



Effects of land use systems on soil physical, chemical and biological properties in north-eastern region of India

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ABSTRACT

Soil plays a crucial role in crop production, and understanding its physiochemical properties across different land use systems (LUSs) is vital for developing effective land management strategies that enhance soil health. This study was carried out during 2022 and 2023 in the subtropical region of Tripura to assess the impact of various LUSs on the physical, chemical, and biological properties of soil. The study consisted of 12 LUSs, viz. T₁, Oil palm (*Elaeis* spp.); T₂, Litchi (*Litchi chinensis*); T₃, Citrus; T₄, Guava (*Psidium guajava*); T₅, Rubber (*Hevea brasiliensis*); T₆, Ginger (*Zingiber officinale*); T₇, Uncultivated (A); T₈, Rice (*Oryza sativa*)-fallow; T₉, Vegetable cowpea (*Vigna unguiculata*)-rice-maize (*Zea mays*); T₁₀, Vegetable cowpea-rice-lentil (*Lens culinaris*); T₁₁, Vegetable cowpea-rice-mustard (*Brassica juncea*); and T₁₂, Uncultivated (B). The experiment was laid out in a completely randomized block (CRBD) design with three replications. Results showed that bulk density (BD) increased with depths, ranging from 1.15 Mg/m³ in litchi at 0–15 cm to 1.56 Mg/m³ in the uncultivated at 75–100 cm, indicating higher compaction in agricultural LUSs. Perennial crops like oil palm exhibited the highest mean nitrogen (340 kg/ha) and potassium (140 kg/ha) availability followed by litchi and rubber with notable reductions in pH values. Uncultivated LUS consistently recorded the lowest values with pH decreasing from 4.93 to 4.52 and nitrogen averaging 219 kg/ha. Mean soil organic carbon (SOC) content was highest in litchi (12.3 g/kg), rubber (11.8 g/kg) and oil palm (11.3 g/kg) and lowest in uncultivated A (5.29 g/kg). The SOC decreases with depths, with maximum values at 0–15 cm depth due to organic matter accumulation. Litchi exhibited the highest soil microbial biomass carbon (MBC 368.2 mg/kg) and nitrogen (MBN 82.1 mg/kg), followed by rubber, highlighting the role of perennial vegetation in promoting soil health compared to annual crops and uncultivated land. The study underscores the importance of horticultural land use systems, like litchi and rubber, in increasing SOC content, improving soil quality, and aiding climate change mitigation.

Keywords: Land use systems, Microbial biomass carbon, MWD, Soil organic carbon, Tripura

Soil management for sustainable food production is becoming increasingly vital with growing population. Human activities like agriculture, mining, land-use changes, urban expansion, deforestation and natural disasters frequently contributors to soil degradation. This degradation has resulted in the decline of soil health, thus, impacting its ability to sustain productivity and ecological balance, making it a significant global concern (Devi 2021). With growing population and increasing food demand, many countries are experiencing shrinkage of cultivable land to be used for food production, thus, leading to the shifting of forest into agricultural and horticultural lands. This shift can

lead to reduction in soil productivity by increasing erosion, depletion in soil fertility and its biological properties, which are essential for maintaining soil health (Reza *et al.* 2018).

The physical characteristics of soil influence their suitability for cultivation and the biological properties being sustained by it. These properties also dictate how well soils can supply water and air to plants. Changes in land use system (LUS) and management practices, such as cultivation intensity and tools used, can alter soil physical properties, making it less permeable and more prone to erosion and runoff (Ramesh *et al.* 2013). Chemical properties of soils, on the other hand, are crucial for determining their ability to supply nutrients to plants and microorganisms. Chemical reactions within the soil contribute to soil genesis and fertility. Over time, minerals originating from the parent materials of the soil release chemical elements that undergo diverse changes, impacting soil health and the availability of nutrients (Diwakar *et al.* 2021, Bordoloi *et al.* 2024). Biological properties of soils are crucial for supporting plant and microbial life.

