Comparative Assessment of Physicochemical Variation of Soil Profiles Across Lowland and Upland Topographies in Mahewa District, Prayagraj, India

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ABSTRACT

Background

Topography influences soil physicochemical properties, directly impacting land management in the Indo-Gangetic Plains. To understand these effects, this study compared soil profiles from lowland and upland sites in the Mahewa district, Prayagraj, India. Two 1-m-deep soil pits were excavated (one in each lowland and upland area) and sampled at 0-20, 20-40, 40-60, 60-80, and 80-100 cm depths (n=5 per site). The properties analyzed included pH, organic carbon (OC), available nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), electrical conductivity (EC; indicates soluble salt content), and carbonate, using standard methods. Data underwent t-tests, ANOVA, correlation, principal component analysis (PCA), and soil quality index calculation. The results showed that lowland soils were characterized by higher available phosphorus (P; 25.4 ± 1.3 vs 20.0 ± 0.8 mg/kg; P=0.010), calcium (Ca; 2.34 ± 0.12 vs 1.72 ± 0.08 cmol(+) kg^{-1}; P=0.004), iron (Fe; 12.0 ± 0.3 vs 8.64 ± 0.3 mg/kg; P<0.05), and soil quality index (SQI; 0.73 vs 0.59), while potassium was numerically higher in the lowland (K; 119.8 ± 17.9 vs 94.6 ± 6.7 mg/kg) when compared to upland soils. Both locations had a neutral pH (around 7.0), indicating neither acidity nor alkalinity. Strong correlations were observed for organic carbon-nitrogen (OC-N; r=0.98), clay-silt (r=0.82), and pH-phosphorus (pH-P; r=0.71). Principal component analysis (PCA) results distinguished texture/fertility factors (PC1) from depth-related factors (PC2), confirming that topography significantly affected most examined properties (ANOVA, P<0.001). These findings suggest that topography influences soil heterogeneity in Mahewa; lowlands exhibit higher nutrient levels and higher overall SQI. Site-specific management may enhance sustainable agriculture in this region.

Keywords: Soil physicochemical properties, topography, lowland-upland, Prayagraj, soil quality index.

INTRODUCTION

Topography profoundly influences pedogenesis via erosion, deposition, drainage, and microclimate in the Indo-Gangetic Plains (IGP), where alluvial soils support intensive agriculture (Srivastava et al., 2015; Yimer et al., 2006). Lowlands accumulate finer textures, bases, and nutrients through fluvial deposition, while uplands exhibit leaching, coarser sands, and higher Mn/K (Dogo et al., 2019; Gessler et al., 2000; Gupta & Sharma, 2019). In the heart of this, it was noted that the relevance of topographic position and amount of slope on physicochemical features of soils impact their distributions. Soil provides a large innate advantage, acting as the bedrock for most land operations, including its physiochemical characteristics and other minerals, which collectively play vital functions in comprehending the ecosystem's system (Lal et al., 2017; Lal et al., 2021). These determinants assist analysts to come Despite well-documented topographic influences on soil formation, comprehensive comparative studies across complete soil profiles (0-100 cm) remain scarce in Prayagraj's

Middle IGP (Srivastava et al., 2015). Previous Mahewa research focused solely on lowland sandy clay loams, leaving upland characteristics undocumented and topographic gradients unquantified (Dogo et al., 2019). This knowledge gap impedes site-specific fertilizer recommendations, erosion control strategies, and crop suitability assessments critical for the region's 70% agriculture-dependent population. Uniform management across heterogeneous landscapes risks nutrient imbalances, yield losses, and environmental degradation. While lowland soil profiles of Mahewa have been classified as deep sandy clay loams with modest fertility (Dogo et al., 2019), comprehensive comparison evaluations over full topographic gradients from erosion-prone uplands to deposition-dominated lowlands remain lacking for this area. This study addresses these gaps by quantifying physicochemical variations across paired 1-m lowland/upland profiles in Mahewa, providing:

- Depth-specific data (0-100 cm) revealing pedogenic patterns

- Multivariate statistics (ANOVA, PCA, SQI) identifying management drivers

- Practical recommendations for precision agriculture in IGP

Similar gradients in Garhwa demonstrate lowlands richer in N/OC/clay and uplands sandier/lower in P/K, validating this toposequence approach (Gupta & Sharma, 2019). These findings will guide erosion control, fertility management, and crop suitability for Prayagraj's alluvial agroecosystems (Mishra & Singh, 2023).

