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Assessment of soil physico-chemical properties in the Tamgarda-Erani Interbasin region of Uttarakhand

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Abstract
The major challenges in agricultural cultivation within hilly regions are primarily attributed to the challenging topography, which includes steep slopes leading to soil erosion, limited arable land, difficulties in water management, and the need for terracing. These factors, in combination with the risk of natural disasters, collectively present formidable obstacles for farming practices in these regions. To address the multifaceted challenges of agricultural cultivation in hilly regions, a comprehensive strategy involving soil conservation, soil analysis-driven practices, and risk mitigation is essential. By conducting a thorough physico-chemical analysis of the soil, understanding its topographic characteristics, optimizing land use on limited arable areas, managing water resources effectively, selecting suitable crops based on soil conditions, implementing terracing techniques, practicing precision agriculture, and accounting for potential natural disasters and climatic variability, farmers can collectively enhance productivity and sustainability in these challenging terrains while mitigating risks and optimizing resource utilization. In the current research, soil characteristics were assessed in the Tamgarda-Erani inter-basin, located within India's Champawat district in the state of Uttarakhand. Most of the soils in this area, both at the surface and sub-surface levels, were identified as sandy loam with an acidic pH. When categorizing the soils based on their content of available Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), and Magnesium (Mg), it was evident that these nutrients were predominantly in low supply, indicating poor nutrient levels in the soil. Copper (Cu) content in most surface soils (0-15 cm)) was categorized as medium, whereas in the sub-surface soils (15-30 cm), it fell into the high Copper (Cu) content category. Meanwhile, the Sulfur(S), Zinc (Zn), and Manganese (Mn) content across different parts of the study area exhibited variations ranging from low to high levels. In the texture analysis of soil, it can be concluded that most of the study area has sandy loam soil with an average PH of 6.7 for both surface and Sub-surface soil. Additionally, it was observed that the most significant negative correlation existed between sand and silt (correlation coefficient of 0.751), followed by sand and clay (correlation coefficient of 0.702). Conversely, in terms of soil micronutrients, the highest positive correlation (0.57) was found between Nitrogen (Na) and Iron (Fe).

Keywords: Categorization, conservation, correlation, management, nutrients, physico-chemical, properties, texture

Introduction
Soil is a complex and diverse mixture of minerals and organic materials that can support plant life (Ayoub *et al.*, 2003) [2]. Within the soil, one can find 13 out of the 16 elements essential for plant growth, as highlighted (Raven *et al.*, 2016) [11]. However, these crucial plant nutrients' availability is limited, as (McLean and Watson, 2015) [9] pointed out. Nutrients become accessible to plants through processes like mineral weathering and the breakdown of organic matter into inorganic minerals, which plants absorb as ions.
The availability of soil nutrients significantly impacts the potential for agriculture. This availability is influenced by several factors, including Soil Organic Matter (SOM) content, soil pH, adsorptive surface properties, soil texture, and the interactions between different nutrients. Additionally, efforts to enhance macro and micronutrients in soil face constraints due to the reliance on outdated data. These interventions rely on information from major national soil surveys dating back to the 1980s, as highlighted by the Food and Agriculture Organization (Shand *et al.*, 2006) [13]
Globally, millions of hectares of land are facing deficiencies in available micro-nutrients, and these deficiencies have been exacerbated by the increased demands of faster-growing crops for readily accessible micro-nutrients, as noted by (Rengel, 2007) [12] and (Alloway, 2008) [1]. The solubility and accessibility of these micro-nutrients are greatly influenced by factors such as clay content, pH levels, Soil Organic Matter (SOM), Cation Exchange Capacity (CEC), soil

phosphorus levels, and agricultural practices, as highlighted by (Fisseha, 1992) [5].
Soil-related constraints that impact crop productivity, including nutrient-related disorders, can be identified by assessing the fertility status of soils. Soil testing provides essential information about nutrient availability in the soil, forming the basis for fertilizer recommendations to maximize crop yields. The original geological substrate and subsequent geochemical and pedogenic processes primarily determine the composition of soil micro-nutrients. However, the total amount of micro-nutrients present rarely indicates their availability to plants, as availability is contingent on factors such as soil pH, organic matter content, adsorption surfaces, and various physical, chemical, and biological conditions in the rhizosphere. Plants absorb nutrients from different fraction within the soil and extract varying quantities. Because different element fractions exhibit varying solubility, their availability is contingent on a range of soil characteristics.
Furthermore, exploring the relationships between the major physical and chemical properties of soils and their available forms is crucial to understanding the soil's available nutrient pool. This information is invaluable for predicting nutrient bioavailability, rates of metal leaching, and transformations between different chemical forms in agricultural and contaminated soils. Maintaining soil fertility is a matter of paramount importance for achieving higher crop yields. Evaluating soil fertility can help in planning suitable cropping systems for a region; with these considerations in mind, an endeavour was undertaken to assess the soil characteristics in the Tamgarda-Erani inter-basin, located within the Champawat district of Uttarakhand state in India.

Materials and Methods

Our investigation focused on assessing the soil characteristics within the Tamgarda-Erani interbasin in the Champawat district of Uttarakhand, India. This region is geographically defined by its boundaries, with Pithoragarh district to the north, Nepal to the east, Udham Singh Nagar district to the south, Nainital district to the west, and Almora district to the northwest. The study area is positioned at a longitude of 80˚ 10'E and a latitude of 29˚ 60' N, with an elevation ranging from 1700 to 1800 meters above mean sea level. The area experiences a sub-humid temperate climate, characterized by mean maximum temperatures of 28.2 °C and mean minimum temperatures of-1.2 °C.

