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Comparative analysis of soil physicochemical properties under *Melia composita*- and *Populus deltoides*-based agroforestry systems and monoculture cropping

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Introduction: Soil degradation and declining soil organic carbon stocks pose major challenges to agricultural sustainability. Agroforestry systems are increasingly recognized for their potential to enhance soil quality, nutrient cycling and carbon sequestration, yet comparative information on *Melia composita*- and *Populus deltoides*-based systems under subtropical conditions remains limited.

Methods: A two-year (March 2021 - February 2023) factorial randomized block field experiment with six replications was conducted in the subtropical Jammu region of India to compare *Melia composita*- and *Populus deltoides*-based agroforestry systems across tree species, distance from the tree base and soil depth. The agroforestry systems were further evaluated against their respective adjacent monoculture cropping controls. Cowpea (*Vigna unguiculata*) and turmeric (*Curcuma longa*) were grown in rotation during each crop cycle. Eight key indicators-pH, electrical conductivity (EC), bulk density (BD), organic carbon (OC), available nitrogen (N), available phosphorus (P), available potassium (K) and soil organic carbon (SOC) stock were quantified.

Results: Among the two agroforestry systems, the *Populus deltoides*-based agroforestry system consistently exhibited superior soil properties, characterized by lower pH and bulk density, higher electrical conductivity and nutrient availability compared with the *Melia composita*-based agroforestry system. Significant spatial variations were observed within AFS, with soil quality significantly improving closer to the tree base and in the upper soil layer. After two crop rotations, both agroforestry systems showed increases in organic carbon, available nutrients and soil organic carbon stock relative to the first rotation. When compared with conventional monoculture, both agroforestry systems significantly enhanced soil organic carbon and available nutrients while reducing soil bulk density. Baseline soil properties at the two control plots were broadly comparable, with no statistically significant differences ($p > 0.05$). Pearson correlations confirmed strong positive associations among OC, N, P, K and SOC stock and negative associations of these properties with pH and BD.

Conclusions: The findings demonstrate that tree-based agroforestry systems, particularly those incorporating *Populus deltoides*, improve soil health, enhance system resilience and promote sustainable land management while contributing to carbon sequestration in subtropical agricultural landscapes.

KEYWORDS

carbon sequestration, distance gradient, organic carbon, soil nutrients, subtropical agroecosystems, sustainable land use, tree-crop interactions

1 Introduction

Soil is fundamental to civilizations, supporting more than 95% of global food production (Borrelli et al., 2020). However, the escalating global crisis of soil degradation poses a significant threat to agricultural sustainability and food security. An estimated 33% of the world's land area is affected by soil degradation, resulting in substantial productivity losses (Smith et al., 2024). In India, the situation is particularly alarming, with approximately 120.72 million hectares out of 328.73 million hectares affected by land degradation (Srinivasarao et al., 2021). In many parts of India, average soil organic carbon (SOC) has declined from about 1% to 0.3% over the past 70 years (Lahmar and Ruellan, 2007), with concomitant reductions in nutrient availability. Unsuitable agricultural practices - deforestation, shifting cultivation, intensive tillage and imbalanced fertilizer use - together with climate change-induced stress, are recognized as major drivers of this degradation (Miralles et al., 2009; Mueller, 2013; Montanarella, 2015; Paustian et al., 2016; FAO, 2020; Borrelli et al., 2020). Given these challenges, innovative and integrative land management approaches are urgently required.

Agroforestry - the intentional integration of trees with crops and/or livestock - is widely recognized as a multifunctional land-use strategy for improving soil health, food security, environmental sustainability and climate resilience (Kumar et al., 2008; Araujo et al., 2012; Nair, 2013; Udawatta et al., 2017). In the subtropical foothills of the Indian Shivaliks, agroforestry has formed a central component of mixed farming supplying timber, fuelwood, fodder and crop diversification on smallholdings. Tree litter and fine-root turnover serve as key inputs of organic matter, replenishing soil fertility and improving aggregate stability (Pralhad et al., 2020; Silva et al., 2011). However, the magnitude and sign of these benefits are highly context-specific, varying with tree species, stand age, density, intercrop and climate (Singh et al., 1989; Szott et al., 1991; Mohsin et al., 1996; Mugendi and Nair, 1997). Fast-growing species with high resource demand may, in fact, depress soil nutrient and moisture status near tree rows, particularly during early crop growth (Jose, 2009; Nasielski et al., 2015; Rivera et al., 2016; Tan et al., 2023).

Populus deltoides (poplar; Salicaceae) is an exotic, fast-growing, winter-deciduous species and is arguably the most economically important industrial agroforestry tree of northern India valued for pulp, plywood and matchwood (Singh and Sharma, 2007). It is commonly planted on field boundaries or in wider-spaced blocks where it permits intercropping of fodder, wheat, sugarcane, turmeric and vegetables. *Melia composita* (locally known as Dek;

Meliaceae) is an indigenous, fast-growing, deciduous tree gaining popularity in subtropical India for high-value timber, biomass and ecosystem services. The wood is also used for packing cases, ceiling planks, building purposes, agricultural implements, pencils, match boxes, splints, musical instruments and tea boxes. Due to their fast growth and multiple uses these tree species are preferred for agroforestry plantations in the states of Punjab, Haryana & Uttar Pradesh (UP) and has the potential of being grown in subtropical area of Jammu & Kashmir (J&K), India.

Among the diverse crops integrated into northern Indian agroforestry, cowpea [*Vigna unguiculata* (L.) Walp.] and turmeric (*Curcuma longa* L.) hold particular promise. Cowpea, as a fodder legume of the family Fabaceae, contributes substantially to soil nitrogen enrichment through symbiotic biological N₂-fixation (typically 30–80 kg N ha⁻¹ per season) and provides protein-rich fodder for livestock (Singh et al., 2003; Pankaj et al., 2024). Turmeric, a *Rabi* rhizomatous spice of the family Zingiberaceae, is known to tolerate partial shade and therefore performs well beneath tree canopies, offering a high-value commercial option for tree-based systems (Dash et al., 2024). The cowpea-turmeric rotation thus couples biological nitrogen replenishment with a shade-tolerant cash crop, generating complementary economic and ecological returns and increasing the year-round utilization of below-canopy space.

Although *Populus deltoides*-based agroforestry has been studied extensively in Indian Punjab, Haryana and Uttarakhand (Sirohi and Bangarwa, 2017; Sharma et al., 2021; Pankaj et al., 2024), comparable data on *Melia composita*-based systems under field conditions are scarce, especially in the Shivalik subtropics. Moreover, four specific knowledge gaps remain: (i) there is little comparative information on the soil response under *M. composita* vs *P. deltoides* when integrated with a legume-spice rotation such as cowpea-turmeric; (ii) within-system spatial heterogeneity - how soil properties change with distance from the tree base - has rarely been quantified together with depth gradients in these systems; (iii) interaction effects (species × distance, species × depth) on soil quality have seldom been reported, despite their agronomic relevance to intercrop placement; and (iv) most existing studies compare AFS with monoculture without explicitly verifying baseline comparability of control plots, which limits attribution of post-experimental differences to the tree component. The present two-year field study addresses all four gaps by evaluating, against baseline-comparable adjacent controls, the effects of *M. composita*- and *P. deltoides*-based agroforestry with a cowpea-turmeric rotation on a comprehensive suite of soil physicochemical properties under subtropical conditions of the Jammu region of India.