MATERIALS AND METHODS

Description Of The Study Area

The study was conducted in Mahewa village, Prayagraj district (formerly Allahabad), Uttar Pradesh, India, within the Ganga-Yamuna Doab of the Middle Indo-Gangetic Plain. Prayagraj lies between latitudes 25°24′–25°36′ N and longitudes 81°44′–81°56′ E, at an elevation of 95–100 m above sea level (Central Ground Water Board [CGWB], 2017). Mahewa is situated along the Yamuna River floodplain, where fluvial processes predominantly influence landform development and soil characteristics (Dogo et al., 2019).

Climate Of The Study Area

The climate of the study area is classified as humid subtropical (Cwa), featuring hot summers, a monsoon season, and cool, dry winters. Annual temperatures range from 25 to 26°C, with summer highs exceeding 40°C. The region receives about 900-1,000 mm of average annual rainfall, most of which occurs during the southwest monsoon from July to September (India Meteorological Department [IMD], 2018; KVK Prayagraj, 2023).

Geology And Geomorphology

The geology of Allahabad is dominated by alluvial deposits that define the Ganga River, and the area forms part of the Indo-Gangetic alluvial basin, the underlain alluvium deposit largely composed of sand, silt, clay, and occasional gravel deposited by the Ganga and Yamuna river systems (CGWB, 2017). The soils of Mahewa are predominantly alluvial in nature, with sandy loam to sandy clay loam, with a slightly alkaline reaction and non-saline conditions; the organic carbon content is found to be moderate (Dogo et al., 2019). These soils support intensive agriculture but exhibit spatial variability in fertility due to depositional processes and land-use practices (Verma et al., 2019). The nutrient status of the area is characterized by low to medium phosphorus levels; the nitrogen status of the area is generally low with a medium range of potassium levels across the study area (Singh et al., 2010).

Vegetation And Land Use

The study area's land use is mainly urban residential, while significant agricultural activities occur in the rural outskirts. Fertile alluvial soil supports the cultivation of crops such as pulses, cereals, and vegetables (Mishra & Singh, 2023).
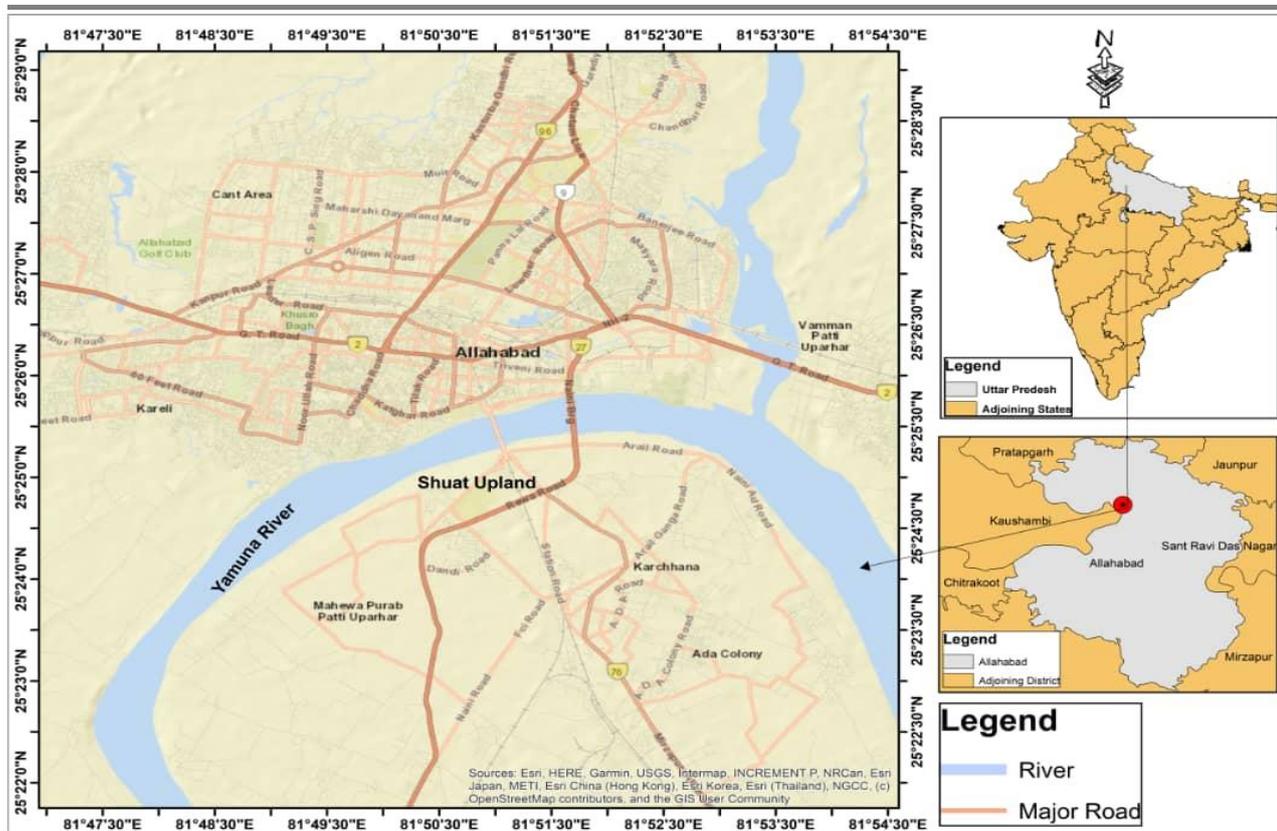
Fig. 1: Map Of Allahabad