Collection and preparation of soil samples

To investigate the physico-chemical properties of the soil, including texture, pH, and electrical conductivity (EC), symbolic soil samples were meticulously collected. Composite soil samples were gathered from various locations within the study area at two distinct depths: 0-15 cm and 15-30 cm. These collected soil samples underwent a series of preparation steps. First, they were air-dried in the shade and then finely ground. Subsequently, the soil was sieved through a 2 mm mesh to obtain a uniform consistency, and finally, the processed soil samples were carefully stored in polythene bags, ready for subsequent analysis. The soil samples underwent a comprehensive analysis, covering a range of parameters, including pH, electrical conductivity (EC), and the availability of various nutrients such as Nitrogen (N) (Subbaiah and Asija, 1956) [14], Phosphorus (P) (Olsen *et al.*, 1954) [10], Potassium (K) (Jackson, 1959) [6], Sulfur (S) (Butters & Chenery, 1959) [4], as well as the levels of extractable Iron (Fe) (Lindsay & Norvell, 1978) [8], Manganese (Mn) (Lindsay & Norvell, 1978) [8], Magnesium (Mg) (Jackson, 1959) [6], Zinc (Zn) (Lindsay & Norvell, 1978) [8], and Copper (Cu) (Lindsay & Norvell, 1978) [8].

Result and Discussion

To address the multifaceted challenges of agricultural cultivation in hilly regions, a comprehensive strategy involving soil conservation, soil analysis-driven practices, and risk mitigation is essential. By conducting a thorough physico-chemical analysis of the soil, understanding its topographic characteristics, optimizing land use on limited arable areas, managing water resources effectively, selecting suitable crops based on soil conditions, implementing terracing techniques, practicing precision agriculture, and accounting for potential natural disasters and climatic variability, farmers can collectively enhance productivity and sustainability in these challenging terrains while mitigating risks and optimizing resource utilization."

Physico-chemical properties

Table 1 shows a descriptive analysis of the collected samples from the sampling stations. While accounting for soil texture, the fraction of sand for the mean value of surface and sub-surface soils was 58.84%, followed by silt (27.72%) and clay (13.30%). Comparative analysis of sand silt and clay was shown in Figures 2 and 3 for surface and sub-surface soil.

Table 1: Descriptive analysis of physico-chemical constitutes of soil

Variable	Range	Minimum	Maximum	Mean	Std. Deviation	Skewness		Kurtosis	
						Statistic	Std. Error	Statistic	Std. Error
N(kg/ha)	229.1	121.54	350.65	258.9	50.62	-0.45	0.44	0.62	0.86
P(kg/ha)	16.71	2.02	18.73	8.24	3.67	0.53	0.44	0.89	0.86
K(kg/ha)	104.9	30.96	135.88	68.21	24.80	0.66	0.44	0.50	0.86
Cu(Mg/kg)	1.19	0.01	1.20	0.30	0.28	2.33	0.44	5.88	0.86
Fe(Mg/kg)	4.91	0.01	4.92	0.88	1.08	2.26	0.44	6.55	0.86
Mn(Mg/kg)	13.29	0.01	13.30	1.77	2.71	3.22	0.44	12.39	0.86
S(Mg/kg)	91.00	4.00	95.00	27.46	29.35	1.79	0.44	1.86	0.86
Zn(Mg/kg)	5.00	0.75	5.75	2.41	1.23	1.01	0.44	0.94	0.86
Ca(Mg/kg)	344.00	144.00	488.00	272.43	103.93	0.80	0.44	-0.48	0.86
Mg(Mg/kg)	60.40	9.60	70.00	46.46	15.59	-0.56	0.44	-0.08	0.86
Na(Mg/kg)	8.00	8.00	16.00	12.54	2.24	-0.14	0.44	-0.63	0.86
Sand (%)	26.39	43.33	69.72	58.84	6.25	-0.66	0.44	0.32	0.86
Silt (%)	18.86	19.96	38.82	27.72	4.55	0.82	0.44	0.35	0.86
Clay (%)	17.86	6.48	24.34	13.30	3.94	0.63	0.44	0.73	0.86

For macro and micronutrient analysis, the highest range is 344 (kg/ha) for Calcium (Ca), and the lowest was 1.19 (kg/ha) for Copper (Cu). The maximum value was 488 kg/ha for Calcium (Ca), and the minimum was 0.01 mg/kg for Iron (Fe), Copper (Cu) and manganese (Mn). All other statistical parameters, like mean, standard deviation, and variance, were maximum for calcium and minimum for copper. It was also found that the highest positive skew data (3.22) was for Manganese (Mn) and the highest negative skew data (0.56) for Magnesium (Mg). The tails of the given distribution contain extreme values by analyzing the kurtosis of the data, which is highest for Manganese (Mn) and lowest for Sodium (Na). Textural analysis suggests that most of the study area's soil can be classified as sandy loam, except for two locations identified as loam.

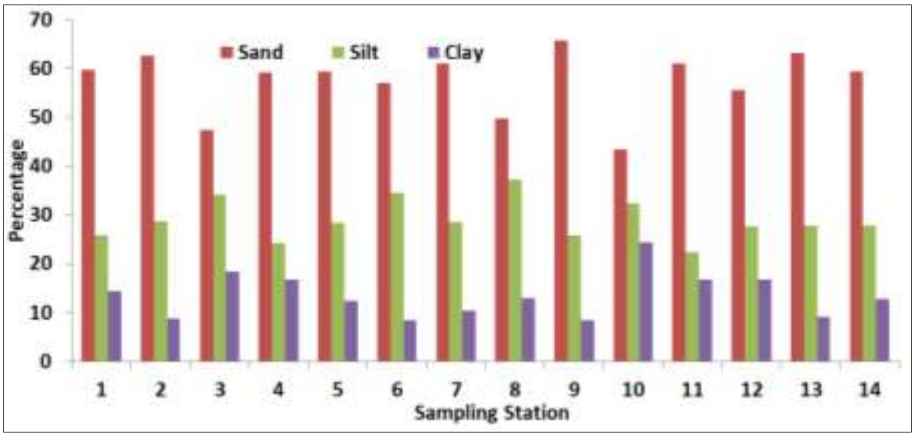


Fig 1: Sand, silt and clay content in surface soils.

