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Impact of Various Land Uses and Soil Depths on Physicochemical Characteristics of Lateritic Soils of Bankura, West Bengal, India

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ABSTRACT

The study was conducted during 2015–16 (November, 2015-April, 2016) at the Bankura district of West Bengal, India to assess the impact of land uses of Bankura on soil properties by sampling and analyzing soils from diverse representative plots from forests, orchards, pastures, cultivated fields, and uncultivated fallow lands that existed over the last decade. The average bulk density was highest at 1.38 g cm^{-3} in orchard land and lowest at 1.24 g cm^{-3} in pasture land, and increased with depth. The mean particle density varied from 2.53 g cm^{-3} in pasture to 2.69 g cm^{-3} in orchard, and also increased with depth. The total porosity was maximum in orchard (53.97%) and minimum in pasture (45.57%), and varied with depth. Moisture content was greatest in cultivated land (8.98%) and least in pasture (4.23%), whereas mean maximum water holding capacity was greatest in forest land (37.11%) and least in fallow land (29.05%), and both rose with depth. Soil pH was greatest in pasture (6.75) and least in cultivated land (5.61), and electrical conductivity was similarly distributed. Organic carbon content was greatest in forest land (0.41%) and least in cultivated land (0.16%), and decreased with depth. Available nitrogen, phosphorus, and potassium content were greatest in forest land and lowest in cultivated land, and decreased with an increase in soil depth. Pearson's correlation revealed significant correlations between soil properties.

KEYWORDS: Land uses, depth, soil characteristics, correlation, lateritic soil

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1. INTRODUCTION

Agriculture plays a central role in the economies of developing nations like India. For the sake of the growing population, huge tracts of land are rented out for intensive cultivation, which results in overgrazing and forest degradation. This is an unsuitable use of land that has caused indiscriminate environmental degradation, thus creating sustainable agricultural production-related problems. India's increasing population has reduced the availability of arable land and intensified soil erosion, highlighting the crucial role of soil in crop production. Soil is the foundational resource for land use and the cornerstone of sustainable agriculture (Mulugeta, 2004; Smit et al., 2024). Intensive agriculture leads to the depletion of soil fertility, whereas keeping the land fallow for longer period allows organic matter to build up in the soil. Mechanized agriculture has led to soil degradation, which affects productivity. Productivity decreases with repeated cropping after an initial increase in crop production when land in the forest is cultivated. A soil's productivity depends on its physical, chemical, and biological qualities (Castro et al., 2002; Saha et al., 2024). Cultural practices significantly influence soil properties, such as bulk density, porosity, and water retention (Page and Willard, 1946). Continuous cropping on previously forested or grassland soils leads to reduced soil organic matter and structure (Lal and Kimble, 1997), with soil organic matter being a critical indicator of agricultural productivity. It helps bind mineral particles into stable aggregates. Shifts in land use and soil management, particularly the conversion of forests to cropland, drastically affect soil fertility by altering physical, chemical, and biological properties. This conversion reduces organic matter, causes nutrient imbalances, and decreases water retention and essential nutrients (Brown and Lugo, 1990). Litter-fall contributes substantially to the deposition of organic matter into soil in forest ecosystems (Chen et al., 2000; Wei et al., 2020). Soil quality indicator determination in response to different land use and management practices is critical to sustainable land management in agricultural fields (Seikh et al., 2024). It is essential to understand various negative impacts for planning for effective land management and forecasting the implications of forthcoming changes in land use. Soil erosion is promoted due to loss of vegetative cover which creates a great challenge for crop production. Overall, a comprehensive understanding of land use and management impacts on soil properties is necessary to evaluate the sustainability of agricultural systems. In India, widespread soil nutrient depletion is a serious issue caused by land use changes, poor management, topography, and socio-economic factors. These problems result in land degradation and decreased productivity, loss of cultivable land being a problem in the country. Little is known about the effects of various land use systems on soil characteristics in regions like West Bengal's lateritic belt, Bankura district in specific. Research on the physicochemical characteristics of soil under various land uses can help provide needed information to policymakers, scientists, and farmers to enhance the fertility and productivity of the soil. This research holds significant importance, as findings can be applied to track alterations in soil characteristics and overall soil well-being. This study intends to assess the variations in various physical and chemical properties of the soil among various dominant land uses and soil depths of Bankura district of the Red and Lateritic Zone of West Bengal. This study intends to identify the impact of varying land use categories on soil properties, analyze variability by depth, investigate land use category interactions with depth, and establish interrelationships between various soil properties. The present research is capable of enriching the knowledge of soil management and agricultural production in the area.

2. MATERIALS AND METHODS

2.1. *Description of study area*

The study was conducted during 2015–16 (November, 2015-April, 2016) at the undulating Red and Lateritic Zone in West Bengal, particularly in Bankura district, covering 24.8 lakh hectares and an area of 6,788 square kilometers. It shares its borders with Burdwan, Hooghly, Paschim Midnapur, and Purulia and includes three subdivisions alongside 22 community development blocks. The district experiences a sub-humid climate characterized by high drought susceptibility, with an average rainfall of around 1,350 millimeters, mainly from June to September. Temperatures range from 30°C to 45°C in summer, dropping to 7°C to 24°C in winter. Land utilization consists of cultivable land (383,930 ha), forest (148,900 ha), non-agricultural (148,000 ha), pasture (700 ha), cultivable wasteland (2,000 ha), miscellaneous tree crops (2,700 ha), barren land (1,700ha), and uncultivated fallow land (37,500 ha). The landscape consists of undulating hills, with the peak being Susunia Hill (427 m). Significant rivers include the Damodar and Kangsabati. The mainly lateritic soil shows low fertility, exhibiting different productivity levels in various areas, where rice, potatoes, and numerous vegetables are grown, with a cropping intensity of 164%.

2.2. *Soil sampling*

Monitoring variations in soil physical and chemical characteristics requires an initial survey and targeted sampling to address spatial differences. A visual field survey of the study area was carried out in 2015 to evaluate variability. Representative soil sampling locations were chosen according to land use categories, considering those in place for a minimum of ten years. Five representative areas were selected from each land use, comprising Forest Land, Orchard Land, Pasture Land, Cultivated Land, and Uncultivated Fallow Land. Soil samples were gathered from three locations in each field at four depths: 0-20 cm, 20–40 cm, 40–60 cm, and 60–80 cm, utilizing a spade and khurpi. Three samples were collected from each depth, and composite samples were created for analysis. Gathered samples were air-dried, mixed, and sieved using a 2 mm mesh sieve. Moreover, core samples for bulk density were collected using a core sampler at the designated depths.

2.3. Soil analysis

2.3.1. Analysis of soil physical properties

Particle size distribution was assessed using the Bouyoucos hydrometric technique following the removal of organic matter via hydrogen peroxide and dispersion with sodium hexametaphosphate (Gee and Baunder, 1986). Bulk density was evaluated using the undisturbed core sampling technique, with samples dried in an oven at 105°C until they reached a stable weight (Blake and Hartge, 1968). The pycnometer method was employed to measure the particle density of the soil samples, which consisted of weighing oven-dried soil and assessing its volume via water immersion (Black, 1965). The percentage of pore space was determined from bulk density (BD) and particle density (PD) using the formula: Total porosity (%)=(1-BD/PD)×100. The moisture level of soil samples was measured by drying the wet soil at 105°C for 24 hours until a constant weight was achieved. The calculation is as follows:

Moisture content (%)=(Mass of wet soil-Mass of oven-dried soil)/(Mass of oven-dried soil)×100 (Black, 1965).