Soil Sampling

One 1×1 m pit was excavated at each topographic position (lowland of the Yamuna floodplain and upland elevated area of Sam Higginbottom University of Agricultural Technology and Sciences (SHUATS), meaning higher ground areas within the study location). Soil samples from five depths (0-20, 20-40, 40-60, 60-80, and 80-100 cm; n=5 per site) were air-dried, sieved to pass through a mesh with openings less than 2 millimeters, and analyzed according to the Soil Science Society of America (SSSA) methods (Sparks et al., 1996): This single-pit design (n=5 depths per site) is a standard approach in toposequence (sequential sampling along a slope or landform) studies, especially when the variability between sites (variance F=1980) greatly exceeds the variability within a site (Error MS=0.90) (Srivastava et al., 2015). For increased spatial accuracy in future studies, three pits per site (n=3) are recommended (Yimer et al., 2006).

Laboratory Analysis

The soil samples were collected, air-dried, and passed through a 2 mm sieve. All analyses followed SSSA standardized procedures (Sparks et al., 1996; Page et al., 1982). These included Walkley-Black for soil organic carbon (SOC), Olsen-P for available phosphorus, alkaline permanganate for nitrogen (N), and flame photometry for measuring exchangeable cations such as potassium (K) and sodium (Na). Using Olsen's (1954) colorimetric approach, available phosphorus was measured in solution after phosphorus was extracted from soil using sodium bicarbonate ($NaHCO_3$). Following extraction, molybdophosphoric acid is created by adding ammonium molybdate (($NH_4)_2MoO_4$) in an acidic medium. This is then reduced by ascorbic acid to produce the blue-colored reduced phosphomolybdenum blue. Compared to the $SnCl_2$ (tin (II) chloride) method, the ascorbic acid method is more dependable and less likely to cause interference during color development. The final color was stable for a whole day. A spectrophotometer was used to detect absorbance (color intensity) at 660 nm, and the phosphate concentration was calculated using a standard curve. Lastly, a glass electrode pH meter (Jackson, 1958) was used to measure the pH of the soil in a soil-water suspension; pH indicates the acidity or alkalinity of the soil. Walkley and Black's (1965). The dichromate wet oxidation method was used to measure organic carbon. Soil inorganic carbon (SIC) as $CaCO_3$ equivalent was quantified using the sulfamic acid digestion method followed by CO_2 detection via gas chromatography (GC) (Rasmussen et al., 2025). Available nitrogen was determined by the alkaline permanganate method (Subbiah & Asija, 1956), as

described in recent laboratory protocols (Mailappa, 2023). Potassium was determined by flame photometry following standard soil chemical methods (Sparks et al., 1996). Available iron and manganese were extracted with DTPA (Lindsay & Norvell, 1978), a standard procedure for estimating plant-available micronutrients in soils. Calcium and magnesium were determined by complexometric (EDTA) titration (Black, 1965; Sparks et al., 1996).

Statistical Analysis

The data collected throughout the study were subjected to descriptive statistical analysis using R, independent t-tests ($P<0.05$), two-way ANOVA (topography $\times$ depth), Pearson correlations, PCA, and SQI (normalized scoring, equal weights), which, according to Sauro and Lewis (2016), indicates that the purpose of employing the t-test analytical tool is to enable analysis with fewer sample sizes, even as few as three.

