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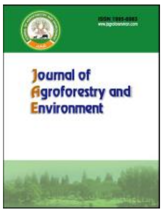

Enhancing Soil Fertility in Arid and Semi-Arid Climates Using Leguminous Trees: A Species-Specific Agroforestry Approach

Muhammad Madnee[1]*, Tanveer Hussain[1], Turkan Hasanova Allahverdi[2], Nugraha Akbar Nurrochmat[3], Mahmuod Abubakar Bashir[4], Md. Manik Ali[4], Muhammad Usman Ghaffar[1] and Mudrika Qanitha[3]

[1]Institute of Forest Sciences, Faculty of Agriculture and Environment, Islamia University of Bahawalpur, Bahawalpur, 63100, Pakistan; muhammad.madnee@iub.edu.pk; dr.tanveer@iub.edu.pk, usmanghaffar32@gmail.com
[2]Department of Land Surveying and Real Estate Cadastre, Faculty of Ecology and Soil Science, Baku State University. AZ1148, Baku city, Azerbaijan turkanhesenova@mail.ru
[3]Department of Forest Management, Dendrometry and Forest Economics, Institute of Forest Sciences, Warsaw University of Life Sciences, Warsaw 02-776, Poland; nugraha_nurrochmat@sggw.edu.pl; mudrika_qanitha@sggw.edu.pl
[4]Department of Agroforestry and Environment, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh. mbashir34@yahoo.com; manikali@hstu.bd

***Correspondence:** muhammad.madnee@iub.edu.pk , Tel: +92340-2000458

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Abstract: Soil fertility decline is a critical barrier to sustainable agriculture in arid and semi-arid regions. This study evaluated the influence of four native leguminous tree species; *Albizia* lebbeck, *Dalbergia sissoo*, *Prosopis cineraria* and *Vachellia nilotica* on soil physicochemical properties at four depths (0–15 cm, 15–30 cm, 30–45 cm and 45–60 cm) in Bahawalpur District, Pakistan. A three-year field experiment, using a randomized complete block design, assessed soil pH, bulk density, organic matter, organic carbon, moisture, saturation, electrical conductivity and available N, P and K. Results revealed significant differences ($p < 0.05$) among tree species and across soil depths. *D. sissoo* had the highest soil pH (8.26), moisture (19.72%), and saturation (36.77%) at 0–30 cm. *V. nilotica* showed consistent organic matter and had the highest nitrogen content (11.1 mg/kg), while *A. lebbeck* contributed the most potassium (109 mg/kg), and *D. sissoo* led in phosphorus (9.1 mg/kg). *P. cineraria* and *A. lebbeck* significantly reduced soil electrical conductivity. Among all species, *V. nilotica* emerged as the most effective for enhancing soil fertility due to its balanced contributions to nitrogen and organic matter. The findings emphasize the critical role of species selection and depth-specific assessments in designing agroforestry systems aimed at improving soil health and boosting productivity. These findings also provide a robust, evidence-based guide for selecting tree species to integrate into agroforestry systems, offering practical strategies for improving agricultural resilience and smallholder livelihoods in water-scarce environments.

Keywords: Arid; Soil fertility; Agroforestry; Physicochemical; Nitrogen fixing trees.

INTRODUCTION

Arid and semi-arid regions face significant soil degradation due to low organic matter, erratic rainfall, and high temperatures, severely limiting agricultural productivity (Ashraf & Foolad, 2007; Bationo & Bürkert, 2001; Schauberger et al. 2017). In Pakistan, where over 90% of farmland is managed by smallholders, unsustainable land use further exacerbates soil fertility decline (Horst & Watkins, 2022). Agroforestry, the integration of trees with crops, offers a sustainable alternative by improving soil fertility through organic matter addition, nutrient cycling, and erosion control (Kuyah et al. 2019; Safeer et al. 2025). Leguminous trees are especially important due to their nitrogen-fixing capabilities and litter decomposition (Diabate et al. 2005; Madnee et al. 2025a, Sprent, 2009). Despite broad evidence that trees enhance soil fertility, there is limited understanding of species-specific effects and depth-wise variations in soil properties (Nygren et al. 2012; Sileshi et al. 2012). Root architecture and litter quality differ among species, influencing vertical nutrient redistribution and organic matter input (Isaac & Borden, 2019). These dynamics are particularly critical for nutrient uptake in dryland cropping systems but remain underexplored.