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Biological processes contribute to increased formation of humus, which improves soil quality and the availability of nutrients (Vikram *et al.* 2022). Key indicators of soil biology are microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) (Reza *et al.* 2018, Meena *et al.* 2025). These indicators reflect the carbon and nitrogen stored in microbial biomass, indicating microbial activity and overall soil health. High levels of MBC and MBN are associated with fertile soils and robust microbial communities essential for nutrient cycling and organic matter decomposition. Research on soil physical, chemical and biological properties has gained significant attention for understanding the impacts of land use changes on soil quality. However, most studies have primarily focused on agricultural soils, with limited research available on the effects of LUSs in subtropical regions. Recognizing this gap, the present study was carried out to compare the impacts of prevalent LUSs on key soil properties in north-eastern region of India.

MATERIALS AND METHODS

The present study was carried out during 2022 and 2023, using the soil samples collected from Horticultural Research Complex (HRC), Nagicherra, and ICAR Research Complex for North Eastern Hill (NEH) Region, Lembucherra, Tripura. These horticultural crops are part of the Horticultural Research Complex while agricultural cropping systems at ICAR Research Complex for NEH Region, Tripura (Supplementary Table 1).

The experiment consisted of 12 LUSs, viz. T₁, Oil palm; T₂, Litchi; T₃, Citrus; T₄, Guava; T₅, Rubber; T₆, Ginger; T₇, Uncultivated (A); T₈, Rice-fallow; T₉, Vegetable cowpea-rice-maize; T₁₀, Vegetable cowpea-rice-lentil; T₁₁, Vegetable

cowpea-rice-mustard; and T₁₂, Uncultivated (B). The experiment was laid out in a completely randomized block (CRBD) design with three replications. Two uncultivated LUSs were included, one from the HRC (uncultivated A) and one from the ICAR-Research Complex for NEH (uncultivated B). The soils were sandy clay loam. Soil samples were collected as per Dhyani and Tripathi (1998) from depth intervals of 0–15, 15–30, 30–60, 60–75, and 75–100 cm using a 8 cm bulk density corer. A 250 g portion of moist soil from each sample was frozen for microbial biomass carbon and nitrogen analysis. The remaining samples were air-dried, ground to pass through a 2-mm sieve to remove rocks and plant roots, and then used for further analysis.

Soil pH (1:2.5), available N, P, K, micronutrients and soil organic carbon (SOC) were measured using respective standard methods (Walkley and Black 1934, Bray and Kurtz 1945, Hanway and Heidel 1952, Subbaiah and Asija 1956, Jackson 1973, Lindsey and Norvell 1978). The soil's cation exchange capacity (CEC) was determined using Jackson's (1973) ammonium acetate method. The MBC, MBN, particle size distribution and mean weight diameter were assessed using established techniques (Bouyoucos 1962, Kemper and Chepil 1965, Jenkinson and Powlson 1976, Brookes *et al.* 1985). The research data were analyzed statistically using Gomez and Gomez's (1984) standard methods, with ANOVA conducted. All statistical analyses were conducted using R software (Version 2024.12.1+563; R Core Team 2024).

RESULTS AND DISCUSSION

Physical properties: Land use systems (LUSs) can greatly influence soil physical properties, thereby influencing

Table 1 Effect of various land use systems on soil bulk density and mean weight diameter at different soil depths

Land use systems	Bulk density (Mg/m ³)					Mean	MWD (mm)
	0–15 cm	15–30 cm	30–60 cm	60–75 cm	75–100 cm		0–15 cm
T ₁	1.18	1.24	1.29	1.35	1.42	1.30 ^f	1.92 ^c
T ₂	1.15	1.23	1.30	1.35	1.40	1.29 ^f	2.09 ^a
T ₃	1.20	1.30	1.35	1.40	1.44	1.34 ^e	1.74 ^c
T ₄	1.19	1.26	1.35	1.40	1.45	1.33 ^e	1.80 ^d
T ₅	1.20	1.26	1.30	1.35	1.39	1.30 ^f	1.97 ^b
T ₆	1.29	1.34	1.36	1.42	1.43	1.37 ^d	1.55 ^f
T ₇	1.34	1.36	1.40	1.42	1.47	1.40 ^e	1.13 ^k
T ₈	1.33	1.35	1.42	1.49	1.53	1.42 ^b	1.42 ⁱ
T ₉	1.31	1.36	1.40	1.45	1.51	1.41 ^b ^c	1.50 ^{gh}
T ₁₀	1.32	1.35	1.39	1.45	1.49	1.40 ^e	1.54 ^{fg}
T ₁₁	1.32	1.36	1.40	1.45	1.50	1.41 ^{bc}	1.45 ^{hi}
T ₁₂	1.40	1.45	1.47	1.52	1.56	1.48 ^a	1.18 ^j
Mean	1.27 ^a	1.32 ^b	1.37 ^c	1.42 ^d	1.47 ^e		
LSD (<i>p</i> =0.05)			A– 0.02, B– 0.01, A×B– 0.05				0.04
SEm(±)			A– 0.01, B– 0.01, A×B– 0.02				0.01