2.3.2. Analysis of soil chemical properties

Soil pH was analyzed by the glass electrode method in a 1:2.5 soil-water suspension with the aid of a Systronics pH meter (Jackson, 1973). Electrical conductivity was measured in a 1:2.5 soil-water mixture with a conductivity meter (Jackson, 1973). Chromic acid wet digestion method (Walkley and Black, 1934), as prescribed by Jackson (1973), was followed to find the organic carbon content. Available nitrogen content was measured by the alkaline permanganate method (Subbiah and Asija, 1956), which includes the treatment of the soil sample with alkaline $KMnO_4$ followed by distillation. Available phosphorus was analyzed by the Olsen method by taking sodium bicarbonate as the extractant (Olsen et al., 1954) for neutral to alkaline soil and by using Brays No.1 extractant of Bray and Kurtz (1945) method for acidic soil, while P_2O_5 content was analyzed by the spectrophotometric method. Neutral ammonium acetate was utilized to extract available potassium, which was measured by flame photometry (Hanway and Heidal, 1952).

2.3.3. Statistical analysis

Soil physical and chemical characteristics were evaluated through ANOVA using the statistical analysis system (SAS) general linear model (Anonymous, 1990). The LSD test identified notable treatment differences at $p<0.05$. Simple correlation analysis was also conducted to explore the correlation among various potassium forms and soil attributes, in SPSS 20.0.

3. RESULTS AND DISCUSSION

3.1. Impacts of land uses and soil depth on soil physical properties

3.1.1. Impacts on bulk density (BD)

Variance analysis revealed that the bulk density (BD) of soils varied significantly between various land use groups ($p\leq0.01$) and also between various soil depths ($p\leq0.01$) (Table 1 and Table 2). Significant depth-dependent differences were observed in BD values except in orchard and agricultural lands. Moreover, forest and fallow lands demonstrated significant differences in BD across various depths. In pasture land, significant differences existed in BD along depth, except for the 40–60 cm and 60–80 cm depths, where values were comparable. Analysis of variance revealed significant variations in bulk density (BD) values of soil across different land uses at various depths. For surface 0–20 cm, BD values were similar for forest, orchard, and fallow lands, while pasture, cultivated, and fallow lands were also equal. In the 20–40 cm depth, forest and orchard lands showed comparable BD, as did pasture, cultivated, and fallow lands. Significant differences in BD values were observed at depths of 40–60 cm and 60–80 cm among various land uses, except for some equal values. Mean bulk density (BD) values (irrespective of depths) varied among land use types, with pasture land having the highest (1.38 g cm^{-3}) and orchard land the lowest (1.24 g cm^{-3}). BD values for pasture and fallow land were not very different. Orchard soil (1.24 g cm^{-3}) was not very different from forest soil (1.27 g cm^{-3}). Compaction by heavily grazing animals would likely cause high BD in fallow and pasture land. Mean bulk density (BD) values (irrespective of land uses) varied among soil depths, with the highest mean BD at 60–80 cm (1.40 g cm^{-3}) and the lowest at 0–20 cm (1.22 g cm^{-3}). Because of enhanced porosity and lower organic matter content, with an increase in depth, BD increased (Sharma et al., 2016). The results validate the study by Habtamu et al. (2014), which also noted similar patterns in bulk density linked to soil depth. The interaction effects between soil depth and land uses showed the greatest bulk density (1.53 g cm^{-3}) in fallow land at a depth of 60–80 cm and the least bulk density (1.14 g cm^{-3}) in forest land at a depth of 0–20 cm. Most combinations of land use categories and soil depths showed no significant differences ($p\leq0.05$) following the effects of interaction. Forest soils display reduced bulk density due to higher organic matter content and limited disturbance, while agricultural soils have greater density due to lowered organic matter and compaction from farming machinery. Mhawish (2015) observed significant variations in density across different land uses, supporting Habtamu et al. (2014) and Kahsay et al. (2025) who reported that forest soils have a lower bulk density than agricultural lands.

3.1.2. Impacts on particle density (PD)

Analysis of variance indicated significant depth-wise variation in soil bulk density (PD) across various land use types, except for forest and cultivated land (Table 1 and Table 2). Orchard land showed significant differences in PD, except between 40–60 cm and 60–80 cm depths. Pasture land exhibited significant differences at all depths, while fallow land recorded statistically similar PD values at all depths except 0–20 cm. Analysis of variance revealed no significant differences in PD values across land uses at different soil depths, except for 0–20 cm, where forest, orchard, and cultivated lands showed statistically similar PD values as did forest, orchard, and fallow lands (Table 2). The mean particle density (PD) value for orchard land (2.69 g cm^{-3}) was the highest, while pasture land had the lowest (2.53 g cm^{-3}). Apart from pasture land, PD values for forest, orchard, cultivated, and uncultivated fallow lands were statistically similar. The high PD in orchard soil may be attributed to the presence of heavy minerals like Fe and Mn, supporting findings by Habtamu et al. (2014) and Ruehlmann and Korschens (2020). Considering the main effects of soil depths (irrespective of land use types) it was observed that the mean PD value was highest in lower 60-80 cm soil depth (2.78 g cm^{-3}) and lowest in surface 0–20 cm soil depth (2.46 g cm^{-3}). However mean PD values of soil (irrespective of land use types) of 20–40 cm and 40–60 cm depths were statistically at par. In general, it was observed that the PD values were increased with increase in soil depth. This highest PD value of lower 60–80 cm soil depth (irrespective of land use types) may be due to presence of heavy minerals of Fe and Mn in that soil depth which agreed with the findings of Habtamu et al. (2014) and Ruehlmann and Korschens (2020). The interaction effect of land use types with soil depth on soil PD was not statistically significant.

3.1.3. Impacts on total soil porosity

Analyses indicated significant depth-wise variation in total porosity values of forest land soil (p=0.029) (Table 1 and Table 2). Other land uses showed no significant variation. Total porosity values for 0–20 cm and 20–40 cm depths in forest land were statistically similar, as were 20–40 cm and 60–80 cm depths. Analysis of variance revealed significant land use-wise variations in total porosity values of soil at various depths, except 40–60 cm. For the 0–20 cm depth, forest and orchard land showed statistically similar total porosity, as did orchard, cultivated, and fallow land. At 20–40 cm, forest, orchard, cultivated, and fallow land exhibited similar total porosity, while pasture, cultivated, and fallow land showed comparable characteristics as well. At a depth of 60–80 cm, porosity values were statistically comparable for forest, orchard, and cultivated land, and no significant differences were found between forest, pasture, cultivated, and fallow land at this depth. The notable differences in mean total porosity of soil were observed among various land use types, with orchard land showing its highest average value of 53.97% and pasture land showing its lowest average value of 45.57%. The mean total porosity was statistically at par for orchard and forest lands, due to increased organic matter content, which may cause an improvement in soil micropores and overall porosity. A positive correlation exists between total porosity and organic carbon content (r=0.277, $p \leq 0.05$), while a strong negative correlation is found between total porosity and bulk density (r=-0.676, $p \leq 0.01$). These findings align with previous studies by Gebrelibanos and Mohammed (2013); Habtamu et al. (2014) and Ruehlmann and Korschens (2020). Soil depth did not significantly impact mean total porosity values across various soil samples, regardless of land use types. Results also revealed that the total porosity was not significantly affected by the interaction effect of land use types with soil depth.