In Pakistan, soils typically have low organic content and rely on precipitation, canal and groundwater for irrigation (Qadir et al. 2003). Farmers use methods like mulching, crop residues, farmyard manure and intercropping to improve soil fertility (Bayala et al. 2011). However, excessive reliance on chemical fertilizers is unsustainable and environmentally detrimental (Saidou et al. 2012; Ribeiro-Barros et al. 2018). Native leguminous trees, resilient to harsh edaphic and climatic conditions, enhance soil nutrient availability and have been associated with increased yields (Adams et al. 2010; Bruning & Rozema, 2013; Tomar et al. 2021; Inamagua-Uyaguari et al. 2023).

Agroforestry systems with scattered trees and shrubs are prevalent in arid and semi-arid regions (Wezel et al. 2000; Bayala et al. 2011). These trees improve soil properties and offer additional benefits such as fodder, fuel and income generation (Cunningham & Abasse, 2005; Boffa, 2000; Faye et al. 2011). Decomposing litter contributes to organic matter build-up, enhancing soil fertility (Saidou et al. 2012). Soils under tree canopies generally show higher fertility than open land (Wezel et al. 2000; Grouzis & Akpo, 2006; Jaquetti et al. 2016). Agroforestry improves soil structure, increases nutrient content and supports biodiversity, thereby enhancing agricultural output and farmer income (Bayala et al. 2012; Pinho et al. 2012; Isaac & Borden, 2019). Tree-soil interactions affect microbial activity and decomposition, both key to nutrient cycling (Mathieu et al. 2005; Hättenschwiler, 2005; Ristok et al. 2019; Suárez et al. 2018).

Soil biological properties are influenced by tree arrangement and species-specific traits (Cezar et al. 2015; Santos et al. 2019; Lana et al. 2018; Esquivel et al. 2008). These factors include a higher concentration of soil nutrients (Gómez et al. 2004) and the growth of seedlings and agricultural plants beneath their canopy benefits (Martínez-Sánchez, 2006). The arrangement and features of trees in cropping significantly influence soil biological parameters (Cezar et al. 2015; Rodríguez et al. 2021). The quantity and diversity of soil micro-fauna can be affected by the particular trophic and microclimatic conditions surrounding the trees (Santos et al. 2019). The presence of scattered trees enhances soil fertility (Casal et al. 2014). The degree of this enhancement depends on the particular tree species and their functional traits (Lana et al. 2018). The configuration and geographical distribution of trees, along with the management strategies implemented, also affect their influence on the physical and chemical properties of soil (Esquivel et al. 2008; Gutiérrez et al. 2012).

Agroforestry systems that incorporate both trees and crops or livestock can address ecological challenges while providing economic resilience (Dollinger & Jose, 2018; Méndez et al. 2013; Mbow et al. 2014; Maia et al. 2025; Madnee et al. 2025b). Native leguminous species like *A. lebbeck*, *D. sissoo*, *P. cineraria* and *V. nilotica* serve multiple functions, from fuelwood and fodder to nitrogen enrichment (Orwa et al. 2009; Anonymous, 2023; National Forest Monitoring System, 2025). In this study, we examine the effects of four native leguminous tree species; *Albizia lebbeck*, *Dalbergia sissoo*, *Prosopis cineraria* and *Vachellia nilotica* on soil physicochemical properties across four depths (0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm). We hypothesize that (1) soil fertility enhancements differ by species due to variations in litter chemistry and root depth, and (2) nutrient availability decreases with depth but is moderated by species-specific traits. This study aims to quantify the depth-wise, species-specific contributions of these trees to soil fertility, thereby providing a scientific basis for selecting optimal species for agroforestry systems in arid and semi-arid regions of Pakistan and similar agro-ecologies worldwide.