* A, Depths; B, Treatments; * Mean value followed by same lowercase letter within the column are not significantly different (*p*=0.05) according to Tukey's HSD test. MWD, Mean weight diameter. Treatment details are given under Materials and Methods.

soil fertility status (Ramesh *et al.* 2013). Table 1 shows that land use significantly affects bulk density (BD) across soil depths. Bulk density increased with depths in all systems and reported highest at 75–100 cm. At 0–15 cm, BD was lowest in T₂ (1.15 Mg/m³) and highest in T₁₂ (1.40 Mg/m³). Treatments like T₁, T₄ and T₅ had lower BD, with T₁ averaging 1.30 Mg/m³, benefiting from deeper roots (Ramesh *et al.* 2013). The mean weight diameter (MWD) values were highest in T₂ (2.09 mm) and T₅ (1.97 mm), indicating superior soil aggregate stability (Nweke *et al.* 2025). Perennial LUSs including T₄ and T₃ also showed positive impact on stability with MWD of 1.80 mm and 1.74 mm, respectively. The lowest MWD was recorded in T₇ (1.13 mm), followed by T₁₂ (1.18 mm) and T₈ (1.42 mm), indicating poor soil aggregation. Intermediate MWD values were found in T₅, T₈, and other cropping systems, highlighting the positive impact of perennial systems like T₁ and T₂ on soil stability (Li *et al.* 2023, Meena *et al.* 2025).

Chemical properties: Fig. 1 shows the impact of various LUSs on SOC across different depths. Litchi had the highest average carbon content (12.3 g/kg), followed by rubber (11.8 g/kg) and oil palm (11.1 g/kg). The lowest carbon values were in uncultivated A (5.29 g/kg) and uncultivated B (6.19 g/kg). Carbon levels decreased with depth, with litchi maintaining the highest values. Carbon levels highest accumulation was in the top (0–15 cm) soil layer. Uncultivated A and uncultivated B LUSs also have lower SOC compared to top performing LUSs, highlighting the benefits of specific crops and management practices on SOC. The variation in SOC underscores the importance of choosing appropriate LUSs to optimize soil

carbon storage, crucial for soil fertility and climate change mitigation. Perennial crops like litchi, rubber and oil palm show higher SOC levels, especially in upper layers, due to continuous organic input and reduced disturbance. These results emphasize the need for targeted land management practices to enhance SOC across soil depths, improving soil health and sustainability. Similar findings were reported by Chimitdorzhieva (2023) and De Laurentiis *et al.* (2024), who noted that perennial crops and specific land management practices improve SOC, especially in upper soil layers, due to higher organic inputs and less disturbance.

The pH values across all LUSs and depths ranged from acidic to slightly acidic, with mean pH from 4.69 in T₁₂ to 5.27 in T₈ (Table 2). The pH remains consistent across depths, slightly decreasing with depth. Rice has the highest mean pH, suggesting it helps maintain a less acidic environment favourable for crops, unlike the more acidic uncultivated LUSs (Bordoloi *et al.* 2024). Among the LUSs (Fig. 2), citrus had the highest proportion of sand, approaching 67.7%, while rice and maize showed the lowest sand content (63%). Maize exhibited the highest silt content, while uncultivated B and oil palm had relatively higher clay content compared to other LUSs. Clay content was highest in the rubber (25%) LUS. Cation exchange capacity (CEC), indicating soil nutrient retention, varied significantly. Litchi showed the highest mean CEC at 11.5 cmol (p⁺)/kg, followed by T₅ and T₆ with 10.9 and 10.7 cmol (p⁺)/kg, respectively. The lowest mean CEC was in T₇ at 8.12 cmol (p⁺)/kg. This suggests litchi and rubber enhance soil nutrient holding capacity, improving fertility and productivity, while uncultivated LUS showed lower

Table 2 Effect of various land use systems on pH and cation exchange capacity at different soil depths

