



RESEARCH ARTICLE

Soil fertility status and variation across different land use systems of the Bada micro-watershed (4D4F2j05) in Karnataka state

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Abstract

Land use systems play a crucial role in regulating soil fertility, nutrient availability and overall soil quality by influencing organic matter dynamics and nutrient cycling. This study evaluated the impact of various existing land use systems on soil chemical properties and nutrient status at the micro-watershed level in the northern transition zone of Karnataka state. Four prevailing land use systems namely forest, barren land, agriculture and horticulture were selected in the Bada micro-watershed through participatory techniques and soil samples were collected using the grid sampling method at 320 m intervals. A total of 50 soil samples (forest-5, barren land-5, agriculture-20 and horticulture-20) were collected and analysed in the laboratory to assess variations in soil fertility. The findings revealed considerable variations in soil fertility among the evaluated land use systems. Forest soils exhibited the highest mean soil organic carbon content (8.16 g kg⁻¹), followed by horticultural (5.07 g kg⁻¹), agricultural (3.96 g kg⁻¹) and barren land (1.92 g kg⁻¹) soils. This gradient reflects the combined influence of vegetation cover, organic matter inputs, human interventions and crop management intensity. The findings of this study indicate that the forest land use system exhibited a higher soil fertility status compared with other land use systems, with greater mean values of macronutrients such as nitrogen (N) (323.40 kg ha⁻¹), phosphorus (P) (56.88 kg ha⁻¹), potassium (K) (328.74 kg ha⁻¹) and sulphur (S) (43.84 kg ha⁻¹), as well as micronutrients including iron (Fe) (12.61 mg kg⁻¹), manganese (Mn) (11.01 mg kg⁻¹), copper (Cu) (1.97 mg kg⁻¹) and zinc (Zn) (0.68 mg kg⁻¹). In contrast, continuous cultivation without sustainable land management practices contributed to the depletion of these essential soil nutrients in cultivated land use systems. These results highlight that the conversion of degraded and agricultural lands into agroforestry, agri-horticultural and horticultural land uses reduce soil disturbance, representing a potentially effective approach for enhancing soil quality.

Keywords: land use system; micro-watershed; soil fertility

Introduction

Soil serves as a primary reservoir of mineral nutrients essential for crop production. However, these nutrients are not replenished under continuous cultivation due to nutrient depletion through crop uptake, leaching and other losses (1). The dynamic characteristics of soils are significantly affected by both anthropogenically activities and natural processes involved in soil formation. Poor soil management practices in cultivated lands have resulted in increased soil erosion rates, reduced crop yields, productivity and deterioration of soil quality (2). Approximately 1.7 billion people globally reside in regions where crop productivity is reduced by a minimum of 10 % due to anthropogenic induced land degradation, including processes such as soil erosion, deforestation and unsustainable agricultural practices (3). Soil fertility is a fundamental characteristic of soils that directly influences its productivity. It refers to the capacity of the soil to support plant growth and maximise crop yields through the provision of essential nutrients (4). Land use systems significantly influence nutrient availability and cycling and while also affecting secondary succession and biomass production (5). Management of land use systems strongly influences soil properties and soil erosion dynamics.

The adoption of appropriate land use practices combined with effective crop rotation strategies can enhance the availability of macronutrients and micronutrients (6). Although existing studies have predominantly focused on individual soil properties or single land use systems, with limited attention has been given to comparative assessments of soil nutrient status across diverse land use systems within a micro-watershed. Addressing this research gap is essential for understanding the crucial impacts of land use changes on soil fertility and for improving long-term sustainability of land management. Hence, the present study was conducted to assess variability in soil fertility status across prevailing land use systems within the Bada micro-watershed situated in the northern transition zone of Karnataka state.

Materials and Methods

Study area

The study was conducted in the Bada micro-watershed (watershed code: 4D4F2j05) located in Shiggaon taluk of Haveri district in the northern transition zone (agroclimatic zone - 8) of Karnataka state

