHC, and silt (%). The soil samples were well separated along PC1 and PC2 in the PCA biplot, with the strongest contributions to soil differentiation coming from sand, clay, SOM, WHC, N, P, and K.

3.3 Linear mixed model

Different seasonal responses among soil physico-chemical characteristics were studied using linear mixed-effects models. Soil pH did not vary significantly across seasons ($F_{2,61}$ = 2.124, $p = 0.11$) (Fig. 4). There were no visible seasonal variations in bulk density ($F_{2,61}$ = 0.02, $p = 0.984$), water-holding capacity ($F_{2,61}$ = 1.10, $p = 0.340$), total nitrogen ($F_{2,61}$ = 0.17, $p = 0.846$), available phosphorus ($F_{2,61}$ = 0.12, $p = 0.886$), silt content ($F_{2,61}$ = 0.29, $p = 0.749$), and water-holding capacity ($F_{2,61}$ = 1.05, $p = 0.340$). There was

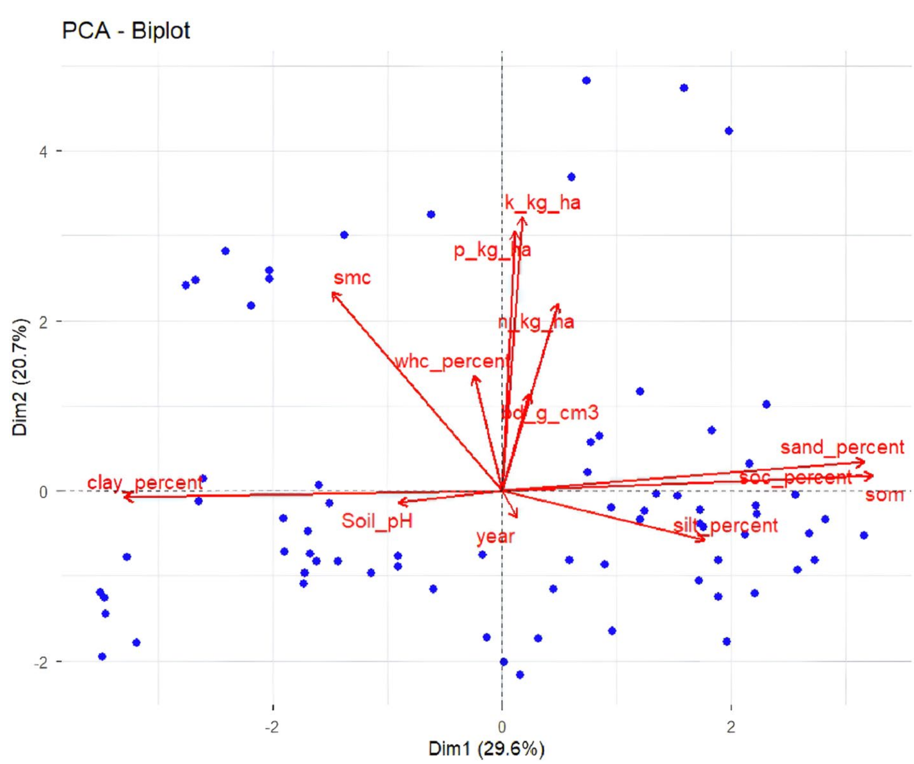

Fig. 2 Principal component analysis (PCA) biplot

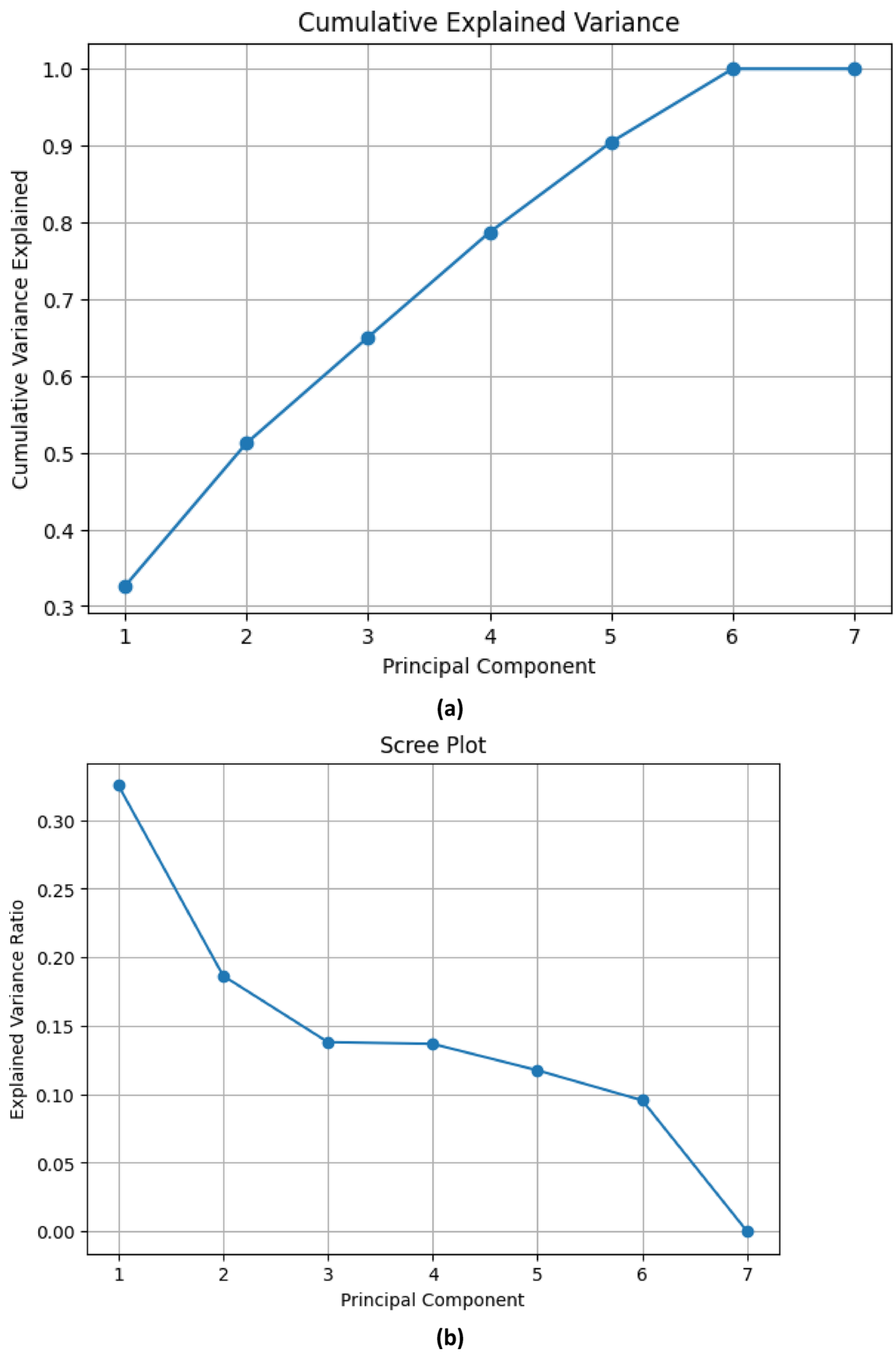

Fig. 3 **a** Cumulative explained variance. **b** Scree plot

a very significant seasonal fluctuation in soil organic matter and soil organic carbon ($F_{2,61}$ = 43.08, p = < 0.001). While there was no apparent difference between pre- and post-monsoon periods, post-hoc comparisons showed that SOC and SOM were considerably greater during pre-monsoon and post-monsoon seasons as compared to the monsoon. Seasonal differences in soil moisture content were significant ($F_{2,61}$ = 6.58, $p = 0.003$), with higher values denoting wetter times. Significant differences were also seen in potassium (K) values ($F_{2,61}$ = 7.1, p = < 0.001). Components of soil texture showed