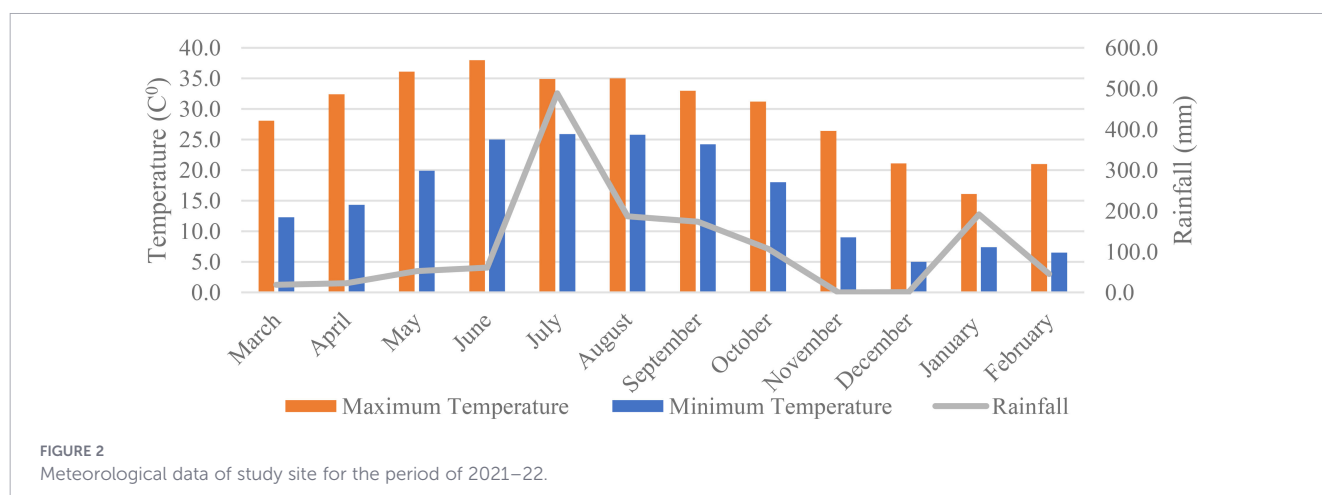
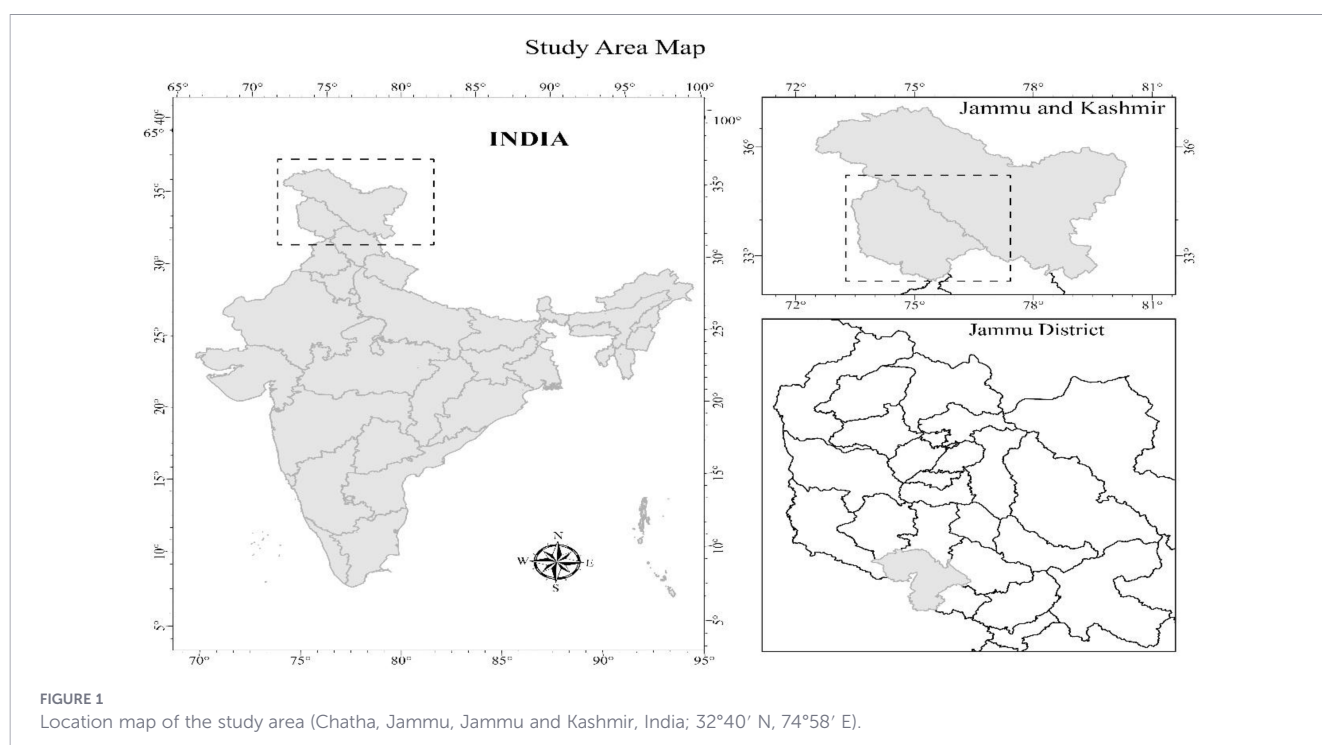
2 Materials and methods

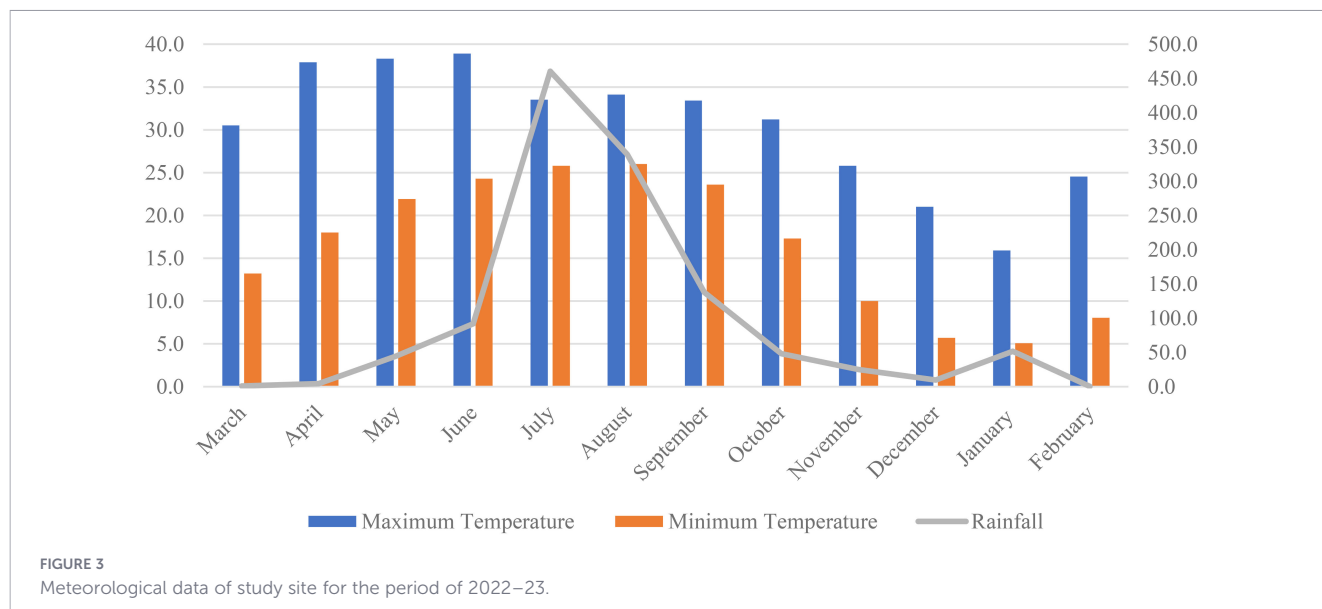
2.1 Study site description

The two-year field experiment was conducted from March 2021 to February 2023 at the experimental farm of the Division of Silviculture and Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu (SKUAST-J), located at Chatha, Jammu and Kashmir, India ($32^{\circ}40' \text{ N}$, $74^{\circ}58' \text{ E}$; 332 m a.m.s.l.; [Figure 1](#)). The site lies in the Shivalik subtropical foothill agro-climatic zone, characterized by hot, dry summers (April–June; maximum temperature $42\text{--}45^{\circ}\text{C}$), a humid south-west monsoon (July–September) and cool winters. The coldest months are December and January, during which the mean monthly minimum temperature falls to approximately $6\text{--}8^{\circ}\text{C}$, with extreme minima occasionally below 5°C in January. The long-term average annual rainfall ranges from 1,100 mm to 1,250

mm. During the experimental period, total annual rainfall was approximately 1,347 mm in 2021–22 and 1,213 mm in 2022–23. Detailed monthly rainfall and temperature distributions are presented in [Figure 2](#) (2021–22) and [Figure 3](#) (2022–23).

Prior to the experiment (February 2021), baseline soil samples were collected from both the *Melia composita* and *Populus deltoides* plantations and from their respective adjacent control plots. To match the post-experiment sampling design, three composite samples were drawn at each of the three pre-defined distances (0–1 m, 1–2 m and 2–3 m from a reference tree-row position) and at two depths (D1: 0–15 cm; D2: 15–30 cm) and the corresponding values were averaged across distances for the baseline summary. Baseline soil properties at the two control plots (C1 adjacent to S1; C2 adjacent to S2) were broadly comparable, with differences within the typical spatial variability of agricultural soils of the region ([Table 1](#)) and no statistically significant variation was absorbed in pH, EC, bulk density, organic carbon, available N, P or K between





C1 and C2 (independent t-test, $p > 0.05$). This baseline comparability supports valid attribution of subsequent differences to the tree component.