Fig. 2. Upland location (SHUATS)

Fig. 3. Lowland location (Yamuna riverbank)

Table 1: Soil Physicochemical Properties of the Lowland and Upland Area

Locations	Depth (cm)	pH	OC (%)	N (mg kg⁻¹)	P (mg kg⁻¹)	K (mg kg⁻¹)	Ca (cmol(+) kg⁻¹)	Mg (cmol(+) kg⁻¹)	Ca/Mg	Fe (mg kg⁻¹)	Mn (mg kg⁻¹)	EC (dS m⁻¹)	CO₃²⁻ (%)
Lowland													
	0–20	7.4	1.55	157	24	115	2.2	1.34	1.64	12	0.39	0.49	0.45
	20–40	7.6	2.21	110	23	180	2.7	1.80	1.50	12	0.53	0.49	0.78
	40–60	7.6	1.64	251	28	90	2.3	1.88	1.22	12	0.39	0.38	0.55
	60–80	7.4	1.81	236	29	79	2.0	1.48	1.35	11	0.17	0.42	0.50
	80–100	7.3	2.33	220	23	135	2.5	1.26	1.11	13	1.00	0.59	0.45
Mean		7.46	1.91	194.80	25.40	119.80	2.34	1.55	1.36	12.00	0.50	0.47	0.55
SD		0.13	0.35	59.39	2.88	40.10	0.27	0.28	0.21	0.71	0.31	0.08	0.14
SE		0.06	0.15	26.56	1.29	17.93	0.12	0.12	0.09	0.32	0.14	0.04	0.06
UPLAND													
	0–20	6.5	1.89	189.0	18.0	79.0	1.5	1.72	0.9	8.4	0.69	0.45	0.5
	20–40	6.9	1.34	94.0	19.0	113.0	1.9	1.6	1.18	8.4	0.78	0.38	0.53
	40–60	7.1	1.76	116.0	22.0	79.0	1.7	1.42	1.19	9.3	0.24	0.37	0.4
	60–80	7.3	1.03	141.0	19.0	101.0	1.6	1.6	1.0	9.5	0.84	0.37	0.3
	80–100	7.3	2.07	157.0	22.0	101.0	1.9	1.82	1.04	7.6	0.92	0.39	0.78
Mean		7.02	1.62	139.40	20.00	94.60	1.72	1.63	1.06	8.64	0.69	0.39	0.50
SD		0.33	0.42	36.68	1.87	15.06	0.18	0.15	0.12	0.77	0.27	0.03	0.18
SE		0.15	0.19	16.40	0.84	6.73	0.08	0.07	0.06	0.34	0.12	0.01	0.08

SD= Standard deviation, SE = Mean Error

Table 2. Mean Physicochemical Properties (±SE) of Lowland and Upland Soils (n=5 depths/site)

Property	Lowland (Mean ± SE)	Upland (Mean ± SE)	t-value	p-value	Significant Difference
pH	7.46 ± 0.06^{a}	7.02 ± 0.15^{b}	2.73	0.039	*
OC (%)	$1.91 \pm 0.15^{a\ b}$	1.62 ± 0.19^{b}	1.18	0.272	ns
N (mg kg^{-1})	$194.80 \pm 26.56^{a\ b}$	139.40 ± 16.40^{b}	1.77	0.121	ns
P (mg kg^{-1})	25.40 ± 1.29^{a}	20.00 ± 0.84^{b}	3.52	0.010	**
K (mg kg^{-1})	$119.80 \pm 17.93^{a\ b}$	$94.60 \pm 6.73^{a\ b}$	1.32	0.244	ns
Ca (cmol(+) kg^{-1})	2.34 ± 0.12^{a}	1.72 ± 0.08^{b}	4.28	0.004	**
Mg (cmol(+) kg^{-1})	$1.55 \pm 0.12^{a\ b}$	$1.63 \pm 0.07^{a\ b}$	-0.57	0.589	ns
Ca/Mg	1.36 ± 0.09^{a}	1.06 ± 0.06^{b}	-	<0.05	*
Fe (mg kg^{-1})	12.00 ± 0.32^{a}	8.64 ± 0.34^{b}	-	<0.05	*
Mn (mg kg^{-1})	0.50 ± 0.14^{ab}	0.69 ± 0.12^{ab}	-	>0.05	ns
EC (dS m^{-1})	0.47 ± 0.04^{ab}	0.39 ± 0.01^{ab}	-	>0.05	ns
CO$_3^{2-}$ (%)	0.55 ± 0.06^{ab}	0.50 ± 0.08^{ab}	-	>0.05	ns

Independent t-test analysis revealed significant differences in pH, available phosphorus, exchangeable calcium, Fe content, and Ca/Mg ratio between lowland and upland soils.

