doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

Research Article

Land use-induced changes in soil chemistry: a comparison of five plantation systems in Idukki, Kerala

V. Jayasuriya[1], Prabha Susan Philip[2]*

[1]Department of Soil Science and Agricultural Chemistry, College of Agriculture, Kerala Agricultural University, Vellanikkara, Kerala, India.
[2]Radiotracer Laboratory, College of Agriculture, Kerala Agricultural University, Vellanikkara, Kerala, India.

(Manuscript received: 14.08.2025, Revised: 12.10.2025, Accepted: 15.10.2025)

ABSTRACT

The conversion of forests to plantation agriculture in regions such as Idukki profoundly impacted soil chemical characteristics; however, comparative assessments of different plantation systems are limited. This study was conducted in the Idukki district of Kerala to define the unique soil chemical properties of five dominant plantation systems: tea, coffee, coconut, cardamom, and rubber. We have analyzed 14 key soil chemical properties from 25 sites using univariate (ANOVA) and multivariate (PCA and LDA) statistical methods. The results revealed significant differences ($p< 0.05$) in soil organic carbon (OC), calcium (Ca), and copper (Cu). Coffee systems maintained significantly higher OC than rubber systems, tea plantations showed significant Cu accumulation, and coconut systems had the highest Ca levels. Although many individual properties were not significantly different, multivariate analysis demonstrated that the combined soil properties created a distinguishable set of characteristics for each land use, with linear discriminant analysis classifying the systems with 92% accuracy. The findings confirmed that land use is one of the primary drivers of soil chemical characteristics, with each plantation type creating predictable and quantifiable trade-offs. This study provides a critical scientific basis for developing targeted land management strategies that can balance agricultural productivity and soil conservation in this ecologically important region.

Keywords: cardamom, coffee, multivariate analysis, rubber, soil fertility, tea.

Introduction

The escalating global demand for agricultural commodities has precipitated an unprecedented conflict between economic imperatives and the preservation of ecosystem integrity in biodiversity hotspots (Molotoks *et al*., 2017). This competition reaches a critical juncture in the Idukki district, which is part of the Western Ghats, where the proliferation of plantation agriculture, particularly coffee and tea cultivation, has emerged as the predominant driver of forest conversion and landscape transformation (Shashikumar *et al*., 2022). At the foundation of this environmental crisis lies soil, the critical substrate upon which both natural ecosystems and agricultural productivity depend, experiencing profound degradation that manifests as reduced organic carbon stocks, altered chemical properties, and compromised microbial communities following forest conversion (Karthika *et al*., 2024; Velmourougane, 2016). The cascading effects of soil degradation extend far beyond immediate productivity concerns, fundamentally impairing the region's capacity for carbon sequestration, disrupting hydrological regulation through altered rainfall interception and soil moisture dynamics (Narayana and Kumble, 2023), and threatening the long-term viability of both agricultural systems and endemic biodiversity that depend on intact soil ecosystems. Understanding these complex environmental trade-offs between different land management

*Corresponding author: prabha0825@gmail.com

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

practices has become an urgent scientific imperative, particularly in heavily impacted regions such as the Idukki district, as the Western Ghats faces accelerating conversion pressures that could irreversibly compromise both its global conservation significance and the ecosystem services on which millions of people depend.

Over the past century, the landscape of the Idukki region has been fundamentally altered as native forests have been converted to plantation agriculture, which now dominates the local economy of the region. Perennial crops such as cardamom, tea, rubber, and coffee account for more than half of the total cropped area (Department of Mining and Geology, 2016) in the Idukki district. This large-scale transformation has significant ecological repercussions. This conversion has led to catastrophic biodiversity losses; for example, studies on understory avian insectivores show that their populations are substantially higher in forests than in agricultural lands, reflecting a global trend of decline linked to landuse intensity (Sreekar *et al*., 2015). Furthermore, the carbon sequestration capacity of the ecosystem has been significantly reduced. Natural evergreen and semi-evergreen forests are critical to the region's hydrology, contributing to the majority of the water yield, a vital service that plantations do not provide to the same extent (Chacko *et al*., 2019).

The impact on soil presents a complex picture. While the overall soil quality has demonstrably declined, with quality indices dropping from 0.836 in natural forests to 0.634 in coffee land use (Karthika *et al*., 2020), the effects on specific nutrients vary among studies. For instance, forest systems generally maintain higher total nitrogen pools than agricultural systems (Jagadesh *et al*., 2022). In contrast, management inputs associated with coffee cultivation have led to improved status for other nutrients. Some coffee systems show improved phosphorus availability, and studies have recorded increases in exchangeable bases, available nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), and copper (Cu) in plantation soils compared to adjacent forest soils (Karthika *et al.,* 2020).

Although the general impacts of land use change are well documented, a comprehensive comparative assessment across the five predominant plantation systems (tea, coffee, coconut, cardamom, and rubber) within the unique geo-climatic context of the southern Western Ghats is currently lacking. Most studies have focused on a single crop or a limited set of soil parameters. Consequently, a significant knowledge gap exists regarding how these different land uses and management practices associated with them collectively influence the full spectrum of soil fertility indicators, from soil reaction and organic carbon to the availability of macro- and micronutrients. Understanding these distinct soil chemical properties is critical for developing evidence-based sustainable land management policies.

This study aims to address this gap by providing a robust comparative analysis of soil chemical characteristics under five principal land use systems in the region. The primary objectives of this study isto quantify and compare 14 key soil chemical properties across tea, coffee, coconut, cardamom, and rubber plantation systems, determine the interrelationships between these soil properties through multivariate statistical analysis, and interpret the findings in the context of sustainable land management.

Materials and methods

Study area description

This investigation was conducted in the Idukki district of Kerala, India, specifically in the Anjuruli, Devagiri, Elapara, Mundiyeruma, and Pampadumpara regions. Idukki occupies approximately 4,358 km² and rises from 500 m to 2,695 m above sea level. Climatically, this region falls within the Köppen Am/Cwb zones, representing a tropical monsoon climate modified by altitude, with cool, wet summers

doi:10.25081/jpc.2025.v53.i1.9848
Research Article
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

and mild, drier winters (Abraham *et al*., 2019). The mean annual temperature is 24.4°C, decreasing by approximately 0.6 °C per 100 m elevation gain (Devika *et al*., 2023). Orographic uplift yields a mean annual precipitation of 2,979 mm, with the southwest monsoon (June–September) delivering approximately 65% of the annual rainfall and the northeast monsoon (October–December) contributing another 18% (Abraham *et al.,* 2019; Devika *et al.,* 2023). The underlying geology comprises Precambrian Peninsular Gneiss, including high-grade metamorphic charnockites, granulites, and migmatite–gneiss complexes of the southern granulite terrain, which are extensively lateritized under tropical weathering (Sulal and Archana, 2019). Four major soil types were encountered in the district. The soils are forest loams, lateritic soils, brown hydromorphic soils, and alluvial soils. Approximately 60 % of the district is covered by forest loams, which are the product of the weathering of rock under forest cover (Department of Mining and Geology, 2016).

Experimental design and soil sample collection

An exploratory comparative study was designed to evaluate the influence of five dominant agricultural land use systems on soil chemical properties. All sites were chosen from long-term plantations to reflect a mature land-use history under continuous cultivation. The established stands varied in age: tea (30-60 years), coffee (20-30 years), rubber (>12 years), and coconut (>10 years), while the cardamom sites had been continuously cultivated with that crop for over two decades. Field sampling was executed during the pre-monsoon period between January 2025 and March 2025. The sampling design consisted of five independent plantation sites for each of the five land use systems. The geographical coordinates for these 25 locations are provided in Table 1. To ensure a representative sample from each site, a composite sample was created from 10 sub-samples collected from the topsoil (0-15 cm depth). These sub-samples were collected in a 'W' pattern across a representative plot within each plantation to account for spatial variability. The 10 sub-samples were then thoroughly mixed to form a single composite sample for that site. All sub-samples were consistently collected from similar topographic positions to reduce the confounding influence of terrain.

