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RESEARCH ARTICLE

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Investigating soil properties on the north and south slopes at different elevations in Al-Jabal Al-Akhdar, Libya

Moussa Masoud[a,b], Hazandy Abdul-Hamid[a,c], Johar Bin Mohamed[a,c] and Attia Alsanousi[a,b]

[a]Department of Forestry Science and Biodiversity, Faculty of Forestry and Environment, Universiti Putra Malaysia, Serdang 43400, Selangor, Malaysia; [b]Department of Forestry, Faculty of Natural Resources and Environmental Sciences, University of Omar Al-Mukhtar Al-Bayda, Libya; [c]Laboratory of Bioresource Management, Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia (UPM) Serdang, Selangor, Malaysia

ABSTRACT

This scholarly study investigated the physicochemical characteristics of soil in the Al-Jabal Al-Akhdar forest, Libya, with a specific focus on the influence of elevation and slope aspects. Fifty-six sample plots were established across varying elevations, each subdivided into four subplots, totaling 224. Soil samples were collected from each subplot at 0-15 cm depth. Results demonstrate significant variations in clay, silt, and sand content with elevation, indicating lower clay and higher sand content at higher elevations. Available water capacity (AWC) increased with altitude on the northern slope, while consistently lower values were observed on the southern slope. Bulk density (BD) decreased with increasing altitude, suggesting less compacted soils at higher elevations. Available phosphorus (Pav), available potassium (Kav), and pH values decreased with increasing altitude on both slopes. Cation exchange capacity (CEC) values varied at altitudes on the northern slope, with higher values observed at mid to high altitudes. Calcium carbonate (CaCO3) decreased with increasing altitude on the northern slope while showing inconsistent trends on the southern slope. Soil organic matter (SOM) content increased with altitude on both slopes. Pearson's correlation and Principal Component Analysis (PCA) examined relationships among soil properties, elevations, and aspects. Elevation positively correlated with AWC and SOM and negatively correlated with clay content, Kav, BD, and pH. PCA identified elevation, aspect, silt content, CaCO3, and electrical conductivity (EC) as primary influencers. SOM exhibited positive correlations with AWC and negative correlations with BD. Soil pH showed a negative correlation with SOM and a positive correlation with CaCO3. Additionally, CaCO3 content was positively correlated with the cation exchange capacity (CEC). These findings contribute to understanding soil property relationships, elevation, and aspect, emphasizing their role in shaping soil ecosystems and nutrient dynamics. Further research is warranted to explore additional factors influencing soil properties and to develop effective nutrient management strategies.

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1. Introduction

Altitude exerts a notable influence on the characteristics of soil ecosystems, where the interaction between soil organisms and mineral particles results in a diverse and intricate environment (Jeyakumar et al., 2020). The influence of altitude on the physicochemical characteristics and biodiversity of soil ecosystems is evident through documented variations in physicochemical properties in several geographical regions (Kumar et al., 2019). As altitude increases, there is a corresponding drop in temperature, resulting in a greater variety and scarcity of plants. Additionally, at higher altitudes, the soils are consistently frozen. The fluctuating climatic circumstances impact the cycles of plants and soil nutrients as the gradient increases. The nutrient cycling process at higher elevations varies greatly from that at lower altitudes due to the fluctuating climatic conditions, precipitation patterns, vegetation composition, and parent rock characteristics (Jeyakumar et al., 2020).

Kooch et al. (2008) employed Principal Component Analysis (PCA) to detect the variability of soil parameters. The findings revealed significant correlations between certain soil factors and the PC1 and PC2 axes. Additionally, among the various soil factors, the distribution of forest types was primarily influenced by specific soil characteristics, including acidity, bulk density, texture, phosphorous, organic carbon, total nitrogen, and cation exchangeable capacity. Liu et al. (2020) examined soil characteristics at different altitudes in the Hengduan Mountains of China. The researchers

CONTACT: Moussa Masoud moussa.masoud@omu.edu.ly; hazandy@upm.edu.my

discovered a correlation between altitude and soil nutrient availability. Higher altitudes were associated with reduced levels of available nutrients in soil, such as nitrogen and potassium. PCA analysis indicated that altitude-related factors were responsible for a substantial proportion of the variation in soil nutrient concentrations. Dede et al. (2024) found that the formation of soils is influenced by various natural environmental factors such as land-form, elevation, slope, climate, parent material, and vegetation. These factors interact dynamically and lead to variations in soils' physico-chemical and mineralogical properties, especially in local areas with changing elevations. In general, an increase in elevation is associated with a notable decrease in pH, base saturation, BD, exchangeable salt percentage, and fine silt-sized particles. In contrast, higher elevations are associated with increased organic matter, soil aggregate stability, water repellency, and coarse sand-sized particles (Badía et al., 2016). Furthermore, the essential nutrients present in soils at elevated altitudes, such as carbon (C), nitrogen (N), phosphorus (P), and potassium (K), exhibit significant differences compared to those found in low-lying plains (Jeyakumar et al., 2020).

The climate and the parent material significantly shape the properties of the soil (Yang et al., 2008). Türkeş et al. (2022), in their study of Periglacial landforms and soil formation on the summit of Mount Ida (Kaz Dağı), Biga Peninsula-Turkey, reported climate and the parent material not only affect soil physico-chemical properties but also influence soil mineralogical properties. Altitude variations introduce climate changes, thereby influencing soil properties and pedogenic processes through alterations in the types and rates of chemical, physical, and biological phenomena and the composition of vegetation species (Unger et al., 2012). High-altitude habitats exhibit specific characteristics such as low temperatures, frequent temperature variations, reduced air pressure, and intense solar radiation (Winkler et al., 2016).

Several studies have provided evidence that soil physical and chemical properties, such as temperature, moisture content (Sidari et al., 2008), and N content (Yimer et al., 2006), which significantly influence soil productivity and development (Sung et al., 2017), show variations depending on the slope. Variations in slope angle and aspect impact water availability, resulting in disparities in soil nutrient content and influencing the uptake of minerals by plants (Gxasheka et al., 2023). On slopes facing south, the soil moisture content and the water holding capacity experience significant decreases. At the same time, the northern aspect of the Garhwal region in the Indian Himalayas shows higher values of moisture content, water holding capacity, and organic C, P, K, and N. Numerous studies have investigated the relationship between soil properties and slope aspect (Sharma et al., 2010), with Nieves-Hernández et al. (2009) reporting lower cation exchange capacity (CEC) and pH in soils found in the northern aspect compared to other aspects. Tunçay et al. (2020) observed that topography significantly impacts soil's physical, mineralogical, and morphological properties in the local region. This influence can occur directly or indirectly, even when the soils are created from the same parent material and under the same climatic conditions.

The Al-Jabal Al-Akhdar region encompasses a diverse landscape of flat areas in plains, valleys with elongated stretches, and natural forests and shrubs on steep canyons and terra rosa slopes (Alawamy et al., 2020). Although this region represents only 1% of the total land area of Libya, it is a significant hotspot of Mediterranean biodiversity, accounting for 90% of its forested areas (Figure 1) (Al-Zeni & Bayoumi, 2006). With an estimated area of approximately 300,000 hectares, it is the only natural forest in North Africa, between Lebanon and Tunisia (Masoud, 2016). The study hypothesis suggests that altitude gradients have a major impact on soil properties, whereby higher altitudes are linked to notable variations in soil characteristics, including organic matter content, pH, and CEC. In addition, some slope characteristics also influence these connections, resulting in variances in soil quality across different areas. Hence, this study thoroughly examines soil properties at various altitudes on both the northern and southern slopes, elucidating the

Figure 1. Al-Jabal Al-Akhdar Forest.

impact of height gradients on soil features. This comprehensive analysis enhances our comprehension of soil dynamics in mountainous areas, frequently distinguished by various environmental factors. The study employs Pearson's correlation analysis and Principal Component Analysis (PCA) to investigate soil qualities, elevations, and aspects comprehensively. This analytical methodology offers a more profound understanding of the connections among different soil parameters, revealing intricate interconnections that may not be evident through single-variable analysis alone. Given the limited knowledge and detailed information available regarding the variability of physical and chemical soil properties in different elevations and slope aspects in the Al-Jabal Al-Akhdar region, as well as the need for additional data to support sustainable development decisions, this study aims to investigate the influence of elevations and slope aspects on selected soil physicochemical properties in the forests of Al-Jabal Al-Akhdar in northeast Libya.