MATERIALS AND METHODS

Study site: The study was conducted from 2021 to 2023 on a privately owned, contiguous farm of 50 hectares located in the Yazman tehsil of Bahawalpur District, Pakistan (Centroid coordinates: 28°52'12.5"N, 71°27'36.8"E). The site was selected for its homogeneity in soil type and management history, having been under a uniform, low-input wheat-cotton rotation for over a decade prior to the establishment of the experiment. This ensured a consistent baseline for evaluating tree effects. The region features a semi-arid climate with extreme temperatures (summer max: ~40°C, winter average: ~22°C) and low annual rainfall (<250 mm). Irrigation is provided via a canal system. The soil at the experimental site is classified as a Typic Haplocambid (USDA Soil Taxonomy) with a sandy loam to loam texture, inherently low in organic matter (<0.5%) and phosphorus, which is representative of the larger district (Aamer et al. 2015). The district has covered a land area of 24,830 km^2 with a population of 4,284,964 individuals in 2023 and a minimal forest cover 0.01% (GoP 2023; Madnee et al. 2025b).

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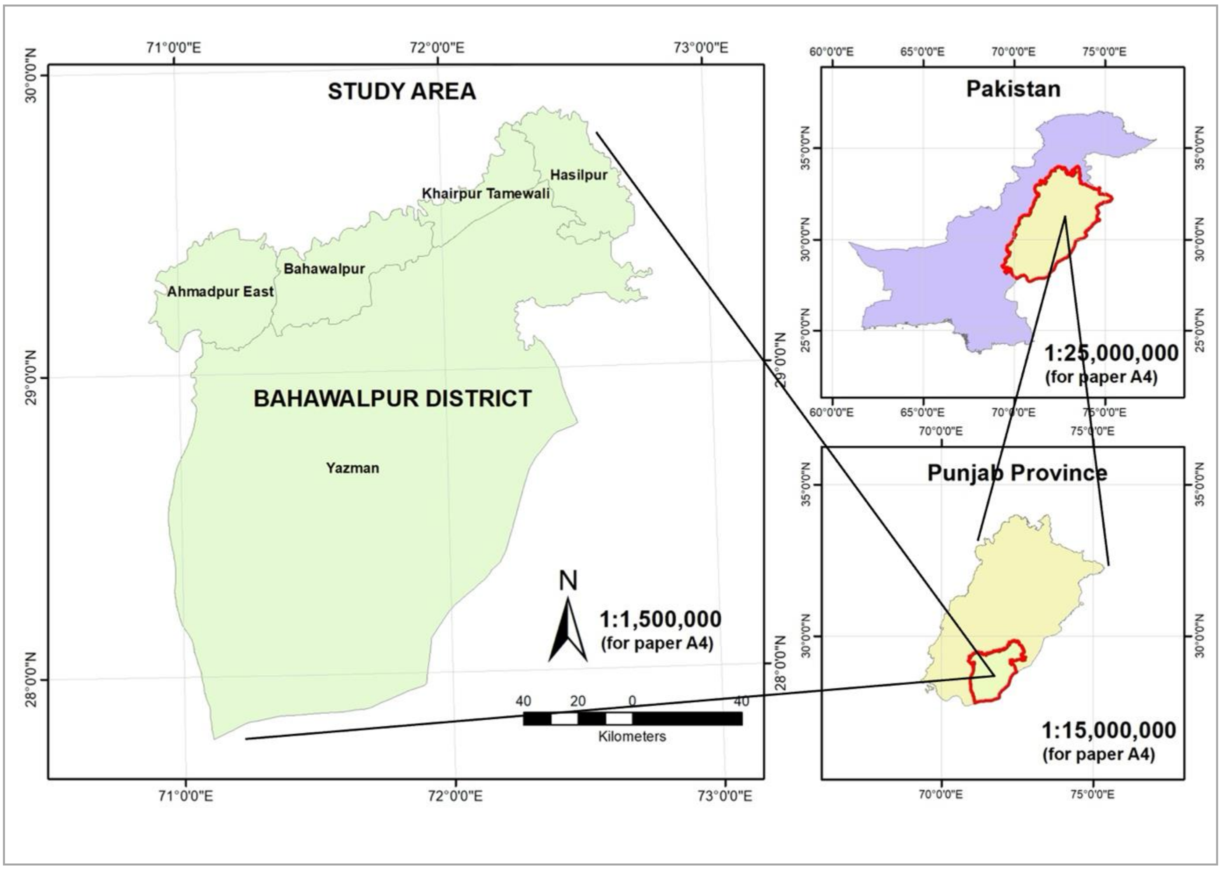

Figure. 1 Geographic Map of the Study area.