Table 1: Geographical coordinates and location of the 25 sampling sites

Sample Name	Place	Latitude (°N)	Longitude (°E)
Cardamom 1	Pampadumpara	09°47'37.0"	77°09'39.9"
Cardamom 2	Devagiri	09°48'48.9"	77°10'43.7"
Cardamom 3	Elapara	09°47'53.7"	77°09'43.5"
Cardamom 4	Elapara	09°38'01.3"	77°00'02.7"
Cardamom 5	Elapara	09°38'00.9"	76°59'57.8"
Coffee 1	Pampadumpara	09°47'50.8"	77°09'46.0"
Coffee 2	Mundiyeruma	09°48'50.2"	77°10'44.4"
Coffee 3	Devagiri	09°50'22.0"	77°06'44.2"
Coffee 4	Elapara	09°38'51.0"	76°59'43.3"
Coffee 5	Elapara	09°38'52.2"	77°59'36.4"
Coconut 1	Mundiyeruma	09°48'49.7"	77°10'43.9"
Coconut 2	Mundiyeruma	09°48'49.5"	77°10'45.4"
Coconut 3	Devagiri	09°50'21.9"	77°06'44.2"
Coconut 4	Devagiri	09°50'19.5"	77°06'41.6"
Coconut 5	Pampadumpara	09°47'53.7"	77°09'43.4"
Rubber 1	Devagiri	09°50'21.9"	77°06'46.4"

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

Sample Name	Place	Latitude (°N)	Longitude (°E)
Rubber 2	Devagiri	09°50'19.7"	77°06'41.3"
Rubber 3	Devagiri	09°50'23.2"	77°06'46.9"
Rubber 4	Anjuruli	09°45'30.5"	77°04'56.5"
Rubber 5	Anjuruli	09°45'38.9"	77°04'52.2"
Tea 1	Pampadumpara	09°48'07.9"	77°09'37.5"
Tea 2	Elapara	09°38'11.2"	76°59'45.5"
Tea 3	Elapara	09°38'06.4"	76°59'54.0"
Tea 4	Elapara	09°38'08.6"	76°59'59.6"
Tea 5	Elapara	09°38'10.7"	77°00'12.0"

Note: Coordinates are presented in Degrees (°), Minutes ('), and Seconds (").

The samples were air-dried at room temperature (≈25°C) for 72 hours, after which all visible roots and coarse fragments were manually removed. The dried soil was then gently crushed using a wooden mortar and pestle and passed through a 2 mm stainless-steel sieve to ensure homogeneity. The processed fine-earth fraction was stored in airtight containers until it was analyzed.

Site management practices

Information on existing management practices was gathered through direct consultation with the plantation managers. The nutrient management strategies were highly specific to each land use system (Table 2).

Table 2: Description of nutrient and pest management practices

Land use	Management practices
Cardamom	This land use was the most intensively managed, receiving fertilizer applications three times per year. The annual schedule included applications of a 10:26:26 NPK mixture (150 g/plant), Rajphos (150 g/plant), and muriate of potash (MOP, 75 g/plant) in July and January. An application in September consisted of rock phosphate (125 g/plant), urea (50 g/plant), and MOP (100 g/plant). This was supplemented with foliar-applied micronutrients: Rexolin CXK, a multi-nutrient mixture containing iron (Fe, 3.4%), manganese (Mn, 3.2%), zinc (Zn, 4.2%), copper (Cu, 0.8%), boron (B, 1.5%), and magnesium (Mg, 1.2%). Pest and disease management also involved the reported use of pesticides, such as neonicotinoids, organophosphates, and pyrethroids.
Coconut	Coconut land usewasdiverse. Some plantations were fertilized and some relied primarily on organic inputs. 1kg urea, 2kg superphosphate and 2kg MOP with 50g micronutrient mixture are applied to each palm per year in 2 split dose during May and September. Nutrient management in unfertilized plantations consisted of applications of concentrated organic manures, such as neem cake, and other bulky organic amendments like farmyard manure.
Coffee	Management involved biannual applications (in May and August) of a balanced 16:16:16 NPK complex fertilizer to support plant growth and berry development.
Rubber	Fertilizer management was less frequent, consisting of a single annual application of a 12:8:12 NPK mixture with leguminous undercover.
Tea	The fertilization schedule was timed with the pre- and post-monsoon periods, involving applications of nitrogenous and potassic fertilizers (urea and MOP) in May and September at a rate of 300:300 N:K. A micronutrient spray (Rexolin CXK) was given in May. Occasional applications of magnesium sulphate (50 kg/ha) were also reported. Crop protection involved the use of pesticides (including neonicotinoids, organophosphates, and pyrethroids) and the frequent application of copper-based fungicides to control blister blight.

Despite the differences in nutrient inputs, lime application to manage soil acidity was a widespread and common practice across all five plantation types.

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

Laboratory analysis

A comprehensive suite of 14 soil chemical parameters was analyzed for each of the 25 composite samples, using established standard protocols. The pH was determined in a 1:2.5 (soil: water) suspension using a glass electrode pH meter. Electrical conductivity (EC) was measured on the same 1:2.5 suspension using an EC meter (Jackson, 1973).

The organic carbon content was estimated using 0.5 mm-sieved samples via the wet digestion method (Walkleyand Black, 1934). Available nitrogen was determined using the alkaline potassium permanganate method, as outlined by Subbiah and Asija (1956). Available phosphorus was estimated using Bray's I extraction, as all samples had a pH of less than 6.0 (Bray and Kurtz, 1945). The concentration of available potassium in the extract with neutral normal NH_4OAc was measured using a flame photometer (Jackson, 1973). Available calcium and magnesium were extracted by neutral normal ammonium acetate (NH_4OAc) and measured using atomic absorption spectrophotometry (AAS) (Jackson, 1973), and available sulphur by the turbidimetric method (Williams andSteinbergs, 1959). The hot water extraction procedure was used for boron estimation (Gupta, 1967). HCl was used for micronutrient (Fe, Mn, Cu, and Zn) extraction and measured using AAS (Simsand Johnson, 1991).

Statistical analysis

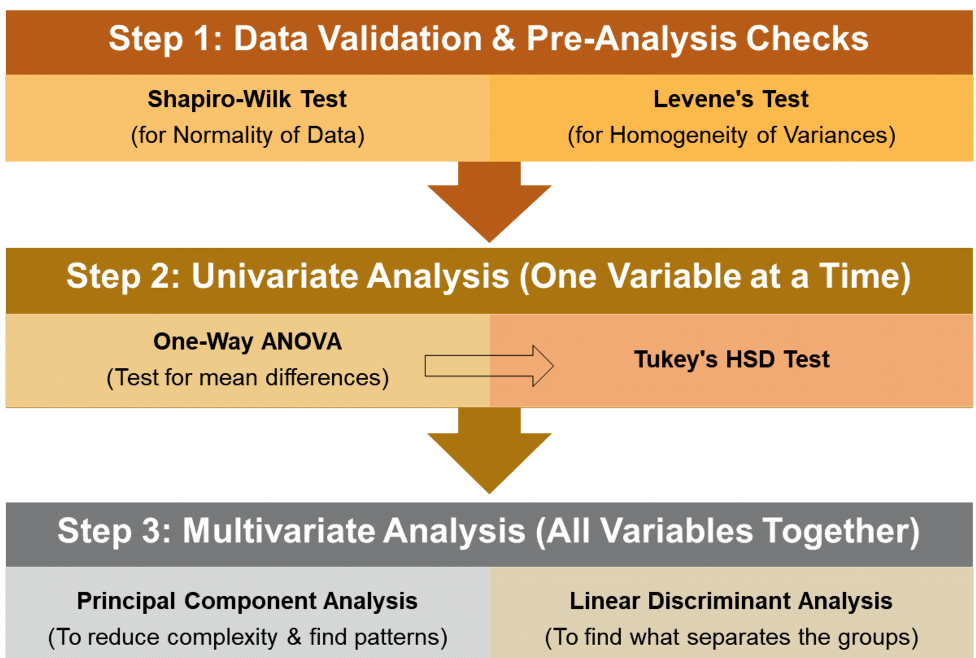

Fig. 1: Flow chart of the statistical analysis performed

All data were organized and statistically analyzed using the R software environment (version 4.5.1). A flowchart of the statistical analysis is shown in Figure 1.