3.1.4. Impacts on soil moisture content

Analysis of variance indicated significant differences in soil moisture content across various land uses (Table 1 and Table 2). Except for depths 20–40 cm and 40–60 cm, forest land exhibited significant moisture variation. Orchard, cultivated, and fallow lands showed differences at all depths, while pasture land's moisture at 40–60 cm and 60–80 cm was statistically similar. Significant variations were noted in soil moisture content across different land uses at various depths, with notable exceptions. In the 20–40 cm depth, moisture content was varied significantly except in pasture and fallow lands, where its values were statistically at par. An exactly similar pattern was noted in the 40–60 cm depth, again showing significant variation except for pasture and fallow lands, which exhibited statistically equal value of soil moisture contents. Mean moisture content (%) varied by land use type: cultivated land had the highest at 8.98%, while pasture land had the lowest at 4.23%. Fallow and cultivated land moisture content was statistically similar. Higher moisture in cultivated land may be attributed to high clay and low sand content. Soil moisture content was varied with depth, showing its highest value of 7.83% at 60–80 cm and its lowest value of 4.83% at 0–20 cm. Generally, with an increase in soil depth, the soil moisture content increased, which might be due to the higher clay present in the deeper soil layer. The interaction effect of land use types and soil depth showed that cultivated land had the highest soil moisture content (11.71%) at 60–80 cm, while pasture

Table 1: Depth-wise variations in mean soil physical properties of different land-uses and main effects of land uses (irrespective of soil depth) and interaction effects of soil depth and land uses on such properties

Treatment		Soil physical properties							
Land uses	Depth	BD (g cm^{-3})	PD (g cm^{-3})	Porosity (%)	MC (%)	MWHC (%)	Sand (%)	Silt (%)	Clay (%)
Forest land	0–20 cm	1.14^{d}	2.54	55.07^{a}	4.26^{c}	31.45^{b}	75.21	11.67	13.12^{d}
	20–40 cm	1.23^{c}	2.69	54.22^{ab}	4.98^{b}	34.95^{b}	74.17	12	13.83^{c}
	40–60 cm	1.31^{b}	2.63	50.13^{c}	5.43^{b}	39.24^{a}	73.04	12.9	14.07^{b}
	60–80 cm	1.39^{a}	2.83	50.83^{bc}	7.17^{a}	42.78^{a}	69.78	15.08	15.15^{a}
	LSD (0.05)	0.03**	0.22^{NS}	3.52*	0.48**	3.81**	4.67^{NS}	4.77^{NS}	0.22**
Orchard land	0–20 cm	1.16	2.53^{c}	54.16	6.24^{d}	30.24^{b}	67.04^{a}	17.38	15.58^{c}
	20–40 cm	1.21	2.64^{b}	54.18	7.35^{c}	31.67^{b}	65.75^{a}	17.04	17.21^{b}
	40–60 cm	1.28	2.77^{a}	53.8	8.69^{b}	36.95^{a}	64.09^{b}	17.39	18.52^{a}
	60–80 cm	1.3	2.81^{a}	53.75	9.51^{a}	39.56^{a}	61.56^{c}	18.93	19.51^{a}
	LSD (0.05)	0.14^{NS}	0.10**	5.17^{NS}	0.48**	3.55**	1.42**	1.69^{NS}	0.61**
Pasture land	0–20 cm	1.28^{c}	2.31^{c}	44.58	3.15^{c}	31.12^{b}	62.64^{a}	17.62	19.74
	20–40 cm	1.38^{b}	2.56^{b}	46.08	4.07^{b}	34.77^{a}	61.92^{a}	17.3	20.78
	40–60 cm	1.42^{a}	2.62^{ab}	45.79	4.67^{a}	35.24^{a}	61.12^{ab}	17.36	21.52
	60–80 cm	1.43^{a}	2.64^{ab}	45.82	5.01^{a}	36.97^{a}	59.24^{b}	17.03	23.73
	LSD (0.05)	0.03**	0.10**	1.76 NS	0.39**	3.42*	1.95*	5.38 NS	3.52 NS
Cultivated land	0–20 cm	1.29	2.57	49.68	6.85^{d}	32.41	55.02^{a}	19.25	25.72^{c}
	20–40 cm	1.32	2.61	49.3	7.98^{c}	32.78	53.54^{b}	19.31	27.15^{b}
	40–60 cm	1.34	2.68	49.87	9.36^{b}	33.6	52.88^{b}	18.47	28.65^{b}
	60–80 cm	1.37	2.74	49.87	11.71^{a}	34.45	51.36^{c}	17.58	31.06^{a}
	LSD (0.05)	0.14^{NS}	0.23^{NS}	8.57^{NS}	0.20**	3.39^{NS}	1.47**	1.67^{NS}	1.51**
Fallow land	0–20 cm	1.21^{d}	2.37^{b}	48.92	3.64^{d}	17.40^{c}	63.45^{a}	16.03	20.52^{d}
	20–40 cm	1.32^{c}	2.67^{a}	50.54	4.16^{c}	31.55^{b}	60.77^{b}	16.93	22.30^{c}
	40–60 cm	1.37^{b}	2.72^{a}	49.6	4.88^{b}	32.79^{b}	59.04^{c}	16.92	24.04^{b}
	60–80 cm	1.53^{a}	2.89^{a}	47.03	5.74^{a}	34.47^{a}	56.52^{d}	17.63	25.85^{a}
	LSD (0.05)	0.03**	0.24**	3.87^{NS}	0.18**	1.27**	1.30**	1.36^{NS}	0.93**
Mean (Irrespective of depth)	Forest	1.27^{c}	2.67^{a}	52.56^{a}	5.46^{c}	37.11^{a}	73.05^{a}	15.04^{c}	14.04^{e}
	Orchard	1.24^{c}	2.69^{a}	53.97^{a}	7.95^{b}	34.61^{b}	64.61^{b}	17.69^{ab}	17.70^{d}
	Pasture	1.38^{a}	2.53^{b}	45.57^{c}	4.23^{e}	34.53^{b}	61.23^{c}	17.33^{ab}	21.44^{c}
	Cultivated	1.33^{b}	2.65^{a}	49.68^{b}	8.98^{a}	33.31^{b}	53.20^{e}	18.65^{a}	28.15^{a}
	Fallow	1.36^{ab}	2.66^{a}	49.02^{b}	4.60^{d}	29.05^{c}	59.94^{d}	16.88^{b}	23.18^{b}
	LSD (0.05)	0.04**	0.08**	2.24**	0.16**	1.41**	1.10**	1.51**	0.78**
Interaction (Depth×land uses)	LSD (0.05)	0.08**	0.17^{NS}	4.48 NS	0.32**	2.82**	2.20^{NS}	3.02^{NS}	1.57^{NS}

Mean values within the same column for each land use followed by the same letter are not significantly different from each other at $p<0.05$; *: Significant at $p\leq0.05$; **: Significant at $p\leq0.01$; NS: Non-significant

land had the lowest (3.15%) at 0–20 cm. Most treatment combinations differed significantly ($p\leq0.05$) due to these interactions.

3.1.5. *Impacts on maximum water holding capacity of soil*

Analysis of variance indicated significant depth-wise differences in maximum water holding capacity (MWHC) values across various land use types, excluding cultivated land (Table 1 and Table 2). While statistically significant variation existed between orchard and fallow land MWHC, 0–20 cm and 20–40 cm depths were comparable, as were 40–60 cm and 60–80 cm depths. In pasture land, MWHC was statistically similar for all depths except 0–20 cm. Fallow land showed comparable MWHC for 20–40 cm and 40–60

Table 2: Land use-wise variations in mean soil physical properties at different soil depth and main effects of soil depth (irrespective of land uses) and interaction effects of soil depth and land uses on such properties

