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Spatial Variability and Multivariate Assessment of Soil Physico-Chemical Properties in Kanger Valley National Park, India

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Abstract— *Soil physicochemical properties are basic soil fertility parameters and soil ecosystem function in tropical forests as they control soil nutrient cycling, soil organic matter decomposition and the productivity of vegetation. In the present study, spatial variations of soil physicochemical properties were explored in Kanger Valley National Park, Chhattisgarh, India, by Pearson correlation analysis and Principal Component Analysis (PCA). Nine representative sites were sampled and composite samples of the surface soil (0-10 cm and 10-20 cm) were taken for each sample site, and analyzed for pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), available phosphorus (P), available potassium (K), particle density (PD), and bulk density (BD). Soils were found to be non-saline (pH 5.03 to 6.05) and had low electrical conductivity (0.08 to 0.34 dS m^{-1}), which is good for forest vegetation. Organic carbon content ranged between 0.64–0.72%, available nitrogen (160.25–179.75 ppm), phosphorus (9.23–13.05 ppm), and potassium (153.50–178.75 ppm) showed moderate fertility of the soil. The Pearson correlation values showed that there were high positive correlations between the available K and available N with organic C, and soil pH with organic C and available N, suggesting that these are more influenced by organic C than by bulk density, while the bulk density had significant negative correlations with most of the fertility parameters, indicating adverse effects of soil compaction on nutrient availability. Based on the Principal Component Analysis, the total variance was explained by two principal components with eigenvalues larger than one, accounting for 63.9% of the total variance. The first principal component (47.3%) explained the soil fertility gradient, which was dominated by soil organic carbon, pH, available soil N and soil K, and second principal component (16.6%) reflected variations in soil physical properties, mainly particle density and bulk density. PCA site scores and the biplot were able to clearly separate nutrient-rich sites from relatively nutrient-poor sites, indicating that there was a high degree of soil quality variability across the study area. The results show that organic carbon is the most important factor for soil fertility, while bulk density and particle density are secondary factors for soil variation. The results present a good baseline data for monitoring soil quality and aid sustainable conservation and management of the tropical forest ecosystems in Kanger Valley National Park.*

Keywords— Soil fertility; Soil physicochemical properties; Principal Component Analysis; Pearson correlation; Organic carbon; Tropical forest; Kanger Valley National Park.

I. INTRODUCTION

Soil is one of the most vital components of terrestrial ecosystems, and offers many ecosystem services such as nutrient cycling, water regulation, carbon sequestration, conservation of biodiversity, maintenance of vegetation productivity etc. These ecological functions are largely dependent on the physical, chemical and biological properties of the soil, which all influence the availability of nutrients, the activity of soil microorganisms, organic matter breakdown and plant growth. Therefore, the evaluation of soil physicochemical properties is an essential part of soil quality assessment, monitoring of forest ecosystems and sustainable land management. Recent developments in Soil Science have further highlighted the concept of soil health as the continuous capability of the soil to perform its functions as a living ecosystem sustaining plants, animals and human beings and also contributing to climate control and sustainability of the environment (Lehmann et al., 2020; Maurya et al., 2020; Lal et al., 2021).

Forest soils are one of the biggest terrestrial stores of organic carbon and are vital for ecosystem stability because of the constant breakdown of litter, the recycling of nutrients and the activity of living organisms. The inputs of organic matter from plant litter, fine roots and microbial biomass increase soil organic carbon (SOC) which has positive effects on soil aggregation, water holding capacity, cation exchange capacity, nutrient retention and soil fertility. SOC is recognized as one of the most significant indicators of soil quality and ecosystem function because it encompasses physical, chemical and biological processes in soils. Furthermore, the conservation and enhancement of SOC is becoming more and more crucial in the era of climate change mitigation through long-term carbon sequestration in addition to its role in enhancing productivity and ecosystem resilience within forest areas (Lal, 2020; Devi, 2021; Lal et al., 2021; Veldkamp et al., 2020).

Soil physical-chemical properties are of great relevance for assessing soil fertility and functioning of ecosystems and among the different soil quality indicators the most informative properties are soil pH, electrical conductivity (EC), soil organic carbon, available nitrogen (N), phosphorus (P), potassium (K), bulk density (BD) and particle density (PD). Soil pH has significant impact on the solubility of nutrients, diversity of microorganisms, and enzymatic activity, while EC indicates the soluble salt concentration and the mobility of nutrients. Soil organic carbon controls nutrient mineralization and microbial metabolism, bulk density and particle density control soil porosity, aeration, water infiltration and root penetration. These properties affect directly nutrient availability, the productivity of the vegetation and the stability of the ecosystem. For this reason, they have an integrated assessment that gives a holistic view of soil fertility condition and ecological sustainability (Maurya et al., 2020; Lehmann et al., 2020; Pachani & Kashyap, 2020).