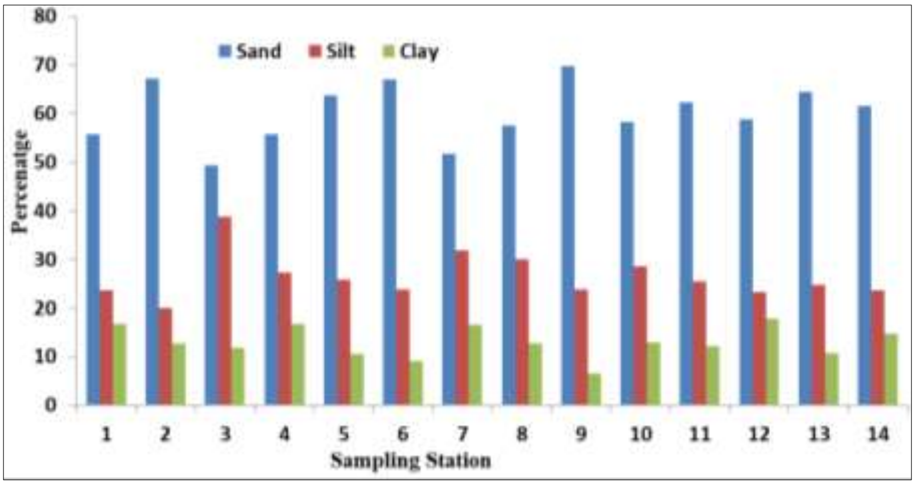


Fig 2: Sand, silt and clay content in sub-surface soils.

PH: The pH values (Tables 2 and 3) for various soil samples, representing both surface and sub-surface layers. These values consistently indicate that the soil in both layers falls within the acidic range, with pH levels ranging from 6.5 to 6.9 and an average pH of 6.7.

Table 2: Physical and chemical properties of sub-surface soils (15-30 cm)

Sample No.	Elevation (m)	Sand (%)	Silt (%)	Clay (%)	Soil texture	pH	EC µS/cm
1	1672	55.684	23.61	16.71	Sandy loam	6.6	280
2	1681	67.33	19.96	12.71	Sandy loam	6.8	230
3	1686	49.33	38.82	11.85	Sandy loam	6.7	270
4	1696	55.762	27.408	16.83	Sandy loam	6.8	280
5	1684	63.72	25.8	10.48	Sandy loam	6.5	260
6	1707	67.036	23.884	9.08	Sandy loam	6.7	260
7	1695	51.72	31.8	16.48	Loam	6.7	280
8	1715	57.6	30.03	12.67	Loam	6.6	280
9	1714	69.72	23.8	6.48	Sandy loam	6.6	270
10	1714	58.33	28.67	13	Sandy loam	6.8	290
11	1715	62.33	25.55	12.12	Sandy loam	6.6	280
12	1705	58.88	23.33	17.79	Sandy loam	6.7	260
13	1708	64.55	24.72	10.722	Sandy loam	6.8	270
14	1700	61.54	23.67	14.78	Sandy loam	6.6	280

Table 3: Micro and macronutrient content in surface soils

Sample No.	N (kg/ha)	P (kg/ha)	K (kg/ha)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	S (mg/kg)	Zn (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Na(mg/kg)
1	220.00	5.05	30.96	0.24	1.48	1.60	21	2.45	208	52	13
2	270.26	11.12	67.56	1.16	0.05	0.01	5.8	2.8	192	50	16
3	235.07	6.08	52.16	0.4	0.91	2.50	36	0.9	400	68	13
4	276.22	9.04	43.32	0.18	0.38	1.70	34	1.65	320	64	12
5	292.78	10.51	37.64	0.56	1.4	0.01	20	1.7	232	56	16
6	260.41	11.12	31.88	1.2	0.04	0.10	95	3.15	144	44	9
7	121.54	8.71	82.96	0.13	0.15	0.40	17	1.6	488	70	16
8	232.41	4.39	106.48	0.21	0.94	0.01	4	5.05	272	58	8
9	204.25	3.27	63.32	0.11	0.2	0.70	12	1.4	470	60	11
10	302.26	3.02	68.60	0.44	0.33	3.30	4	2.15	360	48	13
11	191.48	4.14	48.28	0.12	0.3	1.00	21	5.75	176	25	11
12	252.00	6.95	79.72	0.4	0.28	13.30	17	4.3	192	33.6	13
13	306.72	5.13	48.36	0.28	0.93	2.60	11	3.2	208	67.2	14
14	216.24	2.02	71.96	0.01	0.08	1.30	15	1.9	232	14.4	13

Electrical conductivity (EC): The electrical conductivity of the surface soil ranged from 250 µS/cm to 290 µS/cm, with an average value of 265 S/cm. In contrast, electrical conductivity values ranged from 230µS/cm to 290 µS/cm for the sub-surface soil, with an average of 270µS/cm.

In the current research (Table 1), a soil analysis was conducted within an elevation range of 1672 meters to 1708 meters above Mean Sea Level (MSL). The primary soil texture observed was "Sandy Loam." The pH values ranged from 6.6 to 6.9, indicating a slightly alkaline to neutral pH. The electrical conductivity (EC) values were moderate, falling within the range of 250 to 280 µS/cm, suggesting a moderate level of nutrient availability. The sand content ranged from 43% to 65.72%, while the clay content was relatively low. Notably, one sample was classified as "Loam."