2. Materials and methods

2.1. Study Area

Located along the southern coast of the Mediterranean, Libya spans latitudes of 19° 30 ′ N to 33° 10 ′ N and longitudes of 09° 30 ′ E to 25° 00 ′ E. The country is predominantly arid, characterized by desert landscapes with limited vegetation. However, the northeastern region known as Al-Jabal Al-Akhdar is an exception, experiencing a relatively higher annual rainfall ranging from 250 to 650 mm. Figure 2 illustrates the region located south of the coastal belt and extending approximately 300 km between latitudes 32° 00 ′ N to 32° 56 ′ N and longitudes 20° 19 ′ E to 23° 08 ′ E (Al-Zeni & Bayoumi, 2006). Covering an estimated area of around 1.149 million hectares, Al-Jabal Al-Akhdar is a high plateau with rocky terrain featuring numerous stones. It rises to approximately 882 meters above sea level and exhibits an undulating surface that gradually slopes southward. The geographical area is often characterized by deep ravines that traverse the landscape in an eastward, westward, and northward direction. These canyons finally lead to a precipitous escarpment that descends toward the sea or a limited coastal plain (Alawamy et al., 2020).

2.2. Soil Sampling and Preparation

Al-Jabal Al-Akhdar's Soils are classified according to WRB into Fluvisols, Yermosols, Xerosols, and Solonchaks (Figure 3). According to the US soil taxonomy, Al-Jabal Al-Akhdar has five soil orders: Entisols, Aridisols, Alfisols, Vertisols, and Mollisols (Yigini et al., 2013).

To evaluate fluctuations in soil attributes regarding changes in elevation and slope aspect, a comprehensive set of 56 sample plots, each measuring 20 m × 20 m, was erected throughout the forests in the Al-Jabal Al-Akhdar region. The sample plots were strategically placed at different elevation levels and slope aspects, including north and south-facing slopes, using the stratified random sample technique, in which random quadrats were placed (Table 1). Each plot was carefully marked for accurate identification and precise physical measurements. Each 20 m × 20 m plot was partitioned into four more minor subplots, each with 10 m × 10 m dimensions. Soil samples were obtained from discrete subplots using a soil

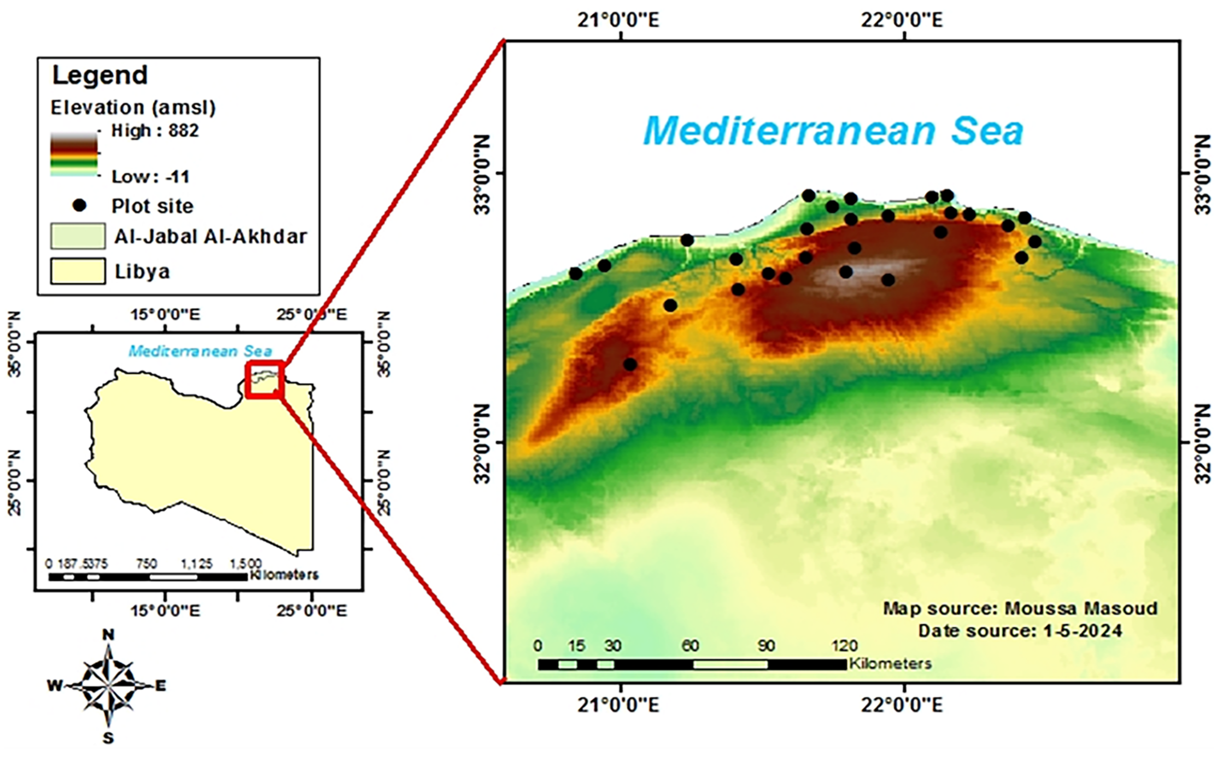

Figure. 2. Location of Al-Jabal Al-Akhdar and study area. (amsl = above mean sea level).

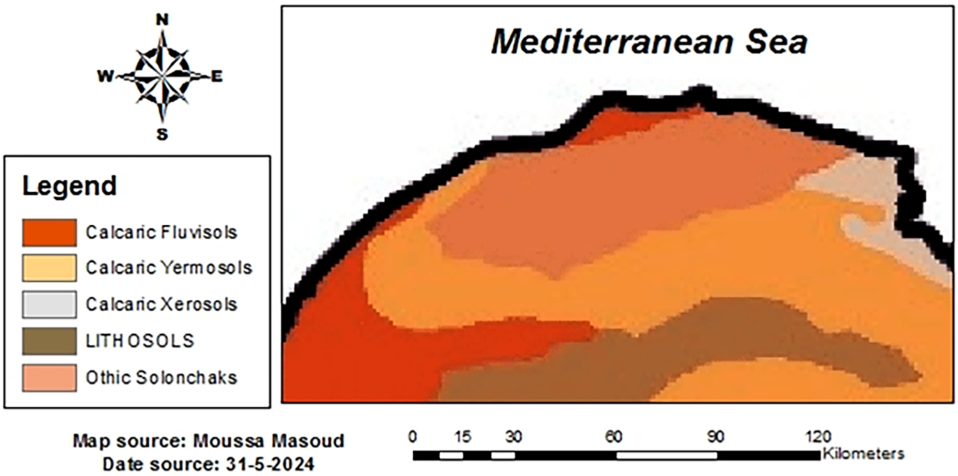

Figure 3. Soil map of Al-Jabal Al-Akhdar - Libya (FAO, 2002).