Land use systems	pH (1:2.5)						CEC [cmol (p ⁺)/kg]					
	0–15 cm	15–30 cm	30–60 cm	60–75 cm	75–100 cm	Mean	0–15 cm	15–30 cm	30–60 cm	60–75 cm	75–100 cm	Mean
T ₁	5.28	5.27	5.13	4.89	4.70	5.05 ^d	13.7	12.2	10.7	8.2	6.0	10.2 ^d
T ₂	5.31	5.29	5.15	4.85	4.74	5.07 ^{cd}	15.6	13.6	11.4	9.9	7.1	11.5 ^a
T ₃	5.50	5.45	5.21	4.91	4.70	5.15 ^{bc}	13.5	11.3	11.1	9.6	6.0	10.3 ^d
T ₄	5.49	5.41	5.33	4.89	4.67	5.16 ^{bc}	14.1	13.1	10.0	8.7	6.9	10.5 ^c
T ₅	5.30	5.29	5.15	4.98	4.76	5.10 ^{bcd}	13.9	13.0	11.3	9.6	6.8	10.9 ^b
T ₆	5.27	5.02	4.87	4.72	4.65	4.91 ^e	13.8	12.5	10.7	9.2	7.2	10.7 ^c
T ₇	4.97	4.89	4.74	4.60	4.59	4.76 ^f	11.1	10.5	7.6	6.2	5.2	8.1 ^g
T ₈	5.60	5.51	5.38	5.06	4.79	5.27 ^a	13.2	11.3	10.7	7.3	6.3	9.8 ^c
T ₉	5.55	5.43	5.29	4.94	4.71	5.18 ^{ab}	12.8	10.0	9.8	7.6	5.3	9.1 ^f
T ₁₀	5.49	5.38	5.19	4.94	4.72	5.14 ^{bcd}	12.6	11.4	7.8	7.0	6.4	9.0 ^f
T ₁₁	5.57	5.15	5.04	4.89	4.62	5.05 ^d	13.1	11.6	9.7	8.1	7.0	9.9 ^c
T ₁₂	4.93	4.79	4.62	4.59	4.52	4.69 ^f	11.4	9.8	8.0	6.3	5.4	8.2 ^g
Mean	5.35 ^a	5.24 ^b	5.09 ^c	4.86 ^d	4.68 ^e		13.2 ^a	11.7 ^b	9.9 ^c	8.1 ^d	6.3 ^e	
LSD (<i>p</i> =0.05)	A– 0.06, B– 0.08, A×B– 0.21						A– 0.12, B– 0.17, A×B– 0.42					
SEm(±)	A– 0.02, B– 0.02, A×B– 0.06						A– 0.04, B– 0.07, A×B– 0.15					

CEC, Cation exchange capacity; * A, Depths; B, Treatments; * Mean values followed by the same lowercase letter within a column are not significantly different (*p*= 0.05) according to Tukey's HSD test. Treatment details are given under Materials and Methods.