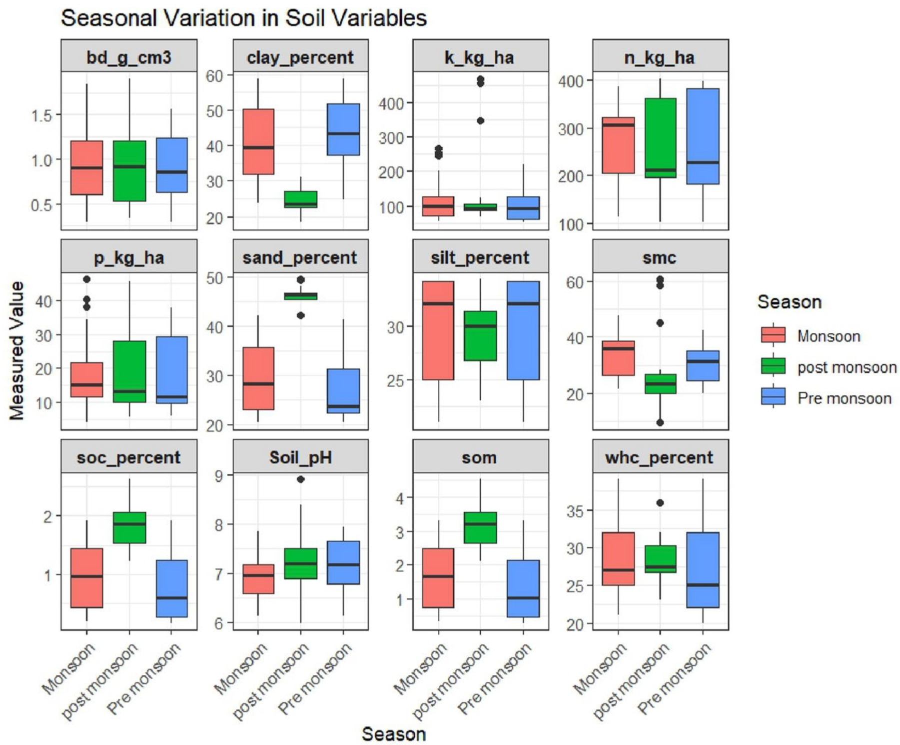

Fig. 4 R plot (linear mixed model)

strong seasonal influences. Seasonal fluctuation was evident in the amount of sand ($F_{2,61}$ = 177.64, $p < 0.001$) and clay ($F_{2,61}$ = 68.22, $p < 0.001$). The seasons had a major impact on carbon fractions, soil moisture, potassium, sand, and clay, while pH, bulk density, nitrogen, phosphorus, water-holding capacity, and silt stayed rather constant.

Soil depth had a significant effect only on sand content ($F = 5.09$, $p = 0.03$), whereas the remaining soil properties did not differ significantly between the 0–15 cm and 15–30 cm soil layers ($p > 0.05$). A significant season and depth interaction was detected for bulk density ($F = 7.18$, $p = 0.002$), indicating that seasonal changes in bulk density differed between soil depths. No significant interaction effects were observed for the other soil properties ($p > 0.05$).

4 Discussion

Seasonal redistribution of finer particles and moisture-driven structural changes are shown by the preponderance of clay loam to loam during the monsoon and sandy clay loam and sandy clay during the post-monsoon. Increased percolation and subsurface storage are suggested by higher moisture retention at lower soil depth during the monsoon, especially at Site S5, where a favourable texture probably supported higher soil moisture content (SMC). Adak et al. [34] examined soil characteristics in Malihabad (Lucknow) mango orchards and found that bulk density, porosity, and soil organic carbon varied with depth, indicating shifts in soil structure and moisture retention. Less water retention capacity or somewhat coarser fractions may be the cause of lower SMC at Sites S4 and S6. The pH range of 6.5 to 8.12 suggests generally good circumstances for nutrient availability. Sharma et al. [35] observed sodic and related soils at the CSSRI experimental farm close to Lucknow and concluded that the Indo-Gangetic alluvial plains were characterized by alkaline soil responses and heterogeneity in soil texture.

Increase in available nitrogen after the monsoon probably result in improved mineralization after heavy rains and breakdown of organic waste. Microbial activity and active litter turnover in higher layers are further supported by nitrogen and phosphorus surface enrichment. Seasonal mobilization and exchange mechanisms affected by moisture dynamics are suggested by the observed rise in potassium from S1 to S5 and its greater post-monsoon levels. Strong functional relationships between soil properties are revealed by correlation analysis. The research area's coarse-textured soils can promote organic matter buildup, maybe as a result of improved aeration and litter assimilation, as indicated by the negative connection between SOC and clay and the positive correlation with sand. Potassium and phosphorus have a significant positive correlation, which suggests that their mobilization mechanisms or geochemical controls are comparable. Tiwari and Misra [36] demonstrated how nutrient mobility and availability alter in sodic soils in Lucknow by reporting increased accessible phosphorus and potassium with fertilizer inputs.

