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Impact of Altitude on Soil Quality in Current Jhum Fields of Churachandpur, Manipur, India

LK Thang Ngaihte*, Elizabeth Nemhoihkim, O.P. Tripathi and B.P. Mishra

Department of Environmental Science, School of Earth Sciences and Natural Resources Management (SES and NRM), Mizoram University, Tanhril 796 004, Mizoram, India

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ABSTRACT

This study investigated impact of altitudinal variations in soil physical and chemical properties of current jhum (shifting cultivation) fields in Churachandpur district, Manipur. Significant differences were observed across the altitudinal gradient, with higher elevations (>1000 m) exhibiting superior soil moisture content (up to 24.81%), water holding capacity (43.58%), organic carbon (3.53%), available nitrogen (616.75 kg/ha), and potassium (263.68 kg/ha) as compared to lower altitudes (<500 m). Conversely, bulk density decreased from 1.33 g/cm^3 at middle altitudes to 0.94 g/cm^3 at higher elevations. The favourable conditions at higher altitudes, such as cooler temperatures and higher moisture availability, likely reduced organic matter decomposition rates and nutrient losses through leaching and erosion, leading to organic matter accumulation and lower anthropogenic disturbances also contributed to preserving soil quality. At lower altitudes, soil quality was better than middle altitudes, possibly due to greater salt accumulation and presence of base-forming cations, resulting in higher pH and available phosphorus levels. In contrast, the mid-altitude sites exhibited poorer soil fertility indicators, potentially influenced by anthropogenic activities like shifting cultivation practices, felling of trees, and erosion of soil nutrients. Overall, this study contributes to our understanding of the relationships between altitude, soil properties, and agricultural practices, particularly in the context of indigenous farming systems in the hilly regions of northeastern India. The findings have potential implications for optimizing land use, promoting sustainable agriculture, and safeguarding the ecological integrity of these fragile ecosystems.

***Key words**: Jhum cultivation, Soil quality, Altitude, Physico-chemical properties, Churachandpur*

Introduction

In the hilly districts of Manipur, the practice of jhum cultivation, involving indiscriminate cutting and burning of forests, is widely adopted by tribal communities. This practice leads to severe consequences on land such as loss of vegetation, erosion, and the creation of barren wastelands (Singh, 2016). The area under jhum cultivation in Manipur has decreased tremendously due to population growth and mounting pressure on land resources (Singh, 2022). Specifically, in the Churachandpur district, jhum cultivation is carried out in the undulating hills near tributaries of the Manipur River, with cycles shortened to 2-3 years, resulting in deforestation, soil nutrient depletion, and erosion (Singh and Chinglianmawi, 2016). While jhum cultivation supports indigenous livelihoods, its shortened cycles, low productivity, and increasing ecological consequences have emerged as prominent challenges in modern times (Punitha *et al.*, 2018). The study area is known for its rugged setting, which encourages an agrarian lifestyle mostly focused on jhum agriculture, employing 84.6% of the local workforce

(Riyabati and Sarangthem, 2017). The mode of operation of the jhum fields is rather traditional and not scientific.

Soil health is crucial for agricultural productivity and plant growth, as it provides water, nutrient, and mechanical support for plants (Shahane and Shivay, 2021). The pH of the soil, often described as the "master soil variable", has a significant influence on soil biogeochemical processes, affecting plant growth and biomass yield (Neina, 2019). Soil organic matter (SOM) supports multiple soil ecosystem functions such as carbon sequestration, nitrogen mineralization, aggregation, promotion of plant health, and compound retention (Hoffland *et al.*, 2020). Soil pH governs the accessibility of vital nutrients in the soil, which are crucial for plant growth, and maintaining these elements at optimal levels enhances both plant health and soil fertility (Shrivastav *et al.*, 2020; Lal, 2020).

While jhum cultivation is widely practiced by indigenous communities in northeast India, there are limited and meagre studies on the soil fertility and properties at along altitudes of jhum fields. Most research has focused on comparing jhum sites to other land uses or assessing overall regional impacts like Singh and Chinglianmawi (2016), Kumar *et al.* (2018), Sinha *et al.* (2020), Riyabati and Sarangthem (2017), Lallawmkima *et al.* (2023), Singh *et al.* (2020), etc. The effects of altitudinal gradients on soil quality in current jhum fields remains poorly understood. This study aims to address this knowledge gap by analysing key soil physical and chemical properties in current jhum fields along an altitudinal gradient in Churachandpur district, Manipur. The result of the study have the potential to guide jhum farmers towards adopting sustainable land management practices suited to different elevations, potentially enhancing agricultural yield and environmental sustainability.

Materials and Methods

Study site

Churachandpur holds the title for being the most expansive district in Manipur, spanning an impressive 4,570 km^2. The 2011 Census reveals that the district is populated by 274,143 individuals, with 93.30% residing in rural areas, and the Government of Manipur (2021) reports that 25.36% of the district's land is dedicated to agriculture. The district lies between 93°15′ E and 94° 45′ E longitude, and 23°55′ N to 24°30′ N latitudes and shares its borders with Jiribam to the north, Chandel and Bishnupur to the east, Mizoram and Myanmar to the south and Cachar, Assam to the west (Figure 1). The district is largely covered by rough and irregular hills, which form a part of the southern extension of the Naga Hill ranges and the altitude varies from 350 to 1,950 meters above sea level (DSR, 2021). Agriculture, particularly jhum cultivation, is the main source of livelihood in the district. Singh *et al.*

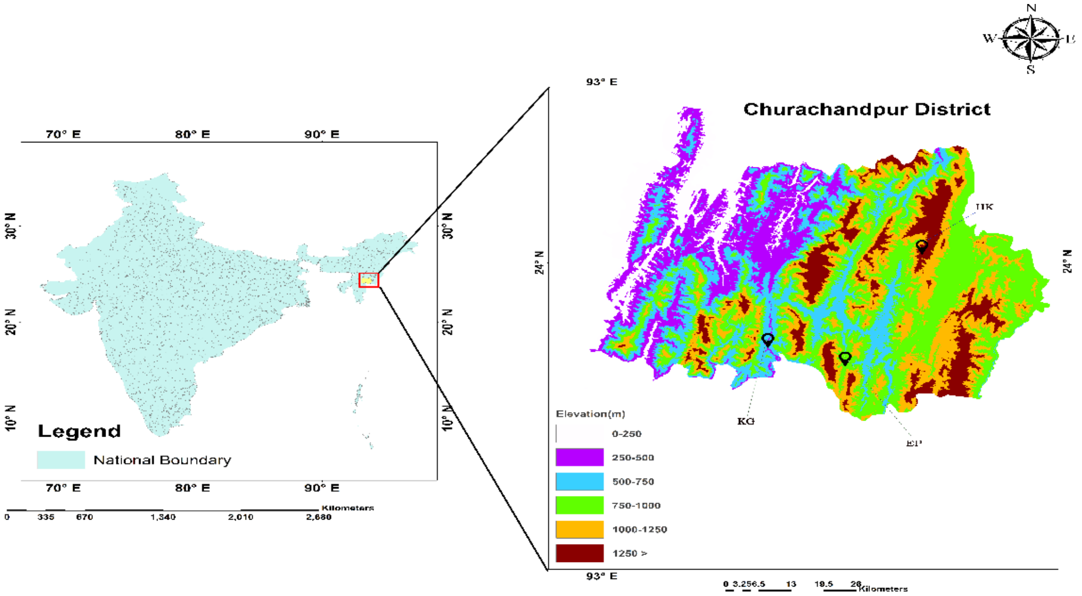

Fig. 1. Study area and elevation map of the study area (Churachandpur)