Table 1. Description of the placement of the plots under the study sites in Al-Jabal Al-Akhdar.

Study Site Name	Region Code	Site	plots
Elevation (0-200 m) above mean sea level	Zone-I	1–7	1–14
Elevation (200-400 m) above mean sea level	Zone-II	8–14	15–28
Elevation (400- 600 m) above mean sea level	Zone-III	15–21	29–42
Elevation (600- 800 m) above mean sea level	Zone-IV	22-28	43-56

auger ranging from 0 to 15 cm. The collected soil samples were then air-dried at room temperature to remove moisture content. Subsequently, the dried samples were crushed, and any present debris was removed. The soil was subjected to a sieving process using a 2 mm sieve to achieve homogeneity. The resulting samples were representative of the soil composition in each specific plot.

2.3. Soil Analysis

The pipette method, as described by Teh and Talib (2006), was used to determine the texture of the soil. The core method was used to evaluate the soil bulk density (Carter, 1990). The sand, silt, and clay fraction classification was based on the USDA soil texture triangle, following the guidelines of Barman and Choudhury (2020). The soil moisture content was determined using the gravimetric method, as Zhao et al. (2016) suggested.

For soil pH and the potassium availability (Kav) measurement, the procedure described by Sparks et al. (2020) was used. CEC is determined using a procedure described by Arifin et al. (2012). The available phosphorus was extracted (Pav) following the method proposed by Olsen et al. (1954). The gasometric technique was used to determine the calcium carbonate concentration (CaCO3) outlined by Black et al. (1965). The Walkley-Black or dichromate oxidation method was employed to evaluate the organic matter content of the soil following the methodology described by Sparks et al. (2020).

2.4 Statistical analysis

A statistical technique, analysis of variance, was used to examine variations in soil physical and chemical properties between different elevations and aspects. The significance of these variations was evaluated using the Tukey range test with a significance level of $p < 0.05$. Pearson's correlation coefficients were calculated to determine the relationships between variables, and Principal Component Analysis (PCA) was performed to explore the underlying patterns and relationships among the various chemical properties of soil at different altitudes on the northern and southern slopes. All data analyses were performed using the statistical software package R.

3 Results and discussion

3.1. Physical properties of the soil at different altitudes on the northern slope and the southern slope

3.1.1. Soil Textural

Significant variations in clay content were observed at different altitudes on the northern and southern slopes ($p < 0.05$). On the northern slope, there was a gradual decrease in clay content with increasing altitude, ranging from 46.52 ± 9.39 in the Zone-I altitude range to 36.54 ± 8.69 in the Zone-IV altitude range. Similarly, the southern slope exhibited a similar decreasing trend, with a clay content ranging from 42.17 ± 6.59 in the altitude range of Zone-I to 36.69 ± 6.90 in the altitude range of Zone-III (Table 2). Variations in clay content along the altitudinal gradient can be attributed to multiple factors. One potential explanation is the influence of climate, which affects the weathering and transportation of clay particles (Nadal-Romero et al., 2014). Precipitation and temperature gradients along the elevation can contribute to clay accumulation and redistribution variations, resulting in the observed patterns. The observed correlation between altitude and clay content on both slopes suggests a decrease in the abundance of fine-textured soil particles at higher elevations. The observed phenomenon can be ascribed to

Table 2. Physical properties of the soil at different altitudes on the northern slope and the southern slope.

Soil properties	Northern slope				Southern slope			
	Zone-I	Zone-II	Zone-III	Zone-IV	Zone-I	Zone-II	Zone-III	Zone-IV
AWC (%)	14.22 ± 2.25a	16.24 ± 2.84bc	17.47 ± 3.05c	19.95 ± 2.04d	11.64 ± 2e	11.99 ± 2.59e	15.29 ± 1.83ab	15.49 ± 1.82ab
BD (g cm^{-3})	1.27 ± 0.03a	1.24 ± 0.03b	1.2 ± 0.05c	1.13 ± 0.05d	1.29 ± 0.04e	1.26 ± 0.04ab	1.24 ± 0.03b	1.17 ± 0.04
Clay (%)	46.52 ± 9.39ab	41.99 ± 11.25b	36.73 ± 11.99c	36.54 ± 8.69d	42.17 ± 6.59a	36.5 ± 6.13cd	35.76 ± 8.47cd	36.69 ± 6.90d
Silt (%)	35.43 ± 6.41	35.79 ± 7.47	38.42 ± 6.88	36.42 ± 5.24	38.55 ± 4.49	35.33 ± 5.72	37.15 ± 4.31	38.20 ± 6.67
Sand (%)	18.02 + 4.74a	22.20 ± 5.45bde	24.83 ± 6.94bc	26.95 ± 7.44c	19.26 ± 3.84ae	28.12 ± 6.16c	27.25 ± 6.78c	25.16 ± 6.80cd

Mean ± standard deviation values in the same row followed by a different letter differ significantly according to the Tukey range test ($p < 0.05$).

erosion mechanisms, in which clay particles are carried downward, or to the impact of additional elements involved in soil formation, such as the composition of the parent material and biological processes (Charan et al., 2013; Saeed et al., 2014).

The altitude can influence the weathering process, producing clay particles, as discussed by Dede et al. (2024) and Türkeş et al. (2022), primarily due to lower temperatures. According to Alaboz et al. (2022), the distribution of soil texture is influenced by the degree and shape of the slope and the erosion process in semiarid ecosystems. The study also found differences in clay minerals in soils formed on limestone under the same climatic conditions and variations in soil formation processes based on physiographic units. Furthermore, vegetation covers and land management practices can affect clay content by influencing organic matter accumulation and nutrient cycling (Warra et al., 2015). Furthermore, the reduced vegetation cover on the mountain site may have influenced soil erosion and, consequently, the selective movement of clay particles, leaving larger particles of sand and silt in situ (Eldiabani et al., 2014).

No significant differences were observed in the silt content at different altitudes on the northern and southern slopes ($p > 0.05$). The northern slope consistently maintained silt content values, ranging from 35.43 ± 6.41 to 38.42 ± 6.88 at all altitudes. Similarly, the southern slope exhibited a stable range of silt content, ranging from 35.33 ± 5.72 to 38.20 ± 6.67 at altitudes. The results presented in this study align with prior research that has examined the fluctuations in silt composition across altitudinal gradients (Eldiabani et al., 2018; AL-Hammaly, 2022). Vegetation covers and land management practices likely stabilize soil particles and reduce erosion, leading to relatively consistent values of silt content (Alawamy et al., 2022).

Significant variations in sand content were observed at different altitudes on the northern and southern slopes ($p < 0.05$). On the northern slope, there was an increase in the sand content with increasing altitude, ranging from 18.02 ± 4.74 in the Zone-I altitude range to 26.95 ± 7.44 in the Zone-IV altitude range. Similarly, the southern slope exhibited a similar increasing trend, with sand content ranging from 19.26 ± 3.84 in the altitude range of Zone-I to 25.16 ± 6.80 in the altitude range of Zone-IV. These findings align with previous studies by Yüksek et al. (2013), which emphasized the significant influence of altitude on the textural class of soils and the proportion of sand. Yüksek et al. (2013) found that soils at elevated altitudes have a sandy loam texture, mainly attributed to the more significant presence of sand particles as altitude increases. These high-altitude soils, derived from weathered rocks, show a relative abundance of sand, gravel, and stones, indicating a slower soil formation process.

