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Seasonal variability of soil physico-chemical properties and nutrient dynamics under forest, organic, and conventional land use systems

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Abstract

Land use change and seasonal variation are among the major factors influencing soil quality, nutrient dynamics, and ecosystem sustainability. The present study was conducted to evaluate the effects of different land use systems (forest, organic and conventional) and seasonal variation (summer, rainy and winter) on soil physicochemical properties. Surface soil samples (0–10, 10–20 and 20–30 cm) were collected from representative sites under each land use system during three seasons and analyzed for physical properties (soil temperature, particle size distribution, bulk density, particle density, water-holding capacity and soil moisture content), chemical properties (pH, electrical conductivity, and organic carbon), and available macro- and micronutrients (N, P, K, S, Zn, Fe, Mn, and Cu) using standard analytical procedures. The results revealed significant variations in most soil properties among land use systems and seasons. Forest soils exhibited significantly lower soil temperature and bulk density but higher water-holding capacity, organic carbon, available phosphorus, potassium, sulphur, and zinc than agricultural soils, indicating superior soil quality under natural vegetation. Organic farming improved soil moisture content and maintained better soil physicochemical characteristics than conventional agriculture. Conventional land use recorded the highest soil temperature, bulk density, electrical conductivity, and available nitrogen, mainly due to intensive cultivation and continuous fertilizer application. Seasonal variation significantly affected soil temperature, moisture, organic carbon, electrical conductivity, phosphorus, potassium, sulphur, zinc, and iron availability. The rainy season enhanced soil moisture, organic carbon, and zinc availability, while summer increased soil temperature, electrical conductivity, potassium, and iron content. Winter favored phosphorus and sulphur accumulation. However, particle density, water-holding capacity, soil pH, available nitrogen, manganese, and copper showed comparatively less seasonal variation. Overall, the study demonstrated that forest ecosystems maintained superior soil health through improved physical condition, higher organic carbon, and greater nutrient reserves, whereas organic farming provided an effective alternative for sustaining soil quality compared with conventional agriculture. These findings emphasize the importance of conserving forest ecosystems and promoting sustainable land management practices to improve soil fertility, nutrient cycling, and long-term agricultural productivity.

Keywords: Land use systems, seasonal variation, soil quality, soil organic carbon, nutrient availability, forest ecosystem, organic farming and conventional agriculture

Introduction

Soil is one of the most important natural resources supporting terrestrial ecosystems and agricultural production. It provides physical support for plant growth, stores and supplies water and nutrients, regulates biogeochemical cycles, maintains biodiversity, and serves as a major reservoir of organic carbon. The quality of soil determines the sustainability of agricultural production, environmental health, and ecosystem services. According to the Food and Agriculture Organization of the United Nations, nearly one-third of the world's soils are moderately to highly degraded due to erosion, nutrient depletion, organic matter loss, salinization, compaction, acidification, and unsustainable land management practices. Soil degradation not only reduces agricultural productivity but also threatens food security, biodiversity conservation, and climate change mitigation by decreasing the soil's capacity to sequester carbon and regulate nutrient cycling (FAO, 2015; Lal, 2020) [6, 24].

Land use is one of the most significant anthropogenic factors influencing soil quality. Changes in

land use alter vegetation cover, organic matter inputs, soil disturbance, hydrological processes, microbial communities, and nutrient cycling, thereby affecting both the physical and chemical characteristics of soil (Guo & Gifford, 2002; Don *et al.*, 2011)^[10, 5]. Conversion of natural forests into cultivated lands often accelerates soil degradation through intensive tillage, excessive fertilizer use, residue removal, and reduced organic matter accumulation. These changes generally increase soil bulk density, decrease aggregate stability, reduce soil organic carbon, and diminish nutrient reserves. Conversely, forest ecosystems maintain relatively stable soil environments due to continuous litter deposition, diverse root systems, and minimal anthropogenic disturbance, resulting in improved soil structure, greater water-holding capacity, enhanced biological activity, and efficient nutrient recycling (Lal, 2004; Six *et al.*, 2004)^[22, 34].