2.2 Experimental design and treatments

The study was conducted in pre-established plantations of *Melia composita* and *Populus deltoides*, both planted at a spacing of 6×4 m. At the commencement of the experiment, the *M. composita* stand was 5 years old whereas the *P. deltoides* stand was 10 years old. The age difference was a deliberate methodological choice: in the Jammu region, *P. deltoides* attains commercially mature canopy structure by approximately 8–10 years, while *M. composita* attains comparable mid-rotation maturity over a somewhat similar time-frame but is often deployed as a 5–7 year short-rotation crop on smallholder lands. Each stand therefore represents a typical mid-rotation farmer-relevant scenario for its species. Equal-age comparisons would have required a fresh, parallel

planting and an additional 5–7 years before agroforestry effects could be detected. As a consequence, the differences attributable to the *P. deltoides* system in this study reflect both species characteristics and canopy maturity (see Sections 4.2 and 5).

The agroforestry experiment followed a factorial randomized block design (FRBD) with six replications and three factors:

- Agroforestry species (S) - two levels: S1 = *Melia composita*-based AFS; S2 = *Populus deltoides*-based AFS.
- Distance from tree base (P) - three levels: P1 (0–1 m), P2 (1–2 m), P3 (2–3 m).
- Soil depth (D) - two levels: D1 (0–15 cm), D2 (15–30 cm).

Within each AFS, cowpea (Kharif fodder) and turmeric (Rabi) were grown in rotation as intercrops for two consecutive crop cycles (cowpea: March 2021–May 2021 and March 2022–May 2022; turmeric: May 2021–February 2022 and May 2022–February 2023). In parallel, two monoculture (sole crop) control

TABLE 1 Baseline (pre-experiment) physicochemical properties of soils at the *Melia composita* and *Populus deltoides* plantation sites and their adjacent control plots, averaged across three distances.

S. no.	Parameter	S1		C1		S2		C2	
		D1	D2	D1	D2	D1	D2	D1	D2
1	pH	7.47	7.61	8.07	8.18	7.29	7.36	7.87	7.95
2	EC (dS m ⁻¹)	0.29	0.26	0.24	0.21	0.31	0.29	0.23	0.20
3	Bulk density (g cm ⁻³)	1.33	1.41	1.40	1.48	1.27	1.35	1.38	1.47
4	Soil organic carbon (%)	0.46	0.41	0.34	0.26	0.55	0.51	0.33	0.26
5	Available nitrogen (kg ha ⁻¹)	241.75	211.67	234.50	217.78	271.78	249.23	246.89	221.34
6	Available phosphorus (kg ha ⁻¹)	14.98	12.91	13.67	11.54	16.94	15.47	13.51	11.86
7	Available potassium (kg ha ⁻¹)	117.42	104.57	106.45	95.52	146.74	137.85	107.24	95.73
8	Total SOC stock (Mg ha ⁻¹)	9.17	8.67	7.14	5.77	10.47	10.32	6.83	5.73

S1, *Melia composita* based AFS; S2, *Populus deltoides* based AFS. C1 is the monoculture control adjacent to S1; C2 is the monoculture control adjacent to S2. D1, 0–15 cm soil depth; D2, 15–30 cm soil depth. No significant differences were observed between control plots C1 and C2 for any parameter (independent t-test, $p > 0.05$).

treatments were maintained, each immediately adjacent to the corresponding AFS but outside the tree influence:

- C1 = sole cowpea-turmeric rotation adjacent to the *Melia composita* stand (treated as control for S1).
- C2 = sole cowpea-turmeric rotation adjacent to the *Populus deltoides* stand (treated as control for S2).

C1 and C2 thus represent two independent monoculture treatments (rather than pseudo-replicates), each spatially matched to its AFS for soil parent material and microclimate. Within each AFS, plots of 4 m × 1 m were laid out at each of the three distances (P1, P2, P3) along randomly selected inter-row strips. Equally sized plots were laid out within each control area for soil sampling.

2.3 Crop cultivation practices

Cowpea (*Vigna unguiculata* L. Walp. cv. CL-367) for fodder purpose was sown in mid-March and harvested in late May of each crop cycle. Sowing was done with seed-cum-fertilizer-drill in rows, 30 cm apart with seed rate of 25 kg ha⁻¹. Prior to sowing seed inoculation was done with liquid biofertilizer *Burkholderia seminalis*. Basal fertilization comprised 18 kg N ha⁻¹ as urea and 55 kg P₂O₅ ha⁻¹ as single super phosphate, applied at sowing. Two manual weeding were undertaken at 10 and 30 days after sowing (DAS). No herbicide was applied. Insect-pest management followed the PAU recommended package of practices (Anonymous, 2021).

Turmeric (*Curcuma longa* L. cv. Punjab Haldi-2) was planted in late May using healthy mother rhizomes at 45 cm × 15 cm spacing furrows, with a seed rhizome rate of 18000 kg ha⁻¹. Before sowing 25–30 tonnes of well-rotten farmyard manure per ha was applied. A basal dose of 25 kg ha⁻¹ P₂O₅ (60 kg Single Superphosphate) and 25 kg ha⁻¹ K₂O (16 Kg Muriate of Potash) was drilled at the time of planting. Five manual weeding were carried out at 30, 45, 60, 90 and 120 DAP, accompanied by light earthing-up at 60 and 90 DAP. Turmeric was harvested at full leaf senescence in February of the following year.

Irrigation was applied uniformly across AFS and control plots through surface flooding. Cowpea received approximately 3 irrigations per cycle (pre-sowing, 25 and 45 DAS) and turmeric received approximately ten (at 15-day intervals from 15 DAP until the end of October, with one further irrigation in December).

2.4 Soil sampling and laboratory analysis

Soil samples were collected from every experimental plot at all three distances (P1, P2, P3) and both depths (D1, D2) at the end of each crop cycle (February 2022 and February 2023). At each distance × depth combination, three sub-samples were obtained with a soil auger and composited to yield one representative sample per plot. Within each AFS, the total replication was therefore n = 6 (replications) × 3 (distances) × 2 (depths) per cycle. Control plots were sampled at the same two depths (D1, D2) with n = 6 replications per depth per cycle. All samples were air-dried under shade, crushed, passed through a 2-mm sieve and stored in labelled

polyethylene bags prior to analysis. The methods used for the laboratory determination of each soil parameter are summarized in Table 2.

2.5 Statistical analysis

Data were analysed using R software (R Core Team). For the AFS experiment, a three-way factorial analysis of variance (ANOVA) was performed with agroforestry species (S), distance from tree base (P) and soil depth (D) as fixed factors. All two-way (S × P, S × D, P × D) and the three-way (S × P × D) interactions were tested. Treatment means were separated using the critical difference (CD) at p ≤ 0.05. For comparisons between each AFS and its corresponding monoculture control (S1 vs C1; S2 vs C2), independent-sample t-tests at p ≤ 0.05 were applied separately for each soil depth and at each sampling event. Where relevant, percentage changes were computed relative to the appropriate control. Throughout the manuscript, significance levels are explicitly stated; the qualifiers “higher” and “lower” are used only where differences were statistically significant.

3 Results

Soil physico-chemical responses are presented in two parts. Section 3.1 isolates the within-AFS effects of tree species (S1 vs S2), distance from the tree base (P1, P2, P3) and soil depth (D1, D2) on eight soil indicators (pH, electrical conductivity, bulk density, organic carbon, available N, P and K and soil organic carbon stock). Section 3.2 then contrasts each agroforestry system with its paired sole-crop control (S1 vs C1 and S2 vs C2). Section 3.3 traces the temporal trend in carbon and nutrient stocks across the two crop rotations and Section 3.4 presents the inter-correlations among the measured properties. Soil moisture, being linked to crop water status rather than to soil chemistry, is treated in a separate section of the paper.

TABLE 2 Soil parameters and methods employed for their laboratory estimation.

S. no.	Parameter	Method of estimation
1	pH	1:2.5 Soil:water suspension (Jackson, 1973)
2	EC (dS m ⁻¹)	1:2.5 Soil:water suspension (Jackson, 1973)
3	Bulk density (g cm ⁻³)	Core tube method (Blake and Hartge, 1986)
4	Soil organic carbon (%)	Rapid titration method (Walkley and Black, 1934)
5	Available nitrogen (kg ha ⁻¹)	Alkaline KMnO ₄ method (Subbiah and Asija, 1956)
6	Available phosphorus (kg ha ⁻¹)	Olsen's method (Olsen, 1954)
7	Available potassium (kg ha ⁻¹)	Neutral 1 N NH ₄ OAc extraction (Merwin and Peech, 1951)
8	Total SOC stock (Mg ha ⁻¹)	Bulk density × OC × depth (Kukal and Benbi, 2009)

3.1 Effects of tree species, distance and depth within agroforestry systems

3.1.1 Effects of tree species on soil properties

Across both rotations, the two AFS differed significantly in nearly all soil indicators (Table 3; Figure 4). At the end of the second rotation (2023), S2 had a 28.6% higher organic carbon content ($p < 0.001$), a 19.4% higher available nitrogen stock, a 25.8% higher available phosphorus level and a 27.6% higher available potassium level than S1 and built up an SOC stock that was 24.0% larger (11.43 vs 9.22 Mg ha⁻¹). Bulk density was significantly lower under S2 (1.28 vs 1.34 Mg m⁻³; $p = 0.006$) and soil reaction was less alkaline under S2 (pH 7.13

vs 7.41; $p < 0.001$). Electrical conductivity was marginally but significantly higher under S2 ($p = 0.018$). The same direction of effects was already evident at the end of the first rotation and intensified during the second.