(2017) estimated that 99,185 people amounting to 34.37% of the district are dependent on jhum cultivation. The district is characterized by a humid subtropical climate, receiving an average annual rainfall of 597 mm. The temperature in the region varies between 4 ºC and 35 ºC (DSR 2021). Furthermore, data from the Manipur Remote Sensing Application Centre in 2024 indicates that forests make up 63.09% of the district's total geographical area.

The study area was further divided into 3 different sites based on the altitudinal gradient or elevation: lower (<500 m asl), middle (500-1000 m asl) and higher (>1000 m asl) where current jhum fields were prevalent as given in Table 1.

Soil sampling and analysis

Soil specimens were collected from the designated jhum fields immediately following the slash-and-burn operation conducted by the *jhumias*, covering the pre-monsoon season (February – May), monsoon season (June – September), and post-monsoon season (October – January). In each season, soil samples for two (2) depths i.e., (0-15 cm and 15-30 cm) were collected and stored and air-dried for analysis.

The physico-chemical properties of the soil samples were analysed using standard laboratory methods. Soil pH and electrical conductivity (EC) were determined by the soil: water suspension (1:2 and 1:2.5 respectively) method, using digital pH and EC meters, Anderson and Ingram's (1993) approach were used to determine the soil moisture content (SMC%), water holding capacity (WHC%) and bulk density (BD g/cm^3). The organic carbon (OC %), Available nitrogen (AN kg/ha), available phosphorus (AP kg/ha), available potassium (AK kg/ha), exchangeable sodium [Exch. Na (cmol(p$^+$)/kg)], and exchangeable calcium [Exch. Ca cmol(p$^+$)/kg)] and exchangeable magnesium [Exch. Mg (cmol(p$^+$)/kg)] were determined using Walkley and Black (1934), Subbiah and Asija (1956), Bray and Kurtz (1945), Hanway and Heidel (1952), Toth and Prince (1949) and Zhang *et al.* (2012) respectively.

Statistical analysis

General statistical parameters such as mean, standard error of mean (SEM), was calculated for each sampling site, Pearson Correlation for correlation analysis, one-way ANOVA and Tukey's HSD test to determine the significant differences between the soil parameters using SPSS 27.

Results and Discussion

The physical properties, chemical properties, Spearman's correlation analysis, ANOVA and Tukey's HSD Post-hoc test of the soils across depths, seasons and sites on selected jhum fields are carried out and data were presented and discussed.

Physical properties of soil

At lower altitude, the soil texture in the surface layer (0-15 cm) was loamy sand in the pre-monsoon and monsoon seasons, but changed to sandy loam in the post-monsoon season. In the subsurface (15-30 cm) layer, the texture remained consistent as sandy loam across all three seasons. Overall, the mean annual texture in the surface layer at lower altitude was loamy sand, while the subsurface layer had a sandy loam texture. At middle altitude, the surface layer exhibited sandy loam texture in the pre-monsoon and post-monsoon seasons, but switched to loamy sand texture during the monsoon season. In the subsurface layer, the texture was sandy loam in all three seasons surveyed. Taking the annual average, both the surface and subsurface layers at site EP had sandy loam as the dominant soil texture. The soil texture at higher altitude was loamy sand in the surface layer across the pre-monsoon, monsoon and post-monsoon seasons. In the subsurface layer, loamy sand texture was found in all three seasons as well. Therefore, the mean annual soil texture at both surface and subsurface layers was loamy sand at the higher altitude. Mishra *et al.* (2018a), Ray *et al.* (2019), and Kenye *et al.* (2019) have documented the presence of sandy loam soil in northeastern India, with additional reports of loamy sand by Mishra *et al.* (2018b).

Table 1. Location of the study sites

Elevation	Sites	Geo-coordinates	Altitude (m)
Lower (<500)	Khuanggin (KG)	24°07'19" N 93°19'41" E	491
Middle (500-1000)	Enpum (EP)	24º02'48" N 93º28'21" E	987
higher (>1000)	D. Hengkot (HK)	24°19'43 N 93°37'17" E	1430

The soil moisture content (SMC %) exhibited an increasing trend with increasing altitude across all seasons. In the pre-monsoon season, the SMC was highest at the higher altitude (22.06±1.02%) at the surface layer and lowest at the low altitude (16.45±0.15%) at the subsurface layer. During the monsoon season, it was highest at the higher altitude (24.04±0.71%) at the surface layer and lowest at the low altitude (19.41±0.15%) at the subsurface layer. In the post-monsoon season, the SMC was highest at the higher altitude (24.81±0.89%) at the surface layer and lowest at the low altitude (16.84±0.53%) at the subsurface layer. SMC showed a positive correlation with altitude (r=0.691), available phosphorus (r=0.441), and available potassium (r=0.667). ANOVA revealed highly significant differences between altitudes (F(2, 51)=23.44, p<0.001), with Tukey's test indicating that the higher altitude had significantly higher SMC than the lower altitude (p=0.01) and mid-altitude (p<0.001).

The water holding capacity (WHC %) followed a similar pattern to SMC, increasing with altitude across seasons. In the pre-monsoon season, it was highest at the higher altitude (39.16±0.02%) at the surface layer and lowest at the middle altitude (32.33±0.10%) at the subsurface layer. During the monsoon season, the WHC was highest at the higher altitude (41.99±0.14%) at the surface and lowest at the middle altitude (36.43±0.13%) at the subsurface layer. In the post-monsoon season, it was highest at the higher altitude (43.58±0.17%) at the surface layer and lowest at the lower altitude (38.44±0.06%) at the subsurface layer. WHC showed positive correlations with seasons (r=0.589), available nitrogen (r=0.642), and exchangeable sodium (r=0.546), but a negative correlation with depth (r=-0.537). ANOVA indicated marginal significance between altitudes (F(2, 51)=3.019, p=0.058), but Tukey's test did not reveal significant pairwise differences.