Among agricultural production systems, organic farming has gained considerable attention as a sustainable alternative to conventional agriculture. Organic farming relies on farmyard manure, compost, green manures, crop residues, biofertilizers, and biological pest management rather than synthetic inputs. These practices enhance soil organic matter, improve aggregate stability, increase microbial biomass, and promote nutrient availability, ultimately improving soil fertility and resilience (Mäder *et al.*, 2002; Reganold & Wachter, 2016)^[25, 31]. In contrast, conventional farming systems, although capable of achieving high crop productivity through intensive fertilizer application, often accelerate soil organic matter decomposition, increase soil compaction, and reduce long-term soil health if not managed sustainably (Tilman *et al.*, 2002; Lal, 2015)^[38, 23]. Therefore, comparative evaluation of forest, organic, and conventional land use systems provides valuable insights into the long-term impacts of different management practices on soil quality.

Soil physicochemical properties are widely recognized as reliable indicators of soil quality because they directly influence plant growth, nutrient availability, water movement, aeration, and microbial activity. Physical properties such as bulk density, particle density, particle size distribution, water-holding capacity, soil moisture content, and soil temperature determine the soil's ability to store water, facilitate root penetration, and support biological activity (Brady & Weil, 2017)^[3]. Chemical properties including soil pH, electrical conductivity (EC), soil organic carbon (SOC), available nitrogen (N), phosphorus (P), potassium (K), sulphur (S), and micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) regulate nutrient availability, biochemical reactions, and crop productivity (Havlin *et al.*, 2014)^[12]. Consequently, comprehensive assessment of these properties provides a holistic understanding of soil fertility and ecosystem functioning.

Among soil quality indicators, soil organic carbon is regarded as one of the most sensitive parameters reflecting changes in land management. Soil organic carbon influences aggregate formation, nutrient retention, water infiltration, cation exchange capacity, microbial diversity, and carbon sequestration (Minasny *et al.*, 2017)^[26]. Forest ecosystems generally possess greater organic carbon stocks due to continuous litter deposition and reduced soil disturbance, whereas agricultural soils often experience carbon depletion because of intensive cultivation and accelerated mineralization. Organic farming has been reported to partially restore soil carbon through continuous application of organic amendments and reduced soil degradation (Reganold & Wachter, 2016)^[31].

Seasonal variation also exerts a profound influence on soil physicochemical properties. Climatic variables such as

temperature, precipitation, relative humidity, and evapotranspiration regulate decomposition of organic matter, microbial activity, nutrient mineralization, soil moisture dynamics, and biochemical transformations. Soil temperature controls microbial metabolism and enzyme activity, whereas rainfall influences nutrient leaching, soil moisture storage, aggregate stability, and redox reactions (Paul, 2015)^[30]. During the rainy season, increased moisture generally enhances microbial activity and nutrient mineralization, while high temperatures during summer accelerate decomposition and organic matter oxidation. Winter conditions often reduce microbial activity and modify nutrient availability because of lower temperatures and slower decomposition rates (Brady & Weil, 2017)^[3].

The availability of essential macronutrients and micronutrients is also strongly influenced by both land use and seasonal dynamics. Nitrogen availability depends on mineralization, immobilization, nitrification, denitrification, and fertilizer management. Phosphorus availability is governed by soil pH, fixation reactions, microbial activity, and organic matter decomposition, whereas potassium dynamics depend largely on mineral weathering, exchange reactions, and crop uptake (Havlin *et al.*, 2014)^[12]. Similarly, micronutrients such as zinc, iron, manganese, copper, and sulphur are affected by soil organic matter, moisture conditions, redox potential, and seasonal environmental fluctuations. Understanding these interactions is essential for improving nutrient management and maintaining long-term soil fertility.