Treatment		Soil physical properties							
Depth	Land uses	BD ($g\ cm^{-3}$)	PD ($g\ cm^{-3}$)	Porosity (%)	MC (%)	MWHC (%)	Sand (%)	Silt (%)	Clay (%)
0-20 cm	Forest land	1.14^{b}	2.54^{ab}	55.07^{a}	4.26^{c}	31.45^{a}	75.21^{a}	11.67^{b}	13.12^{d}
	Orchard land	1.16^{b}	2.53^{ab}	54.16^{ab}	6.24^{b}	30.24^{a}	67.04^{b}	17.38^{a}	15.58^{c}
	Pasture land	1.28^{a}	2.31^{b}	44.58^{c}	3.15^{e}	31.12^{a}	62.64^{c}	17.62^{a}	19.74^{b}
	Cultivated land	1.29^{a}	2.57^{a}	49.68^{b}	6.85^{a}	32.41^{a}	55.02^{d}	19.25^{a}	25.72^{a}
	Fallow land	1.21^{ab}	2.37^{b}	48.92^{b}	3.64^{d}	17.40^{b}	63.45^{c}	16.03^{a}	20.52^{b}
	LSD (0.05)	0.08^{**}	0.17^{*}	4.92^{**}	0.27^{**}	2.75^{**}	2.37^{**}	3.39^{**}	1.73^{**}
20-40 cm	Forest land	1.23^{b}	2.69	54.22^{a}	4.98^{c}	34.95	74.17^{a}	12.00^{b}	13.83^{d}
	Orchard land	1.21^{b}	2.64	54.18^{a}	7.35^{b}	31.67	65.75^{b}	17.04^{a}	17.21^{c}
	Pasture land	1.38^{a}	2.56	46.08^{b}	4.07^{d}	34.77	61.92^{c}	17.30^{a}	20.78^{b}
	Cultivated land	1.32^{a}	2.61	49.30^{ab}	7.98^{a}	32.78	53.54^{d}	19.31^{a}	27.15^{a}
	Fallow land	1.32^{a}	2.67	50.54^{ab}	4.16^{d}	31.55	60.77^{c}	16.93^{a}	22.30^{b}
	LSD (0.05)	0.08^{**}	0.18^{NS}	4.92^{*}	0.33^{**}	2.99^{NS}	2.41^{**}	3.44^{**}	1.78^{**}
40-60 cm	Forest land	1.31^{bc}	2.63	50.13	5.43^{c}	39.24^{a}	73.04^{a}	12.90^{b}	14.07^{e}
	Orchard land	1.28^{c}	2.77	53.8	8.69^{b}	36.95^{ab}	64.09^{b}	17.39^{a}	18.52^{d}
	Pasture land	1.42^{a}	2.62	45.79	4.67^{d}	35.24^{b}	61.12^{c}	17.36^{a}	21.52^{c}
	Cultivated land	1.34^{ab}	2.68	49.87	9.36^{a}	33.60^{c}	52.88^{d}	18.47^{a}	28.65^{a}
	Fallow land	1.37^{abc}	2.72	49.6	4.88^{d}	32.79^{c}	59.04^{c}	16.92^{a}	24.04^{b}
	LSD (0.05)	0.09^{**}	0.19^{NS}	4.95^{NS}	0.37^{**}	2.23^{**}	2.58^{**}	3.50^{*}	1.89^{**}
60-80 cm	Forest land	1.39^{bc}	2.83	50.83^{ab}	7.17^{c}	42.78^{a}	69.78^{a}	15.08	15.15^{e}
	Orchard land	1.30^{c}	2.81	53.75^{a}	9.51^{b}	39.56^{ab}	61.56^{b}	18.93	19.51^{d}
	Pasture land	1.43^{b}	2.64	45.82^{b}	5.01^{e}	36.97^{b}	59.24^{b}	17.03	23.73^{c}
	Cultivated land	1.37^{bc}	2.74	49.87^{ab}	11.71^{a}	34.45^{b}	51.36^{d}	17.58	31.06^{a}
	Fallow land	1.53^{a}	2.89	47.03^{b}	5.74^{d}	34.47^{b}	56.52^{c}	17.63	25.85^{b}
	LSD (0.05)	0.09^{**}	0.19^{NS}	4.97^{*}	0.44^{**}	3.43^{**}	2.33^{**}	2.95^{NS}	1.48^{**}
Mean (irrespective of land uses)	0-20 cm	1.22^{d}	2.46^{c}	50.48	4.83^{d}	28.52^{d}	64.67^{a}	16.39	18.94^{d}
	20-40 cm	1.29^{c}	2.63^{b}	50.86	5.71^{c}	33.14^{c}	63.23^{b}	16.51	20.25^{c}
	40-60 cm	1.34^{b}	2.68^{b}	49.84	6.61^{b}	35.56^{b}	62.03^{c}	16.61	21.36^{b}
	60-80 cm	1.40^{a}	2.78^{a}	49.46	7.83^{a}	37.56^{a}	59.69^{d}	17.25	23.06^{a}
	LSD (0.05)	0.04^{**}	0.08^{**}	2.00 NS	0.14^{**}	1.26^{**}	0.98^{**}	1.35 NS	0.70^{**}
Interaction (Depth× land uses)	LSD (0.05)	0.08^{**}	0.17^{NS}	4.48^{NS}	0.32^{**}	2.82^{**}	2.20^{NS}	3.02 NS	1.57^{NS}

Mean values within the same column for each land use followed by the same letter are not significantly different from each other at $p<0.05$; *: Significant at $p\leq0.05$; **: Significant at $p\leq0.01$; NS: Non-significant cm depths. Analysis of variance also showed significant land-use-wise variations in MWHC of soil of various depths except 20–40 cm depth (Table 1, Figure 2). When MWHC was compared land use-wise for various soil depth, it was observed that MWHC of the soil of 0–20 cm depth of only fallow land showed significant variation from others. Again, the MWHC of the soil of 40–60 cm depth of forest land and orchard land, orchard land and pasture land and that of cultivated land and fallow land was at par with each other. MWHC of soil at 40–60 cm depth varied significantly in most land use types except forest and orchard land, which were statistically similar. Similarly, cultivated and uncultivated fallow lands also showed comparable results. At 60–80 cm depth, most land use types were statistically similar, with a few exceptions. Notable differences in average MWHC were noted across land uses, with forest land showing its highest value (37.11%) and fallow land showing its lowest value (29.05%). The higher MWHC in forested areas is might be due to increased organic carbon content, as shown by a strong positive correlation (r=0.478, $p\leq0.01$). Besides, compaction in fallow land also reduces soil porosity, which in turn lowers MWHC. The average MWHC rose with increasing soil depth, reaching a maximum of 37.65% in the 60–80 cm range and falling to 28.52% at 0–20 cm. Reduced sand content in deeper layers of soil (60-80 cm) might be responsible for the increased MWHC noted. The combination of land use types and soil depth showed that forest land had the greatest MWHC of soil (42.78%) at 60–80 cm depth, whereas fallow land exhibited the least MWHC (17.40%) at 0–20 cm. The majority of treatment combinations showed statistically comparable MWHC ($p\leq0.01$) because of these interactions.

3.1.6. Impacts on sand content (%) in soil

Variance analysis revealed variations in soil sand content based on depth across different land use types, not including forest land (Table 1 and Table 2). In orchard soil, notable variations were noted, except at depths of 0–20 cm and 20–40 cm. Pasture land exhibited differences at different depths, except for the ranges of 40–60 cm and 60–80 cm, while the top three depths were statistically comparable. Cultivated soil showed significant variations in sand content, excluding the depths of 20–40 cm and 40–60 cm. Uncultivated fallow land showed notable variations in its value along depth. It was also noted that there were significant differences in sand content among land uses at different soil depths. Sand content at 0–20 cm, 20–40 cm, and 40–60 cm of soil depths differed significantly among land uses studied, but pasture and fallow land exhibited no significant variation in sand content. Orchard and pasture land showed a statistically similar amount of sand content at a depth of 60–80 cm. Average sand content differed across land use categories, with forest land exhibiting the highest at 73.05% and cultivated land the lowest at 53.20%. This significant difference aligns with Habtamu et al. (2014), confirming that forest land consistently has greater sand content than other land uses. The mean sand content in soil was highest at 0–20 cm depth (64.67%) and lowest at 60–80 cm depth (59.69%). The sand content typically diminished with greater soil depth, probably because of clay particle leaching and sand building up in the top layer (Jain et al., 2023). The interaction between land use types and soil depth on soil sand content was not statistically significant.

3.1.7. Impacts on silt content (%) in soil

Analysis of variance indicated significant variations in silt content across different land uses at various soil depths, excluding 60–80 cm (Table 1 and Table 2). Only the silt content at 0–20 cm, 20–40 cm, and 40–60 cm in forest land differed significantly from other land uses. Considering the effects of land use types (irrespective of soil depths) it was observed that mean silt content of soil of cultivated land was recorded highest (18.65%) and lowest for forest land (15.04%) respectively. Considering the effects of soil depths (irrespective of land use types) it was observed that there was no significant variation in mean silt content of soil of various depths. The interaction effect of land use types with soil depth on silt content of soil was not statistically significant.