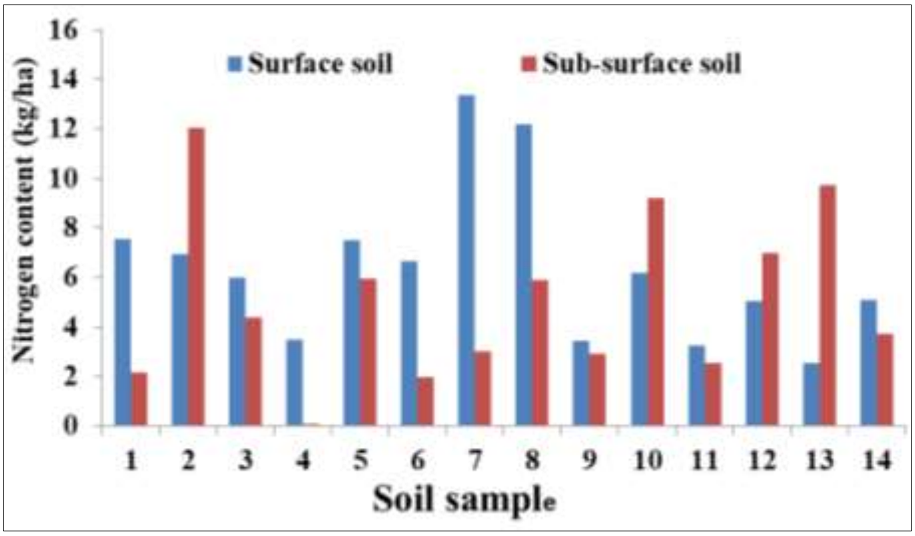
On the other hand, the previous author's analysis (Khedkar *et al*., 2020) [7] covered an elevation range of 1120 meters to 1170 meters above MSL. The predominant soil textures in this analysis were "Clay" and "Sandy Loam." The pH values in this dataset ranged from 6.1 to 6.7, indicating a moderately acidic to slightly acidic pH range. The EC values in authors were lower, ranging from 60 to 160 µS/cm, suggesting a lower level of nutrient availability. In this dataset, the sand content was relatively low, especially in the "Clay" samples, and the clay content was high.

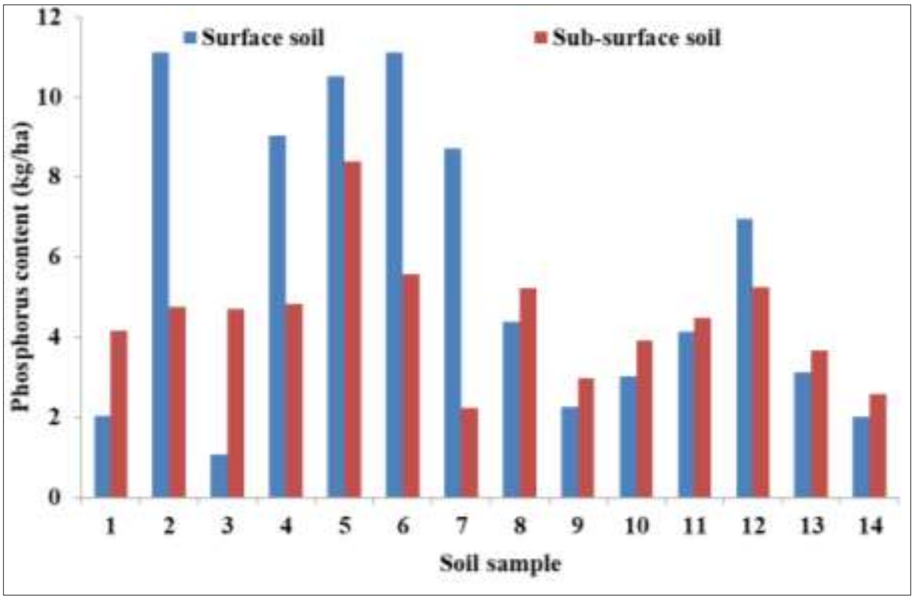
The variations in soil characteristics between the current research and the previous author's analysis are likely influenced by a combination of factors beyond elevation, including regional soil variations, climate, parent material, and land use practices. The consistent presence of "Sandy Loam" in the current research and the variations in the previous analysis highlight the complexity of soil properties and the need for a deeper understanding of effective agriculture and land management in these regions.

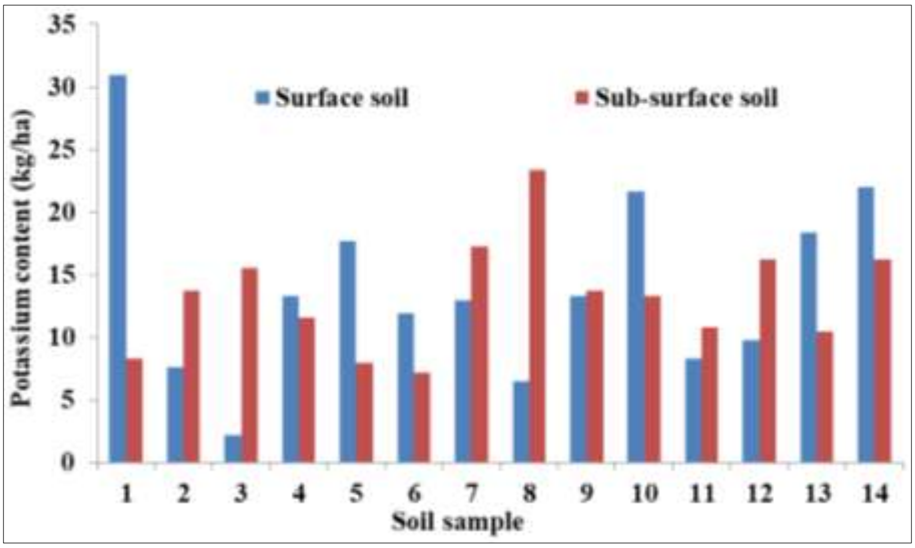
Availability of different macro-nutrients in the soil