On the contrary, lower altitudes tend to have a higher proportion of silt and a lower proportion of sand (Charan et al., 2013). Climate and the parent material are crucial factors that influence soil characteristics (Yang et al., 2008). The increase in sand content with increasing altitude on both slopes suggests selective transport and sedimentation processes. Larger and heavier sand particles are less susceptible to erosion and removal, resulting in their accumulation at higher elevations (Kiani-Harchegani et al., 2019).

3.1.2. Available water capacity (AWC)

Significant differences in AWC were observed at altitudes on the northern and southern slopes ($p < 0.05$). On the northern slope, AWC showed a progressive increase with higher altitudes, ranging from 14.22 ± 2.25 in the Zone-I altitude range to 19.95 ± 2.04 in the Zone-IV altitude range. On the contrary, the southern slope consistently exhibited lower AWC values at all altitudes, ranging from 11.64 ± 2 in the altitude range of Zone-I to 15.49 ± 1.82 in the altitude range of Zone-IV.

These findings are consistent with previous research on soil properties and altitudinal variations, as Badía et al. (2016) reported. Additionally, Zhang et al. (2022) documented similar trends of increasing AWC with altitude in mountain regions, further supporting the results obtained for the northern slope. However, Elnaker and Zaleski (2021) observed lower AWC values with increasing altitude, which aligns with the observations made for the southern slope.

The contrasting patterns observed between the northern and southern slopes can be attributed to various factors. Organic matter acts as a sponge, increasing soil porosity and enhancing water retention capacity (Kumar et al., 2019). This leads to higher AWC values in soils with greater organic matter content (Fuentes et al., 2022). Soils with higher clay content generally have greater water retention capacity due to the small particle size and large surface area of clay minerals, which facilitate water retention through adsorption and capillary action (Elnaker & Zaleski, 2021). Therefore, soils with higher clay content tend to exhibit higher AWC values. Variations in aspect and slope inclination can influence the amount of solar radiation received, moisture retention, and soil characteristics. According to studies conducted by Van Hall et al. (2017) and Elnaker and Zaleski (2021), it has been observed that slopes toward the south have been observed to experience higher solar radiation, which in turn has implications for variables such as temperature, soil moisture, nutrient availability, and soil aggregation processes. However, slopes facing north exhibit diminished solar radiation flux density, resulting in decreased rates of evapotranspiration and lower daily maximum temperatures. This effect is pronounced in summer when water stress is more pronounced (Albaba, 2014).

Additionally, the differences in AWC values between slopes may be attributed to variations in vegetation cover. With less vegetation cover, the south-facing aspect experiences greater soil water evaporation than the north-facing aspect (Albaba, 2014).

3.1.3. Bulk Density (BD)

Significant variations in BD values were observed at all altitudes on both the northern and southern slopes ($p < 0.05$). On the northern slope, BD showed a progressive decrease with increasing altitude, ranging from 1.27 ± 0.03 in the Zone-I altitude range to 1.13 ± 0.05 in the Zone-IV altitude range. Similarly, the southern slope exhibited a decreasing trend in BD, ranging from 1.29 ± 0.04 in the Zone-I altitude range to 1.17 ± 0.04 in the Zone-IV altitude range.

This finding is consistent with the study by Kidanemariam et al. (2012), which reported higher average soil BD at lower-elevation sites compared to higher-elevation sites. It suggests a relationship between altitude and BD, with higher altitudes associated with lower BD values. This trend can be attributed to increased organic matter content at higher altitudes (Saeed et al., 2019). Several factors influence soil BD, including soil structure, texture, organic matter, and freezing and thawing processes (Lu et al., 2021). According to Mondal (2021), the influence of climatic variables, such as temperature and precipitation, on soil compaction and porosity exhibits variability at different altitudes. Furthermore, variations in vegetation cover and land use practices at all altitudes contribute to differences in soil compaction (Alawamy et al., 2022).

The data reveal a negative correlation between altitude and BD, suggesting that soils at higher elevations tend to have lower compaction levels and higher porosity. Increasing organic matter content with altitude could counterbalance the effect of increasing sand content on BD. Organic matter tends to decrease soil density by improving soil structure and increasing pore space, thus reducing BD (Panday et al., 2019; Alawamy et al., 2022). These findings have significant implications for soil fertility, the water infiltration process, and the growth and development of plant roots. Soils with lower BD provide better aeration and water movement, facilitating nutrient availability and root growth (Zhao et al., 2021). Therefore, variations in BD across altitudes can influence soil properties and processes in these ecosystems.

3.2. Chemical properties of the soil at different altitudes on the northern slope and the southern slope

3.2.1. Electrical Conductivity (EC)

The findings of this study suggest minimal variations in EC, an indicator of soil salinity, across altitudes on the northern slope. These variations fell within a narrow range, indicating that salinity levels in the northern slope soils did not change significantly with increasing altitude. Similarly, EC values on the southern slope demonstrated a consistent trend at various altitudes, indicating a marginal decline from the altitude range of Zone-I to the altitude range of Zone-IV (Table 3). This observation implies that the salinity levels in the soils of the southern slope exhibited a consistent and slight fluctuation over the altitudinal gradient.

These observations are consistent with previous studies conducted in similar environments. For example, Charan et al. (2013) conducted a study in a mountainous region and reported similar results, with minor variations in EC values that remained relatively stable across different altitudes. Similarly, Alawamy et al. (2022), conducted at a different geographical location in Al-Jabal Alkhdar, found consistent EC values in soils at various altitudes, supporting the present study's findings.

Variations may influence the slight variations observed in EC across altitudes on both slopes in precipitation, evapotranspiration, and soil characteristics. However, additional research is necessary to understand the fundamental mechanisms and probable factors influencing soil salinity fluctuations in altitudinal gradients.

3.2.2. Soil reaction (pH)

As indicated by pH values, there were significant variations in pH along the altitudinal gradient. On the northern slope, there was a decreasing trend in pH values with increasing altitude, ranging from 8.03 ± 0.37 in the Zone-I range to 7.59 ± 0.40 in the Zone-IV range. Similarly, the southern slope exhibited a slight decrease in pH values as altitude increased, reflecting the patterns observed on the northern slope.

Table 3. Soil chemical properties of the soil at different altitudes on the northern slope and the southern slope.

	Northern slope				Southern slope			
Soil properties	Zone-I	Zone-II	Zone-III	Zone-IV	Zone-I	Zone-II	Zone-III	Zone-IV
CaCO3 (meq 100 g^{-1})	1.28 ± 0.52ab	1.03 ± 0.75b	0.90 ± 0.67b	0.97 ± 0.98b	1.23 ± 0.43b	1.65 ± 0.92a	1.61 ± 0.93a	0.83 ± 0.81b
EC (dS m^{-1})	0.26 ± 0.14ac	0.26 ± 0.12ac	0.32 ± 0.11c	0.22 ± 0.07a	0.33 ± 0.15bc	0.27 ± 0.09ac	0.24 ± 0.06a	0.27 ± 0.07ac
PH	8.03 ± 0.37a	7.79 ± 0.29bc	7.63 ± 0.24c	7.59 ± 0.40d	7.85 ± 0.28ac	7.66 ± 0.29bd	7.85 ± 0.3ac	7.70 ± 0.30bcd
Pav (mg L^{-1})	7.42 ± 1.78a	8.53 ± 1.80b	2.14 ± 1.53c	1.65 ± 1.15c	10.61 ± 1.46d	10.88 ± 1.40d	4.58 ± 2.34e	2.66 ± 1.37f
SOM ()	2.45 ± 0.86a	3.71 ± 1.43b	4.54 ± 1.74c	7.25 ± 2.41c	1.49 ± 0.47d	2.93 ± 1.24ab	2.99 ± 0.89ab	4.77 ± 1.37f
CEC (meq 100 g^{-1})	19.16 ± 5.29a	18.14 ± 5.40a	24.55 ± 7.61	26.18 ± 11.76	24.87 ± 8.61	24.36 ± 4.49	24.85 ± 5.87	24.83 ± 9.58
Kav (meq 100 g^{-1})	2.47 ± 0.65a	2.05 ± 0.6b	1.87 ± 0.58bc	1.50 ± 0.41d	1.62 ± 0.46cd	1.31 ± 0.32df	1.34 ± 0.47df	1.15 ± 0.34f

Mean ± standard deviation values in the same row followed by a different letter differ significantly according to the Tukey range test ($p < 0.05$).