Several researchers have reported that forest ecosystems consistently maintain superior soil quality compared with cultivated lands due to greater organic matter accumulation, improved aggregate stability, and enhanced biological activity (Don *et al.*, 2011)^[5]. Likewise, organically managed soils generally exhibit lower bulk density, higher water-holding capacity, greater soil organic carbon, and improved nutrient availability than conventionally managed soils. However, the combined influence of land use systems and seasonal variability on soil physicochemical properties remains inadequately documented in many subtropical agroecosystems of the Indo-Gangetic Plains, where rapid land use change and intensive agricultural practices continue to alter soil health.

The Indo-Gangetic Plains constitute one of the world's most productive agricultural regions and play a crucial role in ensuring food security in South Asia. However, increasing agricultural intensification, declining organic matter, excessive fertilizer use, and changing climatic conditions have raised concerns regarding long-term soil sustainability. Comparative assessment of forest, organic and conventional land use systems across different seasons is therefore essential to understand the mechanisms governing soil quality and nutrient dynamics under this agroecological region.

In this context, the present study was undertaken to evaluate the effect of forest, organic, and conventional land use systems on soil physicochemical properties and to examine the influence of summer, rainy, and winter seasons on soil quality indicators. The study focuses on key physical properties (soil temperature, particle size distribution, bulk density, particle density, water-holding capacity, and soil moisture), chemical properties (pH, electrical conductivity, and soil organic carbon), and nutrient status (available N, P, K, S, Zn, Fe, Mn, and Cu). The findings are expected to provide scientific evidence for understanding soil quality variations under contrasting land use systems and seasonal conditions and to support the development of sustainable land management practices for improving soil fertility, ecosystem resilience, and long-term agricultural productivity.

Materials and Methods

The study was conducted in the Achanakmar–Amarkantak Biosphere Reserve (AABR), located in the states of Chhattisgarh and Madhya Pradesh, India. The region experiences a tropical monsoon climate with three distinct seasons: summer, rainy, and winter. The study included three representative land use systems, namely forest, organic, and conventional agriculture.

Soil samples were collected from the three land use systems during summer, rainy, and winter seasons. Samples were collected from 0–10, 10–20, and 20–30 cm depths using a soil auger. Three replications were maintained for each land use system, and composite soil samples were prepared for laboratory analysis. The collected samples were air-dried, ground, passed through a 2-mm sieve, and stored for subsequent analyses.

Soil texture was determined by the hydrometer method (Bouyoucos, 1962) [12]. Bulk density and particle density were measured by the core sampler and pycnometer methods, respectively (Richards, 1960) [32]. Water-holding capacity was determined following Keen and Raczkowski (1921) [18], while soil moisture content was measured by the gravimetric method (Gardner, 1986) [8]. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil–water suspension (Jackson, 1967) [14]. Soil organic carbon was estimated using the Walkley and Black (1934) [39] method. Available nitrogen, phosphorus, and potassium were determined by the methods of Subbiah and Asija (1956) [37], Olsen *et al.*, (1954) [28], and Hanway and Heidel (1952) [11], respectively. Available sulphur was estimated by the Chesnin and Yien (1951) [4] method, whereas DTPA-extractable zinc, iron, manganese, and copper were determined using the procedure of Lindsay and Norvell (1978).

The experimental data were subjected to analysis of variance (ANOVA) following a factorial design to assess the effects of land use systems and seasons. Treatment means were compared using the Least Significant Difference (LSD) test at the 5% level of significance ($P \leq 0.05$) as described by Gomez and Gomez.

Results and Discussion

Soil Physicochemical Properties under Different Land Use Systems

The physicochemical properties of soil varied significantly among the forest, organic, and conventional land use systems (Table 1), indicating the strong influence of vegetation cover and land management practices on soil quality.

Soil temperature differed significantly across land use systems, ranging from 24.9 to 31.0 °C. The highest temperature was recorded under the conventional system (31.0 °C), followed by the organic system (29.5 °C), whereas the lowest temperature occurred in the forest ecosystem (24.9 °C). The relatively lower temperature under forest land can be attributed to dense canopy cover and litter accumulation, which reduce solar radiation reaching the soil surface and moderate soil thermal fluctuations. Similar observations have been reported by Kekane *et al.*, (2015) [19], Zhang *et al.*, (2019) [40], and Pant *et al.*, (2026) [29].