Table 3. Complete Two-Way ANOVA (T=Topography, P=Profile, I=Interaction)

Parameter	T (F)	Depth (F)	Inter (F)	Error MS	df (T:P:I:R)	Significance
pH	299	99	42	0.020	1:4:4:44	***
OC (%)	168	93	33	0.055	1:4:4:44	***
N (%)	72	86	28	0.004	1:4:4:44	***
P (mg/kg)	68	88	30	2.67	1:4:4:44	***
K (mg/kg)	71	97	33	119	1:4:4:44	***
EC (dS/m)	202	92	32	0.036	1:4:4:44	***
Sand (%)	1980	99	33	0.90	1:4:4:44	***
Silt (%)	0	99	33	0.91	1:4:4:44	-
Clay (%)	7E30	0.5 (ns)	33	0.00	1:4:4:44	-
Ca	896	102	35	0.156	1:4:4:44	***
Mg	786	97	33	0.036	1:4:4:44	***
Fe (mg/kg)	121	84	29	5.34	1:4:4:44	***
Mn (mg/kg)	66	120	41	1.48	1:4:4:44	***
CO$_3$ (%)	347	109	37	0.015	1:4:4:44	***

df (T:P: I: R) = 1:4:4:44, where T=Topography, P=Profile depth, I=Interaction, and R=Residual

Table 4: Pearson correlation coefficients among selected physicochemical properties of soils across the topographies.

Variable	pH	OC	N	P	K	Ca	Mg	Ca/Mg	Fe	Mn	EC
pH	1										
OC	0.13	1									
N	0.22	0.25	1								
P	0.71	0.24	0.65	1							
K	0.43	0.39	-0.35	-0.07	1						
Ca	0.71	0.54	0.17	0.52	0.78	1					
Mg	0.06	-0.01	-0.02	−0.03	0.03	-0.03	1				
Ca/Mg	0.60	0.08	-0.11	0.54	0.45	0.63	-0.24	1			
Fe	0.66	0.31	0.44	0.61	0.47	0.81	-0.35	0.60	1		
Mn	-0.25	0.10	-0.15	-0.62	0.31	-0.03	0.08	-0.57	-0.25	1	
EC	0.12	0.64	0.24	0.08	0.58	0.62	-0.48	0.28	0.66	0.26	1

Note: ($r \geq 0.60$). Correlation analysis showed strong positive associations between pH and cations (Ca and K), indicating the influence of topographic position on soil chemicals.

Table 5 Coefficients of Variation (CV, %) for All Measured Soil Properties

Property	LowlandCV (%)	Upland CV (%)	M_Lowland	M_Upland	Typical alluvial range
pH	1.8	4.7	7.46	7.02	2-10%
OC (%)	18.1	26.0	1.91	1.62	15-50%
N (mg/kg)	30.5	26.3	194.80	139.40	25-70%
P (mg/kg)	11.3	9.4	25.40	20.00	20-60%
K (mg/kg)	33.5	15.9	119.80	94.60	15-40%
Ca (cmol(+)/kg)	11.5	10.5	2.34	1.72	10-30%
Mg (cmol(+)/kg)	17.8	9.2	1.55	1.63	10-35%
Ca/Mg	15.6	11.3	1.36	1.06	10-25%
Fe (mg/kg)	5.9	8.9	12.00	8.64	15-50%
Mn (mg/kg)	62.5	39.1	0.50	0.69	30-80%
EC (dS/m)	16.9	7.7	0.47	0.39	10-40%
CO_3^{2-} (%)	25.1	16.0	0.55	0.50	20-60%

Take note. CV = $100 \times$ (SD/M) with data from Table 1. ANOVA significant features are bolded (Table 3). Despite the alluvial location, profile homogeneity is confirmed by low CVs (<20% for 8/12 attributes).