Univariate analysis

To test for significant differences in the mean values of individual soil parameters across the five land use systems, a one-way Analysis of Variance (ANOVA) was conducted. The F-statistic was calculated to determine whether the variance between the land use groups was significantly greater than the variance within the groups.

When the ANOVA indicated a significant

doi:10.25081/jpc.2025.v53.i1.9848
Research Article
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

effect (at an α level of 0.05), a Tukey's honest significant difference (HSD) post-hoc test was performed for pairwise comparisons to identify which specific land use systems were significantly different from one another.

Multivariate analysis

Two ordination techniques were employed to investigate the complex multivariate relationships between soil properties and land use systems. Principal component analysis (PCA) was used as an unsupervised, exploratory method to reduce the dimensionality of the 14 soil variables into a smaller set of uncorrelated principal components (PCs). This allowed for the visualization of overall trends and correlations among soil properties.

Linear discriminant analysis (LDA), a supervised method, was then used to determine the linear combination of soil variables that best separates the five predefined land use groups. This analysis allowed us to test the hypothesis that the land use systems create distinct, classifiable soil chemical properties and to identify which soil variables are the most powerful discriminators between the groups.

Results and discussion

The analysis of soil samples from the five land use systems revealed that several key chemical properties were significantly different, and the multivariate analysis demonstrated that each system possesses a distinct, classifiable set of soil chemical properties (Table 3).

Table 3: Soil chemical properties under five different land use systems

Soil property	Tea	Coffee	Coconut	Cardamom	Rubber
pH	4.85 ^{a} (0.23)	5.34 ^{a} (0.44)	5.46 ^{a} (0.28)	5.43 ^{a} (0.54)	5.00 ^{a} (0.19)
EC (dS/m)	0.08 ^{a} (0.05)	0.06 ^{a} (0.04)	0.07 ^{a} (0.02)	0.06 ^{a} (0.02)	0.06 ^{a} (0.02)
OC (%)	2.25 ^{ab} (0.17)	2.34 ^{a} (0.44)	1.83 ^{b} (0.12)	2.25 ^{ab} (0.24)	1.81 ^{b} (0.11)
N (kg/ha)	384.8 ^{a} (40.4)	374.8 ^{a} (46.9)	272.4 ^{a} (38.8)	404.1 ^{a} (34.0)	313.9 ^{a} (13.0)
P (kg/ha)	46.8 ^{a} (18.1)	36.5 ^{a} (20.3)	65.1 ^{a} (29.3)	68.1 ^{a} (43.1)	30.2 ^{a} (5.6)
K (kg/ha)	863.8 ^{a} (278.9)	625.5 ^{a} (349.5)	620.0 ^{a} (202.8)	1037.8 ^{a} (333.9)	417.7 ^{a} (94.9)
Ca (mg/kg)	602.5 ^{b} (261.3)	1084.8 ^{ab} (409.8)	1431.5 ^{a} (353.4)	1149.8 ^{ab} (489.8)	711.0 ^{ab} (270.2)
Mg (mg/kg)	61.1 ^{a} (16.9)	125.1 ^{a} (67.4)	158.0 ^{a} (85.2)	153.2 ^{a} (55.4)	92.5 ^{a} (15.5)
S (mg/ha)	18.1 ^{a} (2.7)	22.1 ^{a} (4.6)	19.3 ^{a} (1.6)	17.7 ^{a} (1.1)	16.5 ^{a} (0.8)
Fe (mg/kg)	231.9 ^{a} (26.3)	41.6 ^{a} (5.1)	86.8 ^{a} (79.9)	36.3 ^{a} (8.1)	47.9 ^{a} (10.9)
Mn (mg/kg)	31.8 ^{a} (11.6)	126.1 ^{a} (51.8)	83.1 ^{a} (30.1)	61.8 ^{a} (26.2)	66.8 ^{a} (33.0)
Zn (mg/kg)	4.8 ^{a} (1.8)	4.42 ^{a} (1.6)	7.4 ^{a} (2.7)	2.9 ^{a} (1.1)	2.7 ^{a} (0.5)
Cu (mg/kg)	14.2 ^{a} (2.9)	7.1 ^{ab} (5.7)	4.1 ^{b} (3.7)	8.2 ^{ab} (7.8)	2.0 ^{b} (0.4)
B (mg/kg)	0.57 ^{a} (0.09)	0.66 ^{a} (0.11)	0.63 ^{a} (0.14)	0.57 ^{a} (0.09)	0.46 ^{a} (0.08)

Values represent the mean, with the standard deviation in parentheses below. Means within a row followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's HSD test.
Note: All nutrient data represent available forms in the soil.

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

Land use-induced changes in individual soil chemical properties

The conversion of natural landscapes to plantation agriculture induced significant changes in several key soil chemical properties. One-way ANOVA revealed that among the 14 properties analyzed, soil organic carbon (OC), calcium (Ca), and copper (Cu) were significantly different across the five land use systems ($p < 0.05$), whereas the other 11 properties were not (Table 4). This indicates that while the overall chemical status is impacted, certain parameters are more sensitive indicators of land use and its management-induced change.

Table 4: Summary of one-way ANOVA results

	F-statistic	p-value
pH	2.29	0.096
EC (dS/m)	0.14	0.965
OC (%)	5.59	0.003
N (kg/ha)	2.42	0.082
P (kg/ha)	1.83	0.162
K (kg/ha)	1.83	0.163
Ca (mg/kg)	5.76	0.003
Mg (mg/kg)	1.70	0.190
S (mg/ha)	2.71	0.060
Fe (mg/kg)	1.30	0.305
Mn(mg/kg)	2.65	0.063
Zn (mg/kg)	0.93	0.469
Cu (mg/kg)	3.39	0.028
B (mg/kg)	0.56	0.696

Values in bold indicate statistical significance at the $p < 0.05$ level.

Among the general soil properties (Figure 2), OC was significantly affected by land use ($p = 0.003$). The coffee plantations maintained the highest mean OC content (2.34%), which was significantly greater than that of rubber plantations (1.81%) according to the Tukey HSD test. This difference is directly linked to management practices. Coffee is often cultivated under a partial shade canopy, which promotes the continuous addition of diverse, high-quality leaf litter from both coffee plants and shade trees, creating optimal conditions for carbon accumulation (Souza *et al*., 2025). The cooler, more humid microclimate under the canopy also reduces the rate of organic matter decomposition (Velmourougane, 2016). In contrast, rubber monocultures typically involve more intensive undergrowth management and produce litter with a higher C:N ratio, which contributes less to the stable soil organic matter pool.This aligns with findings from other tropical systems where agroforestry systems have been shown to maintain soil organic carbon concentrations 40-50% higher than full-sun monocultures (Soto-Pinto and Aguirre-Dávila, 2014).

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

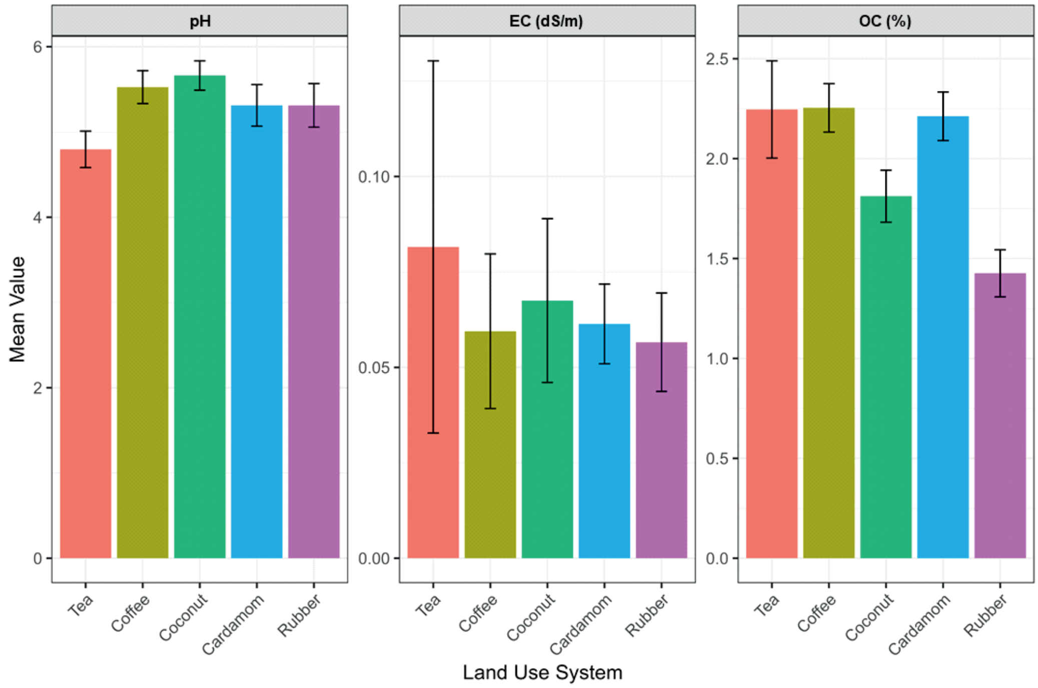

Fig. 2: Mean values of general soil properties (pH, electrical conductivity, and organic carbon) across the five plantation land use systems. Error bars represent the standard error of the mean (n=5).