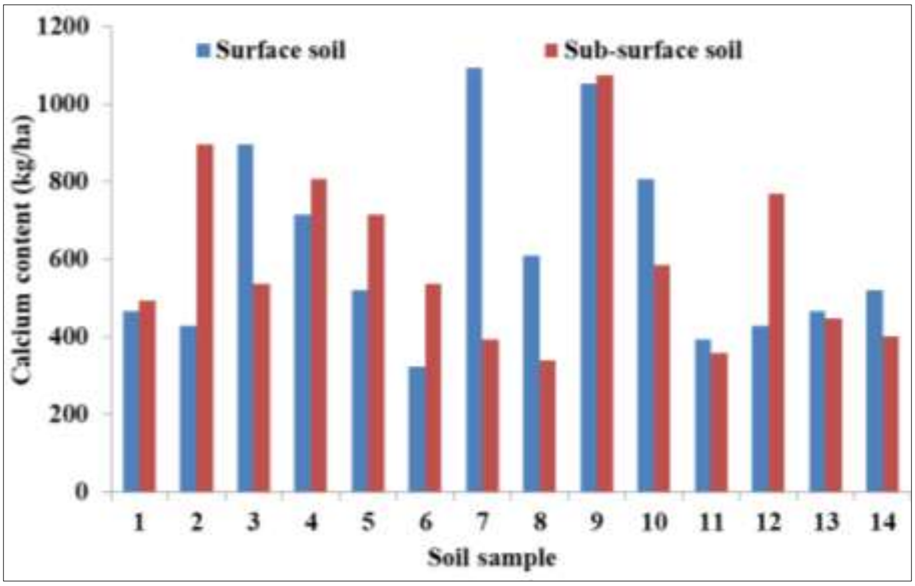
The term "available" denotes the quantity of a nutrient that directly corresponds to the amount absorbed by crops during a single growing season. Consequently, an optimal extracting agent should selectively remove the nutrient from the soil in proportion to the crop's seasonal uptake.

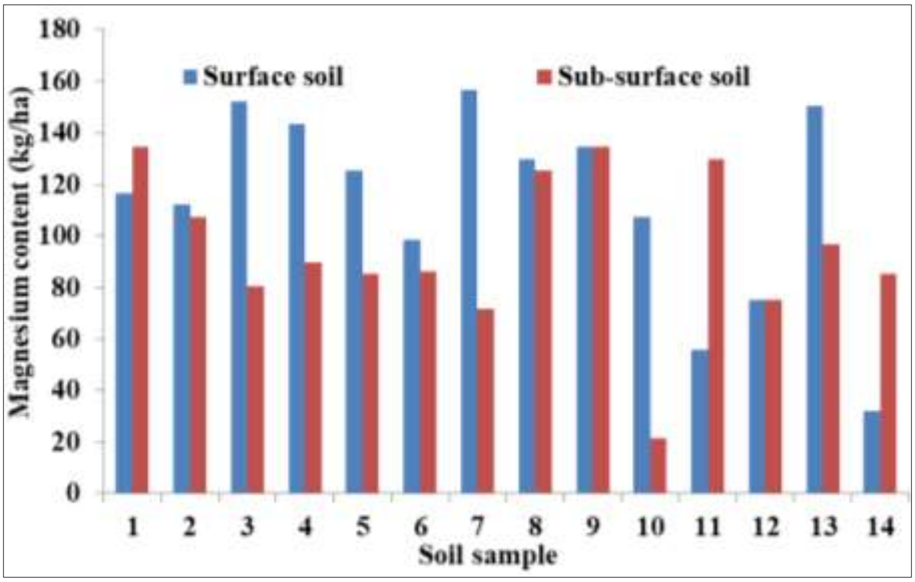
i. Available nitrogen (N): The analysis (Fig 4 and Tables 2 and 3) revealed that the average nitrogen level in the surface soil is 241.55 kg/ha. In contrast, the sub-surface soil exhibited nitrogen, with an average value of 276.25 kg/ha. Under the soil classification, it can be noted that the soils in the study area are categorized as low-nitrogen soils. This classification is substantiated because most of the samples had nitrogen content below 280 kg/ha.




Surface soil
Sub-surface soil
Phosphorus content (kg/ha)
Soil sample
0
2
4
6
8
10
12
1 2 3 4 5 6 7 8 9 10 11 12 13 14


Surface soil
Sub-surface soil
Potassium content (kg/ha)
Soil sample
0
5
10
15
20
25
30
35
1 2 3 4 5 6 7 8 9 10 11 12 13 14


Surface soil
Sub-surface soil
Calcium content (kg/ha)
Soil sample
0
200
400
600
800
1000
1200
1 2 3 4 5 6 7 8 9 10 11 12 13 14



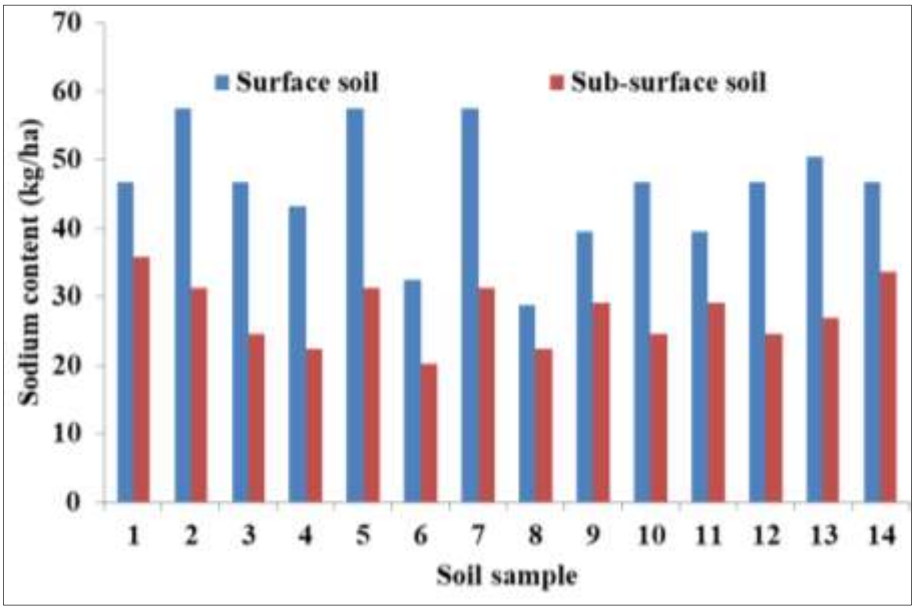


Fig 3: Nitrogen (N), Phosphorus (P), Potassium, Calcium (Ca), Magnisium and Sodium content in surface and sub-surface soils