The relationship between soil properties is complex because the properties of soils are not independent, but are interdependent. Thus, multivariate statistical methods have gained importance in the interpretation of large ecological data sets and the determination of important soil quality indicators. Pearson correlation analysis is popular for measuring the magnitude and direction of the relationships between soil variables, while Principal Component Analysis (PCA) is effective for reducing multidimensional soil datasets into a few orthogonal components accounting for the major sources of variation. These statistical methods enable detection of the main drivers of environmental changes that affect soil fertility, nutrient dynamics, and their spatial variability, thus helping to develop evidence-based forest management and ecological restoration strategies (Maurya et al., 2020; Valani et al., 2021; Zhu et al., 2022).

Soil physicochemical properties of tropical forest ecosystems are highly variable across space due to their parent material, topography, climate, vegetation, litter quality and biological activity. This variability has a strong impact on nutrient cycling, soil carbon sequestration, forest productivity and microbial processes. Moreover, the need for soil resource conservation and ecosystem resistance has been heightened with increasing anthropogenic disturbances and climate change. The spatial distribution and interrelationships of soil properties have therefore become a necessity to design effective conservation strategies, forest management practices that are sustainable, and ecosystem restoration programmes in tropical forests (Veldkamp et al., 2020; Lehmann et al., 2020; Lal et al., 2021).

Kanger Valley National Park in the Bastar Plateau of central India is one of the most ecologically important tropical forest landscapes, with a high degree of biodiversity, unique geology and extensive vegetation. Although its conservation value is high, detailed information on the spatial variability of the soil physicochemical properties and the most important factors that control soil fertility are still scarce. In the case of the protected ecosystem, however, studies that combine conventional soil fertility assessment with multivariate statistical analysis (e.g., Pearson correlation analysis and Principal Component Analysis) have been limited. This study therefore hypothesized that organic carbon would emerge as the primary driver of soil fertility across the study sites, with bulk density exerting a negative influence on nutrient availability, and that multivariate analysis would effectively distinguish sites of differing fertility status. The present study therefore aimed to assess the physicochemical properties of soils at the selected sampling points in Kanger Valley National Park, test the correlation between soil variables by using Pearson correlation analysis and determine the major factors affecting soil fertility using Principal Component Analysis. The results are used to gain baseline knowledge of soil quality, nutrient dynamics and sustainable management of tropical forest ecosystems in central India and also for conservation planning based on evidence.

II. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Kanger Valley National Park, Bastar district, Chhattisgarh, India. The park is located between 18°45′–19°15′ N latitude and 81°45′–82°15′ E longitude, covering an area of approximately 200 km². The region experiences a tropical monsoon climate with distinct summer, monsoon, and winter seasons. The dominant vegetation consists of tropical moist deciduous forests, while the soils are predominantly red and lateritic, supporting diverse forest ecosystems.

2.2 Soil Sampling

Nine representative sampling sites were selected to capture the spatial variability of soil characteristics across the study area, based on accessibility, representativeness of vegetation types, and perceived differences in soil properties. Surface soil samples (0–10 cm and 10–20 cm depth) were collected after removing the litter layer using a stainless-steel auger. Five subsamples from each site were thoroughly mixed to prepare one composite sample. The samples were placed in labelled polyethylene bags, transported to the laboratory, air-dried, gently crushed, and passed through a 2-mm sieve before analysis following standard soil analytical procedures (Jackson, 1973; Anderson & Ingram, 1993). The sampling was conducted during the post-monsoon season (October–November 2022) to ensure consistent moisture conditions across all sites. The characteristics of the nine sampling sites are presented in Table 1.

TABLE 1
CHARACTERISTICS OF SAMPLING SITES IN KANGER VALLEY NATIONAL PARK

Site	Vegetation Type	Dominant Tree Species	Canopy Cover (%)	Slope	GPS Coordinates
Site 1	Moist deciduous	*Sal, Teak, Bamboo*	75-85	Gentle	18°55'N, 82°00'E
Site 2	Moist deciduous	*Sal, Mahua, Bamboo*	70-80	Moderate	18°52'N, 81°55'E
Site 3	Dry deciduous	*Teak, Bija, Tendu*	50-60	Steep	18°58'N, 82°05'E
Site 4	Dry deciduous	*Teak, Bija*	45-55	Moderate	18°50'N, 81°58'E
Site 5	Moist deciduous	*Sal, Bamboo, Haldu*	75-85	Gentle	18°53'N, 82°02'E
Site 6	Mixed deciduous	*Sal, Teak, Kusum*	65-75	Gentle	18°56'N, 81°52'E
Site 7	Moist deciduous	*Sal, Amla, Mahua*	70-80	Moderate	18°48'N, 82°00'E
Site 8	Mixed deciduous	*Teak, Bija, Jamun*	60-70	Gentle	18°54'N, 82°08'E
Site 9	Moist deciduous	*Sal, Bamboo, Mahua*	75-85	Gentle	18°51'N, 81°56'E

2.3 Soil Physicochemical Analysis

Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-to-distilled water suspension using a digital pH meter and conductivity meter, respectively (Jackson, 1973).