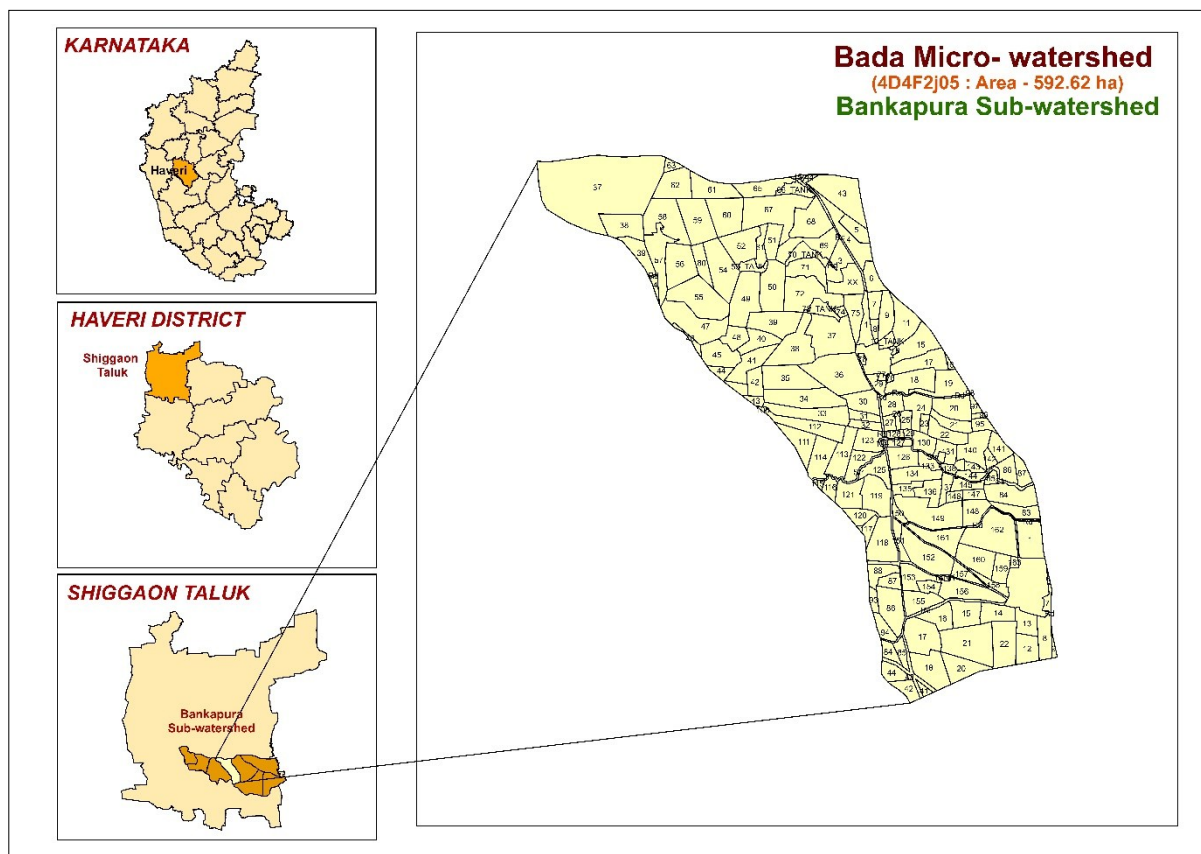


Fig. 1. Geographical representation of the Bada micro-watershed [Source: KRSRAC].

during 2024–25 (Fig. 1). The Bada micro-watershed belongs to the Bankapura sub-watershed and the study area is geographically located between $14^{\circ}55'30''$ – $14^{\circ}58'0''$ N latitudes and $75^{\circ}11'45''$ – $75^{\circ}14'0''$ E longitudes, covering an area of approximately 592.62 hectares (ha). The total geographical area of the northern transition zone is about 1.194 million hectares (Mha). Most of the zone is at an elevation of 450–900 m above the mean sea level. Average annual rainfall of the zone ranges from 620–1025 mm.

Selection of representative land use systems

A preliminary survey combined with participatory methodologies such as field observations, transect walks and both formal and informal group discussions involving farmers and researchers was employed to collect primary data at the field level within the study area. The predominant flora observed in the study area comprises mainly tree and shrub species, such as (*Acacia auriculiformis* A. Cunn. ex Benth.), neem (*Azadirachta indica* A. Juss.), banni (*Prosopis cineraria* (L.) Druce) and jali (*Prosopis juliflora* (Sw.) DC.). The predominant economic activity in the study area is agriculture. Forest, barren land, agriculture and horticulture land use systems were identified and selected for soil fertility evaluation (Fig. 2). The predominant agricultural crops cultivated in the study area include paddy, maize and soybean. In contrast, horticultural land use systems were predominantly represented by cultivation of coconut, arecanut, banana and mango.

Soil sampling and analysis

The number of sampling sites was determined according to the respective area of each land use system within the study area. Soil samples were collected using the grid sampling method. A grid at 320 m intervals were delineated on a cadastral map using overlaid satellite imagery. At each grid point, a soil sample was collected from a depth of 0–20 cm. Collection of these surface soil samples followed

the standard procedure (7). A total of 50 surface soil samples (forest-5, barren land-5, agriculture-20 and horticulture-20) were collected in polythene bags and transported to the laboratory for further processing. Soil samples from different land use systems were air-dried, ground and passed through a 2.0 mm sieve and placed in clearly labelled sample bags for laboratory analysis.

Soil samples from different land use systems were analysed in the laboratory for various soil parameters following the standard procedures. Soil reaction (pH) was determined in a 1 : 2.5 soil-water suspension using a potentiometric method with a glass electrode, whereas electrical conductivity (EC) was measured in the supernatant of a 1 : 2.5 soil-water suspension using a conductivity bridge (7). Soil organic carbon (SOC) was measured by the Walkley-Black's wet oxidation method (8). The cation exchange capacity (CEC) of the soil was determined by extraction using neutral normal ammonium acetate (7). Available nitrogen (N) was determined using the modified alkaline permanganate oxidation method (9). Available phosphorus (P) in acidic soils was extracted using Bray's extractant (0.03 N NH_4F in 0.025 N HCl) and in neutral and alkaline soils was extracted using Olsen's extractant (NaHCO_3) (8). Available potassium (K) of soil was extracted using neutral normal ammonium acetate (1 : 10 soil-to-extractant ratio) and K concentration was determined using a flame photometer (8). Available sulphur in soil was extracted with 0.15 % $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ and determined using the turbidimetric method (8). Exchangeable calcium (Ca) and magnesium (Mg) were extracted using neutral normal ammonium acetate and determined by the complexometric titration method (10). Available micronutrients (iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn)) in soil were determined using an atomic absorption spectrophotometer after extraction of soil samples with diethylenetriaminepentaacetic (DTPA) extractant (11).