The results of this investigation are consistent with previous research conducted in comparable settings. Mosallam et al. (2017) reported a similar decreasing trend in pH values with increasing altitude in their respective studies. Furthermore, Amanullah et al. (2021) conducted a study in different locations. They observed comparable patterns of decreasing pH values along altitudinal gradients, further supporting the present study's findings.

The observed variations in pH values can be attributed to several factors, including changes in vegetation composition (Unger et al., 2012) and weathering processes (Fuentes et al., 2022). These factors can influence the production of organic acids, nutrient availability, and leaching of alkaline minerals, ultimately affecting soil pH.

Egli et al. (2009) reported significant variations in soil fertility characteristics, including pH, along altitudinal gradients. They found that soil pH tends to be slightly acidic and decreases with increasing altitude. The decreased pH can be attributed to the gradual buildup and subsequent breakdown of organic matter, resulting in the release of acidic compounds into the soil.

3.2.3. Cation exchange capacity (CEC)

The findings of this study indicate that the CEC, which represents the ability of the soil to retain and supply nutrients, exhibited variable values at altitudes on the northern slope. The highest CEC values were observed in the altitude ranges of Zone-III and Zone-IV, ranging from 24.55 ± 7.61 to 26.18 ± 11.76, respectively. On the southern slope, CEC values remained relatively consistent at all altitudes, similar to the patterns observed on the northern slope.

The findings above are consistent with previous studies conducted in areas characterized by high terrain. An investigation in Jalisco, Mexico, revealed elevated levels of CEC within the mid to high-altitude regions, as reported by Nieves-Hernández et al. (2009). These findings corroborate the observations made on the northern slope. Similarly, a study by Unger et al. (2012) conducted in the equatorial Andes found relatively stable CEC values across altitudes, further supporting the findings on the southern slope.

The ability of the soil to hold exchangeable cations is determined primarily by various factors, including SOM, pH levels, clay content, and leaching processes (Sidi et al., 2015). The low CEC observed in these soils can be attributed to the characteristics of silicate clay minerals, which have a low CEC and a weak degree of crystallinity (Alawamy et al., 2022). Furthermore, under semi-arid conditions, soil erosion can lead to the loss of the best and most fertile soil fractions, decreasing CEC and soil productivity (Novara et al., 2018).

Variations in CEC at altitudes can be attributed to several factors, including soil properties (such as clay content and organic matter content), weathering processes, and land management practices. The higher CEC values observed in the mid to high altitude ranges on the northern slope may be associated with the accumulation of clay minerals and organic matter, which enhance the soil's ability to retain cations and nutrients (Unger et al., 2012).

Understanding the variations in CEC across altitudes is crucial for assessing nutrient availability and soil fertility in mountain ecosystems. More research is needed to investigate the underlying factors influencing CEC dynamics and their implications for nutrient cycling, plant growth, and ecosystem functioning in these environments.

3.2.4. Calcium carbonate content (CaCO3)

The CaCO3 content exhibited a decreasing trend with increasing altitude on the northern slope, with the highest content observed in the Zone-I range (1.28 ± 0.52), gradually decreasing in the higher altitude ranges. On the southern slope, the CaCO3 content showed variations but did not show a clear altitudinal trend.

These findings align with previous research in the Al-Jabal Al-Akhdar region (Alawamy et al., 2022), indicating agreement in the range and mean values of CaCO3 content. However, the specific factors underlying the observed altitudinal trends and variations in CaCO3 content in the study area require further investigation. Previous research carried out in comparable habitats has documented comparable tendencies. For example, Saeed et al. (2014) research in mountainous areas revealed a negative correlation between altitude and CaCO3 content, which aligns with the observed pattern on the northern slope. Conversely, Amanullah et al. (2021) found significant spatial variations in CaCO3 content across a hilly landscape without a clear altitudinal pattern, which aligns with observations on the southern slope.

Understanding the factors driving the observed patterns in CaCO3 content in different altitudes is crucial for understanding soil formation processes, nutrient cycling, and ecosystem dynamics in mountainous environments.

3.2.5. Available phosphorus (Pav)

The phosphorus content, a crucial nutrient for plant growth, decreased substantially with increasing altitude on the northern slope. The available P levels ranged from 7.42 ± 1.78 in the Zone-I range to 1.65 ± 1.15 in the Zone-IV range. In contrast, the southern slope showed significantly higher P levels than the northern slope, ranging from 10.61 ± 1.46 in the Zone-I range to 2.66 ± 1.37 in the Zone-IV range.

The observed decrease in the P content with altitude on the northern slope aligns with previous research conducted in mountainous regions. The study conducted by Zhang et al. (2022) revealed that the slope aspect had an essential effect on the chemical and physical characteristics of the soil. The data revealed a notable rise in the overall P concentration when comparing slopes oriented toward the north with those oriented toward the south. In a similar vein, Wang et al. (2018) documented a decline in the Pav as elevation increased. In their study, Mishra and Francaviglia (2021) observed the impact of various altitudes in the Mon district on Pav. The results indicated a substantial height influence on Pav, with lower elevations exhibiting the highest P content. Furthermore, statistical analysis revealed that these lower elevations were comparable regarding P content.

Charan et al. (2013) also reported a similar decline in P levels with increasing altitude, attributing it to the P content remaining bound to the SOM, which does not degrade sufficiently at low temperatures. The rate of soil P content decreases with temperature. Thus, the low nutrient status of soils at higher altitudes is due to low temperatures that inhibit mineralization and decomposition. In a recent study conducted by Alawamy et al. (2022) in the Al-Jabal Al-Akhdar mountain, it was shown that the deficiency of P in the soil may be attributed to the CaCO3 fixation process, which becomes more pronounced under alkaline soil conditions.

The contrasting patterns of P content between the northern and southern slopes emphasize the importance of considering topographic gradients when studying the dynamics of nutrients in mountain ecosystems. The availability of P can significantly influence plant growth, nutrient cycling, and overall ecosystem functioning in these environments.

3.2.6 Available potassium (Kav)

The findings of this study indicate a consistent decrease in K content with increasing altitude on both the northern and southern slopes. On the northern slope, the highest K content was observed in the Zone-I altitude range (2.47 ± 0.65), gradually decreasing in higher altitude ranges, suggesting a decrease in Kav with increasing altitude. Similarly, on the southern slope, there was a significant decline in K content as altitude increased, ranging from 1.62 ± 0.46 in the altitude range of Zone-I to 1.15 ± 0.34 in the altitude range of Zone-IV, indicating a decrease in Kav with altitude.