The bulk density (BD g/cm^3) exhibited a decreasing trend with increasing altitude across seasons. In the pre-monsoon season, it was highest at the middle altitude (1.30±0.01 g/cm^3) at the subsurface layer and lowest at the higher altitude (0.93±0.01 g/cm^3) at the surface layer. During the monsoon season, the BD was highest at the middle altitude (1.25±0.01 g/cm^3) at the subsurface layer and lowest at the higher altitude (1.12±0.02 g/cm^3) at the surface layer. In the post-monsoon season, it was highest at the middle altitude (1.33±0.01 g/cm^3) at the subsurface layer and lowest at the higher altitude (0.94±0.01 g/cm^3) at the surface layer. BD showed positive correlations with depth (r=0.491), exchangeable sodium (r=0.393), and exchangeable magnesium (r=0.372), but negative correlations with altitude (r=-0.430), pH (r=-0.509), EC (r=-0.420), organic carbon (r=-0.583), and exchangeable calcium (r=-0.400). ANOVA indicated highly significant differences between altitudes (F(2, 51)=12.114, p<0.001), with Tukey's test revealing that the higher altitude had significantly lower BD than the lower altitude (p<0.001) and mid-altitude (p<0.001).

Several factors, such as climate, vegetation, and land-use practices, could explain the observed variations in soil properties across different altitudes (Imtimongla *et al.,* 2021, Bravo *et al.,* 2023). The higher SMC and WHC at the higher altitude site may be due to cooler temperatures and increased precipitation levels, which decrease evaporation rates and thus maintain soil moisture (Imtimongla *et al.,* 2021). The lower bulk density (BD) at the higher altitude site is consistent with the findings of Kumar *et al.* (2010) and Kumar *et al.* (2010), who reported a negative relationship between BD and altitude in forest soils.

Chemical properties of soil

The soil pH exhibited a decreasing trend with increasing altitude across seasons. In the pre-monsoon season, it was highest at the lower altitude (6.48±0.03) at the surface layer and lowest at the middle altitude (5.70±0.01) at the subsurface layer. During the monsoon season, the pH was highest at the lower altitude (5.62±0.05) at the surface layer and lowest at the middle altitude (5.61±0.02) at the subsurface layer. In the post-monsoon season, it was highest at the lower altitude (6.42±0.02) at the surface layer and lowest at the middle altitude (5.64±0.06) at the subsurface layer. The soil pH showed a positive correlation with EC (r=0.541) and organic carbon (r=0.463) but negative correlations with BD (r=-0.509), available potassium (r=-0.430), and exchangeable sodium (r=-0.461). ANOVA revealed significant differences between altitudes (F(2, 51)=6.667, p=0.003), with Tukey's post-hoc test indicating that the mid-altitude site had significantly lower pH than the lower altitude (p<0.001) and higher altitude (p=0.02). The decreasing trend in soil pH with increasing altitude is in agreement with several studies conducted in mountainous regions (Buri *et al.,* 2020; Mishra and Francaviglia, 2021, Imtimongla *et al.,* 2021). This pattern can be attributed to the higher organic matter content and leaching of base cations at higher elevations (Moslehi *et al.,* 2019). Furthermore, the lower pH at the mid-altitude site could be related to the potential impacts of shifting cultivation practices, which can lead to soil acidification (Thet and Tokuchi, 2021). Lower-altitude sites, with their greater salt accumulation and increased presence of base-forming cations like Ca^{2+}, Mg^{2+}, and K^{+}, tend to have a higher pH than higher-altitude sites (Charan *et al.,* 2012).

The electrical conductivity (EC dSm^{-1}) did not exhibit a clear altitudinal trend but showed higher values at the lower altitude site across seasons. In the pre-monsoon season, it was highest at the lower altitude (0.24±0.02 dSm^{-1}) at the surface layer and lowest at the higher altitude (0.14±0.02 dSm^{-1}) at the subsurface layer. During the monsoon season, the EC was highest at the lower altitude (0.18±0.01 dSm^{-1}) at the surface layer and lowest at the middle altitude (0.11±0.01 dSm^{-1}) at the subsurface layer. In the post-monsoon season, it was highest at the lower altitude (0.26±0.01 dSm^{-1}) at the surface layer and lowest at the higher altitude (0.15±0.02 dSm^{-1}) at the subsurface layer. EC showed positive correlations with pH (r=0.541), available nitrogen (r=0.499), and exchangeable calcium (r=0.421) but negative correlations with depth (r=-0.609), BD (r=-0.420), and exchangeable magnesium (r=-0.388). ANOVA and Tukey's test did not reveal significant differences between altitudes.

The organic carbon (OC %) content exhibited a clear increasing trend with increasing altitude across all seasons. In the pre-monsoon season, it was highest at the higher altitude (3.03±0.13%) at the surface layer and lowest at the lower altitude (2.16±0.03%) at the subsurface layer. During the monsoon season, the OC content was highest at the higher altitude (2.67±0.04%) at the surface layer and lowest at the middle altitude (1.78±0.07%) at the subsurface layer. In the post-monsoon season, it was highest at the higher altitude (3.53±0.17%) at the subsurface layer and lowest at the middle altitude (1.95±0.04%) at the subsurface layer. OC showed positive correlations with altitude (r=0.521), silt (r=0.425), pH (r=0.463), and available nitrogen (r=0.505) but a negative correlation with BD (r=-0.583). ANOVA indicated highly significant differences between altitudes (F(2, 51)=36.15, p<0.001), with Tukey's test revealing that the higher altitude had significantly higher OC content than the lower altitude (p<0.001) and mid-altitude (p<0.001).

Available nitrogen (AN kg/ha) generally increased with increasing altitude, with the highest values observed at the higher altitude during the monsoon and post-monsoon seasons. In the pre-monsoon season, it was highest at the lower altitude (459.95±27.66 kg/ha) at the surface layer and lowest at the higher altitude (219.52±18.11 kg/ha) at the subsurface layer. During the monsoon season, AN was highest at the higher altitude (449.49±10.45 kg/ha) at the surface layer and lowest at the middle altitude (261.33±10.45 kg/ha) at the subsurface layer. In the post-monsoon season, it was highest at the higher altitude (616.75±10.45 kg/ha) at the surface layer and lowest at the middle altitude (386.77±10.45 kg/ha) at the subsurface layer. AN showed positive correlation with seasons (r=0.461), pH (r=0.499), WHC (r=0.642), OC (r=0.505), and available phosphorus (r=0.452) but negative correlations with sand (r=-0.375), depth (r=0.435), and exchangeable magnesium (r=-0.487). ANOVA revealed significant differences between altitudes (F(2, 51)=4.415, p=0.017), with Tukey's test indicating that the mid-altitude had significantly lower Avail. N than the lower altitude (p=0.03).