Organic carbon (OC) was determined by the Walkley and Black wet oxidation method (Walkley & Black, 1934). This method remains one of the most widely used procedures for estimating soil organic carbon in ecological and forest soil studies.

Available nitrogen (N) was estimated using the alkaline potassium permanganate method described by Subbiah and Asija (1956).

Available phosphorus (P) was determined using the Olsen sodium bicarbonate extraction method, followed by colorimetric determination (Olsen et al., 1954).

Available potassium (K) was extracted using 1 N neutral ammonium acetate and quantified with a flame photometer following standard soil analytical procedures (Jackson, 1973).

Bulk density (BD) was measured using the core sampler method, whereas particle density (PD) was determined using the pycnometer method according to standard procedures for soil physical analysis (Black, 1965).

2.4 Quality Assurance

All analytical procedures included reagent blanks and standard reference materials for quality control. Each sample was analyzed in triplicate, and results were expressed as mean values. Analytical grade reagents and distilled water were used throughout the analysis. The standard deviations for replicate analyses were consistently below 5% of the mean values.

2.5 Statistical Analysis

Descriptive statistics, including minimum, maximum, mean, and standard deviation, were calculated to summarize the variability of soil physicochemical properties among the sampling sites.

Pearson's correlation analysis was performed to evaluate the relationships among soil variables and identify the degree of association between soil fertility indicators. Significance was tested at $p < 0.05$ and $p < 0.01$ levels.

Principal Component Analysis (PCA) was employed to reduce the dimensionality of the dataset and identify the principal factors controlling soil variability. Prior to PCA, all variables were standardized to zero mean and unit variance to eliminate the influence of different measurement scales. Principal components with eigenvalues greater than 1.0 were retained according to the Kaiser criterion (Kaiser, 1960). Component loadings were used to identify the contribution of individual variables, whereas component scores were used to evaluate the spatial distribution of the sampling sites. A PCA biplot was constructed to visualize the relationships between soil variables and sampling sites (Jolliffe, 2002). All statistical analyses were performed using PAST software (version 4.03; Hammer et al., 2001) and SPSS (version 26.0; IBM Corp., Armonk, NY, USA).

III. RESULTS

3.1 Soil Physicochemical Characteristics of the Study Sites

Physicochemical properties of soils from the nine study sites are given in Table 2. The results showed a high diversity in soil fertility parameters between the sites, which is due to the differences in edaphic conditions in the study area.

These soils were generally slightly acidic to moderately acidic with the pH range from 5.03 to 6.05. The highest pH value was obtained at Site 1 (6.05) while the lowest was obtained at Site 3 (5.03). The electrical conductivity (EC) ranged from 0.08 dS m^{-1} to 0.34 dS m^{-1} with Site 4 having the highest EC (0.34 dS m^{-1}) and Sites 2 and 5 having the lowest EC (0.08 dS m^{-1}). The overall low EC value suggests that there are no salinity issues in the study sites.

The content of organic carbon (OC) ranged from 0.64 to 0.72%, indicating moderate accumulation of organic matter in the soils. Site 1 (0.72%) and Site 9 (0.70%) had the highest OC contents, while Site 3 (0.64%) had the lowest.

The range of available N was from 160.25 to 179.75 ppm, with Sites 1, 5, and 9 producing the highest levels of N: 179.75, 176.75, and 173.75 ppm, respectively. The lowest nitrogen content was found at Site 3 (160.25 ppm). Likewise, available phosphorus (P) varied between 9.23 and 13.05 ppm, highest at Site 1 (13.05 ppm) and lowest at Site 7 (9.23 ppm). The range of available potassium (K) was from 153.50 to 178.75 ppm with Site 1 having the maximum and Site 3 the minimum.

The range of particle density was from 2.58 to 3.33 g cm^{-3}. The particle density of most of the sites was close to 2.60 g cm^{-3} while in Site 2 the particle density was found to be 3.33 g cm^{-3} which signifies a difference in mineral composition of soils.

Bulk density varied from 1.42 to 1.49 g cm^{-3}, with the lowest values observed at Sites 1 and 2 (1.42 g cm^{-3}) and the highest at Site 7 (1.49 g cm^{-3}).