3.1.2 Effect of distance from tree on soil properties

A gradient of decreasing soil fertility with distance from the tree base was evident for nutrient-related indicators (Table 4; Figure 5). Means at P1 were significantly higher than at P3 for organic carbon (+15.3%), available nitrogen (+19.2%), available phosphorus (+15.1%) and available potassium (+25.6%); the F-tests across the

TABLE 3 Effect of tree species on soil physico-chemical properties under two crop rotations (means across distances and depths; n = 36 per cell).

Parameter (units)	S1 (2022)	S2 (2022)	p (2022)	S1 (2023)	S2 (2023)	p (2023)
pH	7.52 ± 0.03	7.31 ± 0.02	< 0.001	7.40 ± 0.02	7.13 ± 0.02	< 0.001
EC (dS m ⁻¹)	0.285 ± 0.005	0.309 ± 0.002	< 0.001	0.311 ± 0.007	0.332 ± 0.004	0.018
BD (Mg m ⁻³)	1.376 ± 0.021	1.326 ± 0.014	< 0.01	1.338 ± 0.015	1.279 ± 0.014	0.006
OC (%)	0.438 ± 0.011	0.549 ± 0.009	< 0.001	0.462 ± 0.012	0.597 ± 0.010	< 0.001
N (kg ha ⁻¹)	233.9 ± 5.1	270.8 ± 5.0	< 0.001	242.1 ± 4.3	289.0 ± 6.1	< 0.001
P (kg ha ⁻¹)	14.82 ± 0.28	17.19 ± 0.32	< 0.001	16.69 ± 0.36	21.00 ± 0.37	< 0.001
K (kg ha ⁻¹)	114.5 ± 2.1	143.4 ± 2.0	< 0.001	120.2 ± 3.1	153.3 ± 2.8	< 0.001
SOC stock (Mg ha ⁻¹)	9.01 ± 0.23	10.90 ± 0.17	< 0.001	9.22 ± 0.22	11.43 ± 0.17	< 0.001

Values are mean ± SEM.

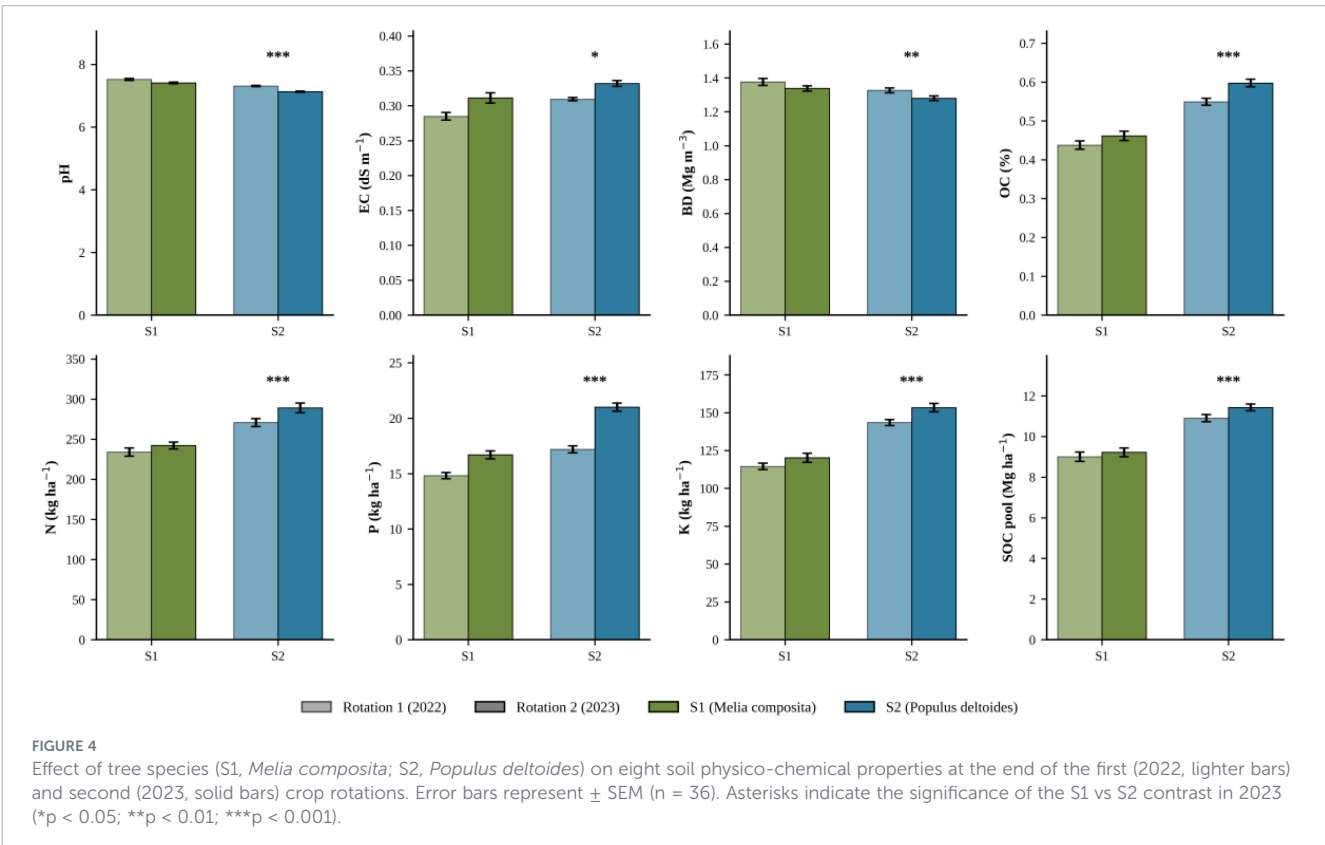


TABLE 4 Effect of distance from tree base on soil physico-chemical properties at the end of the second crop rotation (2022–23).

Parameter (units)	P1 (<1 m)	P2 (1–2 m)	P3 (2–3 m)	F	p
pH	7.17 ± 0.03	7.30 ± 0.04	7.33 ± 0.04	5.90	0.004
EC (dS m ⁻¹)	0.333 ± 0.009	0.321 ± 0.007	0.311 ± 0.006	2.12	0.128
BD (Mg m ⁻³)	1.278 ± 0.015	1.304 ± 0.019	1.344 ± 0.020	3.35	0.041
OC (%)	0.565 ± 0.018	0.533 ± 0.022	0.490 ± 0.016	4.04	0.022
N (kg ha ⁻¹)	290.1 ± 7.4	263.2 ± 7.4	243.4 ± 6.5	10.86	< 0.001
P (kg ha ⁻¹)	20.08 ± 0.59	19.00 ± 0.61	17.45 ± 0.59	4.90	0.010
K (kg ha ⁻¹)	153.5 ± 3.9	134.6 ± 4.3	122.2 ± 4.4	13.99	< 0.001
SOC stock (Mg ha ⁻¹)	10.80 ± 0.33	10.34 ± 0.35	9.83 ± 0.28	2.26	0.112

Values are means ± SEM across both species and depths (n = 24 per distance).

three distances were significant at $p < 0.001$ for N and K and $p < 0.05$ for OC and P. pH and BD increased with distance from the tree base, both reaching their highest values at P3, while EC declined with distance. The SOC stock followed the same direction (P1 > P3) but the F-test did not reach the 0.05 threshold ($p = 0.112$).

3.1.3 Effect of depth on soil properties

The surface layer (D1, 0–15 cm) consistently held more organic carbon, available macronutrients and SOC stock than the sub-surface layer (D2, 15–30 cm) (Table 5; Figure 6). Relative to D1, the D2 means were lower for OC ($p = 0.013$), available N ($p < 0.001$) and available P ($p = 0.007$). pH and BD were significantly higher in

D2 ($p < 0.05$). The depth effect on K and on the SOC stock showed the same direction but did not reach the 0.05 significance threshold in the pooled-species t-test (Table 5); within S2, however, the depth difference in the SOC stock was significant (Figure 6).