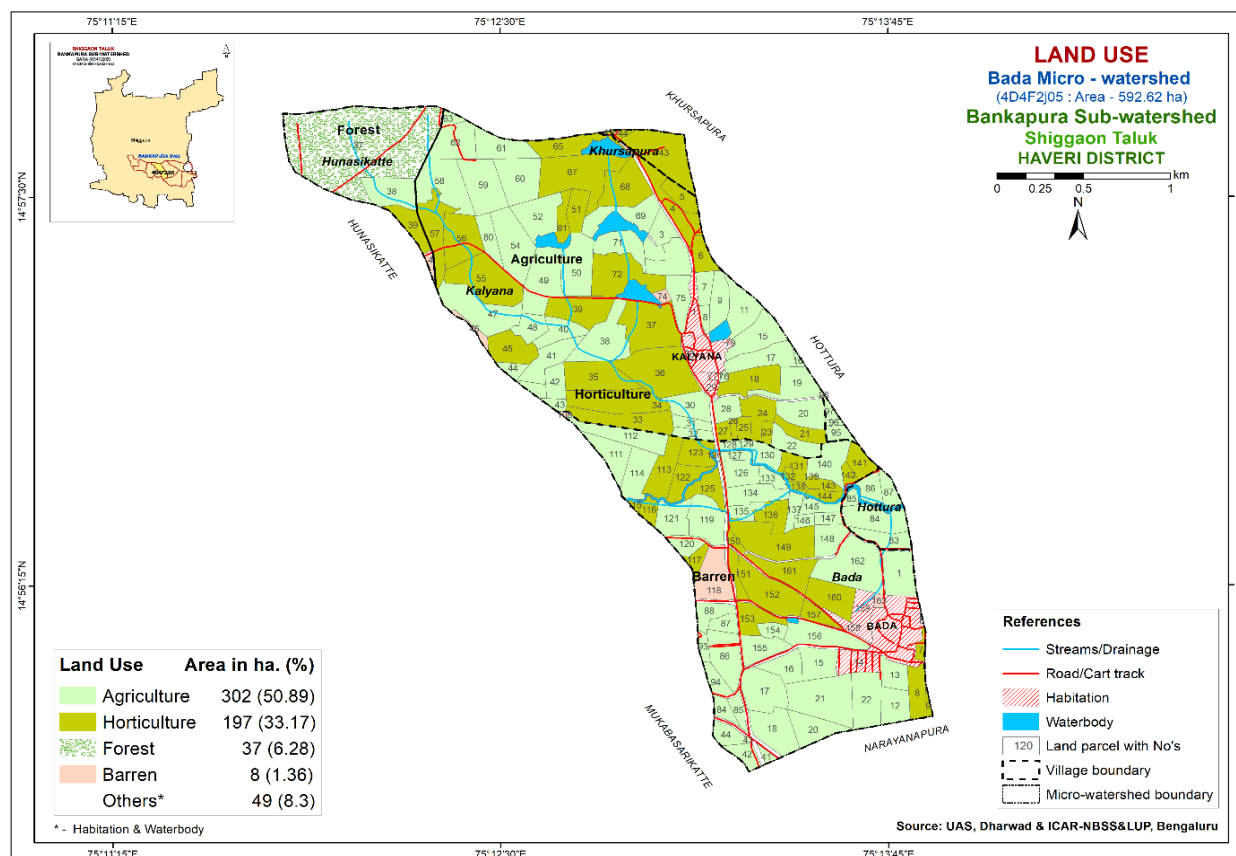


Fig. 2. LULC map of the study area representing various land use systems [Source: KRSAC].

Statistical analysis

The soil characteristic data was subjected to descriptive statistical analyses (range, mean, standard deviation and coefficient of variation) to understand data distribution (12). Inferential statistical analysis, i.e., one-way analysis of variance (ANOVA) was used to evaluate differences among land use systems for measured soil properties. When significant differences were observed ($p < 0.05$), means were compared using Tukey's HSD post hoc test at the 5 % significance level. Statistical analyses were performed using IBM SPSS Statistics, version 27.

Mapping

Cadastral maps and shapefiles were acquired from Karnataka state remote sensing applications centre (KRSAC). Land use and land cover (LULC) classification was carried out using high-resolution satellite imagery, which was subsequently validated through systematic ground truthing, employing GPS-referenced field parcel units. Ground truth data were integrated with spatial layers through georeferencing and overlay analysis to generate a detailed LULC map (Fig. 2) using ArcGIS version 10.8.2.

Results and Discussion

The results of the study showed prominent variations in soil pH among different land use systems. Soil pH across the different land use systems ranged from slightly acidic to alkaline (5.78–8.36) (Table 1). The highest mean soil pH was observed in barren land soil (8.11), followed by agricultural (7.34), horticultural (7.19) and forest soils (6.10) (Fig. 3A). The slightly acidic pH in the forest land use system might be attributed to increased soil organic matter decomposition, which produces organic acids that release H^+ ions into the soil solution, thereby lowering soil pH, as also reported

by (13). The noticeable decrease in soil pH under cultivated land uses compared with barren land may be related to depletion of base-forming cations through leaching and greater uptake by crops. Additionally, enhanced microbial oxidation processes release organic acids, collectively contributing to a slight reduction in soil pH (14, 15). The observed variability in soil pH reflects the influence of land use and management practices on soil chemical processes and nutrient availability, thereby influencing overall soil productivity.

Soils under different land uses showed minimal variation with respect to salinity and were categorised as non-saline soils. Within the study area, EC values ranged from 0.07–0.38 $dS\ m^{-1}$. The highest mean EC (0.34 $dS\ m^{-1}$) was observed in barren land. Among cultivated land use systems, agricultural land use (0.23 $dS\ m^{-1}$) exhibited higher mean EC than horticultural land use (0.20 $dS\ m^{-1}$) (Fig. 3B). The lowest mean EC value (0.10 $dS\ m^{-1}$) was recorded in forest soil. The lower EC observed in the forest land use system might be attributed to leaching of soluble salts through increased percolation, as higher soil permeability is characteristic of forest soils. This trend aligns with previous findings (16). Lower EC values in forest soils compared with cropped lands were documented (17). The elevated levels of EC in barren land soils can be attributed to sparse vegetation and reduced organic matter. In the absence of plant cover and humus, which typically bind and stabilise ions, results in the accumulation of salts (18).

Soil organic carbon content showed significant variation among land use systems. The highest mean value was recorded in forest soil (8.16 $g\ kg^{-1}$) followed by horticultural (5.07 $g\ kg^{-1}$) and agricultural (3.96 $g\ kg^{-1}$) land use systems, whereas the lowest was recorded in barren land soil (1.92 $g\ kg^{-1}$) (Fig. 3C). Forest soil exhibited approximately twice the SOC of agricultural soil, which could be attributed to increased biomass turnover and recalcitrance of

Table 1. Descriptive statistics for chemical properties of soil across different land use systems