Available phosphorus (AP kg/ha) generally increased with increasing altitude, with the highest values observed at the higher altitude during the pre-monsoon and monsoon seasons. In the pre-monsoon season, it was highest at the higher altitude (29.05±0.76 kg/ha) at the surface layer and lowest at the middle altitude (19.44±1.26 kg/ha) at the subsurface layer. During the monsoon season, AP was highest at the higher altitude (38.10±2.86 kg/ha) at the surface layer and lowest at the middle altitude (24.63±0.91 kg/ha) at the subsurface layer. In the post-monsoon season, it was highest at the lower altitude (30.22±0.96 kg/ha) at the surface layer and lowest at the middle altitude (20.40±0.64 kg/ha) at the subsurface layer. AP showed positive correlations with sand (r=0.384), SMC (r=0.441), WHC (r=0.748), and AN (r=0.452) but negative correlations with depth (r=-0.377), silt (r=-0.382), and exchangeable magnesium (r=-0.365). ANOVA indicated highly significant differences between altitudes (F(2, 51)=11.422, p<0.001), with Tukey's test revealing that the lower altitude had significantly higher AP than the mid-altitude (p<0.001) and higher altitude (p<0.001).

Available potassium (AK kg/ha) exhibited a less consistent pattern, with the highest values observed at the middle altitude site during the pre-monsoon season and at the higher altitude during the monsoon and post-monsoon seasons. In the pre-monsoon season, it was highest at the middle altitude (249.82±1.58 kg/ha) at the surface layer and lowest at the lower altitude (158.80±1.57 kg/ha) at the subsurface layer. During the monsoon season, AK was highest at the higher altitude (263.68±1.76 kg/ha) at the surface layer and lowest at the lower altitude (166.87±3.62 kg/ha) at the subsurface layer. In the post-monsoon season, it was highest at the higher altitude (244.08±1.68 kg/ha) at the surface layer and lowest at the lower altitude (153.14±1.10 kg/ha) at the subsurface layer. AK showed positive correlations with altitude (r=0.754) and SMC (r=0.667) but a negative correlation with pH (r=-0.430). ANOVA indicated highly significant differences between altitudes (F(2, 51)=170.531, p<0.001), with Tukey's test revealing that the lower altitude had significantly lower Avail. K than the mid-altitude (p<0.001) and higher altitude (p<0.001).

The increased organic carbon (OC) levels at sites of greater elevation align with the results of previous research conducted in hilly areas (Klimek *et al.*, 2016; Kumar *et al.*, 2010; Imtimongla, 2021; Sharma *et al.*, 2022). At greater altitudes, the lower temperatures and increased humidity can slow down the breakdown of organic materials, resulting in a buildup of OC (Sun and Chaturvedi, 2016, Kumar *et al.*, 2010). Additionally, the lower disturbance levels at higher altitudes due to limited human activities could contribute to the higher OC content (Buri *et al.*, 2020). The altitudinal trends in AN and AP are similar to those reported by Nie *et al.* (2023) in subtropical karst mountains of China. The increased availability of nutrients at sites of higher elevation may be due to the higher OC content and reduced nutrient depletion through processes like leaching and erosion (Buri *et al.,* 2020). Conversely, the lower nutrient availability at the mid-altitude site could be related to the potential impacts of humans and felling of trees leading to erosion of soil nutrients (Rashmi *et al.*, 2022; Kodaparthi, 2024).

Exchangeable sodium (Exch. Na cmol(p$^+$)/kg) did not exhibit a clear altitudinal trend, but the values were generally higher during the monsoon season across sites. In the pre-monsoon season, it was highest at the lower altitude (1.33±0.01 cmol(p$^+$)/kg) at the surface layer and lowest at the high altitude (1.39±0.02 cmol(p$^+$)/kg) at the subsurface layer. During the monsoon season, Exch. Na was highest at the lower altitude (1.73±0.01 cmol(p$^+$)/kg) at both surface and subsurface layers and lowest at the middle altitude (1.72±0.02 cmol(p+)/kg) at the sur-

Table 2. Soil physical properties of selected jhum fields in Churachandpur district, Manipur