While the inverse link between silt and pH points to possible acidification tendencies in finer fractions, negative correlations between sand and clay validate the predicted textural antagonism. These conclusions are supported by PCA results, which show that the main causes of soil variability are gradients in texture-organic matter (PC1) and nutrient-moisture (PC2). Additionally, linear mixed models show that while pH and key nutrients were mostly constant, seasonal impacts were most noticeable for SOC, SOM, SMC, potassium, sand, and clay. Overall findings demonstrated how seasonally mediated texture-nutrient interactions influence soil fertility trends. According to research done in the Lucknow district, phosphorus in soil varies greatly depending on the cropping pattern, which has a direct impact on crop production responses and nutrient availability [37]. Regional soil studies reveal that intensively farmed fields have moderate to low levels of organic carbon and an unstable nutrient status, which might limit production in the absence of an integrated nutrient management [38]. More studies conducted throughout the Indo-Gangetic Plains show that balanced fertilization and conservation-based methods improve soil structure, water-holding capacity, and nutrient-use efficiency, which in turn raises grain yield and system sustainability [39]. By integrating PCA and LMM, our study highlights knowledge on seasonal changes in soil chemistry and identifies the major factors controlling soil variability in agricultural fields of Lucknow district which further improves understanding of soil nutrient dynamics and provides a scientific basis for sustainable soil fertility management. The significance of this study lies in its contribution to understanding the seasonal dynamics of soil chemical properties in agricultural fields of Lucknow district, Uttar Pradesh. By examining variations in soil fertility indicators across different seasons, the research provides valuable information for improving nutrient management and sustainable agricultural practices. However, our study focussed only on seasonal influence on soil characteristics and there is lack of environmental drivers such as rainfall intensity and microbial activity which play important part in soil characteristics.

5 Conclusion

The moderate to good fertility of the soils in the study area is maintained by stable nutrient interactions and a suitable organic matter condition. Significant organic accumulation is shown by the complete positive correlation between soil organic carbon and soil organic matter as soil organic matter consists of entire organic fraction of soil. Strong correlations between phosphorus and potassium and modest correlations between nitrogen and P and K indicating that soils are nutrient-rich and balanced. While a slightly acidic pH enhances nutrient solubility, enough moisture increases potassium availability. The soils often exhibit a strong capacity for fertility and space for long-term management. The agricultural landscapes seasonal assessment of soil physicochemical characteristics reveals that soil quality is extremely dynamic and tightly controlled by monsoonal impacts and land-use intensity. Significant changes in organic carbon, pH, moisture content, and potassium show temporal variability that is crucial in determining the functional behavior of soil. While the post-monsoon drop in moisture was associated with progressive compaction and decreased biological activity, monsoon-driven increases in SMC and WHC improved nutrient mobility. Seasonal variations in SOC and SOM indicate varying rates of organic matter mineralization and decomposition, which have an immediate impact on nutrient availability. Maintaining balanced chemical conditions for the best crop absorption is further highlighted by the alignment of soil fertility with slightly acidic to neutral pH. Overall, the study offers compelling evidence that sustaining long-term soil production and resilience in the heavily farmed agro-ecosystems of Lucknow requires season-sensitive soil management, such as periodic organic inputs, moisture conservation, and nutrient balancing.

Acknowledgements
The first author is grateful to the Department of Science and Technology, Government of India, New Delhi, for the DST Inspire Fellowship and the financial assistance in conducting this research work. Authors are also thankful to the Krishi Vigyan Kendra Lucknow, Mizoram University, farmers and local field guides during the field work and soil analysis.

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Conceptualization: Nistha Khanna; Om Prakash Tripathi Methodology: Nistha Khanna; C. Lalruatkimi; Kh. Babina Devi Formal analysis: Nistha Khanna; C. Lalruatkimi; Kh. Babina Devi; Gyati Yam , Ahmed Abdallah Adam Investigation: Nistha KhannaWriting – original draft preparation: Nistha Khanna Writing – review and editing: C. Lalruatkimi; Gyati Yam; OP Tripathi.

Funding
This research was funded in the form of Fellowship by the DST (Nistha Khanna vide reference No. (IF220132), New Delhi, Government of India.

Data availability
The data supporting this study findings are available from the corresponding author upon reasonable request.

Code availability
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable. This manuscript is the author's original work, which has not been previously published elsewhere. The manuscript is not currently being considered for publication elsewhere. No human participants are involved in the present research work.

Consent for publication
All the authors have participated and agreed to publish on the submission of this manuscript to your esteemed journal.

Competing interests
The authors declare no competing interests.

Received: 7 April 2026 / Accepted: 18 August 2026
Published online: 30 August 2026

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