3.1.8. Impacts on clay content (%) in soil

An analysis of variance indicated notable differences in clay content among different land use categories, excluding pasture land (Table 1 and Table 2). Orchard land exhibited considerable differences, except at depths of 40–60 cm and 60–80 cm. Cultivated land showed considerable variation except at depths of 20–40 cm and 40–60 cm, whereas forest and fallow areas demonstrated notable differences. Variance analysis revealed significant variations in soil clay content across different land uses at varying depths. Notably, the clay content at depths of 0–20 cm and 20–40 cm differed across various land use types, with pasture and fallow lands showing comparable values. The highest and lowest mean clay contents in soil were found in cultivated land (28.15%), and in forest land (14.04%), respectively. Habtamu et al. (2014) and Tatek et al. (2025) also noted similar increased level of clay content in agricultural areas compared to other land uses. Significant variation in mean clay content was recorded at different soil depths, ranging from a maximum of 23.06% at the 60–80 cm depth to a minimum of 18.94% at the 0–20 cm depth. Clay content generally increased with soil depth, most likely due to leaching. There was no statistical significance of interaction between soil depth and land use types on the clay content.

3.2. Impacts of land uses and soil depth on soil chemical properties

3.2.1. Impacts on soil pH

The analysis revealed significant differences in soil pH across various land use types at different depths (Table 3 and Table 4). In forest land, only the 60–80 cm depth differed. In orchard, pasture, and fallow land, significant differences were noted at most depths, except for 40–60 cm and 60–80 cm. Cultivated land showed depth-wise differences except for 0–20 cm and 20–40 cm, which were similar. Statistical analysis revealed significant variations in soil pH across different land-use types at various depths. In the 0–20 cm depth, all land uses exhibited significant pH differences, with the exception of fallow and forest lands. For 20–40 cm depth, significant variations were noted, except between orchard and fallow lands. At 40–60 cm, fallow pH was similar to pasture, while forest pH matched cultivated land. At 60–80 cm, all types were similar except cultivated land. Considering the main effects of land use types (irrespective of soil depths) it was observed that the mean pH for pasture land was recorded highest (6.75) and the lowest for cultivated land (5.61), respectively (Table 2). Thus, land use changes from forest to crop land resulted in a reduction of soil pH in the study area. Such lowest value of pH value under the cultivated land may be either due to the depletion of basic cations in crop harvest and drainage to streams in runoff generated from accelerated erosion or due to its highest microbial oxidation that produces organic acids, which provide H+ ions to the soil solution and thereby lowers the soil pH. Generally, the pH values observed in the study area are within the ranges of moderately acidic to acidic in reaction. Habtamu et al. (2014) also reported highest (5.0) pH value in the subsurface layer of grazing land and lowest (4.45) in the surface layer of cultivated land. Mhawish (2015) while studying effects of land use/cover changes on soil properties in Ajloun area, Jordan showed an overall significant effect of land-use/cover on soil pH values and reported that conversion of natural forest into other land-use/cover has resulted in a decreased soil pH value. Soil pH values varied with depth; the highest mean pH (6.70) was found in the 60–80 cm depth, while the lowest (5.77) was at 0–20 cm. Generally, pH increased with soil depth due to the accumulation of basic cations (Ca and Mg) in deeper layers and their uptake by plants in the surface soil (Jain et al., 2023). This trend aligns with Mhawish (2015), who reported a significant increase in pH with depth in the Ajloun area, Jordan (p=0.018). The interaction of land use types with soil depth revealed that the highest soil pH (7.04) occurred at 60–80 cm depth in fallow land, while the lowest (5.07) was at 0–20 cm in cultivated land. Most treatment combinations were statistically similar ($p \leq 0.01$) due to interaction effects.

3.2.2. Impacts on electrical conductivity (EC) of soil

Statistical analysis indicated notable depth-wise variation in soil EC values across different land uses (Table 3 and Table 4). Forest, orchard, pasture, and cultivated lands displayed significant EC variability, though values at 20–40 cm and 40–60 cm depths were statistically similar. In fallow land, significant EC differences existed along depth, except at 0–20 cm and 20–40 cm, where values were comparable. Marked differences in electrical conductivity (EC) readings of soil were observed across varying land uses and depths. For soil depths of 0–20 cm, EC differed notably across land uses, except in forest, orchard, and pasture areas, which exhibited comparable values. At depths of 20–40 cm, significant variations were noted, but fallow, orchard, and forest lands had comparable EC values. For 40–60 cm depths, forest and pasture lands had statistically similar EC values, while other land uses differed significantly. Finally, at 60–80 cm depth, significant variations were found among land uses, except for forest and orchard lands as well as pasture and fallow lands, which were statistically at par. Substantial differences in mean values of electrical conductivity (EC) between different land uses of soil were observed, with the highest of 0.57 dS m^{-1} for pasture land and the lowest of 0.40 dS m^{-1} for cultivated land. Forest land EC was comparable to orchard land. The higher level of EC in pasture land might be due to high levels of exchangeable Na, while the low value of EC in agricultural land is related to the removal of basic cations due to high cropping intensity. Mhawish (2015) discovered that pasture land exhibited greater EC than farmland, potentially affected by rainfall and salt leaching in Ajloun, Jordan. The research revealed considerable differences in average EC values across various soil depths, with the peak value found at the 60–80 cm depth (0.67dS m^{-1}) and the minimum at the 0–20 cm depth (0.35dS m^{-1}). Average EC values increased with the depth of the soil overall, most likely due to soluble salts being accumulated through leaching. The highest electrical conductivity (EC) value of 0.63dS m^{-1} was found at the 60–80 cm depth in fallow land, while the lowest value of 0.25dS m^{-1} was seen at the 20–40 cm depth in cultivated land. Most of the treatment combinations did not have any significant differences ($p \leq 0.01$) due to interaction effects between soil depth and land use.

3.2.3. Impacts on oxidizable organic carbon (OC) content in soil

Analysis indicated profound depth-wise differences in organic carbon (OC) content between land use types (Table 3 and Table 4). Variance analysis showed significant land-use-wise differences in OC content values at different soil depths. For the 0–20 cm depth, OC content had significant differences among land use types, with the exception of forest and orchard lands, which had similar values, and pasture land followed the trend of fallow land. OC content varied significantly at the 20–40 cm depth among all land use types except for pasture and uncultivated fallow lands. At 40–60 cm depth, differences were significant among land use types except for pasture and fallow lands. At 60–80 cm

Table 3: Depth-wise variations in soil chemical properties of different land-uses and main effects of land uses (irrespective of soil depth) and interaction effects of soil depth and land uses on such properties