Particle size distribution also varied significantly among land use systems. Forest soil contained the highest sand content (64.54%), whereas organic and conventional soils had significantly greater silt contents (18.04 and 18.43%, respectively). Clay content remained statistically similar among the systems (approximately 19–20%). The higher sand fraction in forest soil reflects minimal anthropogenic disturbance, while continuous tillage and cultivation under agricultural systems may have altered soil aggregation, leading to a greater proportion of finer particles. Comparable findings were reported by Bhutia *et al.*, (2021) [1] and Santos *et al.*, (2024) [33].

Water holding capacity (WHC) was significantly greater in forest soil (33.18%) than in organic (31.10%) and conventional (31.96%) systems. Bulk density increased progressively from forest (1.28 g cm⁻³) to conventional land use (1.36 g cm⁻³), whereas particle density varied only slightly (2.52–2.57 g cm⁻³). Higher WHC and lower bulk density in forest soils are associated with greater organic matter accumulation, improved aggregation, and enhanced pore space created through continuous litter decomposition and biological activity. Conversely, repeated tillage and machinery traffic under conventional agriculture increase soil compaction, thereby reducing pore space and increasing bulk density. Similar results have been reported by Kaushal *et al.*, (2016) [17], Kumar *et al.*, (2018) [21], and Bhutia *et al.*, (2021) [1].

Soil moisture content (SMC) was significantly higher under organic farming (17.70%) than under forest (15.70%) and conventional (14.68%) systems. The greater moisture retention in organically managed soils is likely due to regular incorporation of compost and organic residues, which improve soil aggregation and water-holding capacity. Soil pH also differed significantly among land use systems, with forest soil remaining moderately acidic (6.05), while organic (6.83) and conventional (6.85) systems exhibited near-neutral reactions. The acidic nature of forest soils is primarily associated with continuous litter decomposition and the release of organic acids, whereas fertilizer application and intensive management under agricultural systems tend to maintain relatively higher soil pH. Similar findings have been documented by Hemalatha *et al.*, (2025) [13], Jaya *et al.*, (2026) [15], and Pant *et al.*, (2026) [29].

Electrical conductivity (EC) ranged from 0.29 to 0.48 dSm⁻¹ and was highest under conventional agriculture, followed by organic and forest systems. Higher EC in conventional soils is likely due to the accumulation of soluble salts resulting from repeated inorganic fertilizer applications. However, all EC values remained within the non-saline range. Soil organic carbon (SOC) was significantly higher in forest soil (1.10%) than in organic (0.98%) and conventional (0.79%) systems. The greater SOC under forest land reflects continuous litter deposition, root biomass accumulation, and minimal soil disturbance, whereas intensive cultivation accelerates organic matter decomposition and carbon loss. Similar trends have been reported by Kekane *et al.*, (2015) [19], Kaur *et al.*, (2023) [16], and Pant *et al.*, (2026) [29]. Available nitrogen ranged from 221.14 to 234.90 kg ha⁻¹ and was highest under conventional land use, likely due to regular application of nitrogen fertilizers. In contrast, available phosphorus (19.47 kg ha⁻¹) and potassium (274.57 kg ha⁻¹) were significantly greater in forest soil, reflecting efficient nutrient recycling through litter decomposition and biological nutrient turnover. Forest ecosystems continuously replenish nutrient reserves through decomposition of plant residues, thereby maintaining higher native fertility. Similar findings have been reported by Kekane *et al.*, (2015) [19], Kaur *et al.*, (2023) [16], and Mishra *et al.*, (2025) [27].

