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# Soil nutrient availability and interrelationships in paddy-cultivated *alfisols* of Northern Telangana

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## ABSTRACT

*The Northern Telangana (NT) Zone is a major rice-growing region experiencing imbalanced fertilizer use, declining soil organic carbon, and emerging micronutrient deficiencies; however, comprehensive information on nutrient availability and interrelationships in paddy-cultivated alfisols remains limited. To address this gap, the present study evaluated the physico-chemical properties, nutrient status, and interrelationships among soil parameters in paddy-cultivated alfisols of the region. A total of 45 surface soil samples (0–15 cm) were collected from representative mandals using a stratified random sampling design based on soil type and land use. The samples were analyzed for pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), phosphorus ($P_2O_5$), potassium ($K_2O$), iron (Fe), and zinc (Zn). The soils were neutral to slightly alkaline (mean pH 7.26) and non-saline in nature. Organic carbon content was low to medium, while available nitrogen was generally low to medium. Phosphorus and potassium ranged from medium to high. Iron was adequate in most samples, whereas zinc showed high spatial variability, indicating potential deficiency in certain locations. Correlation analysis revealed mostly weak-to-moderate relationships among soil properties, with a positive association between available nitrogen and phosphorus and a negative relationship between zinc and soil pH and potassium. The results emphasize that it is necessary to implement site-specific nutrient management, particularly for organic carbon improvement and zinc supplementation, to sustain rice productivity in the region.*

***Keywords:*** *Paddy soil; alfisols; soil fertility; Northern Telangana; Nutrient availability; micronutrient deficiency.*

## Introduction

Rice (*Oryza sativa* L.) is one of the most important staple food crops in India, and its productivity is largely governed by soil physico-chemical properties and nutrient availability [1]. In irrigated rice ecosystems, continuous submergence, intensive fertilizer use, and site-specific management practices significantly influence soil reaction, nutrient dynamics, and spatial variability of soil properties. Understanding these variations is essential for sustainable soil fertility management and enhanced crop productivity [2], [3], [4].

Alfisols are a large part of the NT zone and are widely used for growing rice. The region exhibits unique agro-climatic features, marked by low and highly variable rainfall, diverse soil formations, and well-defined cropping periods linked to the kharif and rabi seasons. These soils are generally characterized by moderate fertility, variable texture, and susceptibility to nutrient imbalances, particularly under intensive rice-based cropping systems [5].

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Prolonged flooding in paddy fields alters soil redox conditions, affecting the availability of both macro- and micronutrients, especially nitrogen, phosphorus, iron, and zinc. As a result, nutrient availability in paddy-grown alfisols often shows considerable spatial heterogeneity [6].

Traditional methods for assessing soil fertility based on limited sampling often fail to capture the inherent variability present within large agro-ecological regions. Descriptive statistical analysis offers an initial comprehension of the central tendency, dispersion, and distribution pattern of soil properties, whereas correlation analysis aids in elucidating interrelationships among soil parameters and nutrient dynamics [7]. Such information is critical when creating site-specific nutrient management strategies, particularly in regions with diverse soil and management conditions.

The NT zone represents an important rice-growing belt of Telangana State, where imbalanced fertilizer use, declining organic carbon, and emerging micronutrient deficiencies have been reported recently [8]. However, comprehensive information on the physico-chemical properties, nutrient status, and their interrelationships in paddy-cultivated *alfisols* of NT zone remains limited.

Therefore, the present study was undertaken to (i) assess the physico-chemical properties and available macro- and micronutrient status of surface soils under paddy cultivation in *Alfisols* of the Northern Telangana Zone and (ii) analyze the relationships among soil properties and nutrients using correlation analysis. The findings of this study aim to provide a scientific basis for improving nutrient management practices and sustaining rice productivity in the region.

## Material and Methods

### Description of study area

The present study was conducted in the NT zone of Telangana, India, encompassing the districts of Adilabad, Komaram Bheem Asifabad, Nirmal, Mancherial, Nizamabad, Jagtial, Peddapalli, Kamareddy, Rajanna Sircilla, and Karimnagar. Geographically, the zone lies between approximately 18°15′-19°55′ N latitude and 77°30′-79°45′ E longitude. The region receives an annual rainfall ranging from 867 to 1189 mm, with the majority of precipitation occurring during the southwest monsoon season. The climatic conditions during this period are characterized by maximum temperatures ranging from 31 to 39°C and minimum temperatures between 14 and 25°C. The NT zone comprises 16 different soil types, among which shallow black soils (18.4%), deep calcareous soils (16.6%), and red clayey soils (15.2%) are notable. Overall, red soils of varying textures dominate the zone, covering nearly 45% of the total geographical area, followed by black soils (24%) and calcareous soils (20%). The predominant cropping systems of the zone include rice, maize, soybean, sesame, cotton, red gram, sugarcane, and turmeric.