The total cultivated area of Bahawalpur district is 372,324 hectares. The major crops of the district are cotton, wheat, rice and sugarcane. Vegetation cover is sparse due to higher temperatures, reduced humidity and inconsistent precipitation. The district is one of the hottest locations in Pakistan. Vegetation consists of xerophytic grasses, shrubs and trees. (Shah et al. 2020). The study area consists of flat alluvial plains (slope <2%) historically used for rainfed and irrigated agriculture (cotton, wheat, sugarcane). Native vegetation includes xerophytic grasses (*Cenchrus ciliaris*), shrubs (*Calligonum polygonoides*) and scattered leguminous trees *Prosopis cineraria*, *Vachellia nilotica* (Madnee et al. 2025b).

Experimental Design and Tree Establishment: A randomized complete block design (RCBD) was implemented to test the effects of four native leguminous tree species on soil properties. The experiment comprised four blocks, each representing a replication, to account for any slight topographic or soil gradient across the farm.

Within each block, five 20m x 20m plots were established, resulting in a total of 20 experimental plots (4 species + 1 control × 4 blocks). The four tree species treatments were *Albizia lebbeck*, *Dalbergia sissoo*, *Prosopis cineraria* and *Vachellia nilotica*. The fifth plot in each block was maintained as a control, kept free of trees and managed with the same seasonal wheat-cotton rotation as the surrounding field.

In 2018, three-year-old saplings of each species grown in institute's nursery to ensure genetic uniformity, were planted in their respective plots at a standardized density of 6m x 6m. This pre-established period allowed the trees to reach a mature, ecologically functional state (canopy closure and significant root development) by the time soil sampling began in 2021 as indicated by Oumarou (2016). All plots received identical management; no fertilization or pruning was conducted during the study period and irrigation was applied uniformly across the entire experimental site via the existing canal network. Weed control in tree plots was done manually to avoid herbicide effects on soil biology.

Soil sampling was conducted at the end of the dry season to assess soil conditions under maximum water stress, a critical period for agricultural planning in arid regions. While we acknowledge that continuous monitoring would provide a more comprehensive picture of soil hydrology, this single-time-point measurement serves as a valuable indicator of the soil's capacity to retain residual moisture under tree canopies during a period of high evaporative demand. A composite sample was prepared for each depth by mixing the four cores collected from each of the four cardinal transects. The sample collection was carried out by using a soil auger and a sampling spade. Upon collection, the moist samples were bifurcated into two segments. Concurrently, 100g of fresh moist samples were collected individually in a moisture box for the assessment of moisture content. The residual soil sample was enclosed in distinct polythene bags, transported to the laboratory and subjected to analysis of its physicochemical properties.

Physicochemical properties of soil

The subsequent soil physico-chemical parameters were assessed as outlined by Ryan et al. (2001) and unless otherwise mentioned below.

Soil Structure and texture

Various sizes of sieves were employed to assess soil texture. The hydrometer method was employed for particle size analysis.

%Clay in soil:

%Clay in Soil (w/w) = (Rc - Rb) ×100/ (Oven Dry Soil (g))

% Silt in soil:

%Silt (w/w) = [%Silt + Clay (w/w)]- [%Clay (w/w)]

% Sand in soil:

%Sand (w/w) = Sand weight×100/ (oven-dry soil (g))

Soil reaction (pH)

Soil pH was measured by a digital pH meter.

Soil Electrical Conductivity (EC)

An EC meter was used to measure EC in a saturated paste extract.

Bulk density

Core method was used for the determination of bulk density in soil (Rai, 2015). Bulk density (ρb) was determined as:

$$\rho b\ (\mathrm{Mg\ m^{-3}}) = (\text{Oven Dry Weight of the Soil (g)}) / (\text{Bulk Volume of the soil sample } (\mathrm{cm^3}))$$

Organic Matter Percentage (OM)

The percent soil organic matter (SOM) was calculated by multiplying the percent organic carbon by a factor of 1.724 (Nelson and Sommers, 1996). Organic matter is determined through the equation:

%Organic Matter (w/w) =1.724×%Total Organic Carbon

Soil organic carbon (SOC)

Soil organic carbon stock (SOC) was calculated using the fixed-depth approach with the formula:

$$SOC = \rho b \times D \times \%C$$

Whereas: SOC = Soil Organic Carbon Stock, ρb = Soil Bulk Density, D= the total depth at which the sample was taken. % C = Carbon concentration (%) amounting to 0.47 of biomass or taken from lab measurements (Ali et al. 2020; Magar et al. 2020). While the equivalent soil mass approach is advantageous for comparing soils with different bulk densities, the fixed-depth method was deemed appropriate here as the primary focus was on within-plot depth-wise comparisons under a consistent soil type. Furthermore, visual inspection and sampling confirmed that the coarse fragment (stone) content was negligible (<5% by volume) across all plots and depth, minimizing its potential impact on stock calculations.