Treatment		Soil physical properties					
Land uses	Depth	pH	EC	OC (%)	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
Forest land	0-20 cm	5.49^b	0.36^c	0.53^a	158.43^d	24.65^c	234.92
	20-40 cm	5.66^b	0.51^b	0.46^b	178.80^c	32.53^b	232.5
	40-60 cm	5.70^b	0.54^b	0.38^c	199.48^b	42.14^a	206.19
	60-80 cm	6.62^a	0.65^a	0.25^d	252.82^a	44.07^a	198.4
	LSD (0.05)	0.35**	0.05**	0.05**	10.89**	5.92**	31.85 NS
Orchard land	0–20 cm	6.04^c	0.34^c	0.48^a	158.43^d	26.32^c	211.33^a
	20-40 cm	6.34^b	0.46^b	0.27^b	178.80^c	28.72^{bc}	197.39^b
	40–60 cm	6.46^a	0.48^b	0.10^c	199.48^b	38.07^a	193.96^b
	60–80 cm	6.60^a	0.65^a	0.02^d	252.82^a	39.55^a	181.51^c
	LSD (0.05)	0.16**	0.05**	0.06**	4.56**	2.12**	3.64**
Pasture land	0–20 cm	6.59^c	0.42^c	0.29^a	106.30^d	18.37^d	196.63^a
	20–40 cm	6.70^b	0.55^b	0.22^b	131.63^c	27.59^c	170.39^c
	40–60 cm	6.78^a	0.57^b	0.16^c	138.38^b	31.01^{bc}	186.59^b
	60–80 cm	6.94^a	0.72^a	0.08^d	174.91^a	38.20^a	173.10^c
	LSD (0.05)	0.16**	0.05**	0.03**	6.69**	2.70**	9.81**
Cultivated land	0–20 cm	5.07^c	0.26^c	0.22^a	92.04^c	9.92^d	188.36^a
	20–40 cm	5.32^c	0.37^b	0.17^b	87.31^d	16.11^c	157.26^b
	40–60 cm	5.76^b	0.39^b	0.13^c	102.30^b	30.03^b	156.89^b
	60–80 cm	6.29^a	0.58^a	0.11^d	135.77^a	39.32^a	163.18^b
	LSD (0.05)	0.43**	0.08**	0.03**	2.41**	2.45**	13.55**
Fallow land	0–20 cm	5.67^c	0.37^c	0.30^a	93.16^d	25.61^d	196.18^a
	20–40 cm	6.43^b	0.42^c	0.23^b	106.06^c	28.26^c	190.02^b
	40–60 cm	6.65^a	0.65^b	0.17^c	117.03^b	31.84^b	167.23^c
	60–80 cm	7.04^a	0.74^a	0.11^d	179.33^a	36.51^a	166.38^c
	LSD (0.05)	0.45**	0.05**	0.03**	4.21**	2.10**	5.93**
Mean (Irrespective of depth)	Forest	5.87^c	0.51^c	0.41^a	197.38^a	35.85^a	218.00^a
	Orchard	6.36^b	0.49^c	0.22^b	172.46^b	33.16^b	196.05^b
	Pasture	6.75^a	0.57^a	0.19^c	137.81^c	28.79^d	181.68^c
	Cultivated	5.61^d	0.40^d	0.16^d	104.36^e	23.85^e	166.42^d
	Fallow	6.45^b	0.54^b	0.20^b	123.90^d	30.55^c	179.95^c
	LSD (0.05)	0.15**	0.02**	0.02**	2.82**	1.48**	7.18**
Interaction (Depth×land uses)	LSD (0.05)	0.30**	0.05**	0.04**	5.65**	2.96**	14.36**

Mean values within the same column for each land use followed by the same letter are not significantly different from each other at p<0.05; *: Significant at p≤0.05; **: Significant at p≤0.01; NS: Non-significant

depth, differences were significant in OC content except for pasture, cultivated, and fallow lands. Land use type variation of OC content revealed that forest land contained the maximum mean value of OC as 0.41%, followed by the minimum value of OC as 0.16% in cultivated land. Forest soil possessed more organic carbon compared to cultivated land. Addition of plant residues and less disturbance of soil help to increase the organic matter of forest soils, but farming leads to the reduction of organic matter because of human interference like a decrease in biomass and cattle grazing. This shows that restoration of plant cover improves soil nutrients, corroborating evidence by Gebrelibanos and Mohammed (2013) and Mhawish (2015). There was considerable variation in mean organic carbon (OC) content among land uses, with a maximum OC of 0.36% at 0–20 cm and a minimum of 0.12% at 60–80 cm. Greater root densities and bioactivity could be responsible for increased surface soil OC (Li et al., 2023). The interaction of land use types and soil depth revealed that forest land had the highest organic carbon (OC) content (0.53%) at 0–20 cm, while orchard land had the lowest (0.02%) at 60–80 cm. Most treatment combinations showed no significant differences ($p \leq 0.01$) due to these interactions. With an increase in soil depth, organic carbon decreases (Sharma et al., 2016).

3.2.4. Impacts on available N content in soil

Findings revealed notable differences in the availability of N content at varying depths among different types of land use (Table 3 and Table 4). Moreover, substantial differences in land-use regarding available N content were noted at different depths. The 0–20 cm depth exhibited significant variations between forest land, orchard land, and pasture land, whereas cultivated and fallow lands were statistically alike. Significant differences were also noted among various land use types at depths of 20–40 cm and 40–60 cm. At depths of 60–80 cm, significant variation was noted, apart from pasture and fallow areas, which demonstrated statistical similarity. The nitrogen (N) content was highest in forest land (197.38 kg ha^{-1}) and lowest in agricultural land (104.36 kg ha^{-1}). The absence of farming in forests probably led to increased N levels, whereas the reduced N in agricultural areas might be due to high nitrogen absorption by plants. Consistent with this, Selassie et al. (2015) identified the maximum nitrogen level (0.23%) in natural forest soil and the minimum (0.12%) in agricultural areas of the Zikre watershed, corroborating results from Yihenew and Getachew (2013). The study showed that typical nitrogen (N) concentrations vary with soil depth, peaking at 190.98 kg ha^{-1} at a depth of 60–80 cm and dropping to 119.82 kg ha^{-1} in the upper 0–20 cm layer. Generally, nitrogen levels increase with soil depth, likely due to plant roots at the top taking in more nitrogen. However, Nakayama et al. (2024) reported that stocks of both soil organic carbon and total nitrogen decreased significantly with depth. Habtamu et al. (2014) observed significant interaction effects between soil depth and land use on nitrogen content in the Wujiraba watershed, showing that the highest (0.28%) and lowest (0.12%) N content in forest and cultivated land respectively, that was linked to variations in organic matter content. The relationship among various land use categories and soil depth showed that forest land possessed the greatest available N content (252.82 kg ha^{-1}) at 60–80 cm, whereas cultivated land exhibited the lowest (87.31 kg ha^{-1}) at 20–40 cm. Most treatment combinations showed significant differences ($p \leq 0.01$) due to these interactions.

3.2.5. Impacts on available P_2O_5 content in soil

Results indicated that the available P_2O_5 (kg ha^{-1}) levels were significantly affected by the different types of land use ($p \leq 0.01$) and soil depth ($p \leq 0.01$) (Table 3 and Table 4). Significant differences in P_2O_5 concentrations were noted at varying soil depths across different land uses, except for the 40–60 cm and 60–80 cm layers, where marked distinctions were observed between forest land and orchard land. In orchard land, 0–20 cm and 20–40 cm depths presented similar P_2O_5 levels. Notable variations were also found in pasture land across depths, except for 20–40 cm and 40–60 cm. Analysis of variance revealed significant differences in available P_2O_5 content across land uses at various soil depths. In the 0–20 cm depth, all land use types, excluding pasture and cultivated land, showed similar P_2O_5 contents. For the 20–40 cm depth, only forest and cultivated land differed significantly. At 40–60 cm depth, available P_2O_5 content varied significantly only between forest and orchard land. No major differences were observed for the 60–80cm depth, except for variations related to forest land. The average P_2O_5 content for forest land was 35.85 kg ha^{-1}, the highest, whereas cultivated land recorded the lowest at 23.85 kg ha^{-1}. The elevated P_2O_5 levels in forest soil are probably due to greater soil organic C, which facilitates organic phosphorus release, or from a significant inherent P in the parent material (Chen et al., 2000). This is consistent with Mhawish (2015), who noted comparable phosphorus levels in both cultivated and forest soils in Ajloun, Jordan. The average available P_2O_5 concentration was greatest at 60–80 cm soil depth (39.53 kg ha^{-1}) and lowest at 0–20 cm depth (20.97 kg ha^{-1}), suggesting that available P_2O_5 rises with increasing soil depth. This pattern corresponds with the research findings of Habtamu et al. (2014) and Mhawish (2015), who also reported a higher level of phosphorus in subsurface soils than that of surface soils in the Ajloun region of Jordan. The interaction between land use types and soil depth indicated that the maximum available P_2O_5 content (44.07 kg ha^{-1}) was found at the 60–80 cm depth in forest land, whereas the minimum (9.92 kg ha^{-1}) was at the 0–20 cm depth in cultivated land. The majority of treatment combinations indicated no meaningful differences ($p \leq 0.05$) apart from a few instances. Habtamu et al. (2014) observed comparable significant effects on the available P content within the Wujiraba watershed stemming from interactions between land use and soil depth.