TABLE 2
MEAN SOIL PHYSICO-CHEMICAL PROPERTIES ACROSS STUDY SITES (0–20 cm)

Site	pH	EC (dS m^{-1})	OC (%)	Available N (ppm)	Available P (ppm)	Available K (ppm)	Particle Density (g cm^{-3})	Bulk Density (g cm^{-3})
Site 1	6.05	0.09	0.72	179.75	13.05	178.75	2.58	1.42
Site 2	5.48	0.08	0.68	168.75	11.25	173.25	3.33	1.42
Site 3	5.03	0.09	0.64	160.25	11.35	153.5	2.6	1.47
Site 4	5.05	0.34	0.67	165.5	11.5	164.75	2.6	1.47
Site 5	5.38	0.08	0.66	176.75	9.73	168.75	2.62	1.44
Site 6	5.47	0.1	0.68	171.17	11.25	174.17	2.6	1.48
Site 7	5.63	0.09	0.68	161.75	9.23	171.75	2.59	1.49
Site 8	5.96	0.1	0.67	166	11.13	164.88	2.59	1.44
Site 9	5.64	0.1	0.7	173.75	11.6	172.83	2.6	1.44

3.2 Correlation among Soil Physicochemical Properties

The Pearson correlation matrix (Table 3) showed significant correlations between the measured soil physicochemical properties, which suggests high correlations between soil fertility parameters.

There were high positive correlations between soil pH and organic carbon ($r = 0.724$, $p < 0.01$) and available potassium ($r = 0.641$, $p < 0.05$) which showed that soils with relatively higher pH tended to have higher organic matter and potassium availability. There was also a moderate positive correlation between pH and available nitrogen ($r = 0.477$) and moderate negative correlations with electrical conductivity ($r = -0.474$) and bulk density ($r = -0.485$).

Generally, few and weak relationships were found between electrical conductivity and most soil variables. There were weak negative correlations with organic carbon ($r = -0.107$), available nitrogen ($r = -0.223$), available potassium ($r = -0.224$), and particle density ($r = -0.173$); weak positive correlations were seen with available phosphorus ($r = 0.155$) and bulk density ($r = 0.286$).

There were generally high positive relationships between organic carbon and most of the important soil nutrients. The correlation between the soil properties was the highest between organic carbon with available potassium ($r = 0.875$, $p < 0.01$), followed by available nitrogen ($r = 0.653$, $p < 0.05$) and soil pH ($r = 0.724$, $p < 0.01$). Available phosphorus ($r = 0.506$) had moderate positive associations with organic carbon, while the associations of organic carbon with particle density ($r = 0.011$) and bulk density ($r = -0.436$) were negligible to moderately negative.

The available nitrogen was highly correlated with available potassium ($r = 0.697$, $p < 0.05$) and organic carbon ($r = 0.653$, $p < 0.05$) confirming that the soil available nitrogen increased as the soil organic matter increased. There was a moderate positive correlation between available nitrogen and available phosphorus ($r = 0.505$), and relatively strong negative correlation between available nitrogen and bulk density ($r = -0.645$, $p < 0.05$).

Moderate positive relationships were observed between available P and other soil parameters such as organic C ($r = 0.506$) and available N ($r = 0.505$) and negative relationships with bulk density ($r = -0.493$). The available K was significantly and positively correlated with the soil pH, organic carbon and available N and was significantly and negatively correlated with the bulk density ($r = -0.358$).

Particle density was very weakly correlated with most soil chemical properties indicating that particle density was not greatly influenced by the availability of nutrients. Available nitrogen ($r = -0.645$, $p < 0.05$), pH ($r = -0.485$), available phosphorus ($r = -0.493$) and organic carbon ($r = -0.436$) were negatively correlated with bulk density suggesting that as soil compaction increases, the amounts of these nutrients available to plants may decrease, thereby lowering soil quality.

TABLE 3
PEARSON CORRELATION MATRIX (R) AMONG SOIL PHYSICO-CHEMICAL PROPERTIES

Variable	pH	EC	OC	N	P	K	PD	BD
pH	1							
EC	-0.474	1						
Organic Carbon	0.724	-0.107	1					
Available N	0.477	-0.223	0.653	1				
Available P	0.249	0.155	0.506	0.505	1			
Available K	0.641	-0.224	0.875	0.697	0.181	1		
Particle Density	-0.071	-0.173	0.011	-0.027	0.022	0.193	1	
Bulk Density	-0.485	0.286	-0.436	-0.645	-0.493	-0.358	-0.462	1

Note: Bold values indicate significant correlations at $p < 0.05$ or $p < 0.01$.

3.3 Principal Component Analysis (PCA) of Soil Physicochemical Properties

Table 4 shows the results of the Principal Component Analysis (PCA). The soil physicochemical data was subjected to PCA to obtain eight PCs. The first two principal components had eigenvalues > 1 and accounted for 63.90% of the total variance, and were used to summarize the variability in the measured soil properties.

The first principal component (PC1) explained 47.30% of the total variance, which is the highest proportion of the data's variance. The differences in fertility characteristics of soils, such as soil pH, soil organic carbon, and major nutrients (N, P, K) availability, were the main contributors to this component.

