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Multivariate assessment of soil fertility attributes in Alfisols of the central agro-climatic zone of Telangana, India

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Abstract

Soil fertility degradation remains a critical barrier to sustainable cereal production in semi-arid regions. This study employed multivariate statistical tools to evaluate the physicochemical properties and nutrient dynamics of Alfisols under rice–maize cropping systems in the Central Agro-Climatic Zone of Telangana. Analysis of fifty-nine surface soil samples revealed prevalent deficiencies in organic carbon (OC) and nitrogen, contrasted by high phosphorus and medium-to-high potassium levels. Correlation analysis identified strong OC–N associations and significant P–Fe interactions, indicating complex nutrient antagonism. Principal component analysis (PCA) identified four primary factors—organic fertility, P–Fe fixation, potassium mineral control, and salinity-micronutrient effects—which collectively explained 63.9% of the total soil variability. Ultimately, these results underscore the need for site-specific nutrient management and organic carbon sequestration to overcome nutrient imbalances and ensure long-term soil productivity in the region.

Keywords: Alfisol, soil fertility, principal component analysis, Telangana

1. Introduction

Sustainable agricultural productivity in the semi-arid tropics of India is significantly hindered by soil fertility degradation ^[1]. Alfisols, which are prevalent across southern India, are inherently limited by low organic matter content, moderate nutrient-holding capacity, and a high susceptibility to nutrient imbalances, particularly under intensive cultivation ^[1, 2]. In the Central Agro-Climatic Zone of Telangana, dominant cereal-based systems, such as rice and maize, place heavy nutrient demands on these fragile soils, further exacerbating inherent fertility constraints ^[3].

Soil nutrients and physicochemical properties operate as an interdependent system where processes like organic matter decomposition and nutrient fixation regulate overall availability to crops ^[1]. Because conventional univariate analyses often fail to capture these complex interactions, multivariate statistical techniques are increasingly utilized. While correlation analysis helps examine pairwise relationships, Principal Component Analysis (PCA) is particularly effective for reducing data dimensionality and identifying the dominant drivers of soil variability ^[4].

Recent studies have integrated PCA with geostatistical methods to delineate site-specific management zones (MZs), which have been shown to improve nutrient use efficiency and significantly increase yields in maize systems within Telangana ^[5]. However, comprehensive multivariate assessments focusing on Alfisols of the Central Agro-Climatic Zone of Telangana remain limited. Therefore, the objectives of the present study were to (i) characterize soil fertility status using descriptive statistics, (ii) examine interrelationships among soil properties through correlation analysis, and (iii) identify key soil fertility drivers using PCA for improved nutrient management strategies.

2. Materials and Methods

2.1 Study Area and Soil Sampling

The study was conducted in the Central Agro-Climatic Zone of Telangana, India, covering major cereal-growing districts including Khammam, Warangal, and Medak. The region experiences a semi-arid tropical climate with an average annual rainfall of approximately 996 mm, largely received during the southwest monsoon. Soils are predominantly Alfisols derived from granitic parent material.

A total of 59 surface (0–15 cm) soil samples were collected from rice and maize cultivated fields following standard soil sampling procedures. Composite samples were prepared to ensure representativeness of each site.

2.2 Laboratory Analysis

Soil samples were air-dried, ground, and sieved (<2 mm) prior to analysis. Soil pH and electrical conductivity were assessed in a 1:2.5 soil–water solution utilizing a pH meter and conductivity meter, respectively [6]. Organic carbon was quantified by the Walkley and Black method [7]. Available nitrogen was estimated by the alkaline KMnO₄ method [8]. Available phosphorus was extracted by Olsen's method and quantified using the ascorbic acid reduction method at 660 nm [9,10]. Available potassium was extracted using neutral normal ammonium acetate and quantified with a flame photometer [6]. DTPA-extractable iron and zinc were quantified using atomic absorption spectrophotometry [11].

2.3 Statistical Analysis

To evaluate variability, descriptive statistics such as range, mean, standard deviation (SD), and coefficient of variation (CV) were computed. Pearson's correlation coefficients were generated to examine correlations among soil properties. PCA was conducted on standardized data using the correlation matrix, and components with eigenvalues greater than one were

retained. Variables with absolute loadings ≥ 0.50 were considered significant contributors. Statistical analyses were conducted using standard statistical R-software.