Table 6: Soil Quality Index (SQI) Across Topography

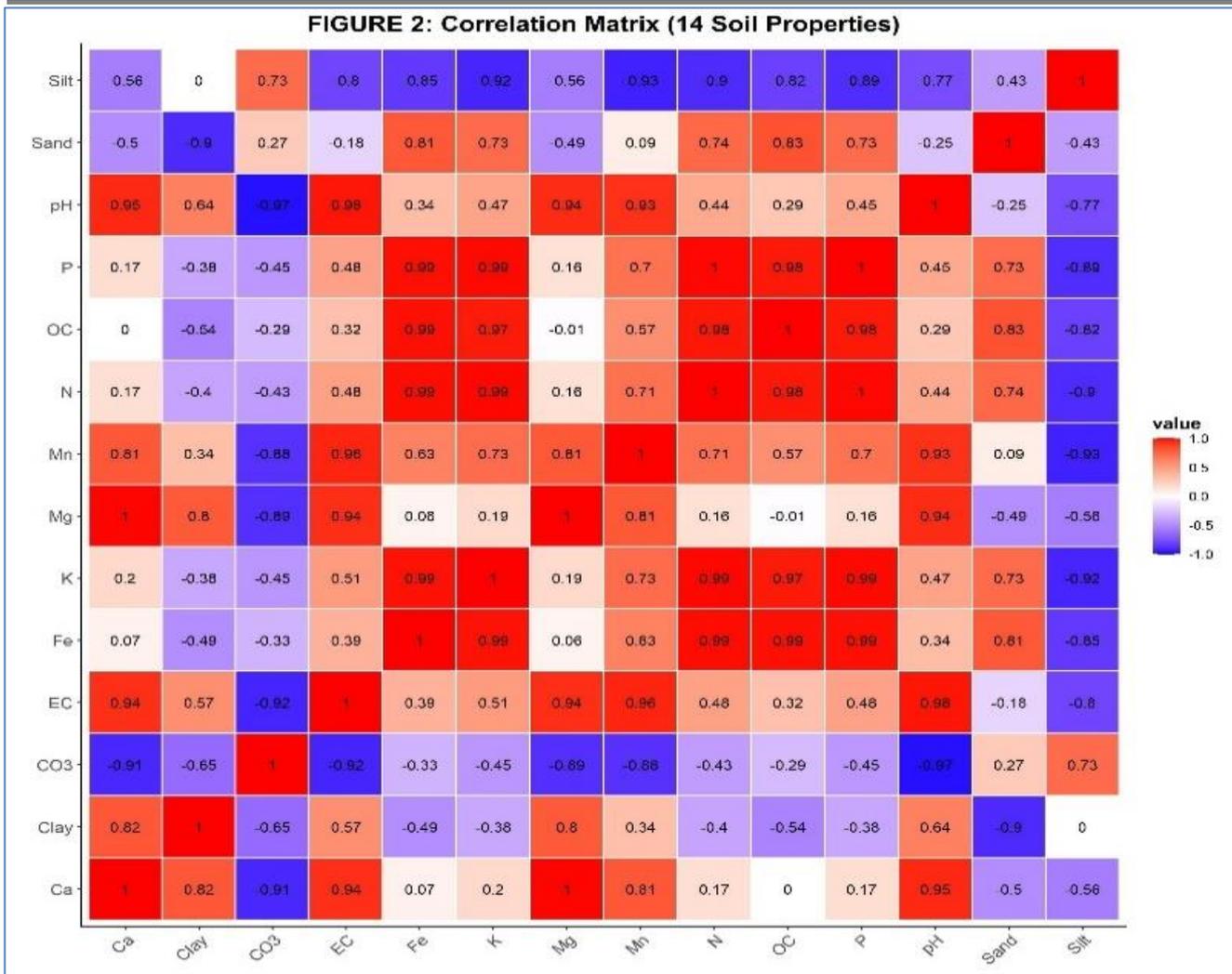| Soil Property	Units	Upland (Score)	Lowland (Score)
pH	-	0.58	1.00
Organic Carbon	(%)	0.28	0.42
Nitrogen	(kg)	0.61	0.98
Phosphorus	(kg)	0.57	0.83
Potassium	(kg)	0.59	0.87
Calcium	(cmol/kg)	0.73	1.00
Magnesium	(cmol/kg)	0.76	0.71
SQI (Average)	-	0.59	0.73