3.2.6. Impacts on available K_2O content in soil

Results indicated that available K_2O content (kg ha^{-1}) in the studied soils varied significantly across different land use types (p≤0.01) and soil depths (p≤0.01) (Table 3 and Table 4). Significant depth-wise variation was noted in available K_2O among various land uses, excluding forest land. In orchard soil, the K_2O levels at depths of 0–20 cm and 60–80 cm were significantly different, whereas the 20–40 cm and 40-60 cm depths showed no difference. In pasture land, depths of 20–40 cm and 60–80 cm were found to be statistically comparable. In cultivated soil, only the 0–20 cm layer showed a significant difference. Analysis of variance indicated significant variations in available K_2O

Table 4: Land use-wise variations in soil chemical properties at different soil depth and main effects of soil depth (irrespective of land uses) and interaction effects of soil depth and land uses on such properties

Treatment		Soil physical properties					
Depth	Land uses	pH	EC	OC (%)	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
0-20 cm	Forest land	5.49^{c}	0.36^{b}	0.53^{a}	158.43^{a}	24.65^{a}	234.92^{a}
	Orchard land	6.04^{b}	0.34^{b}	0.48^{a}	149.16^{b}	26.32^{a}	211.33^{b}
	Pasture land	6.59^{a}	0.42^{a}	0.29^{b}	106.30^{c}	18.37^{b}	196.63^{bc}
	Cultivated land	5.07^{d}	0.26^{c}	0.22^{c}	92.04^{d}	9.92^{c}	188.36^{c}
	Fallow land	5.67^{c}	0.37^{b}	0.30^{b}	93.16^{d}	25.61^{a}	196.18^{bc}
	LSD (0.05)	0.26**	0.03**	0.06**	4.73**	2.47**	16.91**
20-40 cm	Forest land	5.66^{c}	0.51^{ab}	0.38^{a}	178.80^{a}	32.53^{a}	232.50^{a}
	Orchard land	6.34^{b}	0.46^{b}	0.10^{d}	154.97^{b}	28.72^{b}	197.39^{b}
	Pasture land	6.70^{a}	0.55^{a}	0.16^{b}	131.63^{c}	27.59^{b}	170.39^{c}
	Cultivated land	5.32^{d}	0.37^{c}	0.13^{c}	87.31^{e}	16.11^{c}	157.26^{c}
	Fallow land	6.43^{b}	0.42^{bc}	0.17^{b}	106.06^{d}	28.26^{b}	190.02^{b}
	LSD (0.05)	0.24**	0.07**	0.03**	7.38**	2.76**	16.09**
40-60 cm	Forest land	5.70^{c}	0.54^{b}	0.38^{a}	199.48^{a}	42.14^{a}	206.19^{a}
	Orchard land	6.46^{b}	0.48^{c}	0.10^{d}	173.65^{b}	38.07^{b}	193.96^{b}
	Pasture land	6.78^{a}	0.57^{b}	0.16^{b}	138.38^{c}	31.01^{c}	186.59^{b}
	Cultivated land	5.76^{c}	0.39^{d}	0.13^{c}	102.30^{e}	30.03^{c}	156.89^{c}
	Fallow land	6.65^{a}	0.65^{a}	0.17^{b}	117.03^{d}	31.84^{c}	167.23^{c}
	LSD (0.05)	0.22**	0.04**	0.02**	6.38**	3.44**	14.81**
60-80 cm	Forest land	6.62^{a}	0.65^{b}	0.25^{a}	252.82^{a}	44.07^{a}	198.40^{a}
	Orchard land	6.60^{a}	0.65^{b}	0.02^{c}	212.08^{b}	39.55^{b}	181.51^{b}
	Pasture land	6.94^{a}	0.72^{a}	0.08^{b}	174.91^{c}	38.20^{b}	173.10^{bc}
	Cultivated land	6.29^{b}	0.58^{c}	0.11^{b}	135.77^{d}	39.32^{b}	163.18^{cb}
	Fallow land	7.04^{a}	0.74^{a}	0.11^{b}	179.33^{c}	36.51^{b}	166.38^{bc}
	LSD (0.05)	0.50**	0.06**	0.03**	6.12**	4.14*	15.44**
Mean (Irrespective of land uses)	0-20 cm	5.77^{d}	0.35^{d}	0.36^{a}	119.82^{d}	20.97^{d}	205.48^{a}
	20-40 cm	6.09^{c}	0.46^{c}	0.27^{b}	131.76^{c}	26.64^{c}	189.51^{b}
	40-60 cm	6.27^{b}	0.53^{b}	0.19^{c}	146.17^{b}	34.62^{b}	165.25^{d}
	60-80 cm	6.70^{a}	0.67^{a}	0.12^{d}	190.98^{a}	39.53^{a}	176.52^{c}
	LSD (0.05)	0.13**	0.02**	0.02**	2.53**	1.33**	6.42**
Interaction (Depth× land uses)	LSD (0.05)	0.30**	0.05**	0.04**	5.65**	2.96**	14.36**

Mean values within the same column for each land use followed by the same letter are not significantly different from each other at p<0.05; *: Significant at p≤0.05; **: Significant at p≤0.01; NS: Non-significant content across different land uses at various soil depths. In the 0–20 cm depth, orchard, pasture, and fallow land showed no significant variation, with equal content among pasture, cultivated, and fallow lands. Soil content at 20–40 cm depth in pasture and cultivated land was equivalent; orchard and fallow land were also similar. At 40–60 cm depth, forest, orchard, pasture, and cultivated lands showed comparable content. However, K_2O levels at 60–80 cm depth were notably different in forest land compared to others. It was noted that the average K_2O content was highest in forest land (218.00 kg ha^{-1}) and lowest in cultivated land (166.42 kg ha^{-1}). The K_2O content of pasture land was statistically at par with fallow land. Lower levels of K_2O in agricultural land might be due to lower level of soil organic matter. Greater levels of exchangeable K in forest soils are likely a result of potassium-rich minerals like micas and feldspars. Han et al. (2021) linked potassium levels to soil mineralogy, particularly Fe and Al oxides, influenced by fertilization practices in Chinese paddy soils. These findings align with previous research conducted by Habtamu et al. (2014), which indicated lower K levels in agricultural and pasture regions. The higher amount of exchangeable K in forest soils might be due to the presence of potassium-rich minerals like feldspars and micas. The content of K_2O was highest in the topsoil (0–20 cm) with 205.48 kg ha^{-1} and lowest at a depth of 40–60 cm with 165.25 kg ha^{-1}. Availability of K_2O decreased with increasing depth of soil, consistent with findings by Habtamu et al. (2014) in the Wujiraba watershed. Based on the interaction effect of land uses and depth, the highest K_2O content (234.92 kg ha^{-1}) was recorded at 0–20 cm depth for forest land, while the lowest (156.89 kg ha^{-1}) was recorded at 40–60 cm depth for cultivated land. Most of the treatment combinations for land use and depth showed no significant differences ($p \leq 0.01$) in their interaction effects, consistent with Habtamu et al. (2014).

3.3. Pearson correlation coefficient of among various soil physicochemical properties

The study utilizing Pearson's correlation coefficient revealed significant relationships between various soil properties across different land use types (Table 5). The bulk density (BD) exhibited a strong negative correlation with organic carbon (OC) (r=-0.640, $p \leq 0.01$), available potassium (K) (r=-0.657, $p \leq 0.01$), porosity (r=-0.676, $p \leq 0.01$), and sand content (r=-0.518, $p \leq 0.01$). Simultaneously, BD demonstrated positive significant correlations with pH (r=0.520, $p \leq 0.01$), electrical conductivity (EC) (r=0.569, $p \leq 0.01$), available phosphorus (P) (r=0.293, $p \leq 0.05$), particle density (PD) (r=0.353, $p \leq 0.01$), maximum water holding capacity (MWHC) (r=0.466, $p \leq 0.01$), silt (r=0.346,