### Soil sampling and characterization

Soil sampling was conducted using a stratified random sampling design, wherein the study area was stratified based on soil type (Alfisols) and land use (paddy cultivation). A total of forty-five surface soil samples (0–15 cm) were collected randomly from representative mandals of the NT zone under paddy-growing conditions to assess their physico-chemical properties and available major nutrient status. The collected soil samples were air-dried under shade, and a representative portion (approximately 250 g) from each bulk sample was ground using a wooden mortar and pestle, passed through a 2-mm sieve, and preserved in properly labeled bags for subsequent laboratory analysis.

The soil pH was measured with a glass electrode pH meter, and the electrical conductivity (EC) was assessed in the identical soil-water extract utilizing a digital conductivity meter. Exchangeable potassium was extracted with neutral normal ammonium acetate and quantified using a flame photometer (Elico CL 361) [9]. The organic carbon content was determined in air-dried soil samples utilizing the Walkley and Black wet oxidation method [10]. The alkaline potassium permanganate method was employed to ascertain available nitrogen [11]. Available phosphorus was extracted via Olsen's method [12] and quantified colorimetrically using ascorbic acid as the reducing agent with a colorimeter (ECIL GS 5701 SS) at a wavelength of 660 nm [13].

## Results

### Descriptive Statistics of Soil Properties

The descriptive statistics of paddy-cultivated Alfisols (n = 45) of the NT Zone are presented in Table 1, indicating considerable variability in soil physico-chemical properties and nutrient status.

Soil pH ranged from 6.11 to 8.05, with a mean value of 7.26, indicating that the soils were neutral to slightly alkaline in reaction. The low coefficient of variation (CV = 6.16%) suggests a relatively uniform pH distribution across the study area.

Soil electrical conductivity (EC) varied between 0.01 and 0.75 dS $m^{-1}$, with a mean of 0.30 dS $m^{-1}$, indicating that the soils were non-saline in nature. However, EC exhibited a high variability (CV = 59.03%). Soil organic carbon (OC) content ranged from 0.10 to 1.09%, with a mean value of 0.40%, reflecting low to medium organic carbon status. The high CV (43.08%) indicates substantial spatial variability in OC across the paddy fields.

Available nitrogen (N) content varied from 63 to 276 kg $ha^{-1}$, with a mean of 163 kg $ha^{-1}$, indicating an overall low to medium nitrogen status. Available phosphorus ($P_2O_5$) ranged from 24 to 135 kg $ha^{-1}$, with a mean value of 77 kg $ha^{-1}$, while available potassium ($K_2O$) ranged from 118 to 732 kg $ha^{-1}$, with a mean of 369 kg $ha^{-1}$, indicating medium to high potassium availability. Both N and $P_2O_5$ showed moderate to high variability, whereas $K_2O$ exhibited a wide range with considerable variability. Among micronutrients, available iron (Fe) content ranged from 6.61 to 38.66 mg $kg^{-1}$, with a mean of 26.0 mg $kg^{-1}$, while available zinc (Zn) varied from 0.17 to 3.56 mg $kg^{-1}$, with a mean of 1.02 mg $kg^{-1}$. Zinc showed the highest variability (CV = 74.66%) among all parameters studied.

The skewness and kurtosis values indicated that most soil properties exhibited near-normal to moderately skewed distributions, with organic carbon and zinc showing positive skewness and higher kurtosis, suggesting the presence of localized enrichment or depletion zones.

### Interrelationships among Soil Properties

The Pearson correlation coefficients among soil physico-chemical properties and nutrient status of paddy-cultivated Alfisols (n = 45) in the NT zone are presented in Table 2. Overall, most soil parameters exhibited weak to moderate correlations, indicating complex interactions among soil properties under paddy cultivation. Soil pH showed a weak positive correlation with EC (r = 0.219), OC (r = 0.123), and Fe (r = 0.101), while weak negative correlations were observed with $P_2O_5$ (r = −0.032), $K_2O$ (r = −0.132), and Zn (r = −0.111). These weak relationships suggest that soil reaction had a limited direct influence on nutrient availability within the observed pH range. Soil organic carbon (OC) showed significant positive correlations with N (r = 0.127*) and positive correlations with Fe (r = 0.153) and Zn (r = 0.161), while negative correlations were observed with $P_2O_5$ (r = −0.019) and $K_2O$ (r = −0.051).