3. Results

The physicochemical properties and available nutrient status of Alfisols from the Central agro-climatic Telangana Zone (CTZ) are presented in Table 1. The soils were slightly acidic to moderately alkaline, with pH ranging from 6.65 to 7.78 and mean values close to neutral (7.19–7.23) across districts. Electrical conductivity remained low (0.02–0.72 dS m⁻¹), indicating non-saline soils. Organic carbon content varied from 0.19 to 1.09%, with mean values of 0.37–0.50%, classifying the soils under low to medium OC status, with relatively better organic carbon in Khammam soils.

Available nitrogen ranged from 50.18 to 313.60 kg ha⁻¹, with mean values of 122.74 kg ha⁻¹ in Warangal, 156.44 kg ha⁻¹ in Medak, and 237.29 kg ha⁻¹ in Khammam, indicating low to medium nitrogen fertility, particularly low in Warangal soils. Available phosphorus (P₂O₅) ranged from 17.33 to 146.52 kg ha⁻¹. Mean values (75.46–96.53 kg ha⁻¹) suggested medium to high phosphorus status, with higher availability in Khammam and Warangal districts. Available potassium (K₂O) showed a wide range (72–626.63 kg ha⁻¹) and mean values between 280.05 and 335.74 kg ha⁻¹, categorizing the soils under medium to high potassium fertility.

DTPA-extractable iron ranged from 4.87 to 40.74 mg kg⁻¹ and zinc from 0.24 to 3.63 mg kg⁻¹. Mean Fe and Zn contents indicated adequate iron and adequate to marginal zinc status, suggesting potential Zn deficiency in some locations.

Overall, the Alfisols of CTZ exhibited neutral reaction, low salinity, low to medium nitrogen and organic carbon, medium to high P and K, and largely adequate micronutrient availability.

Table 1: Physicochemical properties and available nutrient status of Alfisols of CTZ, Telangana

Districts	No. of soil samples		p ^H	EC (dSm ⁻¹)	OC (%)	Available Nutrients			Micronutrients	
						N	P ₂ O ₅	K ₂ O	Fe	Zn
						(kg ha ⁻¹)			mg/kg	
Khammam	11	Range	6.68-7.60	0.10-0.56	0.25-1.09	113-313.60	56.61-136.48	235.13-419.63	24.02-37.78	0.52-2.18
		Mean	7.19	0.32	0.50	237.29	96.53	335.74	30.99	0.98
Warangal	32	Range	6.65-7.78	0.02-0.72	0.19-0.74	50.18-225.79	48.32-146.52	72-626.63	4.87-40.74	0.24-3.45
		Mean	7.23	0.25	0.37	122.74	94.45	324.60	23.17	1.02
Medak	16	Range	6.68-7.36	0.11-0.43	0.21-0.56	87.98-225.79	17.33-109.86	118.13-573.75	6.65-37.85	0.51-3.63
		Mean	7.19	0.24	0.39	156.44	75.46	280.05	27.95	1.14

3.1 Descriptive Statistics and Fertility Status

The soils were neutral to slightly alkaline, with pH values ranging from 6.65 to 7.78, indicating favorable conditions for cereal crop growth (Table 2). Electrical conductivity values were low overall, suggesting non-saline conditions; however, the high coefficient of variation reflected spatial heterogeneity in soluble salt distribution.

Organic carbon content ranged from 0.19 to 1.09%, with the majority of samples falling in the low category, consistent with the inherent characteristics of Alfisols and continuous cultivation with limited organic residue return. Available nitrogen exhibited wide variability (50–314 kg ha⁻¹), with nearly 97% of samples classified as low, primarily due to low organic carbon levels and rapid mineralization losses under tropical conditions. Similar trends have been reported for Alfisols in other semi-arid regions.

Available phosphorus ranged from 17 to 147 kg ha⁻¹, with approximately 90% of samples categorized as high. This accumulation may be attributed to repeated fertilizer application and limited crop removal, coupled with fixation processes

involving iron oxides. Available potassium showed medium to high status in most soils, reflecting the contribution of potassium-bearing minerals commonly present in Alfisols.