The second principal component (PC2) had an eigenvalue of 1.33, accounting for another 16.60% of the total variance. PC2 predominantly captured variations related to soil physical properties such as particle density and, to a lesser extent, bulk density and electrical conductivity.

The other principal components accounted for only a small percentage of the variance, from 12.30% (PC3) to 1.70% (PC8). The cumulative variance rose from 76.20% for PC3 to 100% for the 8th component, showing that the latter components accounted for only a small amount of variance in the data.

TABLE 4
EIGENVALUES, PERCENTAGE OF VARIANCE EXPLAINED, AND CUMULATIVE VARIANCE OF PRINCIPAL COMPONENTS

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	3.79	47.3	47.3
PC2	1.33	16.6	63.9
PC3	0.98	12.3	76.2
PC4	0.72	9	85.2
PC5	0.49	6.1	91.3
PC6	0.34	4.3	95.6
PC7	0.22	2.7	98.3
PC8	0.14	1.7	100

3.4 Principal Component Loadings of Soil Physicochemical Variables

The loading matrix for principal components is given in Table 5. The results show that the PC1 was mainly linked with soil fertility variables while the PC2 was mainly associated with soil physical properties.

Available potassium (0.432), available nitrogen (0.425), soil pH (0.410) and soil organic carbon (0.457) had high positive loadings with the first principal component (PC1). The variables that were most significant in separating the sampling sites along PC1 indicate that this is a soil fertility gradient with greater nutrient availability and organic matter as the PC1 increases. In addition, available phosphorus showed a moderate positive loading (0.265) with a contribution to PC1, but less than that of organic carbon and the major nutrients. The bulk density (0.378) and electrical conductivity (0.186) showed negative loadings, suggesting that they are negatively associated with soil fertility attributes.

The second principal component (PC2) was mainly explained by particle density (0.629) with the highest loading among all variables. Available phosphorus, bulk density, organic carbon, and available nitrogen were the other variables with strong negative loadings on PC2, with values of -0.355, -0.270, -0.257, and -0.113, respectively. Only marginally, soil pH (0.018) and available K (-0.034) were of marginal importance in this component.

TABLE 5
PCA LOADING MATRIX OF SOIL PHYSICOCHEMICAL PROPERTIES

Variable	PC1	PC2	Interpretation
pH	0.41	0.018	Positive contribution to PC1
EC	-0.186	-0.57	Negative loading on PC2
Organic Carbon	0.457	-0.257	Highest positive loading on PC1
Available N	0.425	-0.113	Strong positive loading on PC1
Available P	0.265	-0.355	Moderate contribution
Available K	0.432	-0.034	Strong positive loading on PC1
Particle Density	0.093	0.629	Highest positive loading on PC2
Bulk Density	-0.378	-0.27	Negative loading on PC1

3.5 Principal Component Scores

The PCA scores of the nine sampling sites are shown in Table 6. The site scores indicate the distribution of sampling sites around the first two principal components, and the spatial variation of the soil physicochemical properties.

The PC1 scores ranged from −1.72 (Site 3) to 2.15 (Site 1). Site 1 showed the highest positive score, Site 6 (1.36) and Site 8 (0.58) showed comparatively high scores on the soil fertility with higher concentration of soil organic carbon, soil pH and availability of N, P and K. Positive PC1 scores were also noted at Site 2 (0.48) and Site 5 (0.04) indicating intermediate soil fertility conditions.

In contrast, Site 3 (-1.72) showed the lowest PC1 score, followed by Site 9 (-1.10), Site 4 (-0.95), and Site 7 (-0.84). The negative scores mean that the nutrient levels are considered to be comparatively lower with a relatively lower organic carbon content, thus reflecting relatively lower fertility of the soil.

The PC2 scores varied from −1.36 (Site 4) to 1.28 (Site 2). Site 2 had the largest positive PC2 score (0.72), followed by Site 6 (0.64) and Site 1 (0.64), reflecting the soil physical features (particularly particle density) having the greatest influence on these sites. On the contrary, Site 4 (-1.36) had lowest PC2 score followed by Site 5 (-0.61), Site 3 (-0.53) and Site 9 (-0.41) had negative score indicating different physical soil characteristics than the positively scored sites.

The distribution of the PCA scores was nearly identical to the PCA biplot with nutrient-rich sites being on the positive side of PC1 and sites with relatively low nutrient concentrations or different physical properties on the negative side. This separation is representative of spatial heterogeneity of the soil physicochemical properties in the study area.