3.1.4 Interaction effects

Three-way factorial ANOVA ($S \times P \times D$) for the 2022–23 dataset revealed highly significant main effects of species (S), distance (P) and depth (D) for most parameters (Table 6). Significant interactions were restricted to a few cases: the $S \times P$ interaction was significant for pH ($p = 0.002$) and for available N ($p = 0.010$) and the $P \times D$ interaction was significant for available N ($p = 0.042$). The $S \times D$ and three-way $S \times$

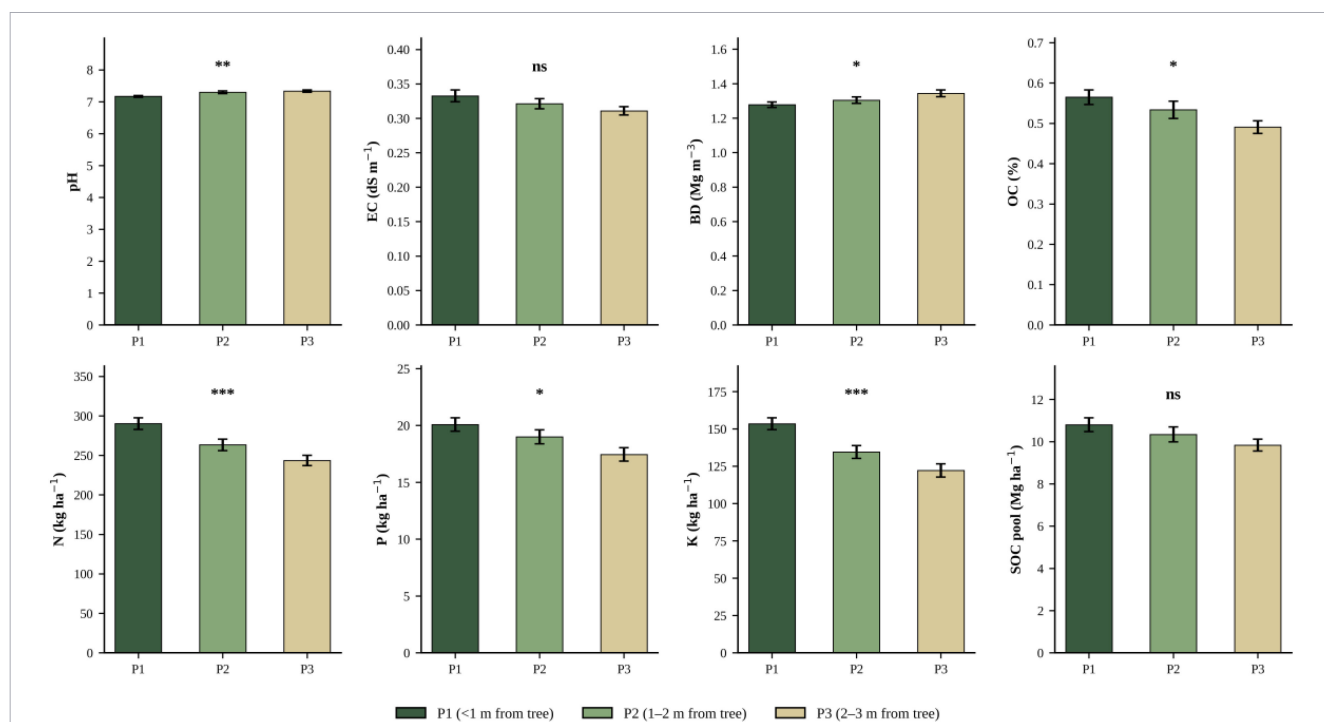


FIGURE 5

Effect of distance from the tree base (P1 < 1 m; P2 1–2 m; P3 2–3 m) on eight soil physico-chemical properties at the end of the second crop rotation (2022–23), averaged across S1 and S2 and across both depths. Error bars represent ± SEM (n = 24). Asterisks indicate the significance of the one-way ANOVA F-test across the three distances (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant).

TABLE 5 Effect of soil depth on physico-chemical properties at the end of the second crop rotation (2022-23), averaged across both species and the three distance positions ($n = 36$ per depth).

Parameter (units)	D1 (0–15 cm)	D2 (15–30 cm)	Δ (%)	p
pH	7.20 $\pm$ 0.03	7.33 $\pm$ 0.03	+1.8	0.004
EC (dS m ⁻¹)	0.329 $\pm$ 0.007	0.314 $\pm$ 0.005	-4.7	0.077
BD (Mg m ⁻³)	1.284 $\pm$ 0.013	1.333 $\pm$ 0.016	+3.8	0.023
OC (%)	0.557 $\pm$ 0.013	0.502 $\pm$ 0.017	-9.9	0.012
N (kg ha ⁻¹)	283.4 $\pm$ 5.7	247.7 $\pm$ 6.0	-12.6	< 0.001
P (kg ha ⁻¹)	19.80 $\pm$ 0.49	17.89 $\pm$ 0.49	-9.7	0.007
K (kg ha ⁻¹)	142.0 $\pm$ 3.9	131.5 $\pm$ 4.0	-7.4	0.063
SOC stock (Mg ha ⁻¹)	10.68 $\pm$ 0.22	9.97 $\pm$ 0.30	-6.7	0.059

$\Delta\%$ is the change at D2 relative to D1.

$P \times D$ interactions were non-significant for all parameters, indicating that the species effect was broadly consistent across depths.

3.2 Agroforestry systems versus monoculture controls

Comparing each AFS with its paired sole-crop control at the 0–15 cm depth at the end of the second rotation revealed large, consistent advantages of agroforestry over monoculture (Table 7; Figure 7). Under S1, organic carbon was 66.7% higher, available N 18.7% higher, available P 31.6% higher, available K 24.2% higher and the SOC stock 56.3% larger than under C1 (all $p < 0.01$). Under S2, the advantages were even larger: OC was 102.0% higher, available N 37.9% higher, available P 60.9% higher, available

K 60.2% higher and the SOC stock 85.8% larger than under C2 (all $p < 0.001$). Soil reaction was significantly less alkaline under both AFS (S1: -7.5%; S2: -9.5%) and bulk density was lower under both (significant for S1, $p = 0.004$; near-significant for S2). Electrical conductivity was 22–28% higher under AFS than under controls, consistent with greater organic matter mineralisation. Baseline C1 vs C2 contrasts at the 0–15 cm depth were not significant for most parameters (Welch t-test, $p > 0.05$), supporting the validity of the paired comparison.

3.3 Temporal trend across two rotations

From the pre-experiment baseline (February 2021) through the end of the second crop rotation (2022-23), the two AFS

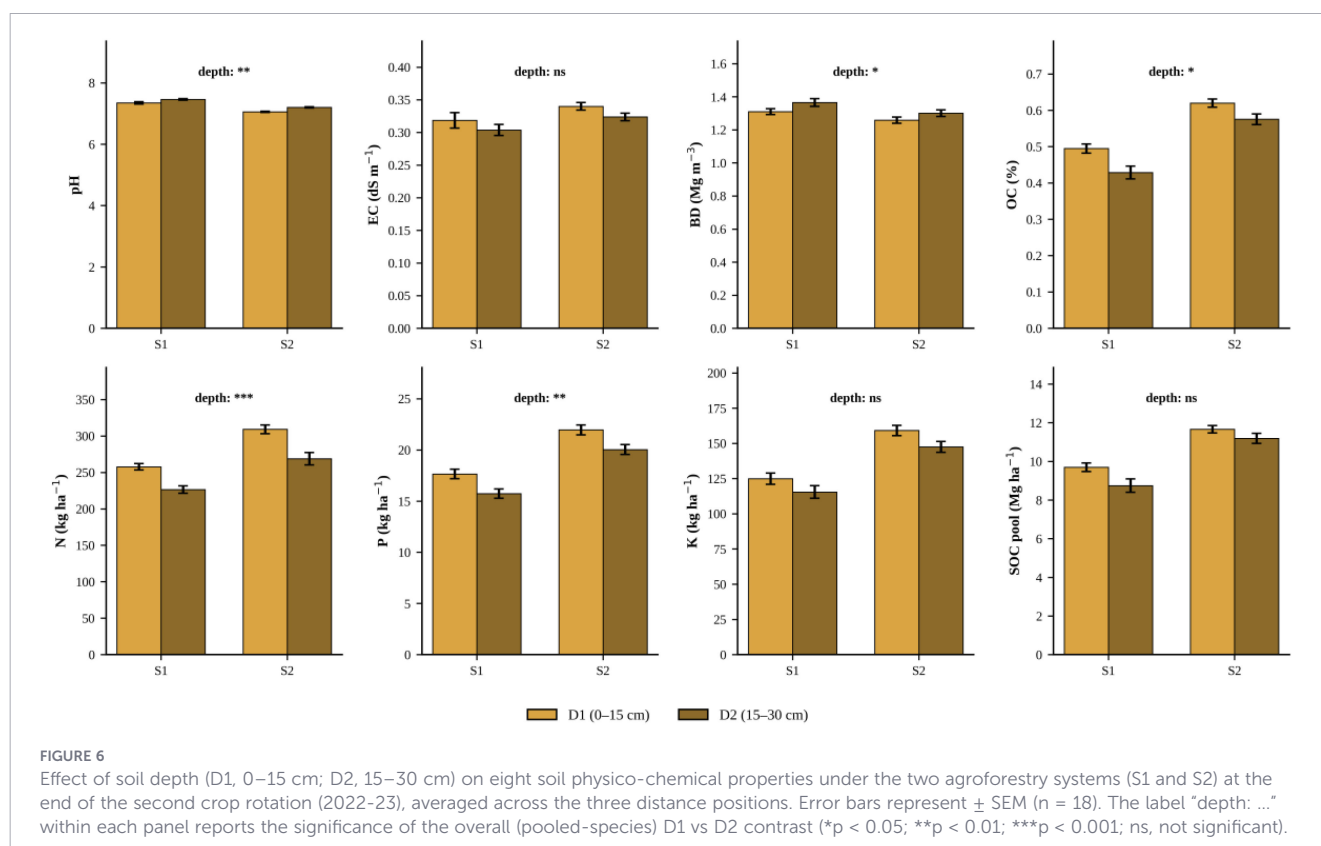


TABLE 6 F-values and significance levels (in parentheses) of main effects and interactions in a three-way factorial ANOVA (species S × distance P × soil depth D) for eight soil indicators, 2022–23.