DTPA-extractable iron was sufficient across all samples, while zinc exhibited high spatial variability, with approximately 29% of samples falling below critical limits. Zinc deficiency in neutral to alkaline soils is commonly associated with reduced solubility and adsorption reactions.

Table 2: Descriptive statistics of soil properties (n = 59)

Soil Parameter	Mean	SD	SEM	CV (%)	Minimum	Maximum
pH	7.21	0.26	0.03	3.67	6.65	7.78
EC (dS m ⁻¹)	0.26	0.14	0.02	54.05	0.02	0.72
OC (%)	0.4	0.16	0.02	40.17	0.19	1.09
N (kg ha ⁻¹)	153.27	62.66	8.16	40.88	50	314
P ₂ O ₅ (kg ha ⁻¹)	89.63	25.15	3.27	28.06	17	147
K ₂ O (kg ha ⁻¹)	314.71	110.8	14.42	35.19	72	627
Fe (mg kg ⁻¹)	25.93	9.79	1.28	37.78	4.87	40.74
Zn (mg kg ⁻¹)	1.04	0.74	0.1	70.73	0.24	3.63

3.2 Correlation Analysis

Correlation analysis revealed a significant positive relationship between organic carbon and available nitrogen ($r = 0.419$), emphasizing the role of soil organic matter as a primary reservoir and regulator of nitrogen availability (Fig.1). This relationship has been widely reported in tropical agricultural soils. Available phosphorus exhibited a significant negative correlation with iron ($r = -0.278$), indicating phosphorus fixation by iron oxides, a well-documented phenomenon in Alfisols. Electrical conductivity showed weak associations with micronutrients, suggesting localized effects of soluble salts on nutrient mobility. Overall, the observed correlations highlight the interconnected nature of soil fertility attributes and the limitations of isolated nutrient evaluation.

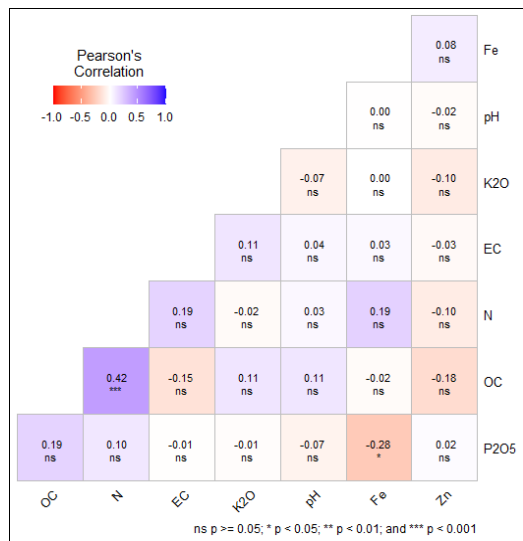


Fig 1: Correlation matrix of soil properties

3.3 Principal Component Analysis

According to the scree plot, four principal components (PCs) were retained (Fig. 2). All these components exhibited eigenvalues greater than 1, with each explaining at minimum of 5% of the data variation, and together representing 63.9% of the total variation in soil attributes (Table 3). The Biplot shows the interrelationships among the soil attributes (Fig. 3). The pH, electrical conductivity, organic carbon, available nitrogen (N), P₂O₅ and K₂O were exhibited a positive correlation with one another, and negative correlation with properties in opposing directions. The OC and P₂O₅ aggregated together, indicating that they necessitate analogous management techniques.

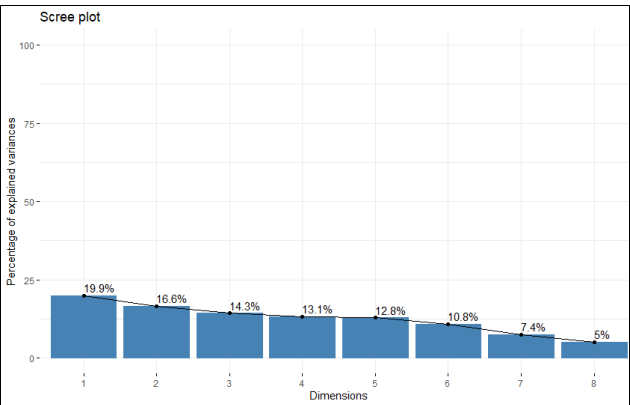


Fig 2: Scree Plot Illustrating Variance Explained by Principal Components

Table 3: Eigenvalues and Percentage of Variance Explained by Principal Components