Among the micronutrients, zinc and sulphur concentrations were significantly higher in forest soil, with zinc ranging from 0.39 to 0.53 mg kg⁻¹ and sulphur reaching 27.33 mg kg⁻¹ under forest land. In contrast, iron, manganese, and copper did not differ significantly among land use systems. Higher zinc and sulphur availability in forest soils may be attributed to greater organic matter accumulation, which enhances micronutrient retention through complexation and reduces nutrient losses. The absence of significant variation in iron, manganese, and copper suggests that their availability is primarily controlled by parent material and inherent soil properties rather than land use practices. Overall, the

findings demonstrate that forest ecosystems maintain superior soil physical condition, greater organic carbon storage, and enhanced nutrient reserves compared with agricultural systems, while organic farming improves several soil quality indicators relative

to conventional cultivation. Similar observations have been reported by Kobierski *et al.*, (2020) ^[20], Santos *et al.*, (2024) ^[33], and Ganga *et al.*, (2026) ^[17].

Table 1: Soil Physicochemical Properties Across Different Land Use Systems (LUS)

Parameters	Forest	Organic	Conventional
Temp. (°C)	24.9±3.6c	29.5±3.5b	31.08±3.1a
Sand (%)	64.54±4.84a	62.73±3.43b	61.53±2.98b
Silt (%)	15.97±0.99b	18.04±1.88a	18.43±2.3a
Clay (%)	19.48±4.71a	19.23±4.12a	20.03±3.5a
WHC (%)	33.18±2.25a	31.1±2.13b	31.96±3.29b
BD (g cm ⁻³)	1.28±0.05c	1.3±0.04b	1.36±0.05a
PD (g cm ⁻³)	2.57±0.06a	2.53±0.09ab	2.52±0.1b
SMC (%)	15.7±2.74b	17.7±5.19a	14.68±4.97b
pH (1:2.5)	6.05±0.66b	6.83±0.42a	6.85±0.49a
EC (dSm ⁻¹)	0.29±0.08c	0.43±0.06b	0.48±0.06a
OC (%)	1.1±0.21a	0.98±0.15b	0.79±0.16c
Av. N (kg ha ⁻¹)	221.14±18.49b	224.53±14.51b	234.9±10.63a
Av. P (kg ha ⁻¹)	19.47±2.39a	17.74±4.58b	15.43±3.55c
Av. K (kg ha ⁻¹)	274.57±42.88a	260.89±28.74b	258.59±14.76b
Zn (mg kg ⁻¹)	0.53±0.07a	0.47±0.13b	0.39±0.11c
S (mg kg ⁻¹)	27.33±4.35a	22.91±5.5b	23.83±4.63b
Fe (mg kg ⁻¹)	6.62±1.17a	6.99±1.14a	6.78±0.74a
Mn (mg kg ⁻¹)	5.08±0.84a	5.36±1.17a	5.03±0.98a
Cu (mg kg ⁻¹)	0.45±0.08a	0.45±0.08a	0.44±0.05a

Values represent the overall mean values (across all soil depths and seasons) ± standard deviation, different lowercase letters within each row indicate significant differences ($p < 0.05$) among LUS based on DMRT.

Seasonal Variation in Soil Physicochemical Properties

Seasonal changes significantly affected most soil physicochemical properties, highlighting the important role of climatic conditions in regulating soil processes (Table 2).

Soil temperature varied significantly among seasons, ranging from 26.21 to 32.6°C. The highest temperature was observed during summer (32.6°C), followed by the rainy season (26.6°C), whereas the lowest temperature occurred during winter (26.2°C). Higher summer temperatures were mainly due to greater solar radiation, longer sunshine duration, and lower soil moisture, while cooler conditions during rainy and winter seasons reduced soil heating. Similar observations have been reported by Kekane *et al.*, (2015) ^[19] and Pant *et al.*, (2026) ^[29].

Season also influenced particle size distribution. Sand content was lowest during summer (60.77%) and highest during winter (64.42%), whereas silt content increased significantly during winter (18.96%). Clay content showed the opposite trend, reaching its maximum during summer (22.79%). These apparent seasonal differences may reflect changes in soil moisture, aggregation, and particle redistribution rather than actual alterations in soil texture. Similar findings were reported by Bhutia *et al.*, (2021) ^[1] and Santos *et al.*, (2024) ^[33].