The results of this study are consistent with previous studies conducted in a tropical montane forest by Soethe et al. (2008), which similarly observed a decline in K levels as altitude increased. Jeyakumar et al. (2020) also found significant differences in essential soil nutrients, including K, between higher-altitude regions and plains. Furthermore, Zhang et al. (2022) highlighted the impact of the slope aspect on soil characteristics, indicating a decrease in total K with a change in slope aspect from north to south.

The observed altitudinal trends in K content can be attributed to various factors. The decrease in Kav may be influenced by plant uptake as well as the clay content of the soil, which affects the amount of dissolved K due to the presence of illite with a high absorption capacity for added K. The K ratio is also influenced by equilibrium and kinetic interactions between different forms of K in the soil, moisture content, and concentration of dications in the soil solution and on exchange surfaces (AL-Hammaly, 2022).

Understanding the altitudinal variations in K content is crucial for assessing nutrient availability and optimizing agricultural practices in mountainous environments. More research is needed to uncover the underlying mechanisms of these trends and investigate their implications for plant growth, nutrient cycling, and ecosystem dynamics.

3.2.7 Soil Organic Matter (SOM)

The findings of this study reveal a distinct altitudinal pattern in the SOM content on both the northern and southern slopes. On the northern slope, the SOM content increased with increasing altitude, ranging from 2.45 ± 0.86 in the Zone-I altitude range to 7.25 ± 2.41 in the Zone-IV altitude range. Similarly, on the southern slope, the SOM content exhibited variations at all altitudes, ranging from 1.49 ± 0.47 in the Zone-I altitude range to 4.77 ± 1.37 in the Zone-IV altitude range. Although the increase in SOM content with altitude was more pronounced on the northern slope, these findings demonstrate the influence of elevation on organic matter dynamics.

The results presented in this study align with other research undertaken by Badía et al. (2016) and Lu et al. (2021), who similarly reported a positive correlation between elevation and organic matter content. The variation in results could be attributed to differences in litter availability and organic matter decomposition rates, which are generally higher on slopes facing north due to increased moisture content (Yimer et al., 2006). Dede et al. (2022) found that the abundant presence of organic matter in the soils of periglacial landforms inhibits the development of soil crusts. The primary factor contributing to the high organic matter (OM) content in the periglacial landforms of the Ilgaz Mountains is the combination of low temperatures and reduced microorganism activity, which are crucial for decomposition.

Zhang et al. (2022) have emphasized the influence of slope aspects on soil properties, noting a decrease in SOM when slope aspects transition from north to south. Van Hall et al. (2017) also found that north-facing slopes had more organic matter than the south-facing slopes along a climatic transect. Khalili-Rad et al. (2011) also reported similar findings related to biochemical and microbiological properties, attributing the accumulation of organic matter on north-facing slopes to lower soil temperatures and reduced moisture evaporation, resulting in less organic matter decomposition and more significant accumulation of organic C and total N.

Climate factors such as precipitation, snowfall, and temperature variations can also influence the accumulation of organic matter in soil along elevation gradients, as mentioned by Mondal (2021). Kumar et al. (2019) noted that the concentration of SOM increases with altitude due to lower temperatures, suppressing the microbial and enzymatic activity responsible for the decomposition of organic matter in high-altitude soil. Consequently, SOM accumulation is not affected by microbial decomposition. Thus, the low temperature with increasing altitude plays a significant role in the observed increase in SOM.

The differences in SOM content between the northern and southern slopes emphasize the importance of considering topographic and latitudinal gradients when studying organic matter dynamics in mountain ecosystems. The accumulation of SOM with increasing altitude can affect soil fertility, water retention capacity, and C sequestration potential in these environments.

3.3 Relationship between soil properties using PCA and Pearson's correlation

This study used Pearson's correlation analysis and PCA to investigate and elucidate the relationships between soil properties, elevations, and aspects. Pearson's correlation coefficients were used to evaluate the linear relationships between specific soil parameters, as presented in Table 4.

The coefficients presented in the analysis offer insight into the magnitude and direction of the linear associations between pairs of variables. Additionally, PCA facilitated a multivariate exploration of the factors underlying the variability observed in the data set. The PCA analysis comprehensively understood the factors driving the data set's variability. The computation was performed to determine the proportion of variation explained by each principal component (PC) (Table 5). The study results indicated that PC1 represented the highest proportion of variance (28.91%), followed by PC2 with 20.20% and PC3 with 13.05%. This result emphasizes the importance of these parameters in encompassing the entire variability present within the data set. The cumulative proportion of variance demonstrated that the first seven PCs collectively accounted for 88.08% of the total variance (Figure 4), underscoring their importance in summarizing the data set.

The first PC1, mainly influenced by elevation, exhibited positive loads for AWC and SOM (Figure 5), indicating that higher elevations are associated with increased AWC and higher organic matter content in the soil. On the contrary, PC1 had negative loadings for clay content and Kav, suggesting an inverse relationship with these variables. The second PC2, primarily influenced by aspect, showed positive loadings for clay content and negative loadings for BD, suggesting a potential relationship between aspect and soil properties. The aspect influences microclimatic conditions, exposure to solar radiation, and moisture retention, affecting the clay content and BD. PC3 had negative loadings for the silt content and positive loadings for CaCO3 and EC, indicating a potential relationship among these variables. PC4, mainly influenced by pH and P, had positive and negative P loadings, suggesting a potential relationship between pH and Pav. The pH of the soil influences the availability of nutrients. It can affect the solubility and uptake of P by plants. PC5 was primarily associated with the content of sand, with positive loads for sand and negative loads for the clay and silt content, indicating a relationship between soil texture and the distribution of particle size fractions. Sand particles contribute to soil drainage and aeration, while clay and silt particles influence nutrient and water retention capacity.

Pearson's correlation analysis revealed significant relationships between elevation and soil properties. Higher elevations were positively correlated with AWC, indicating that the water retention capacity increases with elevation. On the contrary, elevation is negatively correlated with BD, suggesting that higher elevations have lower soil compaction and better soil structure. Similarly, elevation was negatively correlated with clay content, indicating a lower clay content at

Table 4. Pearson's correlation coefficients between the soil properties measured at various altitudes on the northern and southern slopes.

	Elevation	Aspect	AWC	BD	Clay	Silt	Sand	CaCO3	EC	pH	Pav	SOM	CEC
Aspect	0.0												
AWC	0.54***	−0.49***											
BD	−0.74***	0.25***	−0.48***										
Clay	−0.31***	−0.14**	−0.12*	0.29***									
Silt	0.06	0.07	−0.01	−0.14**	−0.68***								
Sand	0.37***	0.14**	0.17***	−0.28***	−0.78***	0.07							
CaCO3	−0.16***	0.18***	−0.12*	0.18***	−0.39***	0.07	0.48***						
EC	−0.13**	0.05	0.01	0.06	0.37***	0.48***	0.09	0.06					
pH	−0.29***	0.01	−0.07	0.23***	−0.11*	0.12**	0.04	0.18***	0.16***				
Pav	−0.77***	0.29***	−0.64***	0.56***	0.06	0.01	−0.09*	0.21***	0.09*	0.15**			
SOM	0.65***	−0.33***	0.50***	−0.91***	−0.31***	0.15**	0.29***	−0.14**	−0.02	−0.22***	−0.48***		
CEC	0.19***	0.17***	0.09	−0.15**	−0.44***	0.11*	0.52***	0.32***	0.20***	0.08	−0.08	0.16***	
Kav	−0.39***	−0.48***	−0.05	0.03	0.05	0.13**	−0.18***	−0.01	0.15**	0.13**	0.19***	0.05	−0.11*

* Significant at $p < 0.05$, ** significant at $p < 0.01$, *** significant at $p < 0.001$, ns = nonsignificant.