Analysis of macro- and secondary nutrients (Figures 3 and 4) showed that only Ca differed significantly between the systems ($p = 0.003$). The highest Ca levels were found in coconut plantations (1431.5 mg/kg), which were significantly higher than in tea plantations (602.5 mg/kg). This is a clear indicator of management-induced alteration. Coconut palms are exceptionally effective at cycling base cations like Ca from deeper soil layers to the surface through litterfall (Somasiri *et al*., 2010). Conversely, long-term tea cultivation involves the application of acidifying nitrogenous fertilizers, which accelerates the leaching of base cations like Ca from the soil profile (Manzoor *et al*., 2024). Studies have documented soil pH decreasing to as low as 3.29 and calcium concentrations declining by 40-60% in long-term tea plantations compared to natural forests (Ye *et al*., 2023; Jia *et al*., 2023).While the low pH in tea soils would typically lead to severe Ca depletion, the observed levels are likely stabilized by the common practice of applying lime to ameliorate acidity, which was reported at the study sites.

Despite not being statistically significant ($p = 0.082$), available Nitrogen (N) showed a notable trend. The highest mean levels were found in the most intensively managed systems, cardamom (404.1 kg/ha) and tea (384.8 kg/ha), while the lowest level was in coconut (272.4 kg/ha). This pattern, though not reaching the threshold for significance, aligns with the known high inputs of nitrogenous fertilizers in tea and cardamom cultivation. This pattern aligns directly with the management practices detailed in Table 2, which reinforces the idea that fertilizer management is a key driver shaping the soil chemistry in these systems.

Research Article
doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

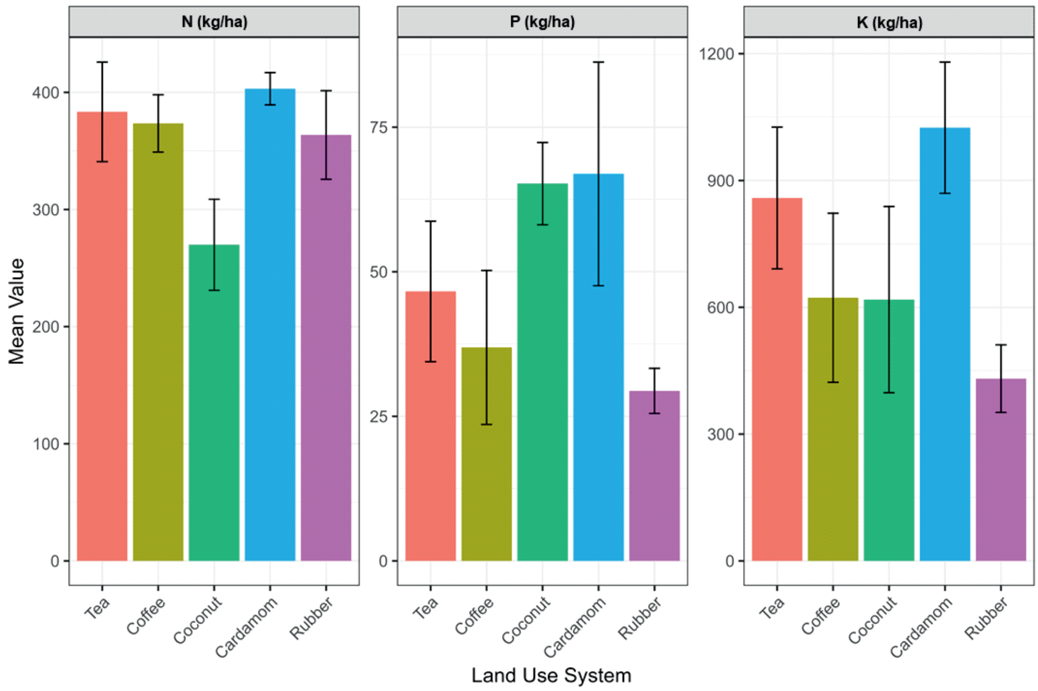

Fig. 3: Mean values of primary macronutrients (Available nitrogen, phosphorus, and potassium) across the five plantation land use systems. Error bars represent the standard error of the mean (n=5).

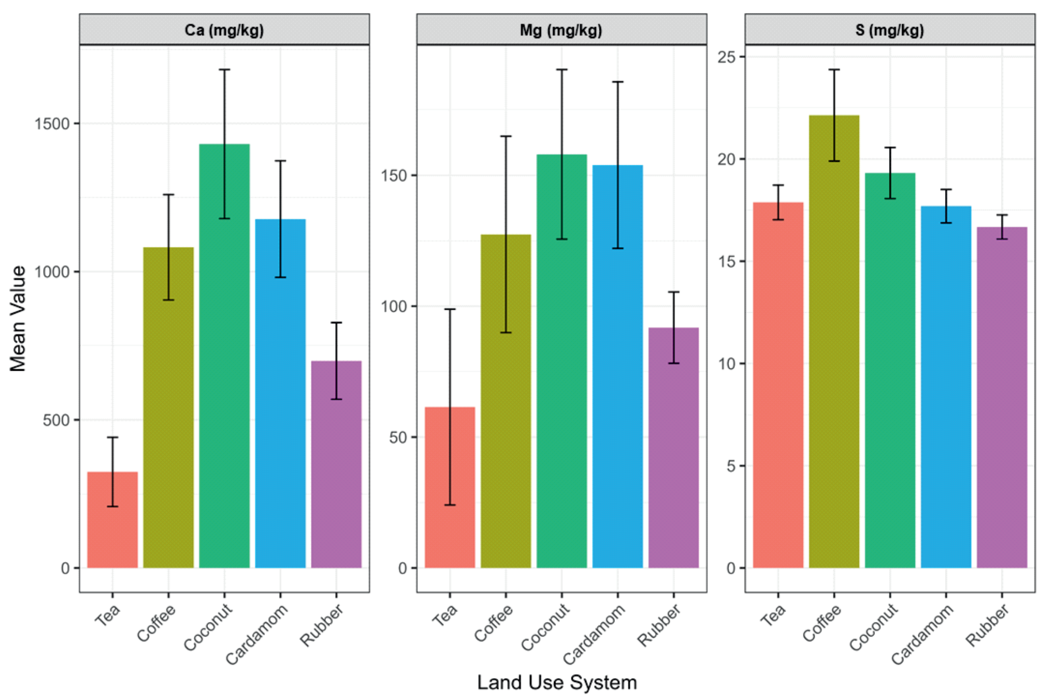

Fig. 4. Mean values of secondary nutrients (Available calcium, magnesium, and sulphur) across the five plantation land use systems. Error bars represent the standard error of the mean (n=5).

doi:10.25081/jpc.2025.v53.i1.9848
Research Article Journal of Plantation Crops, 2025, 53 (1): Page 53-69

Among the available micronutrients (Figure 5), Cu was the only one to show a significant univariate difference ($p = 0.028$). The tea plantations contained the highest mean Cu concentration (14.2 mg/kg), significantly greater than in coconut (4.1 mg/kg) and rubber (2.0 mg/kg) systems. This is a direct influence of the prolonged use of copper-based fungicides, which are standard practice for controlling blister blight disease in tea (Mandal, 2013).Copper from these fungicides is known to persist and accumulate in the topsoil due to its strong binding to organic matter and clay minerals, with studies showing soil copper levels 5-8 times higher in treated versus untreated areas (Alexander *et al.*, 2019).The coffee plantations were notable for having the highest mean level of available manganese (Mn) at 126.1 mg/kg. Although high variability prevented this from being a statistically significant difference, the trend is noteworthy. This elevated manganese availability can be attributed to the unique combination of moderate soil acidity (pH 5.34) and the highest organic carbon content (2.34%) found in the coffee systems. While lower soil pH is known to increase Mn solubility, organic matter acts as a primary controller of its availability in the soil solution, often through the formation of organic complexes (Andrade *et al.*, 2002).This finding highlights how specific crop protection practices can lead to the accumulation of certain elements in the soil, with potential long-term implications for soil health.