Among macronutrients, available nitrogen exhibited a moderate positive correlation with $P_2O_5$ (r = 0.288), suggesting a tendency for higher nitrogen availability in soils with higher phosphorus content. Available $P_2O_5$ also showed a positive correlation with $K_2O$ (r = 0.240) and a significant negative correlation with zinc (r = -0.026*).

## Discussion

### Soil Reaction and Salinity Status

The neutral to slightly alkaline soil pH observed in the paddy-cultivated alfisols of the NT zone is conducive for rice cultivation and can be attributed to submergence effects, base-rich parent material, and periodic flooding under paddy cultivation [14]. The low variability in pH reflects relatively homogeneous soil reaction across the study area. The non-saline nature of soils, as indicated by low EC values, suggests effective leaching of soluble salts under flooded paddy conditions [15], [16], although high CV indicates localized differences possibly due to irrigation water quality and drainage conditions.

**Organic Carbon and Macronutrient Status**

The low to medium organic carbon content observed in the study area may be attributed to rapid decomposition of organic matter under tropical climatic conditions, continuous puddling, and insufficient addition of organic residues. High variability in OC reflects differences in crop residue management, organic amendments, and soil texture [17], [18].

Paddy soils usually have low to medium levels of available nitrogen, which could be due to losses from volatilization, denitrification, and leaching when the soil is flooded. The moderate variability indicates differential fertilizer application and soil management practices across mandals [19], [20]. Available phosphorus levels were generally medium to high, which could be due to regular application of phosphatic fertilizers and reduced P fixation under submerged conditions. However, the variability observed suggests differences in fertilizer use efficiency and soil mineralogy [21], [22]. The medium to high potassium status and wide range of $K_2O$ values indicate the influence of clay minerals, parent material, and long-term fertilizer application. High potassium availability in certain locations may also be attributed to the release of non-exchangeable potassium under continuous wetting and drying cycles [23], [24], [25].

**Micronutrient Status**

The adequate levels of available iron are characteristic of paddy soils, where reduced conditions enhance Fe solubility. However, excessive iron availability in some locations may pose a risk of iron toxicity under prolonged submergence. The high variability and positive skewness of zinc indicate widespread zinc deficiency, which has frequently been linked to the continuous cultivation of high-yielding crop varieties, particularly rice and wheat, in the absence of proper crop diversification or micronutrient supplementation [26]. This condition is often exacerbated under alkaline soil environments, where zinc tends to precipitate into sparingly soluble forms, thereby restricting its availability for plant absorption [27]. In addition, the intensive use of phosphorus-based fertilizers has been reported to further diminish zinc availability through antagonistic nutrient interactions within the soil system [28]. This indicates that there must be site-specific zinc management strategies in the NT Zone.

**Influence of Soil Reaction on Nutrient Availability**

The weak correlations of pH with most nutrients indicate that the narrow pH range (neutral to slightly alkaline) under paddy cultivation minimized its influence on nutrient availability. The negative relationship between pH and Zn availability is consistent with the tendency for zinc precipitation and reduced solubility at higher pH, which is commonly reported in flooded rice soils. An increase in soil alkalinity markedly reduces zinc availability to plants, as zinc readily precipitates into poorly soluble forms, such as zinc hydroxide and zinc carbonate, thereby restricting its uptake by roots [29]. Consequently, lime-induced zinc deficiency is frequently observed in calcareous soils, where zinc solubility declines sharply with each incremental rise in pH, particularly when pH exceeds the range of 6.0–6.8.

**Role of Organic Carbon in Nutrient Dynamics**

The weak positive correlation between OC and available nitrogen highlights the role of organic matter as a source of mineralizable nitrogen [30]. Similarly, the positive association between OC and Fe suggests enhanced iron reduction under organic-rich, anaerobic conditions, which is typical of submerged paddy soils. Similar results were reported in different land use systems [31]. Zinc availability increased with higher soil organic carbon due to the formation of soluble zinc–organic complexes. Similar positive relationships between zinc and organic carbon have been reported [32], [33].

**Macronutrient Interactions**

The moderate positive correlation between available nitrogen and phosphorus suggests that these nutrients are often applied together through fertilizers and may accumulate simultaneously in paddy soils. The positive association between $P_2O_5$ and $K_2O$ further reflects balanced fertilizer management practices or similar retention behavior influenced by clay content and mineralogy in Alfisols.