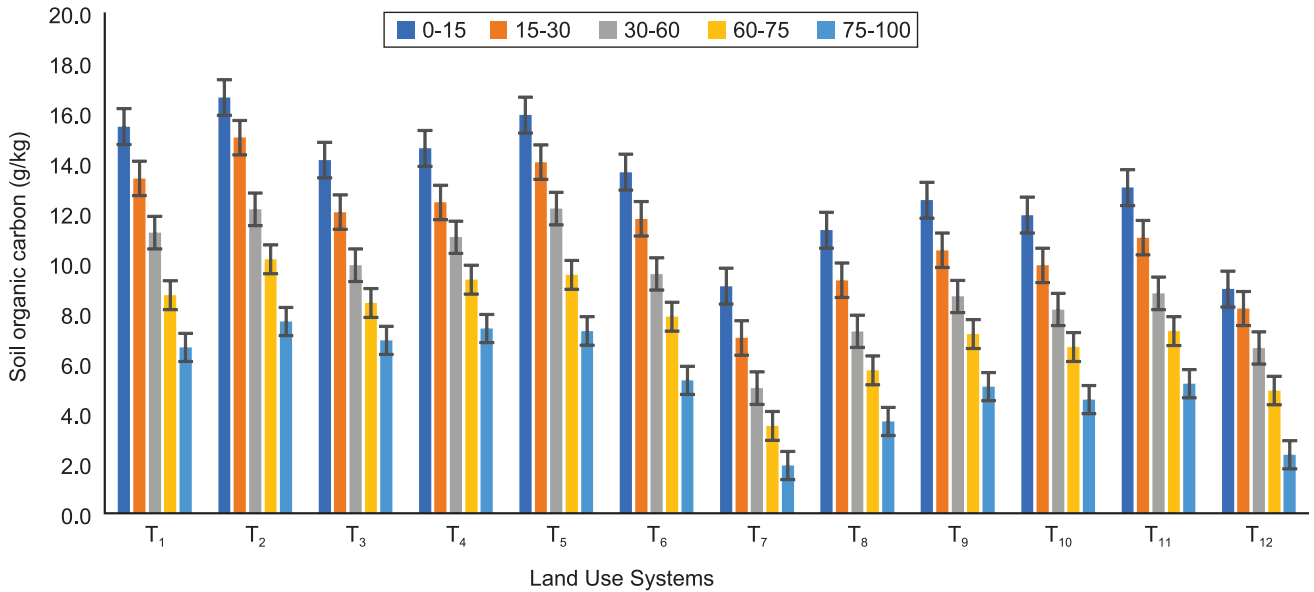


Fig. 1 Effect of various land use systems on soil organic carbon content at different soil depth. Error bars representing standard error of the mean. Treatment details are given under Materials and Methods.

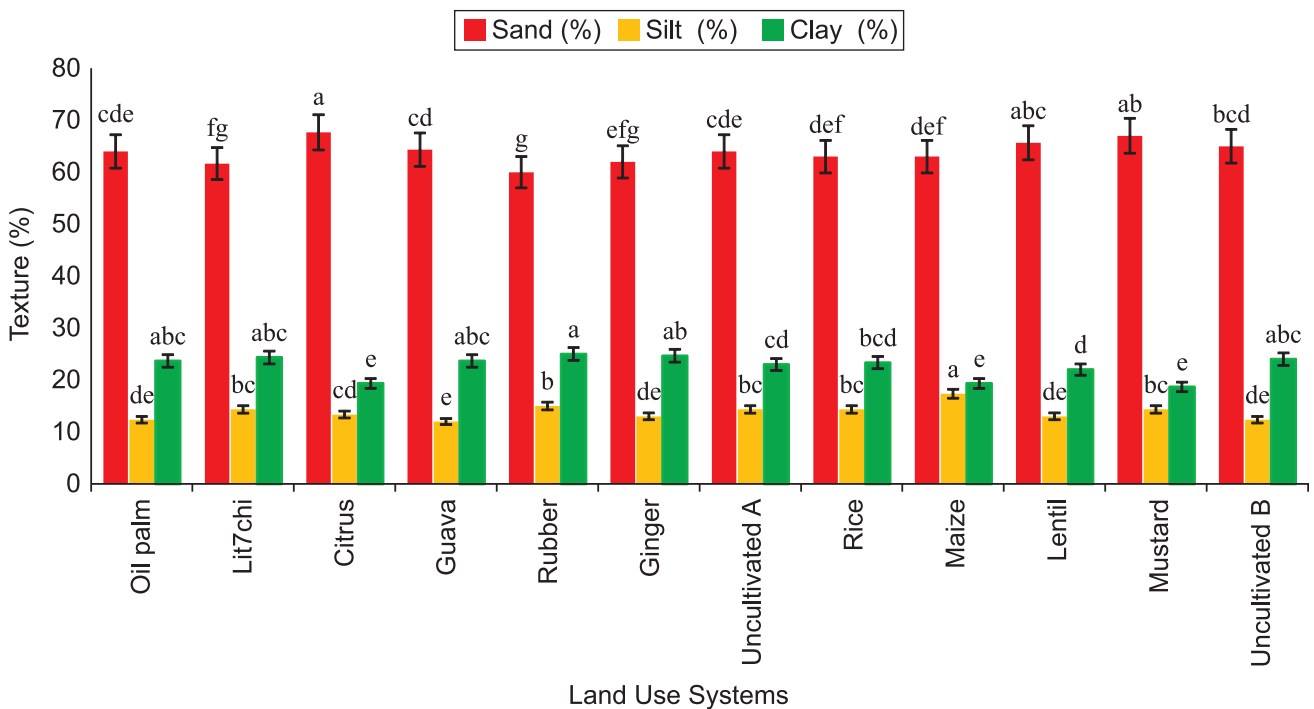


Fig. 2 Effect of different LUSs on soil texture. *Mean value followed by same lowercase letter within the LUSs are not significantly different ($p=0.05$) according to Tukey's HSD test. Treatment details are given under Materials and Methods.