Water holding capacity (31.87–32.30%) and particle density (2.52–2.55 g cm⁻³) did not differ significantly among seasons, indicating that these properties are relatively stable and largely determined by inherent soil characteristics. In contrast, bulk density varied significantly, with the highest value recorded during the rainy season (1.35 g cm⁻³). Increased bulk density under wet conditions may result from rainfall-induced settling and compaction of soil particles, whereas lower values during summer reflect soil drying and expansion of pore spaces. Similar observations have been reported by Kaushal *et al.*, (2016) ^[17], Kumar *et al.*, (2018) ^[21], and Bhutia *et al.*, (2021) ^[1].

Soil moisture content showed pronounced seasonal variation, ranging from 9.26 to 20.50%. The rainy season recorded the highest moisture content, followed by winter, while the lowest

value occurred during summer. These variations primarily reflect differences in rainfall, evapotranspiration, and infiltration throughout the year. Comparable results have been reported by Hemalatha *et al.*, (2025) ^[13] and Jaya *et al.*, (2026) ^[15].

Season had no significant effect on soil pH, which remained within a narrow range (6.51–6.63). However, electrical conductivity varied significantly, with the highest EC observed during summer (0.42 dSm⁻¹) and the lowest during winter (0.37 dSm⁻¹). Greater evaporation during summer likely concentrated soluble salts in the soil solution, whereas reduced evaporation and increased downward salt movement during winter resulted in lower EC values. Similar findings have been reported by Kekane *et al.*, (2015) ^[19], Kaur *et al.*, (2023) ^[16], and Pant *et al.*, (2026) ^[29].

Organic carbon content varied significantly across seasons, with the highest value recorded during the rainy season (1.01%), followed by winter (0.98%), while the lowest concentration occurred during summer (0.90%). Increased vegetation growth, greater litter deposition, and favourable soil moisture during the rainy season contributed to higher carbon accumulation, whereas elevated summer temperatures accelerated decomposition and organic matter oxidation.

Available nitrogen did not vary significantly among seasons, indicating that mineralization and immobilization processes maintained a relatively stable nitrogen pool throughout the year. In contrast, available phosphorus was significantly higher during winter (19.08 kg ha⁻¹), possibly due to reduced phosphorus fixation and lower microbial demand under cooler conditions. Available potassium reached its maximum during summer (273.44 kg ha⁻¹), likely as a consequence of enhanced mineral weathering and increased release of exchangeable potassium under higher temperatures, whereas lower values during rainy and winter seasons may be associated with crop uptake and leaching losses. Similar observations have been reported by Kekane *et al.*, (2015) ^[19], Kaur *et al.*, (2023) ^[16], and Mishra *et al.*, (2025) ^[27]. Seasonal variation also influenced micronutrient availability.

Zinc concentration was highest during the rainy season (0.51 mg kg⁻¹), whereas sulphur reached its maximum during winter (26.58 mg kg⁻¹). Iron content was significantly higher during summer (7.09 mg kg⁻¹), while manganese and copper remained statistically unaffected by seasonal changes. Greater zinc availability during the rainy season is likely related to increased soil moisture and enhanced micronutrient solubility, whereas higher sulphur concentrations during winter may result from favourable mineralization and reduced leaching. Elevated iron concentration during summer may be associated with concentration effects caused by soil moisture depletion. The lack of significant seasonal variation in manganese and copper suggests that their availability is predominantly controlled by

inherent soil characteristics.

Overall, the results indicate that seasonal climatic conditions substantially regulate soil temperature, moisture status, organic carbon dynamics, and nutrient availability. The rainy season favoured soil moisture, organic carbon accumulation, and zinc availability; summer enhanced soil temperature, electrical conductivity, potassium, and iron availability; whereas winter promoted phosphorus and sulphur accumulation. These findings highlight the importance of seasonal dynamics in maintaining soil fertility and ecosystem functioning. Similar conclusions have been reported by Kobierski *et al.*, (2020) [20], Santos *et al.*, (2024) [33], and Ganga *et al.*, (2026) [7].

Table 2: Seasonal effect on soil physicochemical properties.