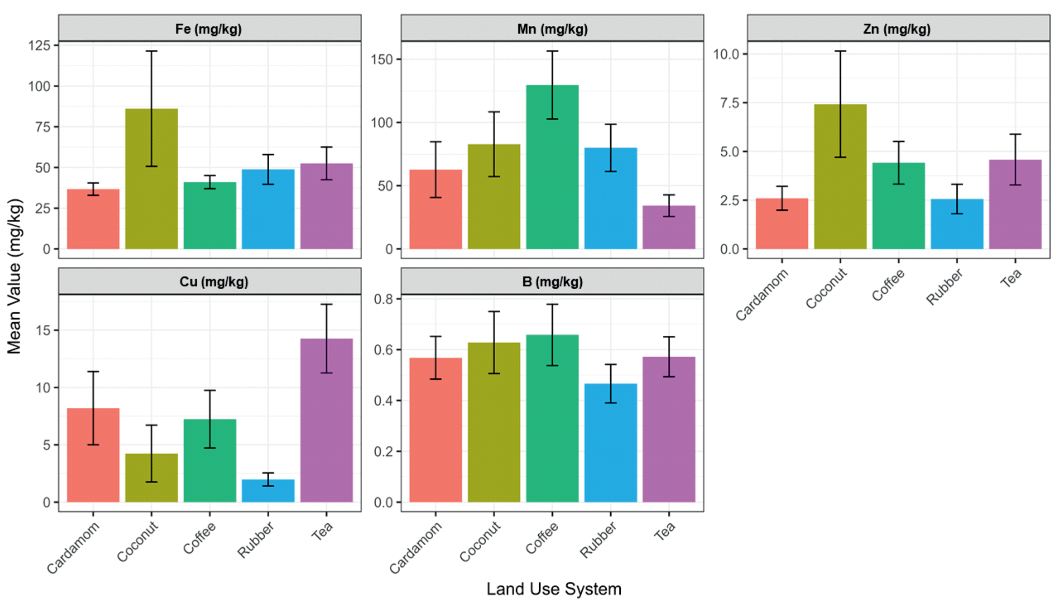

Fig. 5. Mean values of available micronutrients (iron, manganese, zinc, copper, and boron) across the five plantation land use systems. Error bars represent the standard error of the mean (n=5).

Interrelationships between soil properties

The correlation heatmap (Figure 6) reveals the underlying biogeochemical relationships that govern the soil chemistry across the different plantation systems. The most dominant pattern observed is the strong positive correlation between pH and the primary base cations Ca ($r = 0.77$) and Mg ($r = 0.62$), with Ca and Mg also being strongly correlated with each other ($r = 0.73$). This confirms that the concentration of these base cations is a key factor controlling soil acidity in these systems.

Conversely, the heatmap also highlights factors contributing to acidification. A

doi:10.25081/jpc.2025.v53.i1.9848
Research Article
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

significant negative correlation exists between pH and available nitrogen (r = -0.46), which is likely attributable to the acidifying effect of nitrification following the application of nitrogenous fertilizers, a common practice in these plantations. The moderate positive correlation between OC and available N (r = 0.29) is expected, as soil organic matter is the primary reservoir for nitrogen.

Several other strong correlations point towards the influence of specific management inputs. The significant negative correlation between pH and available Cu (r = -0.41) likely reflects the higher mobility and availability of copper in the more acidic soil conditions commonly found in tea plantations, where copper-based fungicides are applied. These fundamental relationships help explain the patterns observed in the multivariate analyses and underscore the necessity of these techniques to distinguish the cumulative effects of the land use systems, especially when many individual properties do not show significant differences.

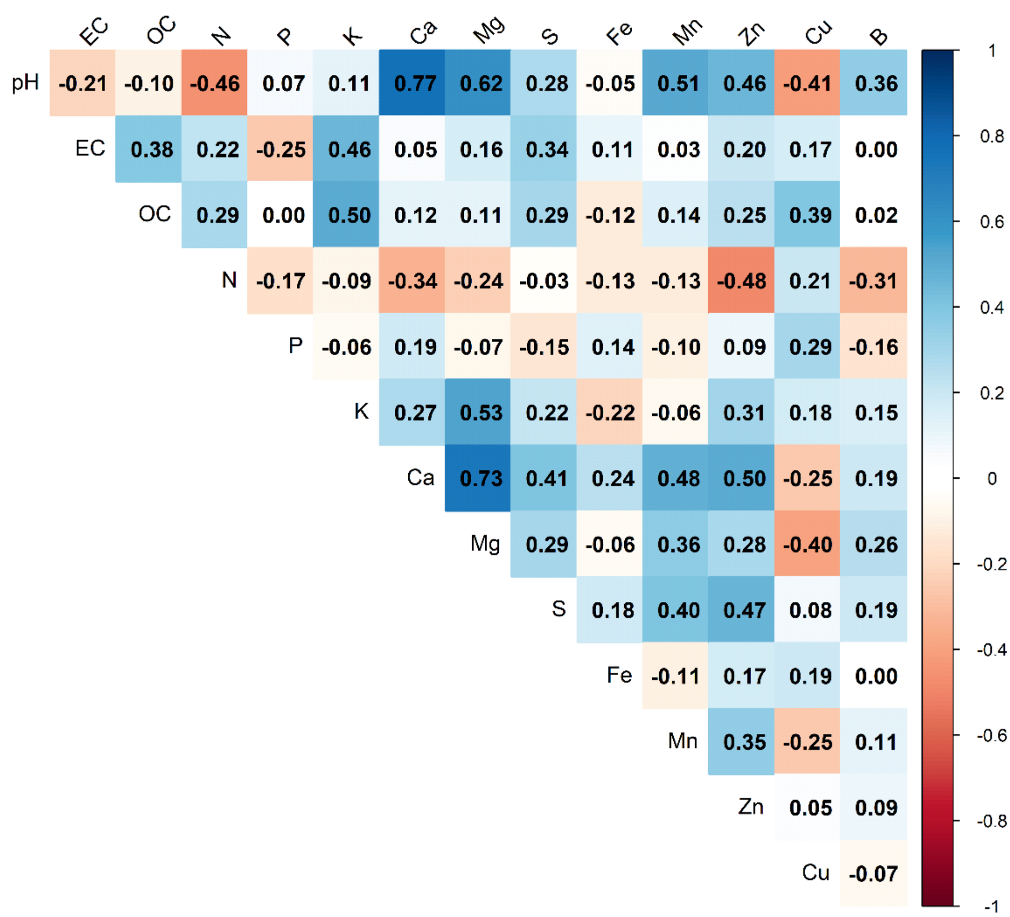

Fig. 6. Heatmap of the Pearson correlation matrix for the 14 measured soil chemical properties. Blue cells indicate a positive correlation, while red cells indicate a negative correlation. The intensity of the color corresponds to the strength of the correlation coefficient, with values shown in each cell.

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

Multivariate analysis: Distinguishing land use systems by their collective chemical properties

While univariate analysis identified key individual changes, multivariate analysis provided a more comprehensive assessment, revealing that the cumulative impact of all 14 variables creates a statistically distinguishable set of chemical properties for each land use system.

Principal component analysis (PCA) effectively reduced the dimensionality of the dataset, with the first three principal components (PCs) collectively explaining 67.1% of the total variance (Figure 7). The first and most important component, PC1 (28.2% of variance), was primarily a gradient of soil base status and acidity. This is evident from the high positive loadings from Ca (0.415), Mg (0.404), and pH (0.396), as detailed in Table 5.