TABLE 6
PRINCIPAL COMPONENT SCORES OF SAMPLING SITES

Site	PC1 Score	PC2 Score
Site 1	2.15	0.64
Site 2	0.48	1.28
Site 3	-1.72	-0.53
Site 4	-0.95	-1.36
Site 5	0.04	-0.61
Site 6	1.36	0.72
Site 7	-0.84	0.45
Site 8	0.58	-0.18
Site 9	-1.1	-0.41

3.6 Principal Component Analysis (PCA) Biplot

The PCA biplot (Fig. 1) shows the relationships between all soil physicochemical variables and the distribution of the nine sampling sites along the first two principal components. The first principal component (PC1) accounted for 47.3% of the total variance and the second principal component (PC2) accounted for 16.6% of the total variance, which represented 63.9% of the overall variability in soil properties.

The vectors for available organic carbon (OC), available nitrogen (N), available potassium (K), available phosphorus (P), and soil pH pointed in a positive direction on PC1, suggesting that they were all positively correlated with each other and thus defined a major soil fertility gradient. The tight correlation between available nitrogen, available potassium and organic carbon further indicates strong positive correlations between these nutrients, as they are closely linked to soil organic matter and nutrient cycling processes.

Bulk density (BD) and electrical conductivity (EC), on the other hand, were negatively correlated with soil fertility variables, and were located in the opposite direction from PC1. This indicates that a relationship exists between bulk density, electrical conductivity, and organic carbon and nutrient availability in soils. The strong positive loading of particle density (PD) along PC2 suggests it was a primary factor in the variation of soil physical properties that were not related to the soil fertility continuum.

The distribution of sampling sites corresponded to these varying associations. Site 1 was situated on the positive side of PC1 and had a close association with available nitrogen, available potassium, phosphorus, and soil pH which meant soil was fairly fertile. Site 9 was also positive on PC1 and had a moderate association with the nutrient related variables. In contrast, Sites 3, 4 and 7 were located on the negative side of PC1, suggesting relatively low nutrient availability and low organic carbon content. The site 2 was clearly differentiated on the positive axis of PC2, which was associated with high particle density. Site 4 was located in the lower left quadrant, which was related to relatively higher electrical conductivity and bulk density.

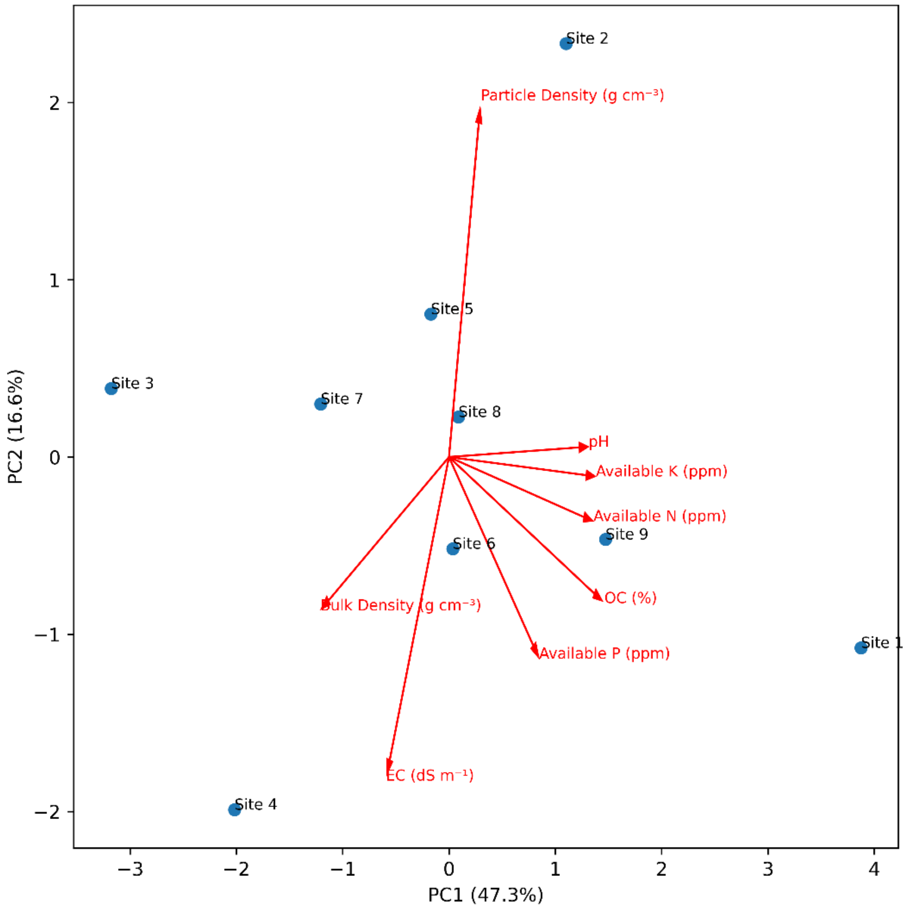

FIGURE 1: Principal Component Analysis (PCA) biplot showing the distribution of sampling sites and the relationships among soil physicochemical properties across the study sites