Available phosphorus (P): The examination revealed that the subsurface soil exhibited a higher concentration of phosphorus, with an average of 10.02kg/ha, in comparison to the surface soil, with an average of 6.47kg/ha (fig 5). Upon assessing the phosphorus content criteria, it was observed that most of the surface soil samples fell into the low category (<10 kg/ha). Conversely, all the subsurface soil samples are enriched in phosphorus content.

iii. Available potassium (K): The average available potassium content in the surface soil is 59.51 kg/ha. Conversely, in the subsurface soil, the available potassium was found with a mean value of 76.90 kg/ha. This data indicates that the subsurface soil contains a higher potassium level than the surface soil (Fig 4). It became evident that the soils in the study area consistently fell into the low category for potassium content.

Calcium contains (Ca): The available average calcium concentration in the surface soils is 278.14 mg/kg, and in subsurface soils, this concentration is 266.71 mg/kg. (Fig 4 and Table 2 &3. Furthermore, the assessment of soil ratings based on calcium content consistently categorized the soil as low in calcium content.

Magnesium (Mg) content: The surface soil contains magnesium on average 50.73mg/kg. Meanwhile, in the subsurface soils, magnesium content is 42.20 mg/kg. (Fig4 and table2&3). The analysis indicated that most soil samples fell within the low magnesium content category.

vi. Sodium (Na) content: The available sodium content in the surface soils is 12.71mg/kg, and subsurface soils contain 12.36kg/ha.

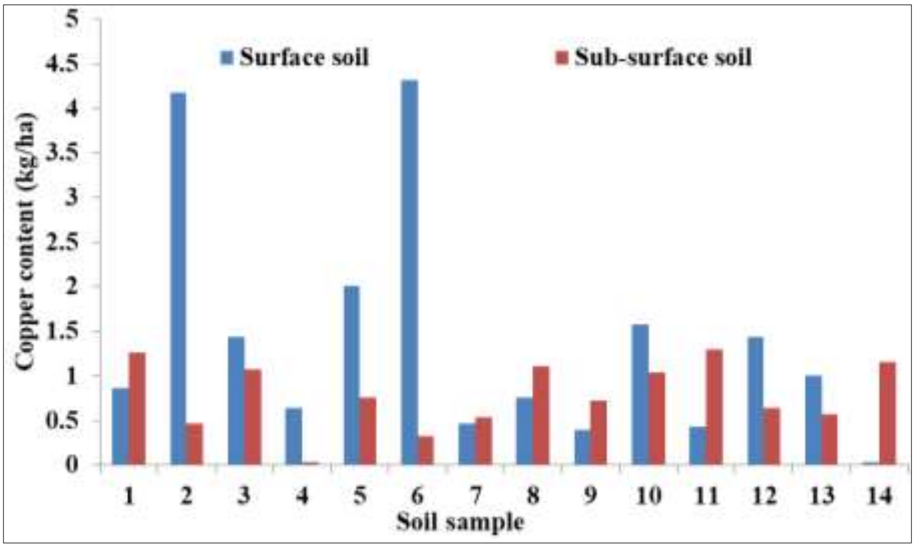
Availability of different micro-nutrients in the soil

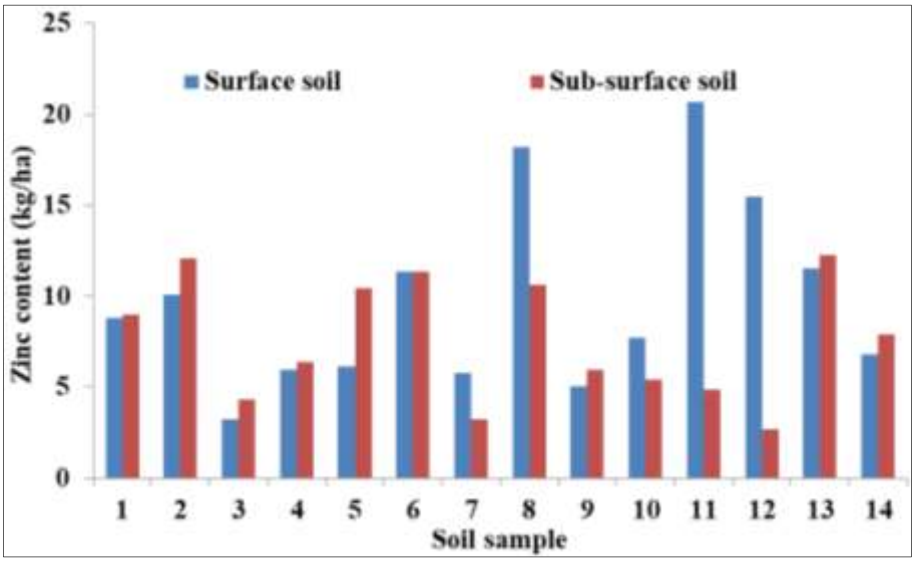
The collective concentration of micronutrients in the study's soils is presented in Tables 2and 3.