Source	pH	EC	BD	OC	N	P	K	SOC
S	210.44***	5.90*	8.57**	122.96***	147.45***	106.54***	159.34***	78.10***
P	28.45***	2.17ns	3.69*	12.36***	48.98***	13.37***	48.07***	4.98**
D	44.99***	3.30ns	6.02*	20.32***	85.73***	21.11***	16.15***	8.13**
S×P	7.22**	0.53ns	0.35ns	2.81ns	4.98**	0.08ns	0.15ns	1.57ns
S×D	0.64ns	0.01ns	0.11ns	0.78ns	1.42ns	0.00ns	0.16ns	0.91ns
P×D	0.53ns	0.02ns	0.13ns	0.44ns	3.36*	0.14ns	0.51ns	0.61ns
S×P×D	0.62ns	0.20ns	0.19ns	0.33ns	0.02ns	0.04ns	0.03ns	0.22ns

Significance: ***p < 0.001; **p < 0.01; *p < 0.05; ns, not significant. Degrees of freedom: S (1), P (2), D (1), S×P (2), S×D (1), P×D (2), S×P×D (2), residual (60).

TABLE 7 Comparison of each agroforestry system with its paired sole-crop control at the 0–15 cm depth, end of the second crop rotation (2022–23).

Parameter	S1	C1	Δ% (S1 vs C1)	S2	C2	Δ% (S2 vs C2)
pH	7.35	7.95	-7.5 (**)	7.06	7.80	-9.5 (***)
EC (dS m ⁻¹)	0.319	0.248	+28.3 (***)	0.340	0.277	+22.6 (***)
BD (Mg m ⁻³)	1.310	1.392	-5.9 (**)	1.258	1.357	-7.2 (ns)
OC (%)	0.495	0.297	+66.7 (***)	0.620	0.307	+102.0 (***)
N (kg ha ⁻¹)	257.7	217.2	+18.7 (***)	309.2	224.3	+37.9 (***)
P (kg ha ⁻¹)	17.65	13.41	+31.6 (***)	21.96	13.64	+60.9 (***)
K (kg ha ⁻¹)	124.9	100.6	+24.2 (**)	159.1	99.3	+60.2 (***)
SOC stock (Mg ha ⁻¹)	9.70	6.20	+56.3 (***)	11.67	6.28	+85.8 (***)

Significance: ***p < 0.001; **p < 0.01; *p < 0.05; ns, not significant (Welch t-tests). Δ% gives the percent change of the AFS mean relative to the corresponding control. Values are means; n = 18 per AFS cell and n = 6 per control cell.

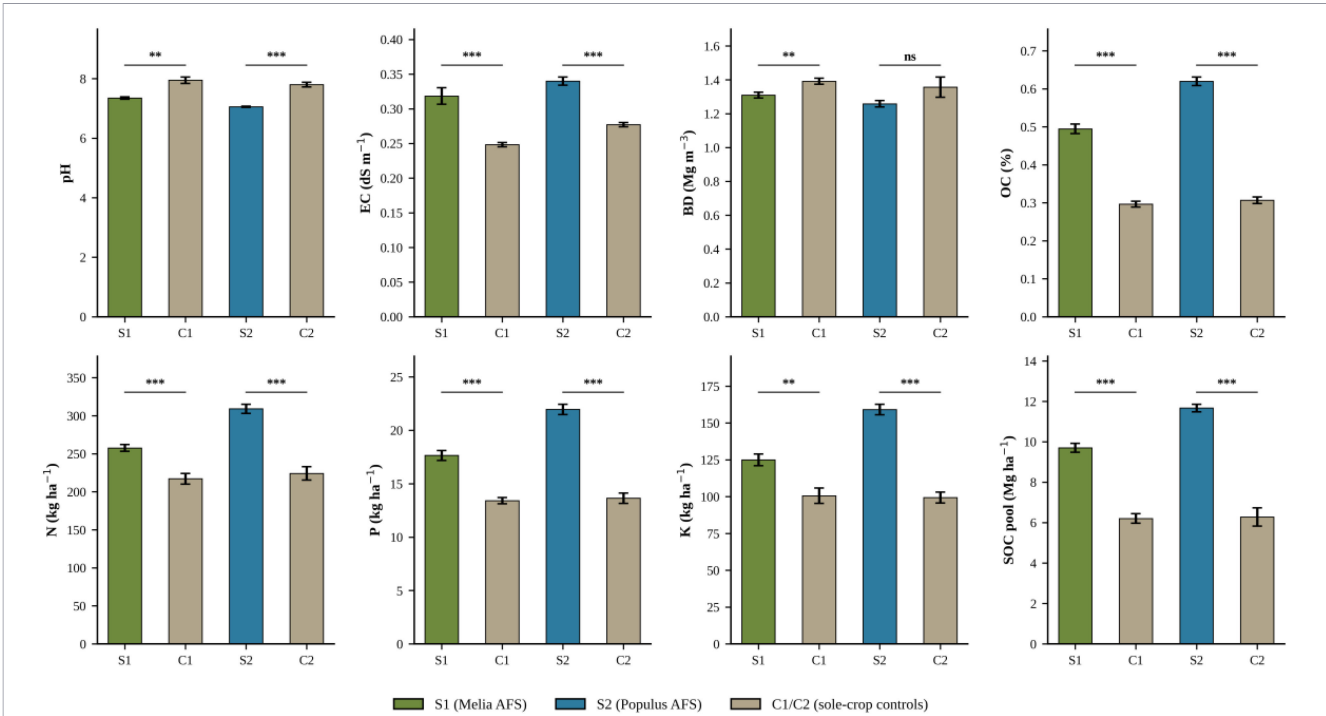


FIGURE 7 Comparison of the two agroforestry systems with their paired sole-crop controls at the 0–15 cm depth at the end of the second crop rotation (2022–23). S1, *Melia composita* AFS; S2, *Populus deltoides* AFS; C1 and C2, corresponding monoculture controls. Error bars represent ± SEM. Brackets and asterisks above the bars denote the significance of the AFS vs control contrasts from Welch t-tests (*p < 0.05; **p < 0.01; ***p < 0.001; ns, not significant).

showed sustained accumulation of organic carbon, available macronutrients and SOC stock, whereas the mean of the two controls either declined or remained stagnant (Figure 8). Under S2, soil quality parameters exhibited a more pronounced improvement across cropping cycles, with consistent increases in soil organic carbon, available N, P and K, as well as SOC stock. In contrast, S1 also showed positive trends, although the magnitude of improvement was comparatively lower. Over the same period the control mean fell for OC, N and K, while available P and SOC stock changed only marginally. The temporal divergence between AFS and controls was sharpest in the second rotation and was greatest under S2.

3.4 Correlations among soil properties

Pearson correlation analysis of the 2022–23 agroforestry dataset ($n = 72$) revealed coherent, biologically meaningful associations among the eight soil indicators (Figure 9). Organic carbon was strongly and positively correlated with the SOC stock ($r = 0.93$, $p < 0.001$), with available N ($r = 0.78$), available K ($r = 0.74$) and available P ($r = 0.63$) - confirming organic matter as the central driver of nutrient supply in these systems. Available N, P and K were mutually intercorrelated ($r = 0.81$ – 0.83). pH was significantly and negatively correlated with all five fertility indicators ($r = -0.68$ to -0.82 , all $p < 0.001$) and bulk density showed moderate negative correlations with OC and available N-P-K ($r = -0.47$ to -0.54). Electrical conductivity showed weaker but significantly positive correlations with the fertility variables ($r = 0.26$ – 0.44).