Soil Moisture

Soil moisture was calculated by the Gravimetric method (Jury and Horton 2004). This method involves weighing a soil sample before and after drying it in an oven at 105°C ± 5°C until a constant mass is achieved. The difference in weight represents the amount of water lost, which is then used to calculate the moisture content as a percentage of the dry soil weight.

%Moisture in Soil (ϴ) = (Wet Soil (g)-Dry Soil (g))/(Dry Soil (g))×100

Saturation percentage

The saturation percentage (SP) was determined using the standard method described in Richards (1954). This involves saturating a soil paste and calculating the water content at full saturation according to the formula:

SP= (Loss in weight after oven drying (g))/ (Total weight of soil after oven dry weight (g)) ×100

Nutrient availability in the soil for plant growth

Available nutrients were determined by the methodology described by Dwivedi et al. (2015). The amount of nitrogen in the soil, primarily in organic form, was determined through wet digestion using the widely recognized Kjeldahl process.

For Total Available Phosphorus in Soil:

Total Available P(ppm)= P (ppm)×A/Wt×50/V

Where: A= Total volume of the digest (mL), Wt= Weight of the air-dry soil (g), V= Volume of digest used for measurement (mL)

Soluble Potassium is the measure of the amount of K extracted from the soil by water.

Soluble K(ppm)=ppm K K (from calibration curve) ×A/Wt

STATISTICAL ANALYSIS

Each mean contains data from four tree species, with twenty samples corresponding to each soil depth. The collected data

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were organized using MS Excel software. The experiment was established under a randomized complete block design (RCBD) with four replicates each. Deeper statistical analysis uses the Shapiro-Wilk test for normality assessment. Some data that were found to be normally distributed were then analyzed with the parametric test two-way ANOVA and a post-hoc test using Tukey HSD. In contrast, data that were determined not to be normally distributed were analyzed using the non-parametric Kruskal-Wallis test and a post-hoc test with the Mann-Whitney test. The statistical analyses were performed using MS Excel, Statistix 8.1 software, and PAST 5 Statistical Software (Madnee et al. 2025b).

RESULTS

The data obtained from this research include 128 samples, which consist of 4 different tree species and a control, across 4 different soil depths. The data collected included 10 parameters: soil pH, soil electrical conductivity, soil bulk density, soil organic matter, soil organic carbon, soil moisture, soil saturation, soil available nitrogen, soil available phosphorus and soil available potassium. Below is a summary of the collected data.