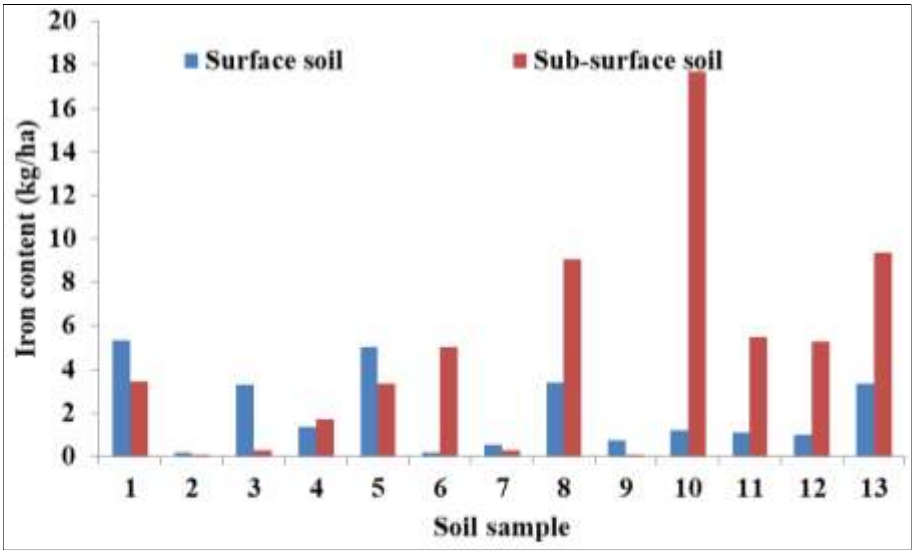
i. Copper (Cu) content: In surface soils, the concentration of available copper is found with an average of 0.39 mg/kg. Conversely, in subsurface soils, the copper content is 0.22 mg/kg (table 2 and 3, Fig. 5).

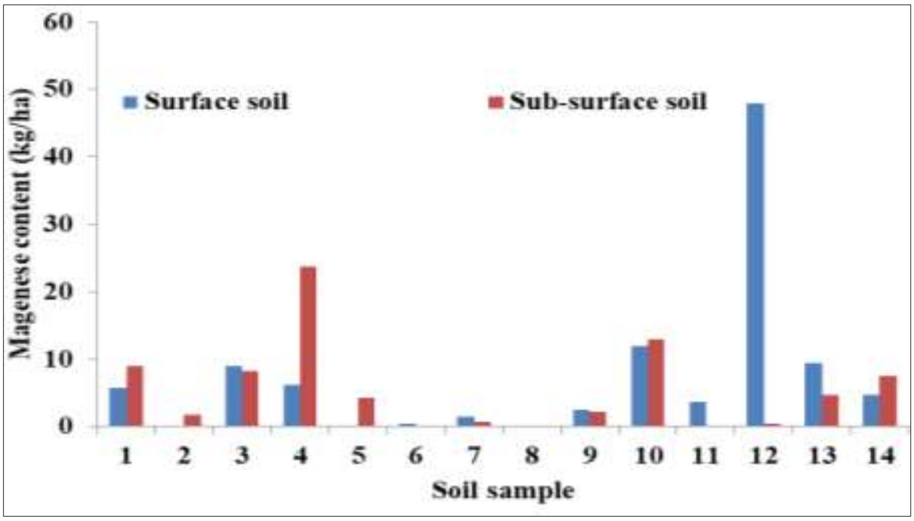
ii. Zinc (Zn) content: The concentration of available zinc in the surface soil, with a mean value of 2.71 mg/kg. Sub-surface soil was found to have a mean value of 2.11 mg/kg, as shown in Fig.5 and Tables2 and 3, respectively. The rating of zinc content in all soil samples was found under the medium category.

iii. Iron (Fe) content: In surface soils, the Iron content is found with a mean value of 0.53 mg/kg. Conversely, subsurface soils exhibited Iron content with a mean value of 1.23 kg/ha.









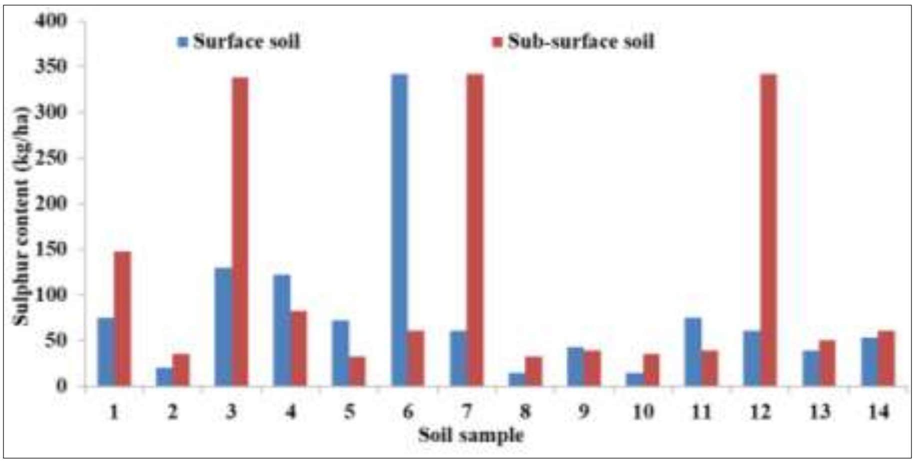


Fig 4: Micronutrient content (Cu, Zn, Fe, Mn and S) in the surface and sub-surface soils

Manganese (Mn) content: The available manganese content in surface soils is 2.04 mg/kg. Conversely, in subsurface soils, the content of manganese is with a mean value of 1.51 mg/kg (Fig.5 and Table 2 &3).

v. Sulfur (S) content: The available sulfur concentration in surface soils with a mean value of 22.34 mg/kg. Conversely, in subsurface soils, it was found with a mean value of 32.57 mg/kg (Fig.5 and Table 2&3).

Pearson correlation coefficient is calculated for different physical constituents and different micro and macronutrients of soil with respect to sampling depth and altitude of sampling station above mean sea level. A significant correlation with level 0.01 was found between sand and silt (-0.751) and sand and clay (-0.702) (Table 4). Whereas for nutrient content, only a positive correlation between Nitrogen (N) and Iron (Fe) is found with the value of 0.441 (Table 5).