4 Discussion

The present two-year field study revealed large, consistent and largely significant improvements in soil physico-chemical quality under both agroforestry systems (S1 = *Melia composita*; S2 = *Populus deltoides*) over their paired sole-crop monoculture controls, together with strong within-AFS spatial gradients ($P1 > P2 > P3$) and vertical stratification ($D1 > D2$). The findings are organised here under six thematic sub-headings that follow the structure of the Results.

4.1 Soil reaction, electrical conductivity and bulk density under agroforestry

Both AFS lowered soil pH and bulk density (BD) relative to the sole-crop controls and raised electrical conductivity (EC) (Section 3.2, Table 7; Figure 7). The narrowing of pH towards near-neutral values is widely attributed to organic-acid release during litter and fine-root decomposition, root respiration generating CO_2 and the displacement of exchangeable bases by H^+ produced during organic-matter mineralisation (Jose, 2009; Pralhad et al., 2020). The somewhat greater pH reduction under S2 is consistent with the larger litter input typical of mature *Populus* stands. BD was lower in S1 than C1 and lower in S2 than C2 at 0–15 cm (Table 7), is in line with the well-documented loosening effect of accumulated organic matter, biopores left by decayed fine roots and increased macro-fauna activity in tree-influenced soils (Udawatta et al., 2017; Sharma et al., 2021). EC was higher under both AFS than under their

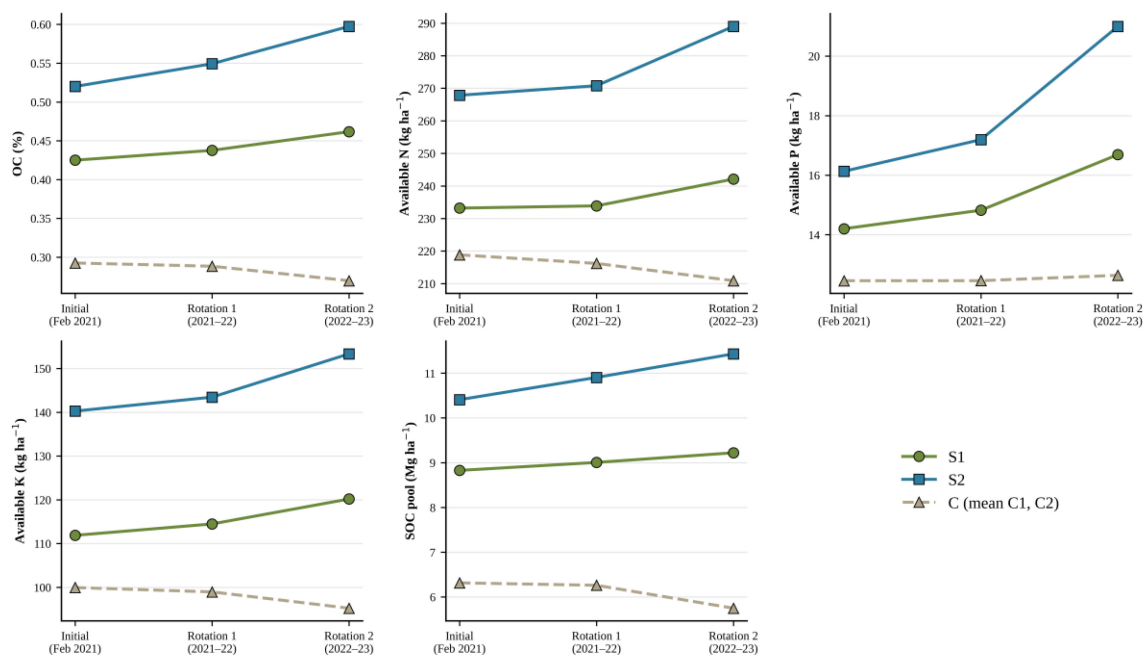


FIGURE 8

Temporal trend in soil organic carbon (OC), available nitrogen (N), available phosphorus (P), available potassium (K) and total soil organic carbon stock (SOC stock) from the pre-experiment baseline (Initial; February 2021) through the end of the first (Rotation 1; 2021–22) and second (Rotation 2; 2022–23) crop rotations. S1, *Melia composita* AFS; S2, *Populus deltoides* AFS; C, mean of the two monoculture controls (C1 and C2). Each point is the mean across all distances and depths.

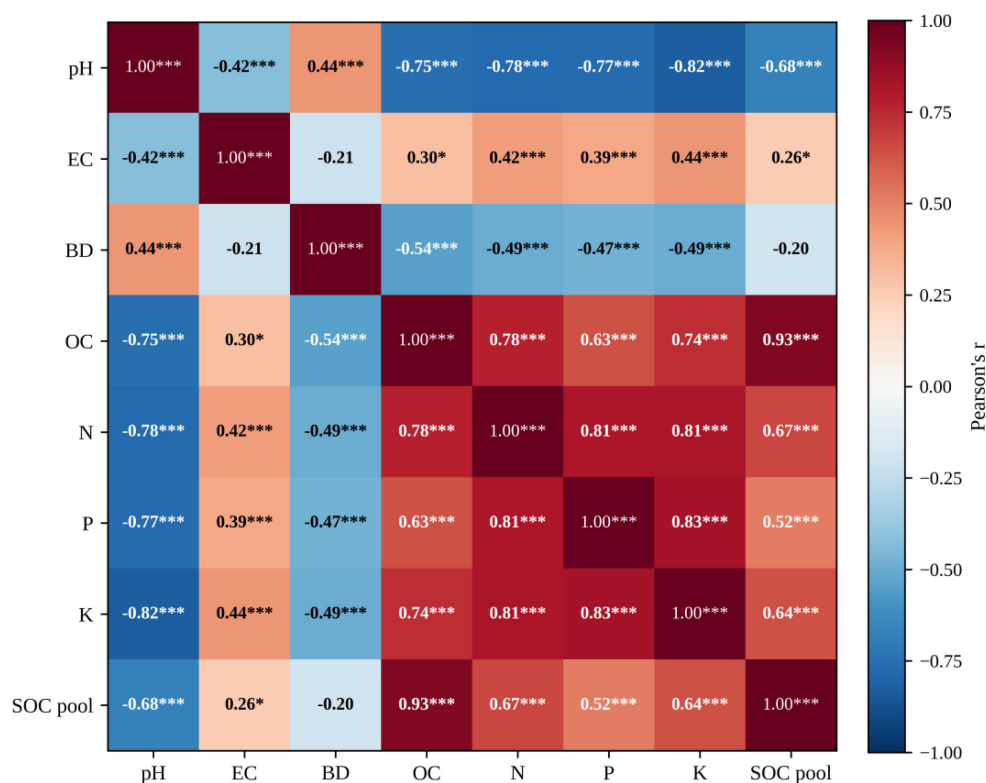


FIGURE 9

Pearson correlation matrix among eight soil physico-chemical properties measured in the two agroforestry systems at the end of the second crop rotation ($n = 72$). Cell values are Pearson correlation coefficients (r) with significance indicated as * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

controls, an effect attributable to enhanced mineralisation of organic-matter-derived soluble salts and to deep-root cycling of subsoil cations by trees (Kumar et al., 2008).

4.2 Soil organic carbon and the SOC stock

The major finding of the study was the magnitude of the soil organic carbon (SOC) advantage under both AFS and the consistent superiority of S2 over S1. Mean SOC at the end of the second rotation was higher under S2 versus S1 and the controls (Section 3.1.1, Table 3; Section 3.2, Table 7). These magnitudes are within and at the upper end of, the range of 30–110% reported for *Populus*- and *Melia*-based AFS in the north-Indian subtropics (Sirohi and Bangarwa, 2017; Sharma et al., 2021; Pankaj et al., 2024) and reflect the dual contribution of above-ground litterfall and continuous fine-root turnover under trees (Mugendi and Nair, 1997; Nair, 2013). The greater SOC build-up under S2 is attributable to two overlapping causes: (i) the larger annual litter input typical of a 10-year-old *P. deltoides* canopy compared with a 5-year-old *M. composita* stand of comparable spacing and (ii) the relatively lower C:N ratio and faster mineralisation-humification trajectory of poplar litter, which favours stabilisation of soil organic matter (Pralhad et al., 2020; Silva et al., 2011). The strong positive correlation between OC and the SOC stock ($r = 0.93$; Section 3.4, Figure 9) confirms organic matter as the central driver of carbon accumulation in these systems. Two important caveats apply, however. First, the 5- vs 10-year age difference between the two stands means the S2 advantage represents combined species and

stand-age effects (Section 2.2); equal-age comparisons are needed to disentangle these. Second, the two-year monitoring window is short relative to the 5–10 years typically required to establish robust long-term SOC sequestration rates (Paustian et al., 2016), so our values should be interpreted as initial evidence of sequestration potential rather than as steady-state rates.