Land use system	Statistical parameter	pH	Electrical conductivity (dS m ⁻¹)	Soil organic carbon (g kg ⁻¹)	Cation exchange capacity (cmol (p ⁺) kg ⁻¹)
Forest	Range	5.78–6.49	0.07–0.14	7.20–9.30	55.10–59.45
	SD	0.30	0.03	0.86	1.61
	CV	4.86	25.98	10.53	2.81
Barren land	Range	7.84–8.36	0.29–0.38	1.50–2.40	15.25–18.35
	SD	0.20	0.03	0.34	1.28
	CV	2.48	10.00	17.82	7.70
Agriculture	Range	6.54–8.02	0.15–0.34	2.10–6.30	41.65–50.05
	SD	0.38	0.06	1.29	2.57
	CV	5.13	27.32	32.66	5.59
Horticulture	Range	6.50–7.65	0.12–0.25	3.00–6.60	45.2–53.85
	SD	0.30	0.04	1.20	2.62
	CV	4.22	20.95	23.58	5.26

below-and-above ground biomass of forest trees (19). Forest ecosystems are typically characterised by fungal-dominated microbial communities, that effectively decompose complex organic residues and facilitate humus formation. In contrast, cultivated soils under consistent tillage practices tend to harbour bacteria-dominated microbial populations that accelerate mineralisation of organic matter, potentially leading to progressive declines in SOC levels (20). Minimal physical disturbance in forest soil is associated with greater organic carbon (21). Among the two cultivated land use systems, the elevated SOC observed in horticultural land might be attributed to increased plant biomass inputs into the soil, mainly through leaf litterfall (22). Reductions in organic carbon were aggravated by frequent tillage practices combined with crop residue removal from agricultural fields (23). The findings underscore the importance of implementing residue incorporation and organic matter management strategies that improve nutrient retention and increased CEC.

The findings demonstrated that soil CEC was significantly affected by different land use systems. Across the study area, cation exchange capacity values ranged from 15.25–59.45 cmol (p⁺) kg⁻¹. The highest mean CEC was recorded in forest soils (57.34 cmol (p⁺) kg⁻¹), followed by horticultural land use (49.76 cmol (p⁺) kg⁻¹), agricultural land use (45.94 cmol (p⁺) kg⁻¹) and barren land (16.67 cmol (p⁺) kg⁻¹) (Fig. 3D). Soil organic carbon exerted a significant influence on soil CEC. Forest soils displayed elevated CEC values, likely attributable to their higher SOC, which provides negatively charged sites thereby enhancing cation retention and exchange. Conversely, barren and agricultural soils exhibited comparatively lower CEC values consistent with similar findings (24).

Available N concentration was significantly influenced by different land use systems (Table 2). Mean available N ranged from a minimum of 182.00 kg ha⁻¹ in barren land to a maximum of 323.40 kg ha⁻¹ in forest land use (Fig. 3E). Among cultivated land use systems, horticultural land use (249.55 kg ha⁻¹) demonstrated a marked superiority, exceeding agricultural land use (222.95 kg ha⁻¹) by

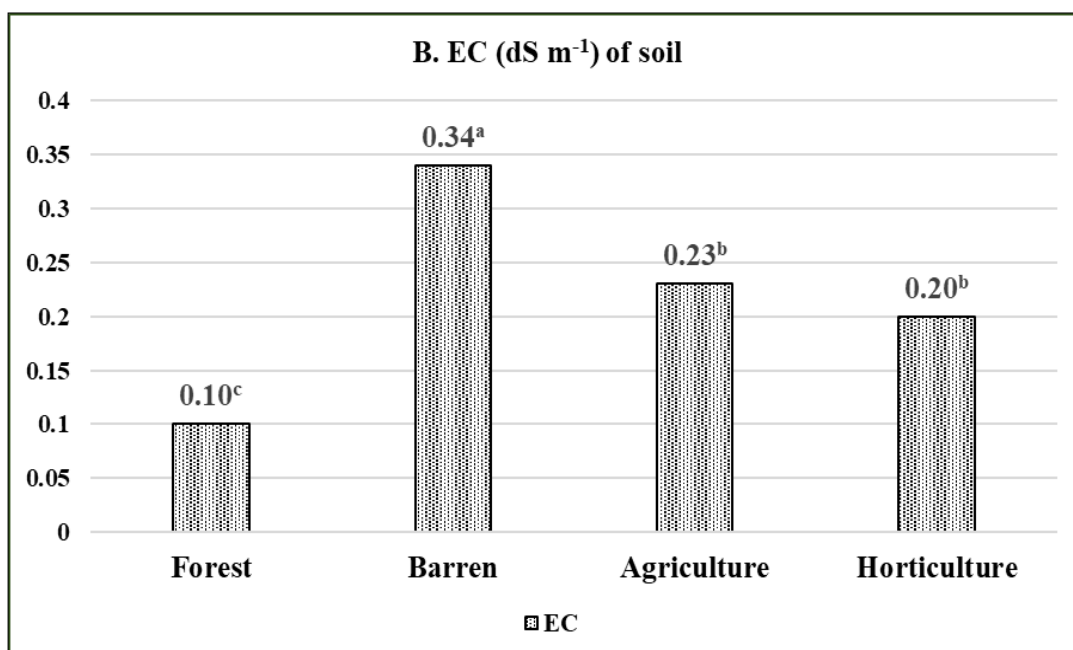
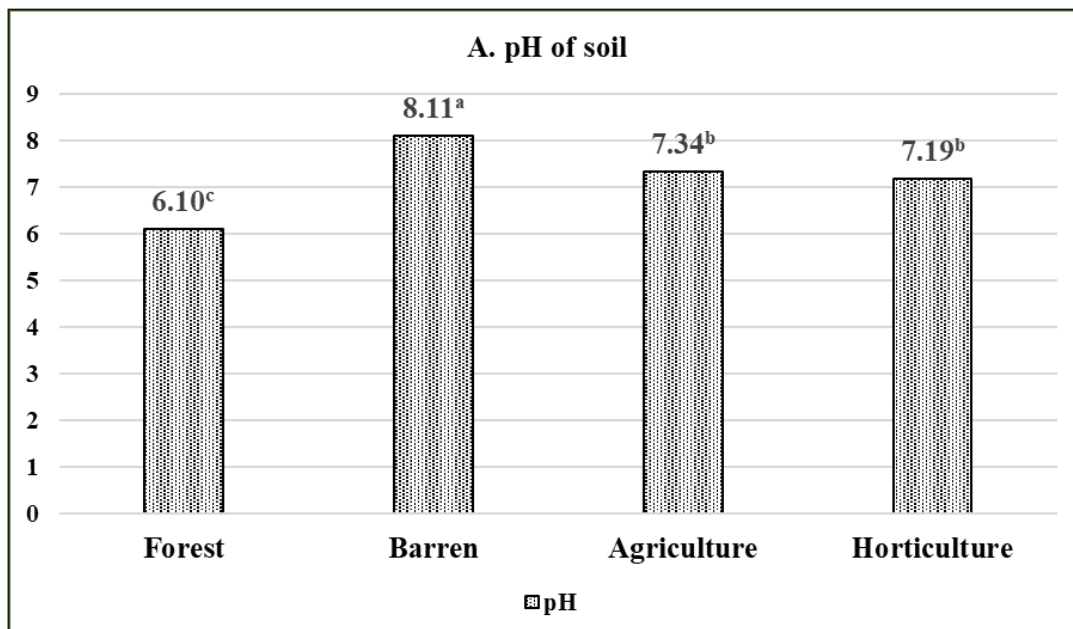
11.93 %. The higher available N content in forest soil might be attributed to greater organic matter content, as it serves as a rich source of N through mineralisation processes. In contrast, soils under cultivated land use exhibited lower N levels, likely due to reduced organic matter content and nutrient leaching losses. Similar findings were reported in the Indore region (25). Compared with horticultural land use, agricultural land use under intensive tillage practices accelerates the oxidation of soil organic matter, thereby reducing N availability (26). In barren land, sparse vegetation was associated with accelerated degradation and depletion of organic matter, leading to N deficiency (27). The results indicate the importance of organic matter in maintaining N availability and promoting sustainable agricultural productivity.