Table 5. Principal component analysis (PCA) of some soil properties in different elevations and aspects.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
Elevation	0.44	−0.07	0.23	−0.14	0.08	0.08	−0.02	−0.09	0.02	0.27	−0.04	−0.73	0.32	0.00
Aspect	−0.12	0.27	0.47	−0.37	−0.01	0.11	0.19	−0.02	0.23	0.21	−0.60	0.24	−0.01	0.00
AWC	0.34	−0.16	−0.13	0.19	0.38	−0.21	−0.27	0.14	−0.10	−0.32	−0.64	0.03	−0.06	0.00
BD	−0.43	0.10	0.06	0.06	0.24	−0.20	−0.27	−0.10	−0.27	0.09	−0.02	0.11	0.72	0.00
Clay	−0.25	−0.47	0.11	0.08	0.09	−0.15	0.19	−0.03	0.32	−0.05	−0.03	−0.08	0.04	−0.72
Silt	0.10	0.31	−0.36	−0.48	0.00	0.21	−0.22	−0.41	−0.10	−0.25	−0.02	−0.01	0.00	−0.45
Sand	0.25	0.38	0.17	0.31	−0.12	0.02	−0.07	0.39	−0.35	0.29	0.05	0.12	−0.05	−0.53
CaCO3	−0.03	0.38	0.09	0.45	−0.09	0.05	−0.42	−0.18	0.64	−0.10	0.02	−0.09	0.02	0.00
EC	0.01	0.29	−0.35	−0.34	0.24	−0.50	0.05	0.44	0.35	0.17	0.13	−0.08	0.02	0.00
pH	−0.11	0.19	−0.20	0.23	0.62	0.56	0.38	0.09	0.06	0.01	0.03	−0.06	0.04	0.00
Pav	−0.37	0.20	−0.05	0.02	−0.37	0.05	0.15	0.37	−0.13	−0.46	−0.24	−0.48	0.07	0.00
SOM	0.42	−0.08	−0.13	0.00	−0.29	0.16	0.25	0.18	0.25	−0.24	0.02	0.36	0.59	0.00
CEC	0.16	0.34	0.11	0.22	0.06	−0.48	0.55	−0.45	−0.12	−0.21	0.03	−0.03	0.00	0.00
Kav	−0.09	−0.05	−0.58	0.25	−0.31	−0.02	0.14	−0.22	0.01	0.51	−0.40	−0.06	0.04	0.00

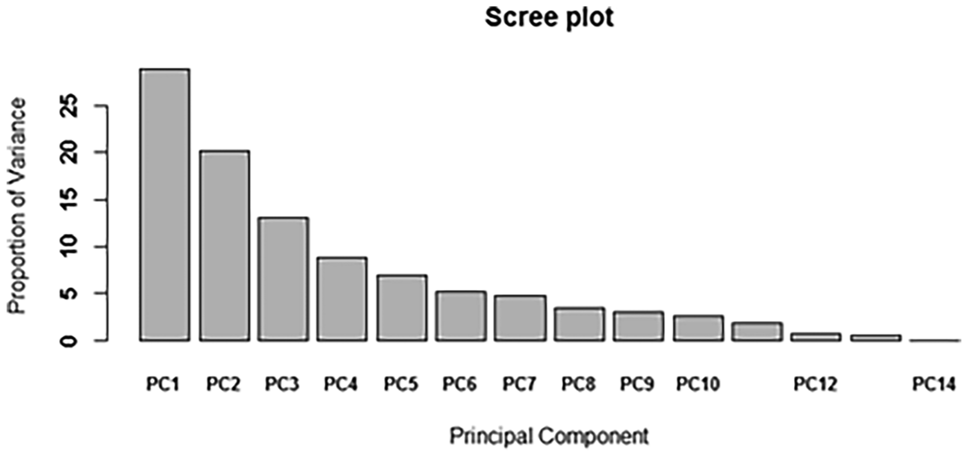

Figure 4. Scree plot for the analysis of principal components.

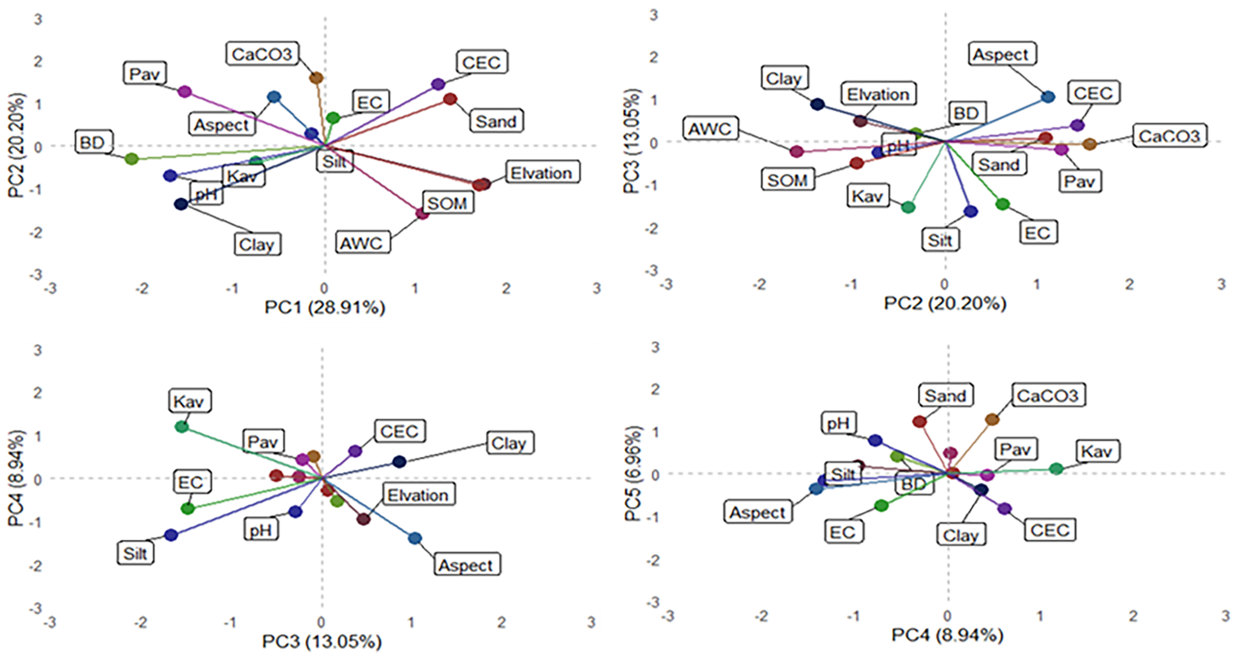

Figure 5. Analysis of principal components (PCA) of some soil properties in different elevations and aspects.

higher elevations. The correlation analysis also revealed a negative relationship between elevation and pH, suggesting slightly more acid soils at higher elevations. Furthermore, elevation showed a negative correlation with Kav, indicating a decrease in Kav with increasing elevation. On the other hand, elevation exhibited a strong positive correlation with the SOM, indicating a higher organic matter content at higher elevations.

The above findings align with other research that has underscored the impact of elevation on soil properties. Jeyakumar et al. (2020) has highlighted the significance of altitude in soil organisms, mineral particles, and soil biodiversity. Kumar et al. (2019) noted that soil ecosystems' physicochemical properties and biodiversity vary with altitude. Badía et al. (2016) revealed a negative correlation between altitude and pH, base saturation, BD, exchangeable sodium percentage, and fine silt-sized particles. On the contrary, height was positively associated with organic matter, soil aggregate stability, water repellency, and coarse sand-sized particles. Jeyakumar et al. (2020) also highlighted significant differences in essential soil nutrients, including C, N, P, and K, between high-altitude regions and plains. The observed correlations between elevation and soil properties provide valuable insights into the influence of altitude on soil ecosystems and highlight the need to consider altitude gradients when studying soil dynamics.