Table 1. Data summary of collected data

Metric	Depth	*D.sissoo*	*V.nilotica*	*P. cineraria*	*A. lebbeck*	Control
Bulk density	0-15cm	1.17 ± 0.12 (n=4)	1.20 ± 0.03 (n=4)	1.24 ± 0.04 (n=4)	1.18 ± 0.16 (n=4)	1.30 ± 0.18 (n=16)
	15-30cm	1.14 ± 0.13 (n=4)	1.25 ± 0.16 (n=4)	1.23 ± 0.09 (n=4)	1.30 ± 0.23 (n=4)	1.46 ± 0.21 (n=16)
	30-45cm	1.27 ± 0.11 (n=4)	1.22 ± 0.10 (n=4)	1.23 ± 0.11 (n=4)	1.35 ± 0.17 (n=4)	1.35 ± 0.14 (n=16)
	45-60cm	1.28 ± 0.08 (n=4)	1.25 ± 0.03 (n=4)	1.29 ± 0.06 (n=4)	1.24 ± 0.16 (n=4)	1.35 ± 0.13 (n=16)
Soil EC	0-15cm	1.53 ± 0.45 (n=4)	1.81 ± 0.65 (n=4)	1.46 ± 0.43 (n=4)	1.63 ± 0.46 (n=4)	1.81 ± 0.38 (n=16)
	15-30cm	1.26 ± 0.62 (n=4)	1.71 ± 0.62 (n=4)	1.05 ± 0.10 (n=4)	1.23 ± 0.13 (n=4)	1.71 ± 0.41 (n=16)
	30-45cm	1.60 ± 0.72 (n=4)	1.70 ± 0.66 (n=4)	1.18 ± 0.24 (n=4)	1.25 ± 0.17 (n=4)	1.62 ± 0.41 (n=16)
	45-60cm	1.34 ± 0.71 (n=4)	1.93 ± 0.47 (n=4)	1.12 ± 0.36 (n=4)	1.60 ± 0.34 (n=4)	1.64 ± 0.38 (n=16)
Soil Moisture	0-15cm	26.03 ± 8.07 (n=4)	21.05 ± 6.32 (n=4)	22.38 ± 7.82 (n=4)	26.33 ± 8.89 (n=4)	15.45 ± 5.99 (n=16)
	15-30cm	26.77 ± 7.48 (n=4)	24.01 ± 8.33 (n=4)	18.98 ± 3.94 (n=4)	26.98 ± 9.20 (n=4)	13.96 ± 4.81 (n=16)
	30-45cm	29.39 ± 4.78 (n=4)	23.80 ± 6.02 (n=4)	19.15 ± 6.63 (n=4)	25.37 ± 9.90 (n=4)	15.17 ± 6.23 (n=16)
	45-60cm	30.16 ± 5.89 (n=4)	24.75 ± 5.18 (n=4)	25.50 ± 9.82 (n=4)	26.55 ± 8.95 (n=4)	16.26 ± 7.56 (n=16)
Soil Available Nitrogen	0-15cm	9.39 ± 1.45 (n=4)	10.98 ± 0.90 (n=4)	6.63 ± 0.48 (n=4)	6.74 ± 1.19 (n=4)	7.16 ± 2.10 (n=16)
	15-30cm	8.39 ± 1.02 (n=4)	8.75 ± 1.89 (n=4)	7.89 ± 0.55 (n=4)	8.03 ± 0.06 (n=4)	6.31 ± 2.05 (n=16)
	30-45cm	9.98 ± 0.00 (n=4)	11.25 ± 1.26 (n=4)	8.97 ± 0.45 (n=4)	9.35 ± 0.53 (n=4)	7.22 ± 1.98 (n=16)
	45-60cm	7.00 ± 0.00 (n=4)	8.72 ± 1.55 (n=4)	7.00 ± 0.00 (n=4)	6.50 ± 0.58 (n=4)	5.82 ± 1.20 (n=16)
Soil Organic Matter	0-15cm	0.54 ± 0.10 (n=4)	0.50 ± 0.11 (n=4)	0.34 ± 0.11 (n=4)	0.39 ± 0.06 (n=4)	0.25 ± 0.14 (n=16)
	15-30cm	0.53 ± 0.19 (n=4)	0.60 ± 0.07 (n=4)	0.35 ± 0.12 (n=4)	0.42 ± 0.04 (n=4)	0.22 ± 0.10 (n=16)
	30-45cm	0.47 ± 0.09 (n=4)	0.48 ± 0.01 (n=4)	0.37 ± 0.07 (n=4)	0.41 ± 0.11 (n=4)	0.25 ± 0.08 (n=16)
	45-60cm	0.39 ± 0.14 (n=4)	0.45 ± 0.09 (n=4)	0.40 ± 0.14 (n=4)	0.41 ± 0.13 (n=4)	0.24 ± 0.12 (n=16)
Soil available Phosphorus	0-15cm	9.68 ± 1.90 (n=4)	8.66 ± 0.44 (n=4)	9.72 ± 0.91 (n=4)	8.55 ± 0.53 (n=4)	5.66 ± 0.92 (n=16)