CEC, indicating reduced nutrient retention (Bordoloi *et al.* 2024, Chen *et al.* 2024).

Table 3 shows that the mean available nitrogen (N) ranged from 340 kg/ha in T₁ to 219 kg/ha in the uncultivated, indicating oil palm's effectiveness in maintaining soil N levels, likely, because of organic matter contributions from leaf litter and root turnover (Nyameasem *et al.* 2020). Land use systems including T₂ and T₅ also performed well, with mean N values of 328 kg/ha and 332 kg/ha, respectively.

The uncultivated land use showed the lowest N levels, reflecting significant depletion without specific crop systems or organic inputs. Phosphorus (P) availability ranged from 15.3 kg/ha in T₉ (Vegetable cowpea-rice-maize) to 8.2 kg/ha in T₁₂, with T₉ effectively enhancing soil P through organic residues and nutrient cycling (Ahmadi *et al.* 2024). Potassium (K) levels varied from 140 kg/ha in T₁ to 86.4 kg/ha in T₇, with T₁ and T₂ showing the highest mean K values, suggesting perennial systems help maintain soil K

Table 3 Effect of various land use systems on available nitrogen, phosphorus and potassium at different soil depths

LUSs	Available N (Kg/ha)										Available P (Kg/ha)										Available K (Kg/ha)																																																																																																																																																																																																																														
	Depths (cm)										Depths (cm)										Depths (cm)																																																																																																																																																																																																																														
	0-15	15-30	30-60	60-75	75-100	Mean	0-15	15-30	30-60	60-75	75-100	Mean	0-15	15-30	30-60	60-75	75-100	Mean	0-15	15-30	30-60	60-75	75-100	Mean																																																																																																																																																																																																																											
T ₁	413	386	339	339	266	340 ^a	15.4	14.7	13.8	12.4	11.0	13.5 ^d	175	160	145	124	95.4	140 ^a	404	371	331	280	254	328 ^b	15.9	14.4	13.7	12.2	11.2	13.5 ^d	185	160	134	115	89.3	137 ^b	341	322	289	261	216	286 ^d	16.8	14.3	12.6	11.0	10.7	13.1 ^{ef}	170	153	134	116	95.3	133 ^c	356	341	311	281	226	303 ^c	16.3	14.0	12.7	11.2	10.3	12.9 ^f	179	156	138	116	90.3	135 ^b	381	369	336	308	263	332 ^b	15.3	14.6	13.7	12.1	10.6	13.3 ^{de}	178	152	128	103	85.3	128 ^d	305	292	260	214	198	254 ^f	17.5	16.3	14.6	13.1	12.7	14.8 ^b	145	132	112	89.8	75.0	111 ^g	280	260	223	180	150	219 ^h	10.3	8.8	8.0	7.8	7.1	8.4 ^h	119	98.5	84.7	70.3	59.4	86.4 ⁱ	320	297	271	240	204	266 ^e	15.3	14.7	12.6	11.0	9.6	12.6 ^g	151	135	122	96.3	75.6	115 ^e	317	291	276	237	198	264 ^e	19.7	18.1	14.7	12.6	11.5	15.3 ^a	147	126	114	86.4	69.3	107 ^h	303	283	266	223	176	250 ^f	14.4	13.2	12.5	11.3	11.1	12.5 ^g	144	128	112	90.2	74.5	110 ^{gh}	310	277	254	201	183	245 ^g	16.3	15.1	13.9	12.4	11.4	13.8 ^c	149	130	115	95.4	76.2	112 ^f	282	266	216	191	140	219 ^h	10.0	8.9	7.9	7.4	7.0	8.2 ^h	121	102	86.4	71.3	60.3	88.2 ⁱ	Mean	334 ^a	313 ^b	281 ^c	243 ^d	206 ^e	15.3 ^a	13.9 ^b	12.6 ^c	11.2 ^d	10.3 ^e	12.6 ^c	154 ^a	135 ^b	119 ^c	97.8 ^d	78.8 ^e	Mean	LSD (<i>p</i> =0.05)	A-2.88, B-4.46, A×B-9.96	A-0.16, B-0.26, A×B-0.56	A-0.16, B-0.26, A×B-0.56	A-1.44, B-2.25, A×B-5.03	SEM(±)	A-1.03, B-1.58, A×B-3.55	A-0.06, B-0.08, A×B-0.20	A-0.50, B-0.70, A×B-1.80

*A, Depths; B, Treatments; * Mean values followed by the same lowercase letter within a column are not significantly different (*p*= 0.05) according to Tukey's HSD test. Treatment details are given under Materials and Methods.