Land use systems significantly influenced available P content. The highest mean value of available P content was observed in forest soils (56.88 kg ha⁻¹), followed by horticultural land use (39.88 kg ha⁻¹), agricultural land use (35.81 kg ha⁻¹) and barren land had the lowest value (19.74 kg ha⁻¹) (Fig. 3E). The higher available P levels detected in forest soils might be attributed to litter accumulation, increased biological activity and efficient nutrient recycling processes occurring in undisturbed environments, thereby improving P availability in soil. These findings were consistent with previous reports from the mid-central valley of Odisha, India (28). The relatively higher levels of available P observed in horticultural land use system among cultivated land use might be attributed to residual effects of sustained application of phosphoric fertilisers and addition of substantial organic matter through leaf litterfall (29, 30). Efficient recycling of organic residues and maintenance of biological activity are fundamental for improving P availability across different land use systems.

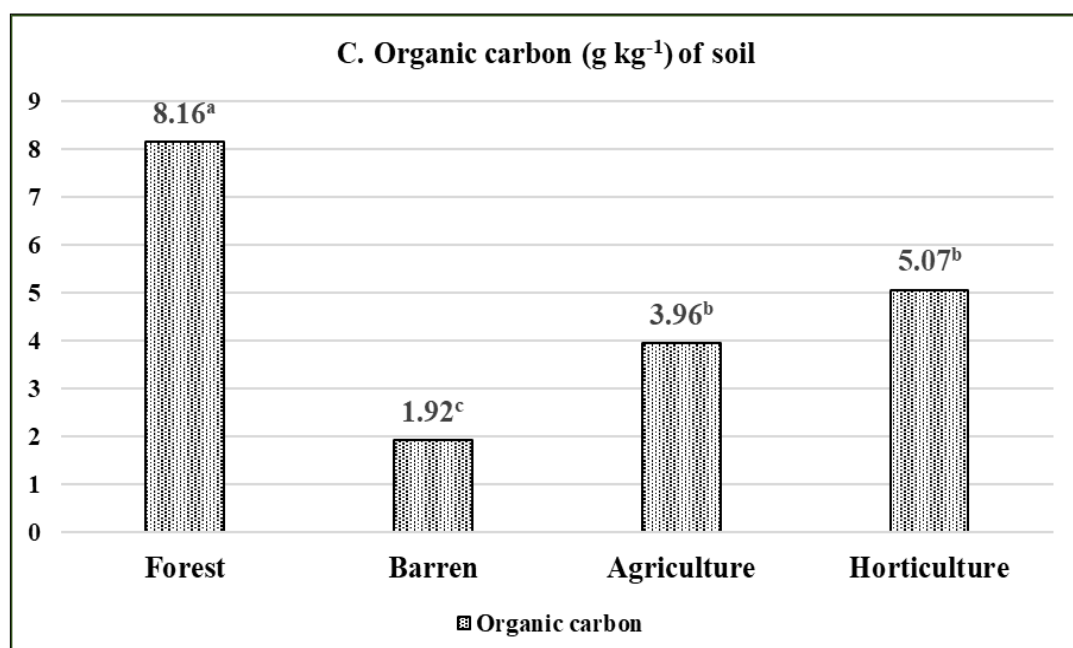
The results revealed that the highest mean value of available K was recorded in forest land use (328.74 kg ha⁻¹), followed by agricultural (251.18 kg ha⁻¹), horticultural (233.32 kg ha⁻¹) and barren land (145.01 kg ha⁻¹) (Fig. 3E). The higher quantity of K was observed

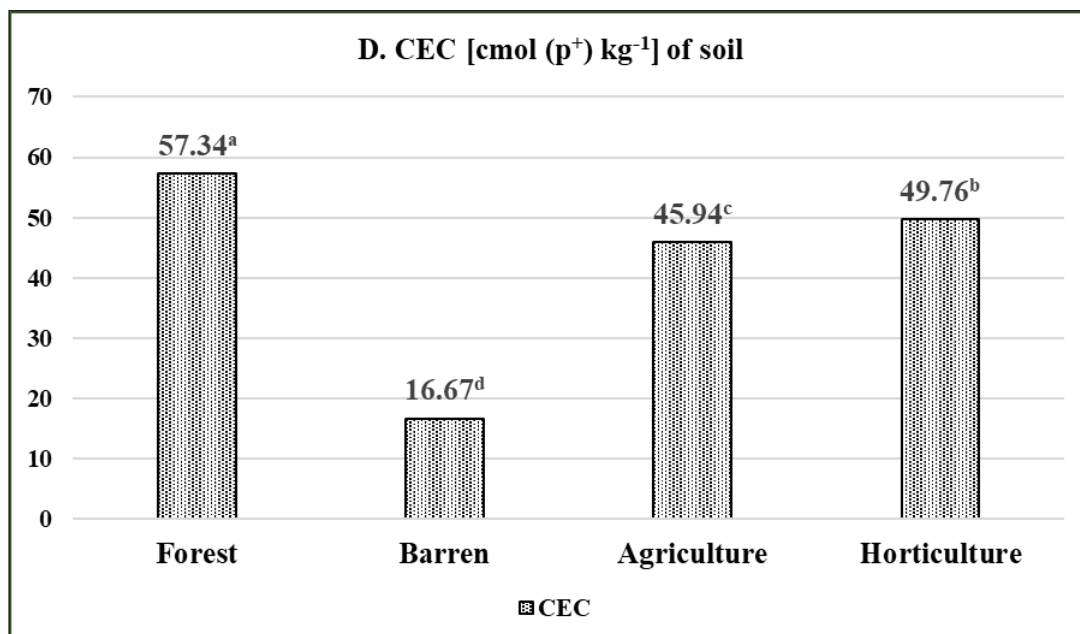
Table 2. Descriptive statistics for primary macronutrients of soil across different land use systems