	15-30cm	8.53 ± 0.38 (n=4)	6.94 ± 0.12 (n=4)	7.69 ± 0.74 (n=4)	8.36 ± 0.25 (n=4)	6.22 ± 0.95 (n=16)
	30-45cm	9.39 ± 0.48 (n=4)	8.00 ± 0.00 (n=4)	8.23 ± 1.82 (n=4)	6.75 ± 0.96 (n=4)	7.12 ± 1.24 (n=16)
	45-60cm	7.73 ± 0.95 (n=4)	5.35 ± 0.81 (n=4)	6.75 ± 0.50 (n=4)	6.87 ± 0.77 (n=4)	6.71 ± 1.28 (n=16)
Potassium	0-15cm	70.03 ± 11.60 (n=4)	85.50 ± 6.40 (n=4)	102.22 ± 1.29 (n=4)	97.25 ± 12.69 (n=4)	63.25 ± 12.07 (n=16)
	15-30cm	65.75 ± 10.14 (n=4)	89.00 ± 8.25 (n=4)	113.32 ± 3.70 (n=4)	102.01 ± 14.48 (n=4)	64.99 ± 11.59 (n=16)
	30-45cm	71.75 ± 7.59 (n=4)	91.00 ± 6.38 (n=4)	96.17 ± 10.22 (n=4)	96.75 ± 4.27 (n=4)	65.63 ± 14.12 (n=16)
	45-60cm	71.50 ± 6.40 (n=4)	91.50 ± 9.26 (n=4)	100.49 ± 9.72 (n=4)	100.00 ± 9.49 (n=4)	69.23 ± 15.58 (n=16)
SOC	0-15cm	0.36 ± 0.13 (n=4)	0.39 ± 0.22 (n=4)	0.21 ± 0.16 (n=4)	0.19 ± 0.07 (n=4)	0.22 ± 0.10 (n=16)
	15-30cm	0.29 ± 0.14 (n=4)	0.21 ± 0.02 (n=4)	0.17 ± 0.04 (n=4)	0.18 ± 0.06 (n=4)	0.23 ± 0.08 (n=16)
	30-45cm	0.19 ± 0.06 (n=4)	0.32 ± 0.02 (n=4)	0.21 ± 0.13 (n=4)	0.28 ± 0.06 (n=4)	0.25 ± 0.07 (n=16)
	45-60cm	0.26 ± 0.13 (n=4)	0.24 ± 0.07 (n=4)	0.26 ± 0.08 (n=4)	0.29 ± 0.06 (n=4)	0.23 ± 0.10 (n=16)
Soil Saturation %	0-15cm	27.34 ± 7.48 (n=4)	27.06 ± 4.96 (n=4)	25.25 ± 6.62 (n=4)	26.88 ± 4.90 (n=4)	22.95 ± 5.51 (n=16)
	15-30cm	29.64 ± 7.25 (n=4)	30.26 ± 6.23 (n=4)	28.57 ± 2.43 (n=4)	28.80 ± 6.41 (n=4)	22.67 ± 6.20 (n=16)
	30-45cm	30.56 ± 6.16 (n=4)	30.51 ± 3.93 (n=4)	27.56 ± 1.73 (n=4)	27.37 ± 4.78 (n=4)	24.18 ± 4.84 (n=16)
	45-60cm	29.65 ± 3.80 (n=4)	29.95 ± 2.43 (n=4)	28.84 ± 2.16 (n=4)	29.41 ± 3.60 (n=4)	26.13 ± 3.93 (n=16)
Soil pH	0-15cm	8.31 ± 0.07 (n=4)	8.20 ± 0.08 (n=4)	8.02 ± 0.52 (n=4)	8.14 ± 0.16 (n=4)	8.18 ± 0.27 (n=16)
	15-30cm	8.15 ± 0.13 (n=4)	7.94 ± 0.11 (n=4)	7.86 ± 0.53 (n=4)	8.05 ± 0.17 (n=4)	8.04 ± 0.30 (n=16)
	30-45cm	8.06 ± 0.16 (n=4)	7.78 ± 0.15 (n=4)	7.79 ± 0.55 (n=4)	7.88 ± 0.32 (n=4)	7.92 ± 0.31 (n=16)
	45-60cm	7.88 ± 0.17 (n=4)	7.50 ± 0.20 (n=4)	7.62 ± 0.52 (n=4)	7.77 ± 0.16 (n=4)	7.78 ± 0.40 (n=16)

Table 1 summarizes the data collection, presenting (mean ± SD and sample sizes) for each soil metric and species from 128 samples. The analysis of soil properties across different species and depths revealed consistent patterns in nutrient and structural features. When stratified by soil depth, most physicochemical parameters' mean values remained relatively stable across the 0–60 cm profile, with only slight variations. Organic matter, soil organic carbon and available nitrogen were generally higher in the upper layers (0–15 cm and 15–30 cm), indicating influences from litter deposition and root activity, whereas deeper layers (30–60 cm) showed lower concentrations. Bulk density tended to increase with depth, consistent with compaction and decreased organic input in subsoil horizons. Differences among species were modest, though minor fluctuations in moisture, phosphorus and potassium suggested species-specific effects on nutrient cycling. Overall, the depth-wise analysis underscores the importance of surface soils for nutrient availability, while deeper layers play roles in soil structure and storage. Further statistical analysis has been conducted and are presented in the following sections.