Sites	Depth	Season	Sand (%)	Silt (%)	Clay (%)	Texture	EC (dSm^{-1})	SMC (%)	WHC (%)	BD (g/cm^3)
KG	**0-15**	Pre-monsoon	79.51±0.02	12.28±0.03	8.20±0.04	Loamy sand	0.24±0.02	19.17±1.18	35.69±0.09	1.12±0.01
		Monsoon	82.75±0.03	6.71±0.02	10.54±0.05	Loamy sand	0.18±0.01	23.01±0.25	43.18±0.12	1.28±0.01
		Post monsoon	75.38±0.03	4.8±0.05	19.82±0.06	Sandy loam	0.26±0.01	17.8±0.23	40.67±0.07	1.19±0.01
		Total	**79.21±1.07**	**7.93±1.12**	**12.86±1.77**	**Loamy sand**	**0.23±0.01**	**19.99±0.86**	**39.85±1.10**	**1.2±0.02**
	15-30	Pre-monsoon	78.24±0.02	12.54±0.02	9.23±0.02	Sandy loam	0.19±0.02	16.45±0.15	33.54±0.04	1.16±0.01
		Monsoon	80.68±0.01	4.82±0.06	14.5±0.06	Sandy loam	0.12±0.02	19.41±0.15	40.17±0.29	1.29±0.01
		Post monsoon	74.85±0.03	11.27±0.25	13.89±0.25	Sandy loam	0.16±0.01	16.84±0.53	38.44±0.06	1.22±0.01
		Total	**77.92±0.85**	**9.54±1.2**	**12.54±0.84**	**Sandy loam**	**0.16±0.01**	**17.57±.49**	**37.38±1**	**1.22±0.02**
EP	**0-15**	Pre-monsoon	71.06±0.30	26.66±0.29	2.28±0.08	Sandy loam	0.18±0.02	21.11±0.23	36.39±0.01	1.14±0.01
		Monsoon	84.74±0.03	5.27±0.04	9.99±0.07	Loamy sand	0.16±0.02	24.62±0.33	40.31±0.25	1.24±0.10
		Post monsoon	75.82±0.05	4.65±0.04	19.54±0.09	Sandy loam	0.23±0.02	20.57±0.42	38.38±0.12	1.18±0.01
		Total	**77.21±2.01**	**12.19±3.62**	**10.6±2.50**	**Sandy loam**	**0.19±0.01**	**22.1±0.66**	**38.36±0.57**	**1.19±0.03**
	15-30	Pre-monsoon	69.15±0.16	28.4±0.17	2.45±0.06	Sandy loam	0.17±0.02	19.23±0.39	32.33±0.10	1.30±0.00
		Monsoon	86.17±0.04	2.33±0.02	11.5±0.05	Loamy sand	0.11±0.01	21.43±0.66	36.43±0.13	1.25±0.01
		Post monsoon	73.69±0.01	15.48±0.31	10.84±0.31	Sandy loam	0.16±0.02	18.84±0.84	36.88±0.04	1.33±0.01
		Total	**76.33±2.55**	**15.4±3.76**	**8.26±1.46**	**Sandy loam**	**0.14±0.01**	**19.83±0.52**	**35.21±0.73**	**1.29±0.01**
HK	**0-15**	Pre-monsoon	81.41±0.04	13.95±0.04	4.64±0.07	Loamy sand	0.21±0.02	22.06±1.02	39.16±0.02	0.93±0.01
		Monsoon	85.71±0.01	5.92±0.06	8.37±0.07	Loamy sand	0.18±0.01	24.04±0.71	41.99±0.14	1.12±0.02
		Post monsoon	63.17±0.03	31.32±0.29	5.51±0.26	Sandy loam	0.23±0.02	21.52±0.36	43.58±0.17	0.94±0.01
		Total	**76.76±3.46**	**17.06±3.75**	**6.17±0.57**	**Loamy sand**	**0.21±0.01**	**22.54±0.54**	**41.58±0.65**	**1±0.03**
	15-30	Pre-monsoon	80.45±0.05	15.85±0.11	3.7±0.12	Loamy sand	0.14±0.02	23.45±0.54	33.77±0.05	1.18±0.01
		Monsoon	87.77±0.03	4.64±0.05	7.61±0.02	Loamy sand	0.12±0.02	25.4±0.37	36.33±0.37	1.2±0.01
		Post monsoon	68.89±0.11	21.85±0.11	9.26±0.06	Sandy loam	0.15±0.02	24.81±0.89	40.59±0.12	1.19±0.01
		Total	**79.03±2.74**	**14.11±2.52**	**6.86±0.82**	**Loamy sand**	**0.14±0.01**	**24.55±0.43**	**36.9±0.1**	**1.19±0.01**

EC – electrical conductivity, SMC – soil moisture content, WHC – water holding capacity, BD – bulk density

Table 3. Chemical properties of soil of selected jhum fields in Churachandpur district, Manipur

Sites	Depth	Season	pH	OC (%)	Avail. N (kg/ha)	Avail. P (kg/ha)	Avail. K (kg/ha)	Exch. Na (cmol/kg)	Exch. Ca (cmol/kg)	Exch. Mg (cmol/kg)
KG	0-15	Pre-monsoon	6.48±0.03	2.71±0.04	459.95±27.66	27.21±1.15	168.47±1.17	1.33±0.01	1.83±0.27	1.33±0.02
		Monsoon	5.62±0.05	2.26±0.03	512.21±10.45	35.36±0.84	212.94±2.87	1.73±0.01	0.83±0.12	1.13±0.06
		Post monsoon	6.42±0.02	2.46±0.04	491.31±10.45	30.22±0.96	181.29±1.99	1.72±0.01	1.63±0.09	0.97±0.03
		Total	6.18±0.14	2.48±0.07	487.82±11.82	30.93±1.29	187.57±6.69	1.59±0.07	1.43±0.18	1.14±0.06
	15-30	Pre-monsoon	6.35±0.06	2.16±0.03	407.68±18.11	22.44±0.69	158.8±1.57	1.35±0.00	0.63±0.09	1.2±0.06
		Monsoon	5.55±0.03	1.8±0.06	365.87±10.45	32.77±0.94	166.87±3.62	1.74±0.01	1.27±0.09	1.41±0.02
		Post monsoon	6.27±0.07	1.95±0.06	271.79±10.45	25.78±0.71	153.14±1.10	1.76±0.01	1.13±0.15	1.6±0.03
		Total	6.06±0.013	1.97±0.06	348.44±21.20	27±1.57	159.6±2.32	1.61±0.07	1.01±0.11	1.4±0.06
EP	0-15	Pre-monsoon	5.9±0.01	2.22±0.08	313.6±18.11	21.66±0.38	249.82±1.58	1.41±0.03	1.88±0.03	1.57±0.05
		Monsoon	5.62±0.05	1.78±0.07	303.15±27.66	31.19±1	262.12±2.26	1.78±0.01	0.67±0.07	1.33±0.11
		Post monsoon	5.71±0.02	2.11±0.03	428.59±10.45	23.91±1.06	253.12±1.91	1.74±0.02	1.76±0.04	1.03±0.12
		Total	5.74±0.05	2.04±0.07	348.44±22.45	25.59±1.50	255.02±2.08	1.64±0.06	1.44±0.19	1.31±0.09
	15-30	Pre-monsoon	5.7±0.01	2.07±0.07	271.79±10.45	19.44±1.26	242.74±3.52	1.49±0.02	0.53±0.13	1.33±0.04
		Monsoon	5.61±0.02	1.5±0.10	261.33±10.45	24.63±0.91	257.2±1.53	1.72±0.02	0.93±0.02	1.43±0.03
		Post monsoon	5.64±0.06	1.95±0.04	386.77±10.45	20.4±0.64	249.29±1.46	1.79±0.04	0.84±0.05	1.66±0.04
		Total	5.65±0.02	1.84±0.09	306.63±20.76	21.49±0.93	249.74±2.40	1.67±0.05	0.77±0.07	1.48±0.05
HK	0-15	Pre-monsoon	6.41±0.04	3.03±0.13	324.05±10.45	29.05±0.76	237.6±1.82	1.37±0.00	1.91±0.07	1.36±0.03
		Monsoon	5.66±0.03	2.67±0.04	449.49±10.45	38.1±2.86	263.68±1.76	1.63±0.12	1.13±0.02	1.15±0.02
		Post monsoon	6.23±0.04	2.96±0.08	616.75±10.45	32.26±0.80	244.08±1.68	1.69±0.01	0.97±0.07	0.95±0.04
		Total	6.1±0.11	2.89±0.07	463.43±42.71	33.14±1.59	248.45±4.02	1.57±0.06	1.34±0.15	1.15±0.06
	15-30	Pre-monsoon	6.26±0.18	2.69±0.10	219.52±18.11	22.44±0.50	231.40±1.65	1.39±0.02	0.7±0.07	1.18±0.02
		Monsoon	5.57±0.57	2.34±0.02	334.51±10.45	34.13±0.73	245.62±2.47	1.73±0.01	1.35±0.07	1.27±0.02
		Post monsoon	6.1±0.12	3.53±0.17	533.12±18.11	29.15±0.77	237.57±2.34	1.74±0.02	0.95±0.04	1.37±0.03
		Total	5.98±0.20	2.86±0.19	362.38±46.49	28.57±1.73	238.2±2.33	1.62±0.06	1±0.10	1.27±0.03

face layer. In the post-monsoon season, it was highest at the middle altitude (1.79±0.04 cmol(p^+)/kg) at the subsurface layer and lowest at the lower altitude (1.72±0.01 cmol(p^+)/kg) at the surface layer. Exch. Na showed a positive correlation with clay (r=0.585) and a negative correlation with silt (r=-0.360). ANOVA and Tukey's test did not reveal significant differences between altitudes for Exch. Na.