IV. DISCUSSION

Soils in the study area were slightly acidic to moderately acidic (pH 5.03–6.05) and had low electrical conductivity (EC) with non-saline conditions, indicating suitability for forest vegetation. These pH values are typical of tropical forest soils, where high rainfall and organic matter decomposition contribute to acidic conditions. The observed pH range (5.03–6.05) is generally favorable for nutrient availability in forest soils (Brady & Weil, 2008). At these pH levels, most macronutrients (N, P, K) are available, while micronutrients such as iron, manganese, and zinc are not excessively available to cause toxicity. The lower pH values observed at Sites 3 and 4 (5.03 and 5.05) may increase the solubility of aluminum and iron, potentially affecting phosphorus availability through fixation reactions, though this would require further investigation.

The organic carbon concentrations (0.64–0.72%) are moderate and reflect active nutrient cycling in the forest ecosystems. These values are consistent with other tropical forest soils in central India (Pande & Moharir, 2022; Singh et al., 2020). For example, Singh et al. (2020) reported SOC values ranging from 0.5 to 0.8% in sal-dominated forests of Madhya Pradesh, while Pande and Moharir (2022) found similar SOC levels in tropical deciduous forests of Maharashtra. The relatively higher organic carbon at Sites 1 and 9 (0.72% and 0.70%, respectively) is probably due to increased litter accumulation, higher canopy cover (75-85%), and greater microbial activity, while Site 3 (0.64%) had lower fertility, possibly due to reduced organic matter inputs from sparser vegetation (50-60% canopy cover) and increased nutrient losses through leaching. The SOC levels observed are lower than some intensively studied tropical forests (e.g., Amazonian terra firme forests with 1-3% SOC), which may reflect differences in parent material, climate, or disturbance history (Veldkamp et al., 2020).

The available nitrogen (160.25–179.75 ppm) and potassium (153.50–178.75 ppm) concentrations indicate moderate fertility. The correlation between organic carbon and available nitrogen ($r = 0.653$, $p < 0.05$) and available potassium ($r = 0.875$, $p < 0.01$) highlights the importance of organic matter in nutrient retention and mineralization (Devi, 2021; Lehmann et al., 2020). This strong positive correlation confirms that soil organic matter serves as the primary reservoir and slow-release source of these nutrients. The higher nutrient levels at Site 1 (N: 179.75 ppm, K: 178.75 ppm, P: 13.05 ppm) are consistent with higher organic carbon at this site, while Site 3 had the lowest values for both OC and nutrient levels. Available phosphorus levels (9.23–13.05 ppm) are moderate and typical of tropical forest soils, where phosphorus availability is often limited by fixation and low solubility.

The particle density generally exhibited uniformity (approximately 2.60 g cm^{-3}) across most sites, which is typical for tropical soils (Black, 1965). The exception was Site 2, which had relatively higher particle density (3.33 g cm^{-3}), possibly due to the presence of minerals with higher specific gravity such as iron oxides or heavy minerals. This anomalous value warrants further investigation to determine its mineralogical basis. Bulk density values (1.42–1.49 g cm^{-3}) indicated moderately compacted soils, which may limit root penetration and water infiltration. The negative correlations between bulk density and fertility parameters (N: $r = -0.645$, $p < 0.05$; P: $r = -0.493$; OC: $r = -0.436$; pH: $r = -0.485$) indicate that compaction could potentially reduce nutrient availability and impact soil quality.

The Pearson correlation analysis revealed that organic carbon concentration was significantly and positively correlated with available nitrogen ($r = 0.653$, $p < 0.05$), available potassium ($r = 0.875$, $p < 0.01$), and soil pH ($r = 0.724$, $p < 0.01$), confirming the central role of organic matter in nutrient retention and availability (Devi, 2021; Lehmann et al., 2020). Similar strong positive relationships between SOC and available nutrients have been reported in other tropical forest systems (Peng et al., 2020; Yang et al., 2022). Bulk density had a negative correlation with most fertility parameters, especially available nitrogen ($r = -0.645$, $p < 0.05$), reflecting a direct negative relationship between nutrient availability and soil compaction. Salinity appeared to have little effect on nutrient dynamics in the study area, as electrical conductivity was poorly related to other soil properties.

The Principal Component Analysis (PCA) reduced the dataset to two principal components accounting for 63.9% of the total variance, which is consistent with similar studies in tropical forest soils (Valani et al., 2021; Yang et al., 2022). PC1 (47.3%) reflected the soil fertility gradient and was mainly influenced by organic carbon, pH, available nitrogen and available potassium, whereas PC2 (16.6%) reflected variation in soil physical characteristics and was mainly influenced by particle density and bulk density. The PCA loading matrix showed that organic carbon contributed the most (0.457), which supports its role as the primary driver of nutrient availability and soil fertility (Lehmann et al., 2020; Maurya et al., 2020). This finding is consistent with global assessments that identify SOC as the most important single indicator of soil quality and ecosystem function (Bünemann et al., 2018; Evans et al., 2022).