Land use system	Statistical parameter	Available nitrogen (N)	Available phosphorus pentoxide (P ₂ O ₅) (kg ha ⁻¹)	Available potassium oxide (K ₂ O)
Forest	Range	301.00–343.00	55.72–58.21	313.54–347.12
	SD	16.71	1.03	13.42
	CV	5.17	1.81	4.08
Barren land	Range	168.00–196.00	18.20–21.22	132.28–158.81
	SD	11.07	1.29	11.00
	CV	6.08	6.54	7.59
Agriculture	Range	175.00–266.00	22.14–45.03	110.88–357.72
	SD	27.18	6.76	74.93
	CV	12.19	18.87	29.83
Horticulture	Range	196.00–287.00	27.90–51.16	151.44–363.96
	SD	25.22	6.68	78.15
	CV	10.10	16.75	33.50

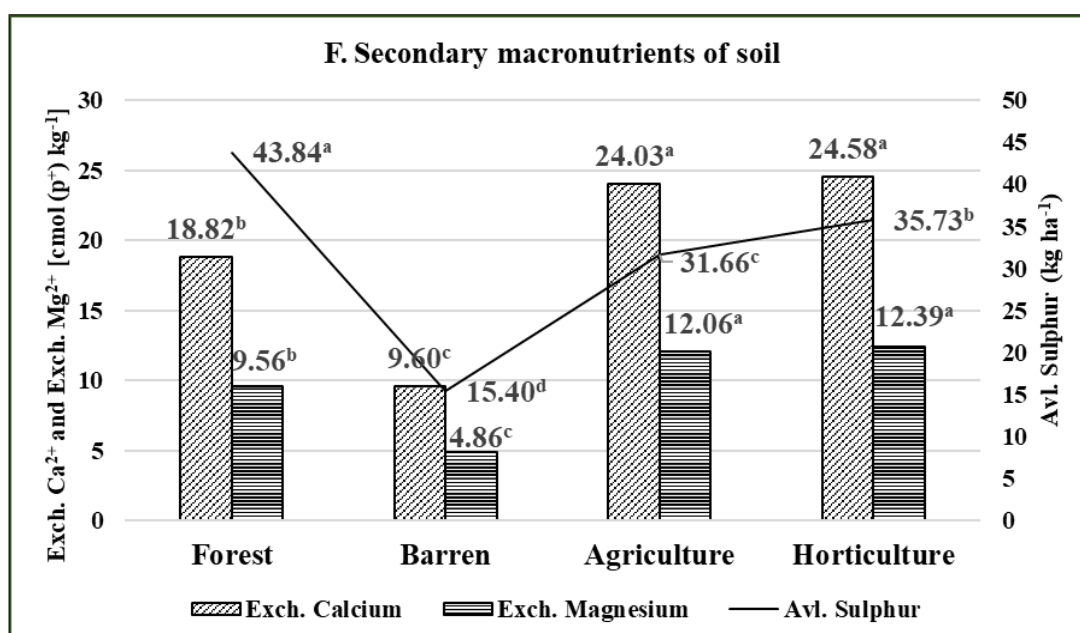
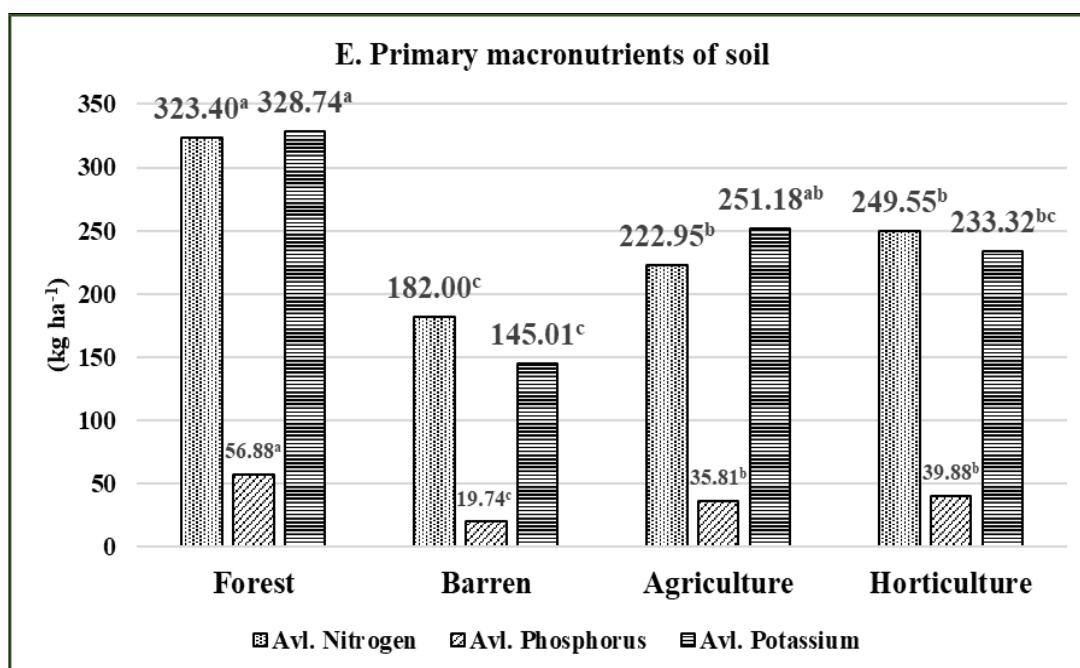


EC: electrical conductivity.