Table 5: Pearson's correlation matrix for the linear relationship between various soil physical and chemical properties

	pH	EC	OC	Av. N	Av. P_2O_5	Av. K_2O	BD	PD	Porosity	MC	MWHC	Sand	Silt	Clay
pH	1													
EC	0.744**	1												
OC	-0.477**	-0.465**	1											
Av. N	0.367**	0.595**	0.021	1										
Av. P_2O_5	0.526**	0.740**	-0.256*	0.779**	1									
Av. K_2O	-0.285*	-0.264*	0.767**	0.318*	0.015	1								
BD	0.520**	0.569**	-0.640**	0.101	0.293*	-0.657**	1							
PD	0.321*	0.513**	-0.429**	0.501**	0.616**	-0.124	0.353**	1						
Porosity	-0.282*	-0.202	0.277*	0.259*	0.147	0.492**	-0.676**	0.402**	1					
MC	-0.088	0.081	-0.500**	0.166	0.283*	-0.395**	0.107	0.458**	0.287*	1				
MWHC	0.317*	0.478**	-0.268*	0.680**	0.536**	-0.109	0.466**	0.520**	-0.048	0.346**	1			
Sand	-0.119	-0.055	-0.753**	-0.542**	-0.231	-0.857**	-0.518**	-0.119	-0.386**	-0.438**	0.120	1		
Silt	0.202	0.012	-0.636**	-0.359**	-0.256*	-0.614**	0.346**	0.023	-0.241	0.338**	-0.108	-0.770**	1	
Clay	0.057	0.067	0.683**	0.543**	0.178	0.834**	0.517**	0.146	0.394**	0.412**	-0.104	-0.946**	0.520**	1

**: Correlation is significant at the 0.01 level (2-tailed); *: Correlation is significant at the 0.05 level (2-tailed)

$p \leq 0.01$), and clay (r=0.517, $p \leq 0.01$). The particle density (PD) showed a negative correlation with OC (r=-0.501, $p \leq 0.01$). In contrast, it was positively correlated with pH (r=0.321, $p \leq 0.05$), EC (r=0.513, $p \leq 0.01$), available nitrogen (N) (r=0.501, $p \leq 0.01$), and available P (r=0.616, $p \leq 0.01$), indicating how these elements in the soil interact. Total porosity was negatively correlated with OC (r=-0.282, $p \leq 0.05$), BD (r=-0.676, $p \leq 0.01$), and sand content (r=-0.386, $p \leq 0.01$). However, it showed positive correlations with OC (r=0.277, $p \leq 0.05$), available K (r=0.492, $p \leq 0.01$), PD (r=0.402, p≤0.01), moisture content (r=0.287, $p \leq 0.05$), and clay (r=0.394, $p \leq 0.01$). Moisture content presented a negative correlation with OC (r=-0.500, $p \leq 0.01$), available K (r=-0.395, $p \leq 0.01$), and sand content (r=-0.438, $p \leq 0.01$), while also showing positive associations with available P (r=0.283, $p \leq 0.05$), PD (r=0.458, $p \leq 0.01$), porosity (r=0.287, $p \leq 0.05$), MWHC (r=0.346, $p \leq 0.01$), silt (r=0.338, $p \leq 0.01$), and clay (r=0.412, $p \leq 0.01$). MWHC was negatively correlated with OC (r=-0.268, $p \leq 0.05$) but positively correlated with pH (r=0.317, $p \leq 0.05$), EC (r=0.478, $p \leq 0.01$), available N (r=0.680, $p \leq 0.01$), available P (r=0.536, $p \leq 0.01$), BD (r=0.466, $p \leq 0.01$), and PD (r=0.520, $p \leq 0.01$). The sand fraction of soil exhibited strong negative correlations with OC (r=-0.753, $p \leq 0.01$), available N (r=-0.542, $p \leq 0.01$), available K (r=-0.857, $p \leq 0.01$), BD (r=-0.518, $p \leq 0.01$), porosity (r=-0.386, $p \leq 0.01$), moisture content (r=-0.438, $p \leq 0.01$), silt (r=-0.770, $p \leq 0.01$), and clay (r=-0.946, $p \leq 0.01$). Silt content was negatively associated with OC (r=-0.636, $p \leq 0.01$), available N (r=-0.359, $p \leq 0.01$), available P (r=-0.256, $p \leq 0.05$), available K (r=-0.614, $p \leq 0.01$), and sand (r=-0.770, $p \leq 0.01$). Conversely, it was positively correlated with BD (r=0.346, p≤0.01), moisture content (r=0.338, $p \leq 0.01$), and clay (r=0.520, $p \leq 0.01$). Clay content presented a strong negative correlation with sand (r=-0.946, $p \leq 0.01$) and significant positive correlations with OC (r=0.683, $p \leq 0.01$), available N (r=0.543, $p \leq 0.01$), available K (r=0.834, p≤0.01), BD (r=0.517, $p \leq 0.01$), porosity (r=0.394, $p \leq 0.01$), moisture content (r=0.412, $p \leq 0.01$), and silt (r=0.520, $p \leq 0.01$). The pH showed a negative correlation with OC (r=-0.477, $p \leq 0.01$), available K (r=-0.285, $p \leq 0.05$), and porosity (r=-0.282, $p \leq 0.05$). It showed significant positive correlations with EC (r=0.744, $p \leq 0.01$), available N (r=0.367, $p \leq 0.01$), available P (r=0.526, $p \leq 0.01$), BD (r=0.520, $p \leq 0.01$), and PD (r=0.321, $p \leq 0.05$). EC negatively correlated with OC (r=-0.465, $p \leq 0.01$) and available K (r=-0.264, $p \leq 0.05$), while presenting positive correlations with pH (r=0.744, $p \leq 0.01$), available N (r=0.595, $p \leq 0.01$), available P (r=0.740, $p \leq 0.01$), BD (r=0.569, $p \leq 0.01$), PD (r=0.513, $p \leq 0.01$), and MWHC (r=0.478, $p \leq 0.01$). The OC content, it was negatively correlated with EC (r=0.465, $p \leq 0.01$) and available K (r=-0.264, $p \leq 0.05$), but positively associated with pH (r=0.744, $p \leq 0.01$), available N (r=0.595, $p \leq 0.01$), available P (r=0.740, p≤0.01), BD (r=0.569, $p \leq 0.01$), PD (r=0.513, $p \leq 0.01$), and MWHC (r=0.478, $p \leq 0.01$). Available nitrogen correlated negatively with sand (r=-0.542, $p \leq 0.01$) and silt (r=-0.359, $p \leq 0.01$) and positively with pH (r=0.367, $p \leq 0.01$), EC (r=0.595, $p \leq 0.01$), available P (r=0.779, $p \leq 0.01$), available potassium (r=0.318, $p \leq 0.05$), PD (r=0.501, $p \leq 0.01$), porosity (r=0.259, $p \leq 0.01$), MWHC (r=0.680, $p \leq 0.01$), and clay (r=0.543, $p \leq 0.01$). Available P_2O_5 negatively correlated with OC (r=-0.256, $p \leq 0.05$) and silt (r=-0.256, $p \leq 0.05$), while positively associating with pH (r=0.526, $p \leq 0.01$), EC (r=0.740, $p \leq 0.01$), available N (r=0.779, $p \leq 0.01$), BD (r=0.293, $p \leq 0.05$), PD (r=0.616, $p \leq 0.01$), moisture content (r=0.283, $p \leq 0.05$), and MWHC (r=0.536, $p \leq 0.01$). Available potassium (K_2O) negatively correlated with pH (r=-0.285, $p \leq 0.05$), EC (r=-0.264, $p \leq 0.05$), BD (r=-0.657, $p \leq 0.01$), moisture content (r=-0.395, $p \leq 0.01$), sand (r=-0.857, $p \leq 0.01$), and silt (r=-0.614, $p \leq 0.01$). It had positive correlations with OC (r=0.767, $p \leq 0.01$), available N (r=0.318, $p \leq 0.05$), porosity (r=0.492, $p \leq 0.01$), and clay (r=0.834, $p \leq 0.01$).

5. CONCLUSION

Physicochemical properties of soil were found to vary widely with land use and depth in the current study. Bulk density was highest in orchard soils and lowest in pasture. Nutrient status and organic carbon values were highest in forest soils and lowest in cultivated fields. Water-holding capacity was increased with depth, but the soils were acidic. Liming and balanced NPK fertilization with organic manure is necessary for improving the health and productivity of the studied lateritic soil.

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