Exchangeable calcium (Exch. Ca cmol(p^+)/kg) did not exhibit a clear altitudinal trend. In the pre-monsoon season, it was highest at the higher altitude (1.91±0.07 cmol(p^+)/kg) at the surface layer and lowest at the higher altitude (0.70±0.07 cmol(p^+)/kg) at the subsurface layer. During the monsoon season, Exch. Ca was highest at the lower altitude (1.27±0.09 cmol(p^+)/kg) at the subsurface layer and lowest at the middle altitude (0.67±0.07 cmol(p^+)/kg) at the surface layer. In the post-monsoon season, it was highest at the lower altitude (1.63±0.09 cmol(p^+)/kg) at the surface layer and lowest at the middle altitude (0.84±0.05 cmol(p^+)/kg) at the subsurface layer. ANOVA and Tukey's test did not reveal significant differences between altitudes for Exch. Ca.

Exchangeable magnesium (Exch. Mg cmol(p^+)/kg) exhibited mixed patterns across altitudes and seasons. In the pre-monsoon season, it was highest at the lower altitude (1.33±0.02 cmol(p^+)/kg) at the surface layer and lowest at the higher altitude (1.18±0.02 cmol(p^+)/kg) at the subsurface layer. During the monsoon season, Exch. Mg was highest at the lower altitude

Table 4. Spearman's Correlation analysis between altitude, seasons depth and soil parameters

	Altitude	Seasons	Depth	Sand	Silt	Clay	pH	EC	SMC	WHC	BD	OC	N	P	K	Ex. Na	Ex. Ca	Ex. Mg
Altitude	1																	
Seasons	0	1																
Depth (cm)	0	0	1															
Sand (%)	-0.042	-.289*	0.003	1														
Silt (%)	.318*	-0.157	0.035	-.831**	1													
Clay (%)	-.510**	.665**	-0.067	0.142	-.669**	1												
pH	-0.080	-0.121	-0.139	-.288*	0.253	-0.067	1											
EC (dSm^{-1})	-0.182	0.100	-.609**	-.321*	0.135	0.188	.541**	1										
SMC (%)	.691**	-0.026	-0.159	.328*	-0.066	-.321*	-.293*	-0.229	1									
WHC (%)	0.080	.589**	-.537**	-0.031	-0.167	.339*	-0.079	0.217	.302*	1								
BD (g/cm3)	-.430**	0.131	.491**	0.186	-.311*	.304*	-.509**	-.420**	-0.133	-0.259	1							
OC (%)	.521**	0.009	-0.241	-.329*	.425**	-.315*	.463**	.343*	.336*	0.258	-.583**	1						
Avail. N (kg/ha	-0.020	.461**	-.435**	-.375**	0.146	0.241	0.184	.499**	0.033	.642**	-.288*	.505**	1					
Avail. P (kg/ha)	0.139	0.238	-.377**	.384**	-.382**	0.166	-0.134	0.054	.441**	.748**	-0.199	0.259	.452**	1				
Avail. K (kg/ha)	.754**	0.053	-0.192	0.044	0.158	-.340*	-.430**	-0.157	.667**	0.100	-0.088	0.083	-0.084	0.029	1			
Ex. Na (cmol/kg)	-0.024	.828**	0.097	0.041	-.360**	.585**	-.461**	-0.178	0.191	.546**	.393**	-.274*	0.200	.323*	0.193	1		
Ex. Ca (cmol/kg)	-0.047	-0.029	-.506**	0.029	-0.126	0.186	0.253	.421**	-0.050	0.131	-.400**	0.213	0.133	0.085	-0.093	-0.202	1	
Ex. Mg (cmol/kg)	-0.118	-0.126	.425**	0.023	0.097	-0.204	-0.139	-.388**	-0.167	-.326*	.372**	-.296*	-.478**	-.365**	-0.036	-0.009	0.001	1

* and ** Correlation is significant at the 0.05 and 0.01 level (2-tailed).

(1.41±0.02 cmol(p^+)/kg) at the subsurface layer and lowest at the higher altitude (1.15±0.02 cmol(p^+)/kg) at the surface layer. In the post-monsoon season, it was highest at the middle altitude (1.66±0.04 cmol(p^+)/kg) at the subsurface layer and lowest at the lower altitude (0.97±0.03 cmol(p^+)/kg) at the surface layer. Exch. Mg showed positive correlations with depth (r=0.425) and BD (r=0.372) but negative correlations with EC (r=-0.388), AN (r=-0.487), and AP (r=-0.365). ANOVA revealed significant differences between altitudes (F(2, 51)=3.656, p=0.033), with Tukey's post-hoc test indicating that Exch. Mg was significantly higher at the mid-altitude compared to the higher altitude (p=0.03).

The variability in exchangeable cations (Na, Ca, and Mg) observed across different altitudes and seasons could be a consequence of a multitude of factors, including the content of organic matter, the nature of the parent material (Yunan *et al.,* 2018; Bashir *et al.,* 2021; Tedontsah *et al.,* 2023), as well as intrinsic processes like weathering, erosion, deposition, and soil formation, and extrinsic local factors such as human activities (Vasu *et al.,* 2016). The elevated levels of Exch. Mg noticed at the mid-elevation location might be linked to the possible effects of changing farming methods, which can modify the soil's capacity for cation exchange and nutrient interactions. The observed seasonal changes in soil quality indicators across the study sites can be ascribed to a combination of interconnected elements, such as patterns of rainfall, temperature fluctuations, changes in plant life, and processes of soil erosion (Semy *et al.,* 2022). The marked increase in SMC and WHC during the monsoon and post-monsoon seasons, particularly at the higher altitude site, is likely a direct consequence of the elevated precipitation levels during these periods. The increased soil moisture availability, coupled with the cooler temperatures at higher elevations, reduces evaporative losses, thereby maintaining favourable moisture conditions (Semy *et al.,* 2022).