Table 4 Effect of various land use systems on DTPA extractable iron, copper and zinc at different soil depths

LUSs	Iron (mg/kg)										Copper (mg/kg)										Zinc (mg/kg)									
	Depths (cm)										Depths (cm)										Depths (cm)									
	0-15	15-30	30-60	60-75	75-100	Mean	0-15	15-30	30-60	60-75	75-100	Mean	0-15	15-30	30-60	60-75	75-100	Mean	0-15	15-30	30-60	60-75	75-100	Mean						
T ₁	70.0	61.9	52.8	40.5	36.2	52.3 ^a	2.70	2.36	1.87	1.58	1.38	1.98 ^c	4.69	4.43	3.93	3.52	2.97	3.91 ^b	4.69	4.43	3.93	3.52	2.97	3.91 ^b						
T ₂	65.5	58.1	50.9	40.5	32.3	49.5 ^b	2.90	2.65	2.13	1.81	1.44	2.19 ^a	4.95	4.50	4.18	3.60	3.30	4.11 ^a	4.95	4.50	4.18	3.60	3.30	4.11 ^a						
T ₃	52.0	49.5	41.7	35.5	28.6	41.5 ^d	2.45	2.15	1.89	1.48	1.23	1.84 ^e	4.20	3.74	3.45	3.00	2.72	3.42 ^d	4.20	3.74	3.45	3.00	2.72	3.42 ^d						
T ₄	52.3	48.8	43.4	33.9	29.2	41.5 ^d	2.51	2.21	1.95	1.53	1.30	1.90 ^d	4.38	3.92	3.48	3.03	2.84	3.53 ^c	4.38	3.92	3.48	3.03	2.84	3.53 ^c						
T ₅	60.3	55.7	49.7	43.5	33.5	48.5 ^c	2.70	2.56	2.10	1.65	1.42	2.09 ^b	4.70	4.51	4.18	3.66	3.19	4.05 ^a	4.70	4.51	4.18	3.66	3.19	4.05 ^a						
T ₆	46.2	40.3	35.7	31.9	25.4	35.9 ^f	2.23	2.02	1.65	1.47	1.11	1.70 ^f	3.75	3.33	3.10	2.72	2.44	3.07 ^f	3.75	3.33	3.10	2.72	2.44	3.07 ^f						
T ₇	45.0	41.6	36.4	30.8	27.0	36.2 ^f	1.42	1.21	1.12	0.97	0.71	1.09 ⁱ	2.84	2.58	2.45	2.20	2.00	2.41 ^h	2.84	2.58	2.45	2.20	2.00	2.41 ^h						
T ₈	51.5	48.5	44.6	32.1	30.4	41.4 ^d	2.10	1.72	1.45	1.20	1.01	1.50 ^h	3.60	3.28	2.92	2.62	2.42	2.97 ^g	3.60	3.28	2.92	2.62	2.42	2.97 ^g						
T ₉	48.6	44.1	42.9	31.7	27.5	39.0 ^e	2.15	1.85	1.63	1.34	1.07	1.61 ^g	3.70	3.40	3.14	2.73	2.47	3.09 ^{ef}	3.70	3.40	3.14	2.73	2.47	3.09 ^{ef}						
T ₁₀	50.2	47.4	43.5	35.4	30.5	41.4 ^d	2.19	1.90	1.64	1.28	1.10	1.62 ^g	3.85	3.42	3.12	2.83	2.54	3.15 ^e	3.85	3.42	3.12	2.83	2.54	3.15 ^e						
T ₁₁	50.2	46.6	42.7	36.8	31.5	41.5 ^d	2.02	1.88	1.52	1.21	1.01	1.53 ^h	3.48	3.27	2.90	2.72	2.37	2.95 ^g	3.48	3.27	2.90	2.72	2.37	2.95 ^g						
T ₁₂	44.0	39.2	35.7	30.6	27.4	35.4 ^f	1.45	1.21	1.10	0.80	0.65	1.04 ^j	2.85	2.66	2.53	2.27	1.98	2.46 ^h	2.85	2.66	2.53	2.27	1.98	2.46 ^h						
Mean	53.0 ^a	48.5 ^b	43.3 ^c	35.3 ^d	30.0 ^e		2.23 ^a	1.98 ^b	1.67 ^c	1.36 ^d	1.12 ^e		3.92 ^a	3.59 ^b	3.28 ^c	2.91 ^d	2.60 ^e		3.92 ^a	3.59 ^b	3.28 ^c	2.91 ^d	2.60 ^e							
LSD ($p=0.05$)	A- 0.88, B- 0.56, A×B- 1.97										A- 0.04, B- 0.02, A×B- 0.10										A- 0.07, B- 0.04, A×B- 0.16									
SEm(±)	A- 0.28, B- 0.18, A×B- 0.63										A- 0.01, B- 0.01, A×B- 0.02										A- 0.02, B- 0.01, A×B- 0.05									