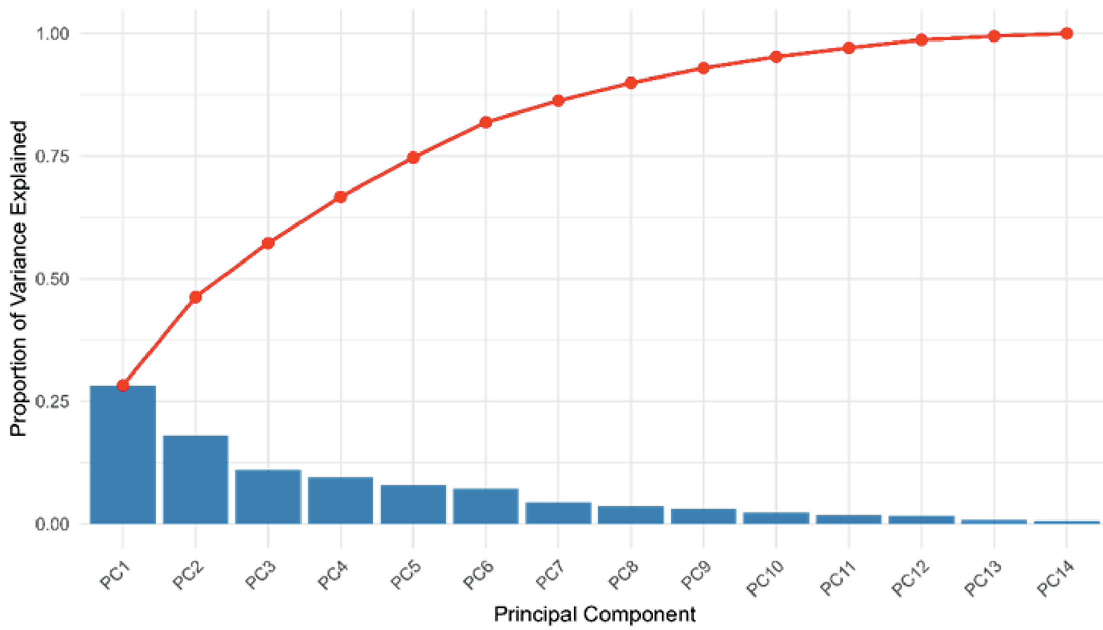

Fig. 7. Scree plot of the principal component analysis (PCA). The blue bars show the proportion of variance explained by each principal component, while the red line indicates the cumulative proportion of variance explained.

Table 5: Loadings on the first three principal components (Pcs)

Soil Property	PC1	PC2	PC3
pH	0.396	0.290	0.028
EC	0.107	-0.447	-0.077
OC	0.115	-0.466	0.053
N	-0.187	-0.323	-0.224
P	-0.050	0.118	0.598
K	0.229	-0.338	-0.038
Ca	0.415	0.124	0.233
Mg	0.404	0.050	-0.103
S	0.319	-0.237	0.110
Fe	0.008	0.020	0.532
Mn	0.316	0.068	-0.119
Zn	0.354	-0.211	0.012
Cu	-0.143	-0.373	0.453
B	0.214	0.060	-0.040

Values in bold indicate the strongest loadings on each principal component.

doi:10.25081/jpc.2025.v53.i1.9848
Research Article Journal of Plantation Crops, 2025, 53 (1): Page 53-69

The PCA biplot (Figure 8) visualizes this relationship, clearly separating the less acidic, base-rich soils of the coconut and cardamom plantations (positive side of PC1) from the more acidic soils of the tea and rubber systems (negative side of PC1). This confirms that long-term management has pushed these systems into chemically distinct spaces defined primarily by their acidity. PC2 was primarily driven by negative loadings from organic carbon, electrical conductivity, and copper, representing a gradient of organic matter content and management-related inputs. PC3 was most strongly influenced by phosphorus, iron, and copper.

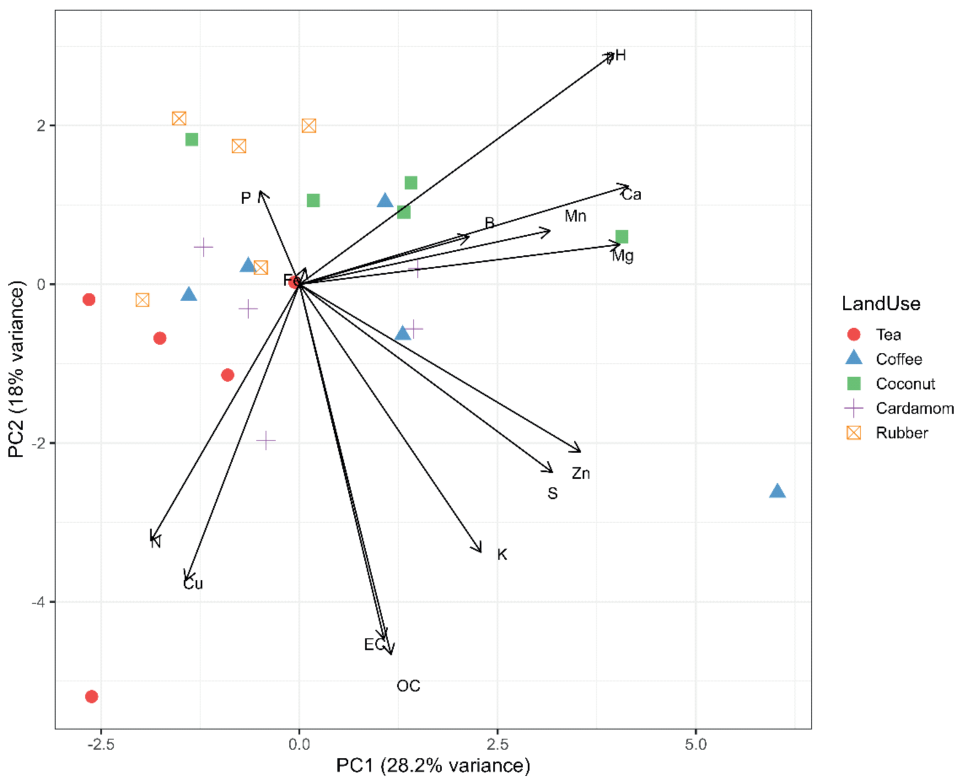

Fig. 8. PCA biplot of the 25 soil samples and 14 soil property variables. Points represent individual samples, color-coded by land use system. Arrows (vectors) represent the soil properties, with the direction and length indicating their contribution to the first two principal components.

Linear discriminant analysis (LDA) was even more powerful in separating the groups, achieving a high cross-validated classification accuracy of 92%. The success of the model was driven by its ability to create functions that maximally separated the groups. PCA finds the axes that explain the most variance in the dataset as a whole, LDA uses the known land use categories to find the axes that create the maximum separation between those groups. The loadings plot (Figure 9) shows that the first discriminant function (LD1) made a strong contrast between soils with high EC, Ca, and Zn on the positive side, and soils with high OC and K on the negative side. This indicates the model distinguished the systems by contrasting the effects of mineral fertilizer inputs (salts and associated cations) with the effects of organic matter management.