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	2.41	26.8	26.8
PC2	1.68	18.7	45.5
PC3	1.22	13.6	59.1
PC4	1.04	4.8	63.9

The first principal component (PC1), accounting for the largest share of variability, was strongly associated with organic carbon (0.81) and (0.84) available nitrogen (table 4), representing a soil organic fertility factor with eigenvalue of 2.41 and explained 26.8% of the observed variations in the soil properties (Table 3). This component underscores the central role of organic matter management in sustaining soil productivity. The second component (PC2) was dominated by phosphorus (-0.77) and iron (0.79), with eigenvalue of 1.68, contributing an additional 18.7% of the overall observed variations in soil attributes, reflecting P-Fe interactions governed by adsorption and fixation mechanisms. The third component (PC3) was primarily influenced by positive loadings of potassium (0.82), possessing an eigenvalue of 1.22 and contributing an extra 13.6% to the overall observed variations in soil attributes, indicating mineralogical control over potassium availability. The fourth component (PC4) showed notable positive loadings of EC (0.71) and zinc (0.74) with an eigenvalue of 1.04, contributing an extra 4.08% to the overall observed variations in soil attributes, representing salinity-related micronutrient dynamics. The PCA results are consistent with earlier studies that identified organic matter, nutrient interactions, and salinity as dominant drivers of soil fertility variability in semi-arid agroecosystems. The clear separation of components demonstrates the usefulness of PCA in simplifying complex soil datasets and identifying management-relevant fertility constraints.

Table 4: Rotated Component Loadings of Soil Properties

Soil Property	PC1	PC2	PC3	PC4
Organic Carbon (%)	0.81	0.18	0.09	-0.05
Available N (kg ha ⁻¹)	0.84	0.12	-0.04	0.06
Available P ₂ O ₅ (kg ha ⁻¹)	0.21	-0.77	0.08	0.04
Available K ₂ O (kg ha ⁻¹)	0.12	0.09	0.82	-0.03
Fe (mg kg ⁻¹)	-0.06	0.79	0.05	0.11
Zn (mg kg ⁻¹)	0.03	0.06	-0.02	0.74
EC (dS m ⁻¹)	-0.11	0.04	0.06	0.71
pH	0.19	0.22	0.11	-0.18

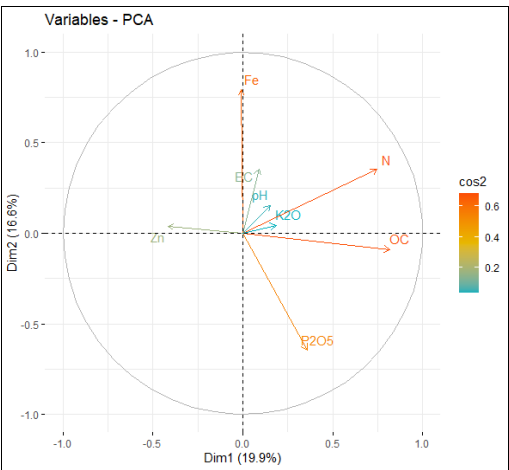


Fig 3: PCA biplot illustrating relationships among soil properties

4. Discussion

The soil organic carbon was typically low in the central zone districts of Telangana, attributed to diminished biomass production from crops and natural vegetation, alongside elevated turnover rates of organic material due to high soil temperatures and microfauna, particularly termite activity. The diminished content is intensified by overgrazing, bush burning, and the removal of soil cover, together with the accelerated breakdown and mineralization of organic compounds^[12, 13].

The low concentrations of nitrogen, was directly due to the low organic C and its continuous mining without adequate replacement. Low available nitrogen status is the common observation in many soils and in many areas of the state as well as country because of the reason that were already enumerated for organic carbon content. The low available nitrogen status of the soil; as common phenomenon across the country is being reported over long time^[14, 15, 16].