**Management strategies**

- **Improve Soil Organic Carbon:** Incorporate farmyard manure, compost, green manure crops, and recycled crop residues to enhance soil organic carbon and overall nutrient availability.
- **Soil Test–Based Fertilization:** Apply fertilizers based on soil test results to ensure balanced and efficient use of nitrogen, phosphorus, and potassium.
- **Nitrogen Management:** Adopt split application of nitrogen and use neem-coated or slow-release fertilizers to reduce losses through volatilization and denitrification under flooded conditions.
- **Phosphorus Management:** Avoid excess phosphorus application in soils testing high in available P to prevent nutrient imbalance and induced zinc deficiency.
- **Zinc Management:** Apply zinc sulphate in zinc-deficient fields through soil or foliar application, particularly in alkaline and intensively cultivated paddy soils.
- **Water Management:** Practice alternate wetting and drying (AWD) instead of continuous submergence to improve nutrient use efficiency and maintain favorable soil redox conditions.
- **Regular Soil Monitoring:** Conduct periodic soil testing to track changes in soil fertility and adopt site-specific nutrient management for sustainable rice production in the region.

*Table 1. Descriptive statistics of Paddy cultivated alfisol (n=45) of Northern Telangana Zone*

| | Range | Minimum | Maximum | Mean | Std. Deviation | Skewness | Kurtosis | CV (%) |
|---|---|---|---|---|---|---|---|---|
| $p^H$ | 1.94 | 6.11 | 8.05 | 7.26 | 0.45 | -0.531 | 0.06 | 6.16 |
| EC | 0.74 | 0.01 | 0.75 | 0.30 | 0.18 | 0.861 | 0.165 | 59.03 |
| OC | 0.99 | 0.1 | 1.09 | 0.40 | 0.17 | 1.769 | 5.392 | 43.08 |
| N | 213 | 63 | 276 | 163 | 49.27 | 0.134 | -0.621 | 30.26 |
| $P_2O_5$ | 111 | 24 | 135 | 77 | 28.89 | 0.383 | -0.716 | 37.30 |
| $K_2O$ | 614 | 118 | 732 | 369 | 110.94 | 0.696 | 2.118 | 30.10 |
| Fe | 32.05 | 6.61 | 38.66 | 26.0 | 8.49 | -0.443 | -0.785 | 32.67 |
| Zn | 3.39 | 0.17 | 3.56 | 1.02 | 0.76 | 1.792 | 3.635 | 74.66 |

*Table 2. Correlation matrix of Paddy cultivated alfisol (n=45) of Northern Telangana Zone*

| | $p^H$ | EC | OC | N | $P_2O_5$ | $K_2O$ | Fe | Zn |
|---|---|---|---|---|---|---|---|---|
| $p^H$ | 1 | | | | | | | |
| EC | 0.219 | 1 | | | | | | |
| OC | 0.123 | -0.171 | 1 | | | | | |
| N | 0.02 | 0.138 | 0.127* | 1 | | | | |
| $P_2O_5$ | -0.032 | 0.059 | -0.019 | 0.288 | 1 | | | |
| $K_2O$ | -0.132 | 0.1 | -0.051 | -0.016 | 0.24 | 1 | | |
| Fe | 0.101 | 0.064 | 0.153 | 0.165 | -0.059 | 0.075 | 1 | |
| Zn | -0.111 | 0.176 | 0.161 | -0.026 | -0.026* | -0.177 | 0.087 | 1 |

## Conclusion

Paddy-cultivated alfisols of the NT Zone are generally neutral to slightly alkaline and non-saline, providing a suitable environment for rice cultivation. However, low to medium organic carbon and nitrogen levels indicate declining soil fertility under intensive rice-based systems. Available phosphorus and potassium were mostly adequate, while iron was sufficient due to submerged conditions. In contrast, zinc showed high spatial variability with deficiency in several locations. Correlation analysis highlighted weak to moderate nutrient interactions, with organic carbon playing a key role in improving nitrogen, iron, and zinc availability. The study underscores the need for balanced and site-specific nutrient management to sustain soil health and rice productivity.

## Future scope of the study:

Subsequent research may incorporate an expanded sample size and assessments across multiple seasons to elucidate spatial and temporal variability in soil nutrient dynamics. Incorporating additional nutrients and indicators of biological soil health would provide a clearer understanding of soil fertility. Advanced geospatial and multivariate techniques can be used to define nutrient management zones that are specific to a site. Long-term field experiments are essential to assess integrated nutrient management practices, particularly organic amendments and zinc supplementation, in order to ascertain their impact on soil health and rice productivity. Connecting information about soil nutrients with information about crop yields will help with precision nutrient management in the area.

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## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None.

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