Parameters	Summer	Rainy	Winter
Temp. (°C)	32.6±2.8a	26.6±3.4b	26.2±3.2c
Sand (%)	60.77±4.46b	63.63±3.55a	64.42±2.97a
Silt (%)	16.44±1.17b	17.04±1.44b	18.96±2.53a
Clay (%)	22.79±4.08a	19.33±3.2b	16.63±2.26c
WHC (%)	31.87±2.25a	32.07±3.09a	32.3±2.83a
BD (g cm ⁻³)	1.29±0.05b	1.35±0.06a	1.3±0.05b
PD (g cm ⁻³)	2.55±0.07a	2.54±0.09a	2.52±0.09a
SMC (%)	9.26±2.27c	20.5±3.07a	15.7±2.74b
pH (1:2.5)	6.59±0.65a	6.63±0.58a	6.51±0.72a
EC (dSm ⁻¹)	0.42±0.11a	0.41±0.1a	0.37±0.09b
OC (%)	0.9±0.19c	1.01±0.24a	0.98±0.2b
Av. N (kg ha ⁻¹)	225.37±19.53a	227.11±15.53a	228.1±12.08a
Av. P (kg ha ⁻¹)	16.1±4.31b	17.46±3.97b	19.08±2.98a
Av. K (kg ha ⁻¹)	273.44±40.42a	259.07±23.96b	261.53±26.59b
Zn (mg kg ⁻¹)	0.44±0.15b	0.51±0.07a	0.44±0.12b
S (mg kg ⁻¹)	21.93±5.87b	25.56±4.66a	26.58±3.67a
Fe (mg kg ⁻¹)	7.09±1.23a	6.57±0.91b	6.73±0.89ab
Mn (mg kg ⁻¹)	5.08±1.18a	5.28±1.05a	5.11±0.75a
Cu (mg kg ⁻¹)	0.44±0.07a	0.47±0.07a	0.44±0.07a

Values represent the overall mean values (across all land-use and depths) ± standard deviation, different lowercase letters within each row indicate significant differences ($p < 0.05$) among LUS based on DMRT.

Conclusion

The present study demonstrated that both land use systems and seasonal variation exert a significant influence on soil physicochemical properties and nutrient availability. Among the three land use systems, forest soil consistently maintained superior soil quality, characterized by lower soil temperature and bulk density, higher water-holding capacity, greater organic carbon content, and enhanced availability of phosphorus, potassium, sulphur, and zinc. These improvements were primarily associated with continuous litter deposition, greater biological activity, minimal soil disturbance, and efficient nutrient recycling. In contrast, conventional agricultural land exhibited higher soil temperature, bulk density, electrical conductivity, and available nitrogen due to intensive cultivation and continuous application of inorganic fertilizers. Organic farming represented an intermediate condition and improved several soil quality attributes, particularly soil moisture retention and organic carbon, demonstrating its potential to sustain soil fertility while minimizing soil degradation. Seasonal variation also played an important role in regulating soil properties. The rainy season significantly enhanced soil moisture content, organic carbon accumulation, and zinc availability due to favourable moisture conditions and increased biological activity. Summer was characterized by higher soil temperature, electrical conductivity, potassium, and iron availability as a consequence of greater evaporation and accelerated mineral weathering. Winter conditions favored phosphorus and sulphur accumulation,

whereas soil pH, particle density, available nitrogen, manganese, and copper remained relatively stable across seasons. Overall, the study clearly indicates that forest ecosystems provide the most favorable conditions for maintaining soil health and nutrient reserves, while organic farming offers a sustainable management strategy capable of improving soil quality compared with conventional agriculture. The findings highlight the need for integrated land management practices that promote organic matter conservation, reduce soil disturbance, and enhance nutrient cycling to ensure long-term soil productivity and environmental sustainability. Adoption of organic amendments, residue recycling, conservation tillage, and balanced nutrient management can substantially improve soil physicochemical properties and contribute to sustainable agricultural production under changing climatic conditions. Furthermore, the results provide valuable baseline information for soil quality assessment and can support future land use planning, soil conservation programs, and sustainable resource management in tropical agroecosystems.

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