4.3 Available macronutrients (N, P and K)

Available nitrogen, phosphorus and potassium followed the same AFS > control hierarchy as SOC, with S2 again exceeding S1 (Section 3.2, Table 7). Three mechanisms plausibly explain these advantages, operating in combination. First, biological nitrogen fixation by the leguminous cowpea intercrop (*Vigna unguiculata*) contributes an estimated 30–80 kg N ha⁻¹ per season under subtropical conditions (Singh et al., 2003; Pankaj et al., 2024); residual cowpea biomass and root nodules then add organic N to the soil profile. Second, leaf-litter and fine-root decomposition under trees release low-molecular-weight organic acids and humic-type substances that chelate Al³⁺ and Fe³⁺, solubilise occluded phosphates and release exchangeable K from mineral interlayers (Nair, 2013; Udawatta et al., 2017). Third, deep tree roots of both *M. composita* and *P. deltoides* act as “nutrient pumps”, capturing ions from subsoil layers below the crop rooting zone and depositing them on the surface as litter - a mechanism well established for poplar in particular (Sirohi and Bangarwa, 2017; Sharma et al., 2021). The greater enrichment under S2 again reflects the longer-established canopy, the larger litter return and the somewhat deeper root

architecture typically reported for *P. deltoides*. The strong positive intercorrelations among OC, N, P and K ($r = 0.63\text{--}0.83$; Figure 9) and the negative correlations of all four with pH ($r = -0.68$ to -0.82) further confirm that organic-matter dynamics and the associated mild acidification jointly drive the observed nutrient enrichment.

4.4 Within-AFS spatial gradients: distance from tree base and soil depth

Within both AFS, soil quality was highest closest to the tree base (P1, <1 m) and declined progressively to P3 (2–3 m). pH and BD followed the opposite pattern, both being lowest at P1 and highest at P3 (Section 3.1.2, Table 4; Figure 5). This spatial pattern is consistent with the well-recognised “tree-island” effect observed under isolated and within-row trees in tropical and sub-tropical AFS (Mugendi and Nair, 1997; Jose, 2009; Pralhad et al., 2020): litterfall is concentrated under and immediately around the canopy, fine-root density is highest near the stem and stemflow preferentially deposits dissolved nutrients at the tree base. The magnitude of the gradient observed here (12–26% over a 2–3 m distance) is broadly comparable with values reported for *Populus* boundary plantations in north-Indian Punjab (Sirohi and Bangarwa, 2017) and is agronomically relevant: it suggests that, in practical terms, intercrops grown 0–1 m from the tree row enjoy soil-fertility subsidies that fall away by 50–60% at 2–3 m. The depth pattern (D1 > D2 for SOC and macronutrients; D2 > D1 for pH and BD; Section 3.1.3, Table 5; Figure 6) mirrors the zero-tillage/litter-input stratification, in which fresh organic inputs accumulate at the surface and root activity, organic anion production and microbial mineralisation are most intense in the 0–15 cm horizon (Lahmar and Ruellan, 2007; Paustian et al., 2016). The three-way factorial ANOVA (Section 3.1.4, Table 6) showed significant $S \times P$ interactions for pH and available N: the S2-over-S1 advantage was therefore not uniform across the distance, being most pronounced near the tree base. The $S \times D$ interactions were non-significant for all parameters, indicating that the species effect was depth-consistent.

4.5 Temporal accumulation and the role of the cowpea-turmeric rotation

The temporal data presented in Section 3.3 (Figure 8) document a progressive divergence between AFS and control plots across the two crop rotations. Under both AFS, OC, available N, P and K and the SOC stock increased between the pre-experiment baseline (February 2021) and the end of the second rotation; under the controls the same variables either declined or remained essentially flat. The largest absolute gains occurred under S2 as compared to S1. This confirms that the trajectory is general to tree-based systems in the region. By contrast, the two-control mean fell over the same two-year period, illustrating the gradual depletion typical of intensive sole-crop systems on subtropical soils (Lahmar and Ruellan, 2007; Srinivasarao et al., 2021). The cowpea-turmeric rotation made a measurable contribution to these dynamics in all four management units. Cowpea, as a short-duration legume, fixes substantial atmospheric N during the kharif season (Singh et al., 2003) and adds nodulated root biomass and leaf litter on termination; turmeric, a partially shade-tolerant rhizomatous spice, develops a dense, fine root mat at 0–15 cm that further enhances organic-

matter turnover and aggregate stability (Dash et al., 2024). The synergy between tree-derived inputs (litter, root C, subsoil-cycled cations) and crop-derived inputs (cowpea-fixed N, turmeric root residues) plausibly explains why the AFS gains exceed those reported for tree-based systems coupled with non-leguminous rotations in the same region. A residual fraction of the AFS-over-control advantage is, however, attributable to the difference in stand age (5 years for S1 vs 10 years for S2): the older *Populus* canopy had accumulated more litter and root biomass before the experiment began, giving it a longer “head start” for soil enrichment.

4.6 Practical implications, limitations and future research

From a practical standpoint, the present results provide quantitative support for integrating *M. composita* and especially *P. deltoides* with a cowpea-turmeric rotation as a soil-restorative land-use option in the sub-tropics of Jammu. After two rotations, both systems significantly improved organic carbon stocks, available macronutrients and bulk density relative to sole-crop monoculture, with effect magnitudes well above those usually expected from organic manures or short fallows alone (Kumar et al., 2008; Udawatta et al., 2017). The within-AFS spatial gradient (P1 > P3) further suggests that intercrops should be preferentially placed within 1–2 m of the tree row to capture the bulk of the soil-fertility subsidy.

Several limitations should, however, temper the interpretation of these findings. (i) The study is restricted to a single site (SKUAST-J Chatha) and the soil-climatic generalisability beyond the Shivalik subtropical foothills is therefore uncertain. (ii) The two-year monitoring window covers only one full cowpea-turmeric rotation cycle and is short relative to the 5–10 years usually required to establish robust SOC sequestration rates (Paustian, 2016). (iii) The 5- vs 10-year age confound means the S2-over-S1 advantage reported here reflects both species and canopy-maturity effects; equal-age comparisons are warranted. (iv) Litter inputs were documented only visually; quantitative litter-trap and decomposition studies would substantially strengthen the mechanistic interpretation. (v) Soil microbial biomass, enzyme activities and aggregate-fraction data - which mediate the link between litter inputs and stable carbon formation - were not measured. (vi) Crop yield and economic-return data, which determine farmer adoption, were beyond the scope of this soil-focused study. Future research priorities therefore include multi-site, multi-year, equal-age comparisons of *M. composita* and *P. deltoides* AFS, ideally with parallel measurements of litter dynamics, soil biology and crop economics, across the range of cropping systems and soil types of the north-Indian subtropics.

5 Conclusion

Two years of factorial field experimentation in the sub-tropics of Jammu demonstrated that integrating *Melia composita* (S1, 5-year-old) and *Populus deltoides* (S2, 10-year-old) with a cowpea (*Vigna unguiculata* cv. CL-367) - turmeric (*Curcuma longa* cv. Punjab Haldi-2) rotation substantially improves soil physico-chemical

quality over sole-crop monoculture. At the end of the second rotation, the S2 system carried 28.6% higher organic carbon, 19.4% more available N, 25.8% more available P, 27.6% more available K and a 24.0% larger SOC stock than S1; both AFS exceeded their paired controls by 56.3% (S1) to 85.8% (S2) in surface SOC stock and by 24–60% in available macronutrients. Soil reaction shifted from alkaline (7.8–8.0) under monoculture to near-neutral (7.1–7.3) under AFS and bulk density decreased by 6–7%. Within the AFS, all fertility indicators declined with distance from the tree base ($P1 > P3$) and with soil depth ($D1 > D2$), with significant species $\times$ distance interactions for pH and available N. The temporal trajectory across the two rotations showed continuing accumulation under AFS and gradual depletion under sole-crop controls, confirming agroforestry as a soil-restorative land-use option for the Shivalik subtropics. Given the 5- vs 10-year age confound between the two stands and the limited two-year window, the results should be regarded as initial quantitative evidence; multi-year, equal-age and multi-site evaluations - coupled with litter, soil-biology and crop-economic measurements - are recommended to consolidate these conclusions.

Data availability statement

The datasets presented in this article are not readily available because Data will be made available when asked. Requests to access the datasets should be directed to souravskuast@gmail.com.

Author contributions

MS: Investigation, Methodology, Project administration, Writing – original draft. KS: Conceptualization, Project administration, Resources, Writing – review & editing. SS: Conceptualization, Formal analysis, Methodology, Resources, Writing – review & editing. VS: Software, Visualization, Writing – review & editing. SK: Software, Supervision, Validation, Visualization, Writing – review & editing. RK: Investigation, Methodology, Project administration, Writing – review & editing. AS: Conceptualization, Project administration, Resources, Writing – review & editing. TL: Investigation, Project administration, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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