CEC: Cation exchange capacity



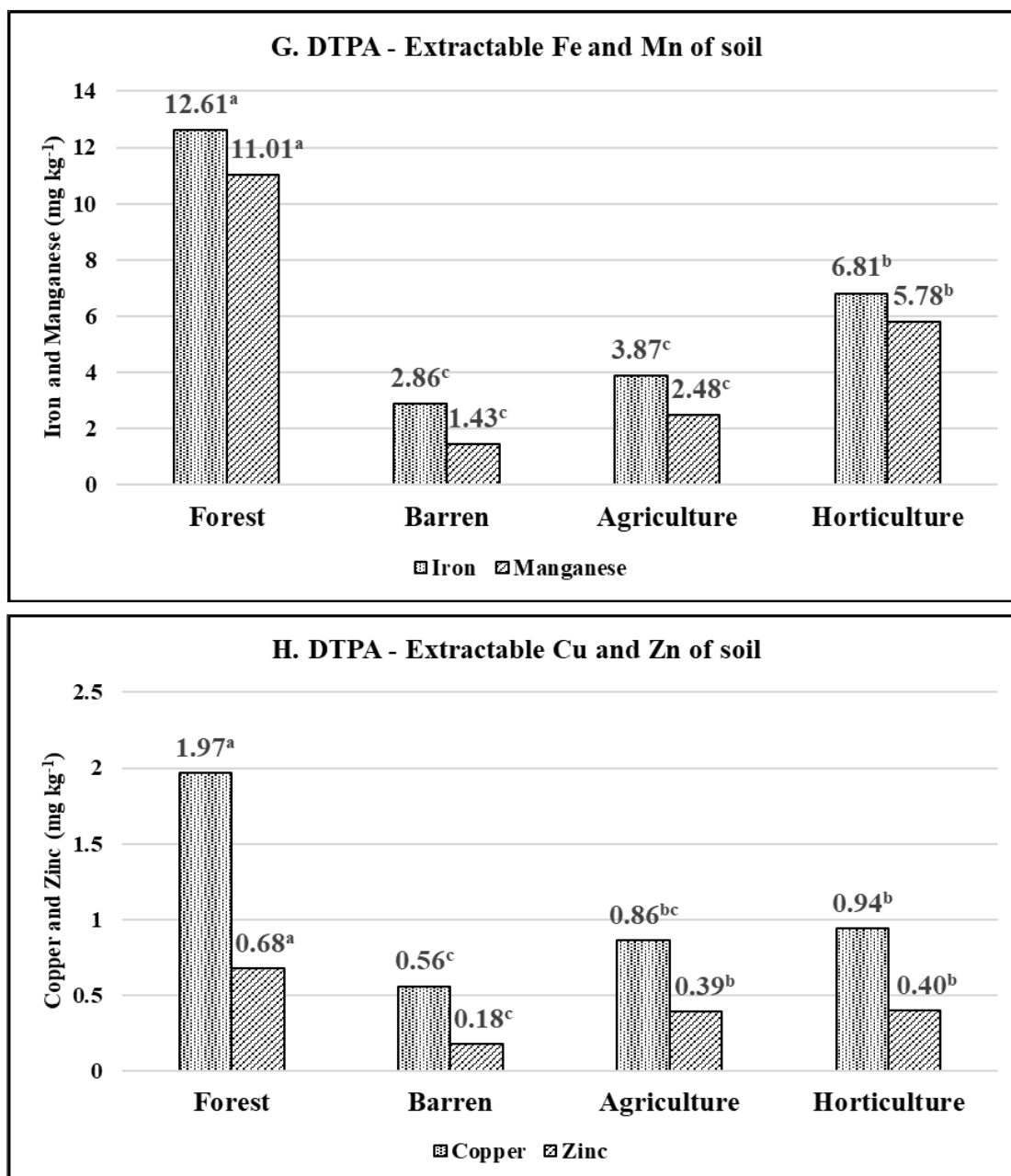


Fig. 3. Graphical representation of experimental mean values for soils across different land use systems. (superscript letters indicate significant differences among land use systems according to Tukey's HSD test at $p < 0.05$).

in agricultural land compared with horticultural land, was associated with rate of K removal by crops. Horticultural crops, especially fruit and vegetable crops, generally have greater K uptake and remove greater amounts of K from the soil due to increased biomass production and fruit harvest (31). Additionally, the application and utilisation of acid-producing inorganic fertilisers influence K distribution within the soil system and contribute to its accelerated depletion. The decreased concentration of available K in barren land use might be attributed to soil degradation and leaching losses (32, 33).

Land use systems exhibited a significant impact on the levels of available S across the study area (Table 3). The highest and lowest mean values of available S were observed in forest soil (43.84 kg ha⁻¹) and barren land soil (15.40 kg ha⁻¹) (Fig. 3F). Among cultivated land use systems, the mean value of 31.66 kg ha⁻¹ and 35.73 kg ha⁻¹ of available S were recorded in agricultural and horticultural soils, respectively. Elevated concentrations of available S in forest soils might be attributed to lower soil pH, which promotes the activity

of S solubilising bacteria, thereby facilitating the transformation of organic forms of sulphur into plant-available forms (34). Similar observations were also recorded in the soils of North Karnataka (35, 36). The limited availability of S in cultivated land uses might be attributed to intensive farming practices combined with insufficient S addition (37, 38).