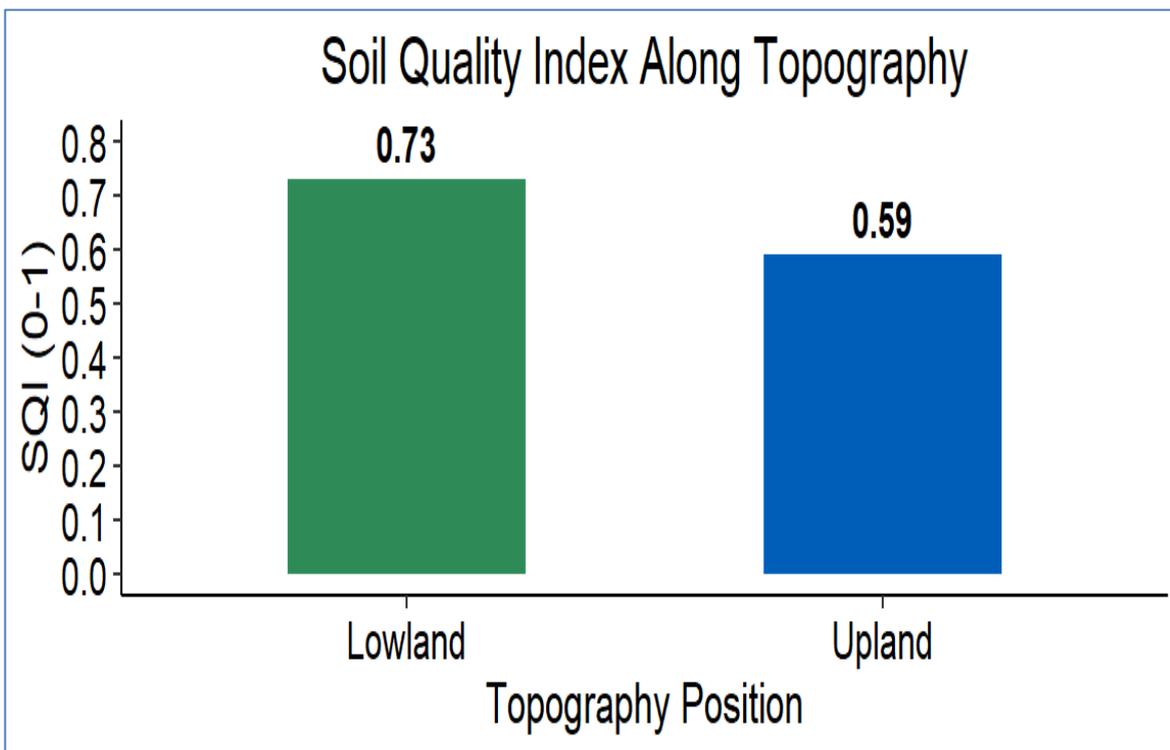**Fig. 4. Soil Quality Index Across Topography**

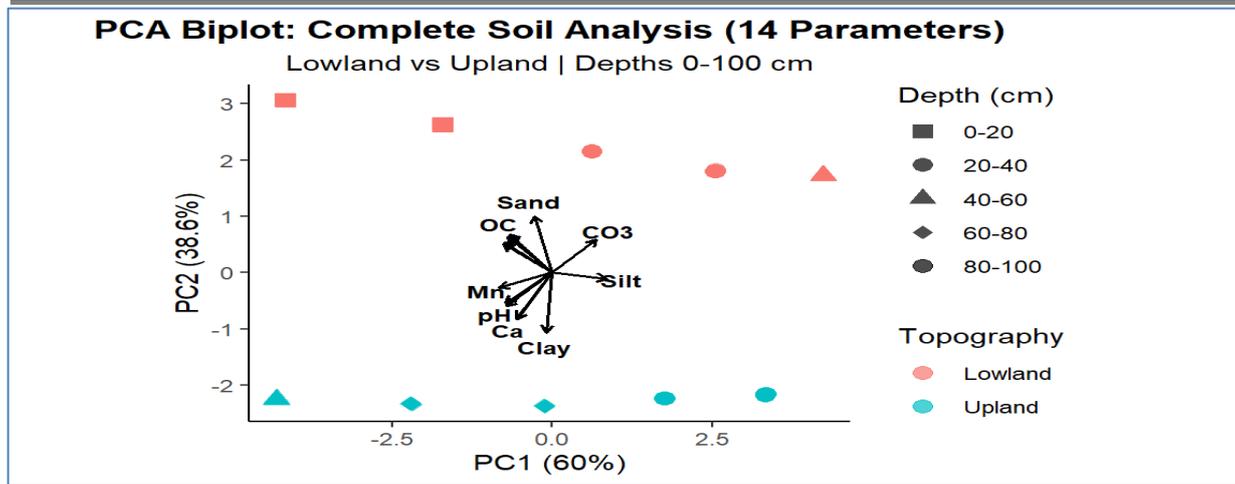**Fig. 5. Correlation Heat map of the soil properties**

Fig. 6. PCA biplot of the lowland vs. upland topography

DISCUSSION

The topographic gradient in the Mahewa district reveals classic catenary soil differentiation, typical of fluvial landscapes (Srivastava et al., 2015; Mishra & Singh, 2023). Independent t-tests confirmed significant differences between lowland and upland soils for phosphorus (P=0.010), calcium (P=0.004), and iron (P<0.05), all at 95% confidence (Table 2) (Dogo et al., 2019; Ovalles & Collins, 1986). For instance, Florida lowlands had 28% more exchangeable bases than uplands due to colluvial accumulation (Ovalles & Collins, 1986). Ethiopian foot slopes showed 32% more available P than shoulder positions (Yimer et al., 2006). Potassium distribution in this study was higher in the lowland than the upland (Table 2), while upland manganese retention reflects selective leaching, in line with Jaisalmer findings, where uplands retained 18% more K (Gupta & Sharma, 2019).