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

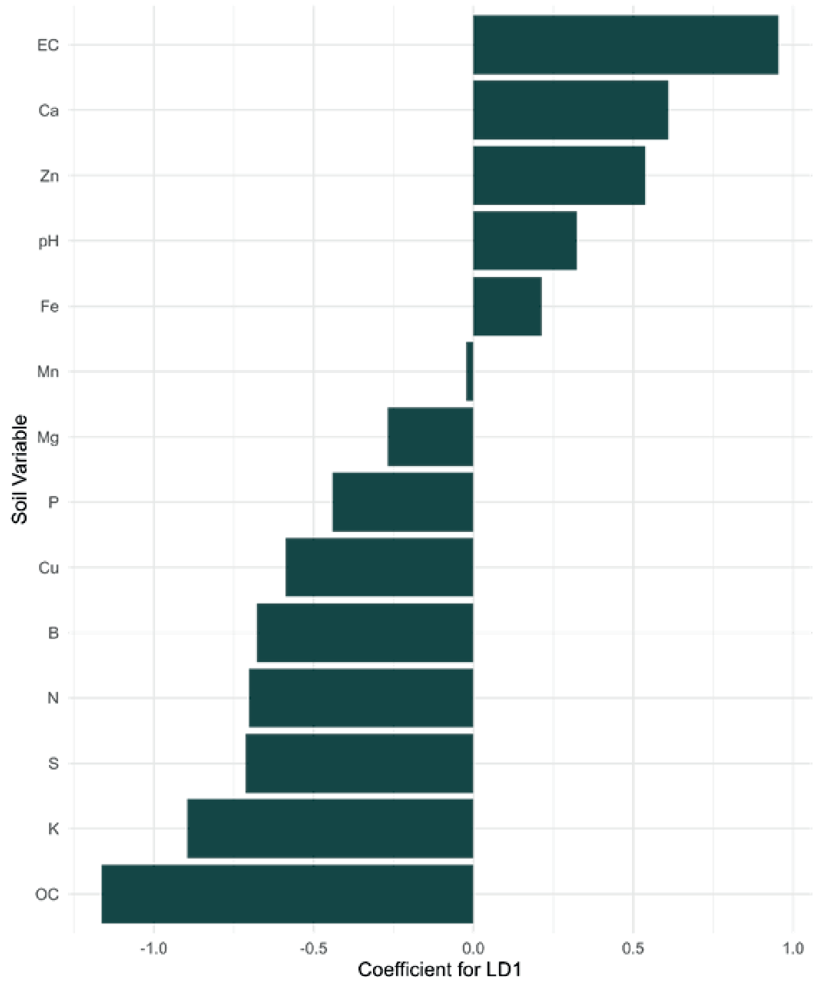

Fig. 9. Loadings of the 14 soil properties on the first linear discriminant (LD1). The length and direction of the bars indicate the relative contribution of each variable to the function that best separates the five land use groups.

This statistical separation is visualized in the LDA plot (Figure 10), where the 95% confidence ellipses for tea and coconut show minimal overlap, confirming their strong chemical dissimilarity. Conversely, the ellipses for coffee and cardamom overlap more substantially, suggesting greater similarity in their overall soil chemistry. This demonstrates that even when individual properties are not significantly different, their combined influence, when analyzed with multivariate techniques, can reliably distinguish one land use from another. Furthermore, while Zinc (Zn) was not significant in the univariate ANOVA ($p = 0.469$), it emerged as an important variable in the multivariate context with a strong positive contribution to both PC1 (loading = 0.354) and LD1, as shown in Table 5 and Figure 9. This highlights the sensitivity of these techniques in detecting the cumulative impact of multiple subtle changes. The importance of zinc as a key discriminatoris strongly explained by the management practices in Table 2, which confirm the use of a zinccontaining micronutrient mixture in cardamom, coffee, and coconut systems.

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

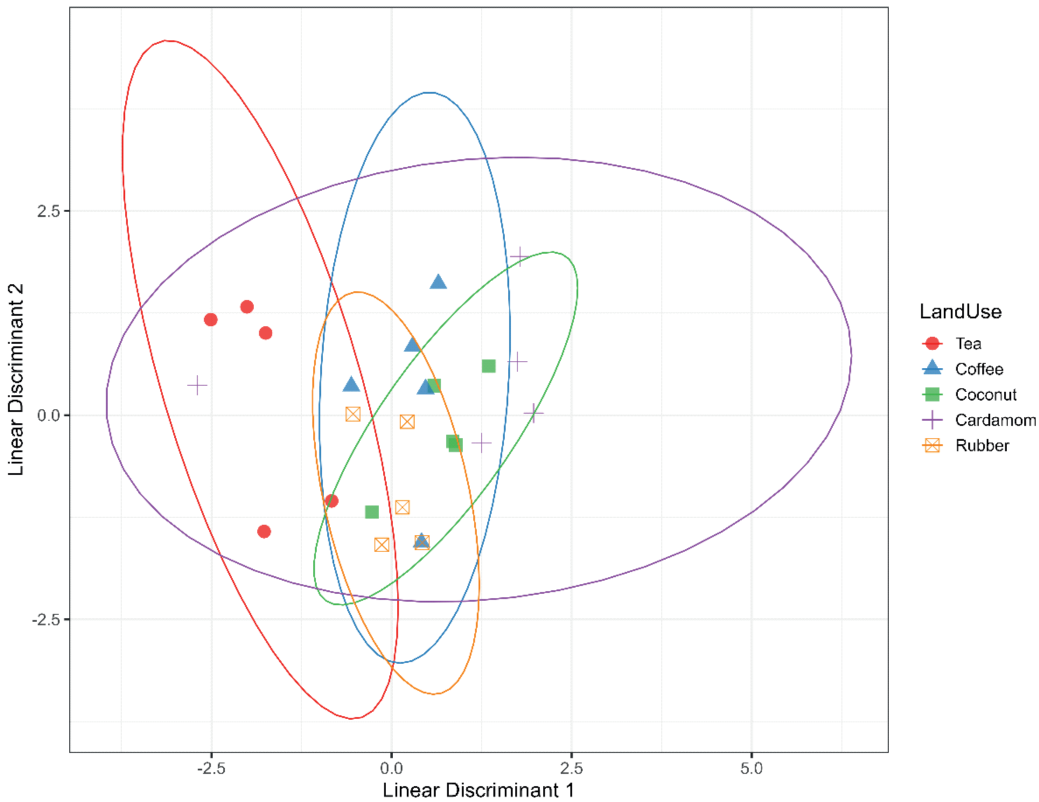

Fig. 10. Separation of the five land use systems based on the first two linear discriminants (LD1 and LD2). Points represent individual samples, and the ellipses represent the 95% confidence interval for each land use group.

Broader implications for sustainable development

The study's findings have direct implications for sustainable land management, particularly regarding soil organic carbon (OC). Land use systems like coffee that maintain higher OC levels actively contribute to climate change mitigation through carbon sequestration (SDG 13: Climate Action). For instance, well-managed agroforestry systems can sequester between 0.29 and 15.2 Mg C ha^{-1} year^{-1}, making them crucial for agricultural landscapes to contribute to climate goals(Ansari *et al*., 2024). Adopting such sustainable practices can simultaneously address land degradation and maintain productivity, contributing to zero net land degradation targets(Mekuria AND Noble, 2013). Furthermore, soils with higher organic matter are more resilient to climate shocks like droughts and intense rainfall, which enhances the climate adaptation capacity of the agricultural landscape.

The study also reveals how different management practices leave distinct chemical characteristics that impact nutrient dynamics. For example, the significantly different calcium levels, with the highest concentrations found in coconut systems compared to tea, highlight how management choices affect long-term soil fertility and nutrient cycling. Similarly, the elevated copper concentration in tea soils is a direct chemical footprint of the system's reliance on copper-based fungicides. Understanding these characteristics is crucial for developing management strategies that enhance productivity (SDG 2: Zero Hunger) while ensuring responsible production patterns that consider the long-term consequences of

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

chemical inputs (SDG 12: Responsible Consumption and Production). Therefore, these results provide a scientific basis for tailoring land use management practices that balance economic needs with ecological stewardship.

Limitations and future research

This study provides a robust characterization of the chemical properties of the soil under different land uses. However, we acknowledge its limitations. The analysis was conducted at a specific point in time and did not capture seasonal variations in nutrient availability. Furthermore, while selecting five distinct sites per land use serves as a form of replication, a more extensive sampling campaign across a wider geographic gradient would be necessary to generalize these findings to the entire Idukki district. Future research should build on this work by incorporating a larger, replicated sampling design and monitoring these sites over time to understand the long-term trajectory of soil health.

Conclusion

This study demonstrated that the five dominant plantation land uses in the Idukki district of Kerala result in distinct and statistically distinguishable soil chemical properties. The findings suggest that long-term management practices inherent to each cropping system are primary drivers of soil chemical properties, with the most significant impacts observed on soil organic carbon, calcium, and copper levels. While systems like coffee demonstrated the capacity to maintain higher organic carbon, intensive practices in tea cultivation led to significant calcium reduction and copper accumulation. Multivariate analyses confirmed that the combined influence of all measured soil properties provides a powerful tool for discriminating between these systems, underscoring that the choice of plantation crop is not neutral but has profound and predictable consequences for the long-term fertility and chemical integrity of the soil. These results provide a critical scientific basis for developing better land use management practices that promote sustainable agricultural practices, balancing economic productivity with the urgent need to conserve the soil resources of this globally significant biodiversity hotspot.