Soil properties are significantly influenced by climate and the parent material, and altitude changes can lead to variations in soil properties and pedogenic processes (Yang et al., 2008). The qualities of soil are influenced by altitude due to its effects on many chemical, physical, and biological processes, as well as the composition of vegetation (Unger et al., 2012). High-altitude environments are characterized by low temperatures, rapid temperature changes, low air pressure, and high solar radiation (Winkler et al., 2016).

Regarding slope aspects, significant correlations were observed with specific soil properties. The aspect showed a negative correlation with AWC, SOM, and Kav, indicating that specific slope aspects may have slightly lower water retention capacity, SOM, and Kav. On the other hand, the aspect exhibited a positive correlation with BD, suggesting that certain aspects may be associated with slightly higher soil compaction.

The influence of the slope aspect on soil parameters has also been documented in previous investigations. For example, previous studies have shown that differences in slope aspect have an impact on many soil characteristics such as temperature, moisture content, and nutrient composition (Sung et al., 2017). The study conducted by Yang et al. (2023) found that the slope aspect substantially affected soil parameters, such as grain size composition, physical characteristics, and chemical characteristics, leading to considerable differences. Consequently, there were variations in the composition and depth of the soil on the different slopes. The slope angle and aspect variations influence the availability of water, affecting the soil nutrient content and the uptake of plant minerals (Gxasheka et al., 2023). South-facing slopes generally have a decreased soil moisture content and water retention capacity compared to north-facing slopes (Sharma et al., 2010). According to Sharma et al. (2010), the northern slopes of the Garhwal region of the Indian Himalayas showed elevated levels of moisture content, water holding capacity, organic C, P and N while showing lower levels of sand content in the soil.

Mountain exposure, which refers to the direction in which the slope is facing, is crucial to soil temperature and radiation absorption (Elnaker and Zaleski, 2021). In the context of the northern hemisphere, it is observed that slopes facing south experience a higher degree of direct radiation, leading to elevated temperatures and enhanced evaporation of soil water. According to Elnaker and Zaleski (2021), there is a tendency for the soil on the north slopes to exhibit higher moisture levels compared to the soil found on the south slopes.

The experiment revealed a significant positive correlation coefficient of 0.50 between SOM and accessible water capacity (AWC), indicating that higher levels of organic matter in the soil are associated with an increased water retention capacity. This finding aligns with previous studies by Kumar et al. (2019) and Fuentes et al. (2022), emphasizing the positive impact of organic matter on soil water retention. These studies demonstrated that organic matter improves soil structure and enhances aggregate stability, facilitating better water infiltration and storage, leading to higher AWC values.

Furthermore, a strong negative correlation coefficient of -0.91 was observed between SOM and BD, suggesting that a higher organic matter content is related to lower values of BD. This result is consistent with the findings of Panday et al. (2019), who highlighted the role of organic matter in reducing soil compaction. Organic matter improves soil porosity and aggregation, resulting in lower BD values. Reduced soil compaction positively affects root penetration, water movement, and nutrient availability, ultimately benefiting plant growth and overall soil health.

Similarly, a negative correlation coefficient of -0.48 between P and SOM suggests that a higher SOM is associated with decreased levels of P. This finding is supported by research conducted by Charan et al. (2013), who observed that a significant portion of P remained bound to SOM, which had limited degradation at low temperatures. The degradation rate of SOM and the release of soil P decreased with decreasing temperatures. Therefore, the low nutrient status of soils at higher altitudes can be attributed to cold temperatures, which inhibit mineralization and decomposition processes.

Unexpectedly, the CEC showed a negative correlation with sand and a positive correlation with clay. It is noted that organic matter increases with altitude, which may be the reason. Organic matter has a strong influence on CEC because of its ability to hold and exchange cations. Higher organic matter content typically leads to higher CEC due to increased surface area and negative charge provided by organic functional groups. Therefore, if organic matter increases with altitude, it is generally expected to positively correlate with CEC (Khorshidi & Lu, 2017; Ramos et al., 2018).

Furthermore, the results of this study indicate a negative correlation between soil pH and SOM, indicating that an increase in organic matter leads to soil acidity. According to the -0.22 negative correlation coefficient between soil pH and SOM, the organic matter content decreases with increasing soil pH. This finding is supported by studies conducted by Fuentes et al. (2022) and Amanullah et al. (2021), which observed an upward trend in SOM content with increasing altitude, while pH showed a downward trend. The observed acidity of the soil and its correlation with altitude can be ascribed to the gradual build-up and subsequent gradual breakdown of organic material, resulting in the release of acidic compounds into the soil (Egli, 2007).

Furthermore, examination of the data collected revealed a significant association between the concentration of CaCO3 and the ability of the soil to exchange cations, as indicated by the CEC, with a correlation value of 0.32 ($p < 0.05$). This finding indicates that higher CaCO3 concentrations are associated with elevated CEC in the soil. This result is consistent with the findings of Wang et al. (2004), who observed that the removal of CaCO3 from calcareous soils decreased CEC, while the addition of CaCO3 to acidic soils increased CEC.

Increased CEC from higher CaCO3 concentrations can improve the availability of nutrients and soil fertility. This finding is consistent with previous studies that highlight the role of CaCO3 in shaping soil properties (Hartono, 2009). However, it is essential to consider other factors that may influence CEC, such as organic matter content, soil texture, and mineral composition. Future research should explore these additional factors to understand the dynamics of soil nutrients and develop comprehensive effective management strategies.

4.1. Conclusions:

This study extensively investigated soil properties at various altitudes on the northern and southern slopes, revealing significant variations in chemical and physical characteristics. The findings showcased consistent trends in soil characteristics, including the gradual decline in clay content with altitude ascent, while the sand content exhibited an increasing pattern. Moreover, essential parameters like AWC, BD, pH, and SOM exhibited distinct alterations in altitude gradients, highlighting the influence of elevation on these properties.

Integrating Pearson's correlation and PCA provided deeper insight, revealing intricate relationships between soil properties, elevations, and aspects. In particular, the positive correlations between SOM and AWC and the inverse correlation between SOM and BD were in line with the PCA results, emphasizing the multifaceted interplay between various soil characteristics.

These findings have substantial implications for informed decision-making in soil management, land use planning, and environmental assessments within the studied area. Incorporating the knowledge derived from the study into forest land management strategies can help conserve soil resources and promote the long-term sustainability of forest ecosystems. Forest managers can implement silvicultural practices that maintain or enhance ecosystem services such as carbon sequestration, afforestation, reforestation, water filtration, and habitat provision by prioritizing soil health and fertility. These practices can contribute to the resilience of forest ecosystems in the face of environmental change and human disturbances.

Future research could explore additional environmental factors and mechanisms to broaden our understanding of soil-landscape interactions. By deepening these associations, further advancements can be made in enhancing strategies to optimize soil quality and environmental sustainability in diverse geographical settings.

ORCID

Moussa Masoud http://orcid.org/0000-0002-6921-6016
Hazandy Abdul-Hamid http://orcid.org/0000-0002-3525-556X
Johar Bin Mohamed http://orcid.org/0000-0001-7330-8282
Attia Alsanousi http://orcid.org/0000-0001-7698-530X

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