A analysis of 31 millet-producing soils in the Sahel zone revealed a strong link between organic carbon and total nitrogen, indicating that under the prevalent zero-input agro-pastoral systems, the nitrogen nutrition of crops significantly relies on the preservation of soil organic matter levels. This study clearly indicates that variations in geographical space, even within a single region, significantly affect the availability of soil nutrients due to substantial variances in soil physico-chemical parameters across the three locations. Consequently, the soils must be handled in a distinct manner.

Ninety percent of these soils exhibited elevated levels of accessible phosphorus ($p > 59$). Elevated phosphorus availability may result from a fixed phosphorus pool comprising inorganic phosphate compounds that exhibit low solubility and organic molecules that are resistant to microbial mineralization in soil. These findings corroborate the results documented by^[18] in the soil of the Tonk district of Rajasthan and^[19].

The potassium availability in Indian soils is reported to be medium to high in any instances^[17, 20, 21]. Potassium rich minerals that varies in different types of soils and hence the present variation in potassium availability of surveyed samples expected^[22, 23].

The management practices at central agro-climatic zone districts that could be relevant to planning site-specific crop production strategies for optimizing yield should focus on Organic carbon, Nitrogen, and available zinc.

In this region, the PCA has also been used to screen soil properties for efficient soil management. The Principal Component Analysis (PCA) successfully reduced the dimensionality of the soil dataset, revealing that four primary factors explain nearly 64% of the total soil variability. This level of explanation is consistent with soil characterization studies in complex agroecosystems, where inherent pedogenic factors and anthropogenic management often overlap.

The Centrality of the Organic Fertility Factor (PC1)

PC1, characterized by high loadings for Organic Carbon (0.81) and Available Nitrogen (0.84), serves as the "Organic Fertility Factor." The clustering of OC and P_2O_5 in the biplot suggests that phosphorus availability in this region is tightly linked to organic matter mineralization rather than purely mineral dissolution. This mirrors the findings of^[24], who observed that in nutrient-limited soils, SOC acts as a primary reservoir for nitrogen and a mediator for phosphorus solubility, necessitating integrated nutrient management (INM) rather than isolated chemical fertilization.

Nutrient Fixation and Mineralogical Constraints (PC2 & PC3)

The inverse relationship between phosphorus (-0.77) and iron (0.79) in PC2 highlights a classic "P-Fe interaction." This interaction is indicative of phosphorus fixation, where iron oxides adsorb phosphate ions, rendering them unavailable for plant uptake.^[25] noted that in soils with high iron activity, the management of pH and organic amendments is crucial to "mask" iron exchange sites and release fixed P.

Furthermore, the mineralogical control over potassium (0.82) in PC3 suggests that K availability is likely governed by the parent material and clay mineralogy (e.g., illite or mica content). As^[26] argue, potassium dynamics are often independent of organic matter cycles, requiring specific monitoring of exchangeable K pools to prevent "hidden hunger" in high-demand crops.

Salinity and Micronutrient Dynamics (PC4)

The association between EC (0.71) and Zinc (0.74) in PC4 points toward salinity-induced micronutrient variability. In semi-arid regions, high electrical conductivity often leads to the formation of insoluble zinc complexes or competitive uptake inhibition. Research by^[27] confirms that in saline-alkali environments, zinc solubility is significantly reduced, suggesting that farmers in areas with high PC4 scores may need to prioritize chelated zinc applications or foliar sprays to bypass soil-binding constraints.

5. Conclusion

This study demonstrates that the integration of descriptive statistics and multivariate analysis—specifically Principal Component Analysis (PCA)—offers a robust framework for decoding soil fertility in the Alfisols of Telangana's Central Agro-Climatic Zone. Our findings identify low organic carbon-driven nitrogen deficiency, iron-mediated phosphorus fixation, and erratic zinc distribution as the primary constraints to cereal productivity. By distilling complex chemical interactions into four actionable thematic areas—organic restoration, fixation mitigation, mineral supplementation, and salinity balancing—this research provides the evidence base needed to transition from generic "blanket" applications to precise, site-specific nutrient management strategies.

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