Acknowledgments

The authors gratefully acknowledge the financial support for this research, which was provided by the Kerala Agricultural University through an M.Sc. research fund awarded to the first authorand the laboratory facilities provided by Radio Tracer Laboratory, College of Agriculture, Vellanikkara. We are also grateful for the logistical support and assistance provided by the Cardamom Research Station, Pampadumpara, during the fieldwork phase of this study.

References

Abraham, M.T., Pothuraju, D. and Satyam, N. 2019. Rainfall Thresholds for Prediction of Landslides in Idukki, India: An Empirical Approach. *Water* 11:2113.

Alexander, A.J., Ramani, P., Sherlin, H.J. and Gheena, S. 2019. Quantitative analysis of copper levels in areca nut plantation area - A role in increasing prevalence of oral submucous fibrosis: An in vitro study. *Indian J. Dent. Res.* 30:261–266.

Andrade, E., Miyazawa, M., Pavan, M.A. and de Oliveira, E.L. 2002. Effect of Organic Matter on Manganese Solubility. *Braz. Arch. Biol. Technol.*45:17-20.

Ansari, M.A., Ravisankar, N., Shamim, M., Rani, M., Prusty, A.K., Singh, R., J, R.K., Joshi, H., Kumar, S., Panwar, A.S. and Kumar, M. 2024. Accounting of carbon sequestration and tradeoff under various climatic scenarios in alternative agricultural system: a comprehensive framework toward carbon neutrality. *Front. Sustain. Food Syst.* 8:1371255.

Bray, R.H. and Kurtz, L.T. 1945. Determination of Total Organic and Available Forms of Phosphorus in Soils. *Soil Sci.* 59:39-45.

Chacko, S., Kurian, J., Ravichandran, C., Vairavel, S. and Kumar, K. 2019. An assessment of water yield ecosystem services in Periyar Tiger Reserve, Southern Western Ghats of India. *Geol. Ecol. Landsc.*5:32–39.

Department of Mining and Geology. 2016. *District survey report of minor minerals (except river sand) Idukki district*. Government of Kerala, Thiruvananthapuram.

Devika, R.S., Devi, M.N., Karthikeyan, C., Dheebakaran, G. and Gangaiselvi, R. 2023. Analysis of Trends in Climate Variables and the Adaptation Strategies Used by Cardamom Growers in Idukki District of Kerala, India. *Int. J. Environ. Clim. Change* 13:2983–2992.

Gupta, U.C. 1967. A simplified method for determining hot-water-soluble boron in podzol soils. *Soil Sci.* 103:424-428.

Jackson, M.L. 1973. *Soil chemical analysis*. Prentice Hall of India Pvt. Ltd., New Delhi.

Jagadesh, M., Selvi, D., Thiyageshwari, S., Kalaiselvi, T., Lourdusamy, K. and Kumaraperumal, R. 2022. Unravelling the carbon pools and carbon stocks under different land uses

doi:10.25081/jpc.2025.v53.i1.9848
Journal of Plantation Crops, 2025, 53 (1): Page 53-69

of Conoor region in Western Ghats of India. *J. Appl. Nat. Sci.* 14:762–770.

Jia, X., Zhang, Q., Wang, Y., Zhang, Y., Li, M., Cheng, P., Chen, M., Lin, S., Zou, J., Ye, J. and Wang, H. 2023. Changes of physiological characteristics, element accumulation and hormone metabolism of tea leaves in response to soil pH.*Front. Plant Sci.* 14:1266026.

Karthika, K.S., Anil Kumar, K.S., Nair K.M., *et al*., 2020. Land quality and soil organic carbon stocks consequent to land use change from natural forest to coffee plantation in a hot humid tropical ecosystem of Western Ghats, South India: Is it restorative enough?. *Authorea*. DOI: 10.22541/au.158221338.81133611.

Karthika, K.S., Anil Kumar, K.S., Madhusoodanan Nair, K.P., Beeman, K., Manickam, L., Sreekumar, P. and Ramamurthy, V. 2024. Assessing changes in soil organic carbon stocks and vulnerability to land degradation in Western Ghats, South India: Is it restorative enough? *Soil Use Manage.*40:e13056.

Mandal, S. 2013. Effect of copper on seed germination, root elongation and shoot elongation of seedlings of commercially cultivated tea varieties. *NBU J. Plant Sci.* 7:5-8.

Manzoor, M., Ma, L., Ni, K. and Ruan, J. 2024. Influence of Organic and Inorganic Fertilizers on Tea Growth and Quality and Soil Properties of Tea Orchards' Top Rhizosphere Soil. *Plants* 13:207.

Mekuria, W. and Noble, A. 2013. The role of biochar in ameliorating disturbed soils and sequestering soil carbon in tropical agricultural production systems. *Appl. Environ. Soil Sci.* 2013:354965.

Molotoks, A., Kuhnert, M., Dawson, T.P. and Smith, P. 2017. Global Hotspots of Conflict Risk between Food Security and Biodiversity Conservation. *Land* 6:67.

Narayana, P. and Kumble, V. 2023. Assessment of rainfall interception, soil moisture dynamics and seasonal headwaters in a micro-catchment of Western ghats. *Water Sci.* 37:169–178.

Shashikumar, R., Santhosh, K.H., Lakshmi, B.S., Rajesh, G. and Ravindranath, B.S. 2022. A Comprehensive review on antihyperglycemic phytochemicals from Western Ghats plant species and their mechanism of action. *Res. J. Biotechnol.*17:144-155.

Sims, J.T. and Johnson, G.V. 1991. Micronutrient Soil Tests. pp. 427–476. In: *Micronutrients in Agriculture*. (Eds.) Mortvedt, J.J., Cox, F.R., Shuman, L.M. and Welch, R.M., Soil Science Society of America, Madison, WI.

Somasiri, L.L.W., Wijebandara, D.M.D.I., Panditharathne, B.D.P., Sabarathnam, S. and Kurundukumbara, C.P.A. 2010. Loss Of Nutrients In a High Yielding Coconut Plantation Through Removal Of Plant Materials From The Field. *COCOS* 15:12–22.

Soto-Pinto, L. and Aguirre-Dávila, C.M. 2014. Carbon stocks in organic coffee systems in Chiapas, Mexico. *J. Agric. Sci.* 7:117.

Souza, J.G. de, Piscoya, V.C., Lima, R.P., Lucena, G.C.P., Shinohara, N.K.S., Melo, R.C.P. and Morais, D.P. de. 2025. Estimating Litter Production in Agroforests and Its Role in Soil Carbon Sequestration. *Rev. Gest. Soc. Ambient.*19:e011676.

Sreekar, R., Srinivasan, U., Mammides, C. *et al*., 2015. The effect of land-use on the diversity and mass-abundance relationships of understory avian insectivores in Sri Lanka and southern India. *Sci. Rep.* 5:11569.

Subbiah, B.V. and Asija, G.L. 1956. A rapid procedure for estimation of available nitrogen in soils. *Curr. Sci.* 25:259–260.

Sulal, N.L. and Archana, K.G. 2019. *Note On Post Disaster Studies For Landslides Occurred in June 2018 At Idukki District, Kerala*. Geological Survey of India, Thiruvananthapuram.

Velmourougane, K. 2016. Impact of organic and conventional systems of coffee farming on soil properties and culturable microbial diversity. *Scientifica* 2016:3604026.

Walkley, A. and Black, I.A. 1934. An Examination Of The Degtjareff Method For Determining Soil Organic Matter, And A Proposed Modification Of The Chromic Acid Titration Method. *Soil Sci.* 37:29-38.

Williams, C.H. and Steinbergs, A. 1959. Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Aust. J. Agric. Res.* 10:340–352.

Ye, J., Wang, Y., Lin, S., Wang, Y., Chen, P., Hong, L., Jia, X., Kang, J., Wu, Z. and Wang, H. 2023. Metabolomics analysis of the effect of acidification on rhizosphere soil microecosystem of tea tree. *Front. Plant Sci.* 14:1137465.