Table 4: Pearson correlation coefficient between various parameters

		Sampling Depth (m)	Sampling Station (MSL)	Sand (%)	Silt (%)	Clay (%)	PH	EC (µS/cm)
Sampling Depth (m)	Pearson Correlation	1						
Sampling Station (MSL)	Pearson Correlation	0	1					
Sand (%)	Pearson Correlation	0.173	0.184	1				
Silt (%)	Pearson Correlation	-0.268	-0.185	-.734**	1			
Clay (%)	Pearson Correlation	0	-0.034	-.708**	0.054	1		
PH	Pearson Correlation	-0.064	0.085	0.1	-0.156	0.045	1	
EC(µS/cm)	Pearson Correlation	0.345	-0.031	-0.272	0.084	0.296	-0.095	1

In comparison with previous research (Khedkar *et al.*, 2020) [7], it is evident that the current study portrays more significant variations due to differences in elevation. While some values match with the author's analysis, this indicates that certain nutrients, such as N and Mg, maintain consistency regardless of elevation. The variation in phosphorus (P) levels in current research suggests that the effect of elevation plays a role in P distribution, which isn't apparent in the author's finding, where values remain relatively constant. This variation could be attributed to the geological influence at different elevations. Potassium (K) levels in current research exhibit more pronounced variations with elevation, differing from the previous study, which shows consistent K content. This suggests that elevation induces changes in K distribution.

Table 5: Pearson correlation coefficient between various parameters of soil samples

		Sample Depth (m)	Sample Station (MSL)	P (kg/ ha)	K (kg/ ha)	Cu (kg/ ha)	Fe (kg/ ha)	Mn (kg/ ha)	N (kg/ ha)	S (kg/ ha)	Zn (kg/ ha)	Ca (kg/ ha)	Mg (kg/ ha)	Na (kg/ ha)
Sampling Depth (m)	r	1												
Sampling Station (MSL)	r	0	1											
P(kg/ha)	r	-0.20	-0.33	1.00										
K(kg/ha)	r	-0.06	0.11	-0.23	1.00									
Cu(kg/ha)	r	-0.31	-0.17	0.57	-0.13	1.00								
Fe(kg/ha)	r	0.32	0.07	-0.10	0.09	-0.10	1.00							
Mn(kg/ha)	r	-0.07	0.02	-0.06	-0.08	-0.07	-0.01	1.00						
N(kg/ha)	r	-0.30	-0.02	0.21	0.02	0.11	0.17	-0.22	1.00					
S(kg/ha)	r	0.17	-0.30	0.11	0.05	0.18	-0.16	-0.09	-0.16	1.00				
Zn(kg/ha)	r	-0.25	0.15	0.14	-0.23	0.06	-0.07	0.15	0.19	-0.37	1.00			
Ca(kg/ha)	r	-0.02	-0.19	-0.11	-0.13	-0.36	-0.20	-0.03	0.15	-0.13	-0.37	1.00		
Mg(kg/ha)	r	-0.29	-0.33	0.13	-0.08	0.14	-0.21	-0.21	0.08	-0.16	-0.10	0.35	1.00	
Na(kg/ha)	r	$-.803^{**}$	-0.07	0.25	0.14	0.32	-0.32	0.08	0.25	-0.22	0.01	0.09	0.37	1.00

Comparing current research with previous authors (Khedkar *et al*., 2020) [7] reveals that nutrients vary significantly due to elevation differences in the current study, while authors display variations primarily attributed to geographical differences between regions. Phosphorus (P) and micronutrients (Fe, Zn, and Cu) in the current study also show variations because of elevation, matching some values with the authors' study. These points to the impact of geographical variation in the author's study and elevation-induced variation in the current study on nutrient content. Potassium (K) in the current study also experiences variations based on elevation, not seen in the previous study, which focused on regional differences. This emphasizes the role of elevation in determining K distribution.
In summary, while some nutrient values in the current study match those in a previous study (Barthwal *et al*., 2021) [3] (Khedkar *et al*., 2020) [7], the discussion highlights that elevation has a distinct impact on nutrient distribution, particularly for P, K, and micronutrients. Understanding these variations is critical for tailoring soil management practices to specific elevations and regions.

Conclusions

Soil Texture and pH

The predominant soil texture in the current study is "Sandy Loam," with pH levels ranging from 6.6 to 6.9, indicating slightly alkaline to neutral pH. These findings suggest that the soil in the study area is well-suited for a wide range of crops and agricultural practices.

Nutrient Availability

- Nitrogen (N) levels in the surface and sub-surface soils are relatively low, categorizing the soil as low in nitrogen content.
- Phosphorus (P) levels vary between surface and sub-surface soils, with sub-surface soils being enriched in phosphorus.
- Potassium (K) content is consistently low in both surface and sub-surface soils.
- Calcium (Ca) content falls within the low category for all soil samples, and magnesium (Mg) content is also generally low.
- Sodium (Na) content is present but does not significantly contribute to the nutrient profile of the soil.

Micro-nutrient Availability

- Copper (Cu) content is generally low in both surface and sub-surface soils.
- Zinc (Zn) content is within the medium category, indicating a moderate presence of this essential micronutrient.
- Iron (Fe) content shows variations, with higher values in sub-surface soils.
- Manganese (Mn) content varies and is generally low to medium.
- Sulfur (S) content is moderate, suggesting a moderate level of this micronutrient.

Correlation and Elevation

- Correlation analysis reveals a significant positive correlation between Nitrogen (N) and Iron (Fe).
- Elevation plays a crucial role in influencing nutrient distribution, particularly affecting Phosphorus (P) and Potassium (K) levels.

Comparative Analysis

- Nutrients such as Nitrogen (N) and Magnesium (Mg) appear consistent regardless of elevation.
- Phosphorus (P) and Potassium (K) levels show pronounced variations due to elevation in the current study, which needed to be evident in the previous research focusing on regional differences.
- The presence of "Sandy Loam" as the predominant soil texture in the current study differs from the previous study's soil classification as "Clay" and "Sandy Loam."

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