In addition, changes in temperature throughout the seasons can affect the activity of soil microbes and the rate at which organic matter breaks down, thereby altering the processes of nutrient mineralization (Babür and Dindaroglu, 2020; Sharma and Kumar, 2023). The higher OC content observed at the higher altitude site during the post-monsoon season could be a result of the lower temperatures inhibiting organic matter decomposition (Klimek *et al.,* 2016; Sharma *et al.,* 2022). Additionally, the enhanced vegetation growth during the monsoon and post-monsoon periods may have contributed to the increased availability of soil nutrients, such as nitrogen and phosphorus, at the higher altitude site through improved nutrient uptake and cycling (Buri *et al.,* 2020; Wang *et al.,* 2022; Zhang *et al.,* 2022). It is important to note that the observed decrease in nutrient availability at mid-altitude locations during specific seasons could be due to the possible effects of human activities. These activities, such as forest fires, land utilization, and deforestation, can result in nutrient loss through processes like leaching and soil erosion (Rashmi *et al.,* 2022). These seasonal variations in soil quality parameters highlight the complex interplay between climatic factors, vegetation dynamics, and land-use practices, which collectively shape the soil ecosystem and its properties.

Conclusion

This research, carried out along an altitudinal gradient in the Churachandpur district of Manipur, India, offers important understanding into the changes in soil quality indicators at various elevations in current jhum fields. The examination of crucial physical

Table 5. Tests of between-subjects effects for One-way ANOVA

	Sum of Squares	df	Mean Square	F	Sig.	
Depth (cm)	Between Groups	0.000	2	0.000	0.000	1.000
	Within Groups	13.500	51	0.265		
Seasons	Between Groups	0.000	2	0.000	0.000	1.000
	Within Groups	36.000	51	0.706		
Sand (%)	Between Groups	29.727	2	14.864	0.326	0.723
	Within Groups	2326.242	51	45.613		
Silt (%)	Between Groups	454.677	2	227.339	3.113	0.053
	Within Groups	3724.729	51	73.034		
Clay (%)	Between Groups	344.153	2	172.076	8.972	0.000
	Within Groups	978.114	51	19.179		
pH	Between Groups	1.799	2	0.899	6.667	0.003
	Within Groups	6.881	51	0.135		
EC (dSm^{-1})	Between Groups	0.007	2	0.004	1.476	0.238
	Within Groups	0.127	51	0.002		
SMC (%)	Between Groups	204.854	2	102.427	23.440	0.000
	Within Groups	222.856	51	4.370		
WHC (%)	Between Groups	58.444	2	29.222	3.019	0.058
	Within Groups	493.573	51	9.678		
BD (g/cm^3)	Between Groups	0.214	2	0.107	12.114	0.000
	Within Groups	0.450	51	0.009		
OC (%)	Between Groups	8.227	2	4.114	36.150	0.000
	Within Groups	5.803	51	0.114		
AN (kg/ha)	Between Groups	93136.320	2	46568.160	4.415	0.017
	Within Groups	537892.295	51	10546.908		
AP (kg/ha)	Between Groups	519.341	2	259.670	11.422	0.000
	Within Groups	1159.429	51	22.734		
AK (kg/ha)	Between Groups	66927.410	2	33463.705	170.531	0.000
	Within Groups	10007.825	51	196.232		
Exch. Na (cmol(p^+)/kg)	Between Groups	0.039	2	0.019	0.624	0.540
	Within Groups	1.580	51	0.031		
Exch. Ca (cmol(p^+)/kg)	Between Groups	0.132	2	0.066	0.286	0.753
	Within Groups	11.826	51	0.232		
Exch. Mg (cmol(p^+)/kg)	Between Groups	0.304	2	0.152	3.656	0.033
	Within Groups	2.118	51	0.042		

Table 6. Multiple Comparisons of Post Hoc Tests (Tukey HSD)

Dependent Variable			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Depth of soil (cm)	KG	EP	0.00	0.17	1.00	-0.41	0.41
		HK	0.00	0.17	1.00	-0.41	0.41
	EP	KG	0.00	0.17	1.00	-0.41	0.41
		HK	0.00	0.17	1.00	-0.41	0.41
	HK	KG	0.00	0.17	1.00	-0.41	0.41
		EP	0.00	0.17	1.00	-0.41	0.41
Seasons	KG	EP	0.00	0.28	1.00	-0.68	0.68
		HK	0.00	0.28	1.00	-0.68	0.68
	EP	KG	0.00	0.28	1.00	-0.68	0.68
		HK	0.00	0.28	1.00	-0.68	0.68
	HK	KG	0.00	0.28	1.00	-0.68	0.68
		EP	0.00	0.28	1.00	-0.68	0.68
Sand (%)	KG	EP	1.80	2.25	0.71	-3.64	7.23
		HK	0.67	2.25	0.95	-4.76	6.11
	EP	KG	-1.80	2.25	0.71	-7.23	3.64
		HK	-1.13	2.25	0.87	-6.56	4.31
	HK	KG	-0.67	2.25	0.95	-6.11	4.76
		EP	1.13	2.25	0.87	-4.31	6.56
Silt (%)	KG	EP	-5.06	2.85	0.19	-11.94	1.81
		HK	-6.85	2.85	0.05	-13.73	0.02
	EP	KG	5.06	2.85	0.19	-1.81	11.94
		HK	-1.79	2.85	0.81	-8.67	5.09
	HK	KG	6.85	2.85	0.05	-0.02	13.73
		EP	1.79	2.85	0.81	-5.09	8.67
Clay (%)	KG	EP	3.26	1.46	0.07	-0.26	6.79
		HK	6.18056*	1.46	0.00	2.66	9.70
	EP	KG	-3.26	1.46	0.07	-6.79	0.26
		HK	2.92	1.46	0.12	-0.61	6.44
	HK	KG	-6.18056*	1.46	0.00	-9.70	-2.66
		EP	-2.92	1.46	0.12	-6.44	0.61
pH of soil	KG	EP	.42056*	0.12	0.00	0.12	0.72
		HK	0.08	0.12	0.80	-0.22	0.37
	EP	KG	-.42056*	0.12	0.00	-0.72	-0.12
		HK	-.34167*	0.12	0.02	-0.64	-0.05
	HK	KG	-0.08	0.12	0.80	-0.37	0.22
		EP	.34167*	0.12	0.02	0.05	0.64
Electrical Conductivity	KG	EP	0.03	0.02	0.25	-0.01	0.07
		HK	0.02	0.02	0.38	-0.02	0.06
	EP	KG	-0.03	0.02	0.25	-0.07	0.01
		HK	0.00	0.02	0.96	-0.04	0.04
	HK	KG	-0.02	0.02	0.38	-0.06	0.02
		EP	0.00	0.02	0.96	-0.04	0.04
SMC (%)	KG	EP	-2.18722*	0.70	0.01	-3.87	-0.51
		HK	-4.76556*	0.70	0.00	-6.45	-3.08
	EP	KG	2.18722*	0.70	0.01	0.51	3.87
		HK	-2.57833*	0.70	0.00	-4.26	-0.90
	HK	KG	4.76556*	0.70	0.00	3.08	6.45
		EP	2.57833*	0.70	0.00	0.90	4.26
WHC (%)	KG	EP	1.83	1.04	0.19	-0.68	4.33
		HK	-0.62	1.04	0.82	-3.13	1.88
	EP	KG	-1.83	1.04	0.19	-4.33	0.68
		HK	-2.45	1.04	0.06	-4.95	0.05