The highest mean value of exchangeable Ca²⁺ was 24.58 cmol (p⁺) kg⁻¹ in horticultural land use, followed by soils of agricultural soils (24.03 cmol (p⁺) kg⁻¹) and forest soils (18.82 cmol (p⁺) kg⁻¹) (Fig. 3F). The lowest mean value (9.60 cmol (p⁺) kg⁻¹) was observed in barren land. Among exchangeable cations, exchangeable Mg²⁺ was lower than exchangeable Ca²⁺ across all land use systems. The highest mean exchangeable Mg²⁺ content was found in horticultural land use (12.39 cmol (p⁺) kg⁻¹), followed by agricultural land use (12.06 cmol (p⁺) kg⁻¹), forest soils (9.56 cmol (p⁺) kg⁻¹) and barren land (4.86 cmol (p⁺) kg⁻¹). The concentration of exchangeable Ca was greater than that of Mg, which might be attributed to the greater mobility of Mg compared

Table 3. Descriptive statistics for secondary macronutrients of soil across different land use systems

Land use system	Statistical parameter	Available sulphur (S) (kg ha ⁻¹)	Exchangeable Calcium ions (Ca ²⁺)	Exchangeable magnesium ions (Mg ²⁺)
			[cmol (p ⁺) kg ⁻¹]	
Forest	Range	40.62–48.38	18.10–19.20	9.00–10.00
	SD	3.30	0.43	0.38
	CV	7.53	2.30	3.96
Barren land	Range	12.92–17.96	9.10–10.50	4.30–5.40
	SD	2.16	0.57	0.44
	CV	14.00	5.94	9.04
Agriculture	Range	26.52–36.36	22.30–25.80	11.00–13.60
	SD	2.94	1.06	0.70
	CV	9.29	4.43	5.78
Horticulture	Range	31.66–39.26	23.60–26.20	10.70–13.50
	SD	2.23	0.86	0.76
	CV	6.24	3.51	6.12

with Ca (39). The higher levels of exchangeable cations under cultivated land use systems might be attributed to regular application of organic manures and fertilisers, which are rich sources of Ca and Mg (40). Horticultural soil exhibited elevated concentrations, partly attributed to deeper rooting patterns commonly associated with horticultural systems, which enhance cation uptake from deeper soil layers (41). Lower decomposition rates and acidic pH of forest soils tend to reduce CEC and increase the leaching of Ca and Mg ions (42). Barren lands were characterised by the absence of vegetation cover and organic matter inputs, resulting in leaching of mobile cations. Comparable results were documented in the Eastern Himalayas (43).

The DTPA-extractable micronutrients (Fe, Mn, Cu and Zn) in soil were significantly influenced by different land use systems (Table 4). The highest mean concentrations of micronutrients were recorded in forest soils (12.61, 11.01, 1.97 and 0.68 mg kg⁻¹ for Fe, Mn, Cu and Zn, respectively), followed by horticultural land use (6.81, 5.78, 0.94 and 0.40 mg kg⁻¹ for Fe, Mn, Cu and Zn, respectively) and agricultural land use (3.87, 2.48, 0.86 and 0.39 mg kg⁻¹ for Fe, Mn, Cu and Zn, respectively) (Fig. 3G and 3H). The lowest concentrations were observed in barren land (2.86, 1.43, 0.56 and 0.18 mg kg⁻¹ for Fe, Mn, Cu and Zn, respectively). The higher micronutrient levels observed in forest and horticultural soils might be attributed to consistent organic matter inputs, which enhance soil microbial activity, thereby facilitating greater nutrient availability compared with agricultural and barren land soils (30). Greater biomass recycling and chelation reactions occurring in forest soils might have contributed to enhanced micronutrient content (44, 45). Agricultural

soils exhibited lower micronutrient content compared with forest and horticultural soils, likely due to intensive cropping, exhaustive tillage practices and repeated soil disturbances. Conversely, reduced micronutrient levels observed in barren land soils might result from factors such as erosion losses, reduced soil aggregation and diminished organic carbon content (46, 47).

Conclusion

Evaluation of soils across four land use systems namely, forest, barren land, agriculture and horticulture in the Bada micro-watershed, revealed significant variations in soil chemical properties and fertility status. Forest soils exhibited higher concentrations of soil organic carbon (SOC), cation exchange capacity (CEC) and essential nutrients compared with other land uses. In contrast, barren lands exhibited the lowest levels of key nutrients, indicating reduced soil fertility. Agricultural and horticultural lands showed a notable decline in SOC, with reductions of 51.47 % and 37.87 %, respectively, compared with forest soils. The SOC emerged as a key factor influencing overall soil fertility through its influence on nutrient availability and microbial activity, thereby playing a crucial role in maintaining soil health. The findings underscore that continuous cultivation practices and the absence of sustainable management interventions exacerbate soil degradation mainly through SOC depletion. Further studies focusing on subsoil characterisation and seasonal monitoring are required to enhance the understanding of nutrient dynamics and soil quality variations among different land use systems in the Bada micro-watershed.

Table 4. Descriptive statistics for micronutrients of soil across different land use systems

Land use system	Statistical parameter	Iron (Fe)	Manganese (Mn)	Copper (Cu)	Zinc (Zn)
		(mg kg ⁻¹)			
Forest	Range	11.37–13.87	9.45–12.05	1.79–2.15	0.61–0.74
	SD	1.04	1.06	0.14	0.05
	CV	8.27	9.62	7.25	7.71
Barren land	Range	2.12–3.56	0.87–2.13	0.48–0.63	0.11–0.24
	SD	0.58	0.51	0.06	0.05
	CV	20.41	35.81	11.15	30.76
Agriculture	Range	0.99–8.36	0.26–6.54	0.51–1.64	0.21–0.70
	SD	2.50	2.00	0.31	0.14
	CV	64.59	80.58	35.68	36.69
Horticulture	Range	4.43–9.32	3.16–8.66	0.48–1.51	0.20–0.76
	SD	1.70	1.80	0.28	0.15
	CV	24.94	31.15	29.61	37.15

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Authors' contributions

SBH contributed to drafting the original manuscript, review compilation and preparation of tables and figures. JBR participated in the review compilation, corrections and preparation of tables and figures. KVB carried out mapping and corrections. PMP, SHM and HJKN performed review corrections and supervised the process. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing

During the preparation of this work, the authors used Wordvice to improve language and readability, with caution. After using this tool, the authors reviewed and edited the content as required and take full responsibility for the content of the publication.

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