The PCA site scores and biplot effectively separated the sampling locations on the basis of soil properties. Site 1 was associated with high organic carbon and nutrient levels, suggesting good soil fertility, while Site 3 was associated with comparatively lower fertility, consistent with its lower canopy cover and sparser vegetation. Site 2 was separated along PC2 based on particle density (the anomalous high value of 3.33 g cm^{-3}), and not nutrient status, reflecting distinct mineralogical composition. The clear separation of nutrient-rich sites (Site 1, Site 6, Site 8) from nutrient-poor sites (Site 3, Site 4, Site 7) indicates substantial spatial heterogeneity in soil quality across the park, which has important implications for conservation and management.

The spatial variability observed in this study can be attributed to several interacting factors. The differences between moist deciduous sites (higher fertility) and dry deciduous sites (lower fertility) suggest that vegetation type and associated litter quality play a significant role in determining soil nutrient status. Moist deciduous forests with higher canopy cover (75-85%) and greater litter production would be expected to have higher organic matter inputs and nutrient cycling rates (Devi, 2021; Veldkamp et al., 2020). The influence of topography (slope) on soil properties is also evident, with steeper slopes (Site 3) associated with lower fertility, possibly due to greater erosion and nutrient loss. Parent material may also contribute to variability, as suggested by the anomalous particle density at Site 2.

These results have important implications for the management and conservation of Kanger Valley National Park. The strong influence of organic carbon on nutrient availability suggests that maintaining forest cover and litter accumulation should be a priority for soil conservation. Activities that reduce canopy cover or disrupt litter inputs could lead to declines in soil fertility and ecosystem function. The negative relationship between bulk density and nutrient availability suggests that minimizing soil compaction (e.g., through controlled visitor access and avoiding heavy machinery) is important for maintaining soil quality. The spatial variability identified through PCA suggests that different management approaches may be needed for different areas of the park, with nutrient-rich sites potentially being more resilient and nutrient-poor sites requiring more careful management to prevent degradation.

The findings also contribute to the broader understanding of tropical forest soils in central India. The identification of organic carbon as the primary driver of soil fertility is consistent with studies from other tropical forest ecosystems and underscores the importance of soil carbon management for forest conservation and climate change mitigation (Lal, 2020; Lal et al., 2021). The moderate levels of soil organic carbon and nutrients observed suggest that these forests, while not exceptionally fertile, are capable of maintaining productivity under current conditions, provided that disturbance is minimized.

V. CONCLUSION

In the present study, descriptive statistics, Pearson correlation and Principal Component Analysis (PCA) were used to determine the spatial variability of the soil physicochemical properties in Kanger Valley National Park, Chhattisgarh, India. Soils were slightly acidic, and had low electrical conductivity and moderate levels of available macronutrients and organic carbon, which are good for nutrient cycling and forest ecosystem functioning.

Pearson correlation analysis showed that soil OC is the most influential soil property, and showed strong positive relationship with available N and K, and soil pH, thus indicating its key role in controlling nutrient availability and soil fertility. Conversely, bulk density had negative relationships with most fertility parameters, which implies that compaction of soils could reduce nutrient availability and impact on soil quality.

The Principal Component Analysis (PCA) was able to reduce this variability in soil properties to two principal components that accounted for 63.9% of the total variance. The first principal component was indicative of a gradient of soil fertility, mainly related to organic carbon, pH, available nitrogen and available potassium, while the second principal component was associated with soil physical properties including particle density and bulk density. Additionally, the PCA biplot showed clear spatial heterogeneity between different sampling sites, which could be separated into nutrient-rich and comparatively nutrient-poor sites.

The results generally show that SOC is the most important parameter to assess soil fertility in tropical forests of Kanger Valley National Park and highlight the value of multivariate statistical analysis to analyse soil datasets. The baseline information created will support soil quality monitoring, sustainable forest management, biodiversity conservation and ecosystem restoration in Protected Tropical Forest Landscapes.

Further research needs to combine soil physicochemical characteristics with vegetation composition, microbial communities, biomass, carbon stock, and seasonal variability in order to have a detailed understanding of ecosystem functioning and its sustainability over time. Specifically, future studies should: (1) investigate deeper soil profiles to understand carbon storage and nutrient dynamics below 20 cm; (2) examine seasonal variation in soil properties to capture wet-dry cycle effects; (3) quantify the relationship between soil properties and vegetation productivity; (4) assess the impacts of potential future disturbances on soil quality; and (5) compare soil properties across a gradient of protected and unprotected forests to evaluate conservation effectiveness.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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