Table 6. *Continued ...*

Dependent Variable			Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
	HK	KG	0.62	1.04	0.82	-1.88	3.13
		EP	2.45	1.04	0.06	-0.05	4.95
Bulk Density (g/cm3)	KG	EP	-0.03	0.03	0.63	-0.10	0.05
		HK	.11667*	0.03	0.00	0.04	0.19
	EP	KG	0.03	0.03	0.63	-0.05	0.10
		HK	.14556*	0.03	0.00	0.07	0.22
	HK	KG	-.11667*	0.03	0.00	-0.19	-0.04
		EP	-.14556*	0.03	0.00	-0.22	-0.07
Organic Carbon (%)	KG	EP	.28222*	0.11	0.04	0.01	0.55
		HK	-.65000*	0.11	0.00	-0.92	-0.38
	EP	KG	-.28222*	0.11	0.04	-0.55	-0.01
		HK	-.93222*	0.11	0.00	-1.20	-0.66
	HK	KG	.65000*	0.11	0.00	0.38	0.92
		EP	.93222*	0.11	0.00	0.66	1.20
Avail. N (kg/ha)	KG	EP	90.59556*	34.23	0.03	7.96	173.23
		HK	5.23	34.23	0.99	-77.41	87.86
	EP	KG	-90.59556*	34.23	0.03	-173.23	-7.96
		HK	-85.36889*	34.23	0.04	-168.01	-2.73
	HK	KG	-5.23	34.23	0.99	-87.86	77.41
		EP	85.36889*	34.23	0.04	2.73	168.01
Avail. P (kg/ha)	KG	EP	5.42556*	1.59	0.00	1.59	9.26
		HK	-1.89	1.59	0.46	-5.73	1.94
	EP	KG	-5.42556*	1.59	0.00	-9.26	-1.59
		HK	-7.31722*	1.59	0.00	-11.15	-3.48
	HK	KG	1.89	1.59	0.46	-1.94	5.73
		EP	7.31722*	1.59	0.00	3.48	11.15
Avail. K (kg/ha)	KG	EP	-78.79722*	4.67	0.00	-90.07	-67.53
		HK	-69.73889*	4.67	0.00	-81.01	-58.47
	EP	KG	78.79722*	4.67	0.00	67.53	90.07
		HK	9.06	4.67	0.14	-2.21	20.33
	HK	KG	69.73889*	4.67	0.00	58.47	81.01
		EP	-9.06	4.67	0.14	-20.33	2.21
Exch. Na	KG	EP	-0.05	0.06	0.66	-0.19	0.09
		HK	0.01	0.06	0.98	-0.13	0.15
	EP	KG	0.05	0.06	0.66	-0.09	0.19
		HK	0.06	0.06	0.55	-0.08	0.20
	HK	KG	-0.01	0.06	0.98	-0.15	0.13
		EP	-0.06	0.06	0.55	-0.20	0.08
Exch. Ca	KG	EP	0.12	0.16	0.73	-0.27	0.51
		HK	0.05	0.16	0.94	-0.33	0.44
	EP	KG	-0.12	0.16	0.73	-0.51	0.27
		HK	-0.07	0.16	0.91	-0.45	0.32
	HK	KG	-0.05	0.16	0.94	-0.44	0.33
		EP	0.07	0.16	0.91	-0.32	0.45
Exch. Mg	KG	EP	-0.12	0.07	0.19	-0.28	0.04
		HK	0.06	0.07	0.64	-0.10	0.23
	EP	KG	0.12	0.07	0.19	-0.04	0.28
		HK	.18056*	0.07	0.03	0.02	0.34
	HK	KG	-0.06	0.07	0.64	-0.23	0.10
		EP	-.18056*	0.07	0.03	-0.34	-0.02

* The mean difference is significant at the 0.05 level.

KG – lower altitude, EP – middle altitude, HK – higher altitude and chemical soil properties unveiled noteworthy trends related to altitude that are significant for soil fertility and sustainable land management strategies in the study area. The soil pH showed a downward trend as altitude increased, with the location at 987 m elevation showing the lowest pH values. The acidic nature of soils at all locations could be due to elements such as increased organic matter content, leaching of base cations, and potential effects of shifting agricultural practices at certain elevations. However, soil electrical conductivity and exchangeable cation concentrations did not exhibit significant variations between sites. Notably, crucial soil quality indicators, including SMC, WHC, OC content, and available macronutrients like nitrogen, phosphorus, and potassium, displayed an increasing trend with rising altitude. The highest elevation site (1430 m) exhibited significantly higher SMC and OC levels, indicating enhanced water retention capacity and organic matter accumulation at higher altitudes. The availability of nitrogen, a key macronutrient for plant growth, was found to be lowest at the mid-elevation site (987 m), and it exhibited a declining trend with increasing soil depth. This pattern could be attributed to potential nutrient depletion caused by anthropogenic activities, such as forest fires, land use changes, and deforestation, which can exacerbate leaching and erosion processes at certain elevations. The findings of this study underscore the enhanced soil quality parameters, including moisture retention, nutrient stocks, and organic matter content, observed at higher elevations in the study area. These characteristics are indicative of a comparatively better soil fertility status in jhum fields located at upper altitudes, which could be attributed to factors such as cooler temperatures, increased precipitation, and reduced human disturbance. The research provides seminal baseline data on soil quality parameters across an altitudinal gradient in jhum cultivation areas, which can inform sustainable land management strategies and contribute to the development of site-specific soil conservation and fertility management practices. By understanding the altitudinal variations in soil properties, stakeholders can develop targeted interventions to mitigate soil degradation, enhance nutrient availability, and promote sustainable agriculture in the mountainous terrain of Manipur and other similar regions.

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