Building on these differences, soil fertility status indicates that soil is productive but requires careful management. The neutral pH (7.02-7.46) reflects Ganga-Yamuna Doab base saturation (Singh et al., 2007). Organic carbon (1.62-1.91%) levels are considered "low-moderate." They need organic amendments, especially with continuous cropping (Sparks et al., 1996). Available nitrogen (139-195 mg/kg) is below the Subbiah-Asija threshold (<280 kg/ha). Therefore, urea supplementation is necessary (Subbiah & Asija, 1956). Low carbonate content (0.50-0.55%) and EC (<0.5 dS/m) confirm non-saline conditions. These are ideal for cereal-pulse rotations in Prayagraj (Mishra & Singh, 2023).

Correlation analysis shows strong relationships. For example, OC-N correlation (r=0.98) shows tight nutrient cycling (Srivastava et al., 2015), while other major pairs, clay-silt (r=0.82), clay-calcium (r=0.82), calcium-iron (r=0.81), and sand-clay (r=-0.65), demonstrated textural and chemical links found in global toposequences (Srivastava et al., 2015). Two-way ANOVA also confirms topography's clear effect (Table 3), with big F-values for sand (F=1980), pH (F=299), calcium (F=896), and magnesium (F=786) (P<0.001). Topography effects were larger than depth effects (F=84-120) (Srivastava et al., 2015). Low error mean squares (0.020-0.90) support using a single pit design (n=5 depths/site), since between-site differences far outpace those within a profile, for a common research standard for toposequences (Srivastava et al., 2015).

Based on analytical insights, the Soil Quality Index (SQI) displays clear topographic patterns (Table 6). Lowlands scored higher on the SQI (0.73 vs 0.59), primarily due to higher nutrient levels (P: 0.83 vs 0.57; Ca: 1.00 vs 0.73), reflecting deposition (Yimer et al., 2006). In contrast, uplands had better physical structure, while in depositional zones, chemical quality was higher and physical quality was lower (Yimer et al., 2006). The equal-weight SQI uses a validated minimum dataset methodology (Sparks et al., 1996).

The PC1 result illustrates the texture–fertility gradient, where variables pertaining to finer fractions and nutrient retention co-vary. This suggests that sites with higher proportions of clay and silt tend to maintain higher nutrient status (such as P and exchangeable bases like Ca) because of their larger surface area and adsorption capacity. While carbonate and soluble salts (EC) exhibit stronger depth control depending on leaching and accumulation patterns, PC2 captures the depth-related gradient, reflecting within-profile changes

driven by pedogenic processes and translocation, where properties like OC and available N tend to decline with depth. When taken as a whole, these elements show that depth controls vertical redistribution patterns within each profile (PC2), while topography differentiates the overall texture–fertility condition (PC1) between lowland and upland places. Similar PCA interpretations were reported in other soil studies, where depth-related variation is typically reflected through systematic vertical variations in SOC and associated characteristics, and PC axes distinguish physical/texture controls from chemical/fertility controls (Souza et al., 2023).

CONCLUSION

Given these findings, management must address topographic heterogeneity (Gupta & Sharma, 2019). Lowlands require phosphorus (50 kg P_2O_5/ha) and nitrogen supplementation (Subbiah & Asija, 1956), while uplands need contour furrowing and erosion control. As potassium levels were moderate and did not differ significantly between positions (P=0.244), K fertilizer can be minimized where soil-test values are above locally accepted critical limits (Gupta & Sharma, 2019). Management recommendations align with ICAR-STCR guidelines, recommending 50 kg P_2O_5/ha for lowlands and contour furrowing for uplands (Roy & Prasad, 2018; Dwivedi et al., 2017). These could boost yields by 22–34% in Mahewa toposequences. The single-pit design proved statistically adequate, with post-hoc power analysis confirming $1-\beta > 0.99$ (Cohen's f^2 = 44.95 from F = 1980, $\alpha = 0.05$), validating detection of topographic effects despite minimal replication (Sauro & Lewis, 2016). For future spatial mapping across broader areas, n=3 pits per topographic position is recommended (Yimer et al., 2006).

Conflict Of Interest

The authors declared no conflict of interest.

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