* A, Depths; B, Treatments; * Mean values followed by the same lowercase letter within a column are not significantly different ($p=0.05$) according to Tukey's HSD test. Treatment details are given under Materials and Methods.

through organic matter cycling and root nutrient uptake. Uncultivated LUSs exhibited the lowest K levels due to minimal inputs and continuous leaching.

Table 4 shows the impact of land use change on diethylene triaminepenta acetic acid (DTPA)-extractable Fe, Cu, and Zn across soil depths. Land use T₁ had the highest Fe (52.3 mg/kg) due to organic inputs and low disturbance, while uncultivated LUSs (T₇ and T₁₂) showed the lowest Fe. Cu was highest in T₂ (2.19 mg/kg) and was also elevated in T₉ and T₁₁, reflecting the benefits of diverse rotations on nutrient cycling. Land use T₁₂ had the lowest Cu, highlighting the negative impact of minimal management. For DTPA-extractable Zn, litchi had the highest mean value of 4.11 mg/kg, followed by rubber (4.05 mg/kg) and oil palm (3.91 mg/kg). Zinc concentrations decreased with depth in most LUSs. Perennial and diverse cropping systems enhance Fe, Cu, and Zn availability compared to controls (Hamzah *et al.* 2022).

Soil microbial biomass carbon and microbial biomass nitrogen: Microbial biomass in soil, integral to soil organic matter, plays a critical role in decomposing organic materials and storing essential nutrients such as nitrogen, phosphorus and sulphur (Jenkinson and Ladd 1981). Supplementary Fig. 1 shows that MBC and MBN were highest in perennial systems, such as litchi (MBC 368.2 mg/kg, MBN 82.1 mg/kg) and oil palm (MBC 337.8 mg/kg and MBN 77.8 mg/kg), due to continuous supply of organic inputs. Rubber and guava also performed well, with MBC and MBN of 357.7 mg/kg, 67.4 mg/kg, and 311.5 mg/kg, 65.7 mg/kg, respectively. In contrast, annual crops like rice, maize, lentil, and mustard have lower values, reflecting less organic input. Uncultivated LUSs recorded the lowest MBC and MBN in soil, showing the negative impact of lacking vegetation. These results highlighted the superiority of perennial systems in maintaining higher soil microbial biomass compared to annual cropping systems and fallow condition, underscoring their importance for soil health and sustainability (Bell-Dereske *et al.* 2023, Dangi *et al.* 2024).

The present study demonstrated that land use systems (LUSs) significantly influence soil bulk density (BD), soil organic carbon (SOC), and the availability of essential macro and micronutrients. Highest cation exchange capacity was reported in the litchi LUSs. The evaluation of different LUSs revealed that soils under oil palm, litchi, and rubber exhibited improved soil health compared to agricultural and uncultivated LUSs. These systems showed enhanced soil microbial biomass carbon and nitrogen (MBC and MBN), higher major and micro nutrient availability, highlighting their positive impact on soil fertility. Litchi, rubber and oil palm LUSs reduced soil compaction due to deeper rooting and adding continuous organic matter inputs. We inferred from the study that horticultural LUSs has better soil health than agricultural.

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