Soil Texture and Structure

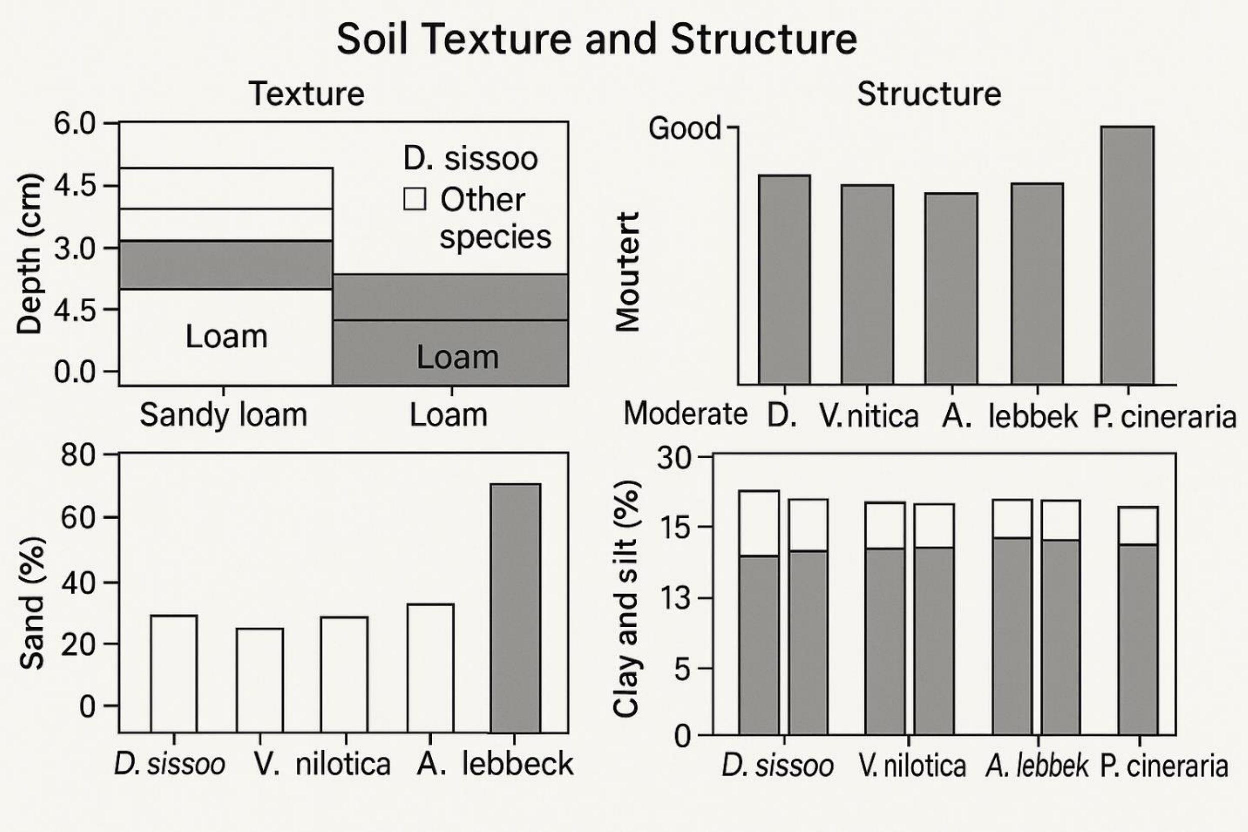

Figure 1. Soil Texture and Structure

Figure 1 shows that at soil depths of 0-15 cm and 15-30 cm in *D. sissoo*, the texture was sandy loam, while at 30-45 cm and 45-60 cm, the texture was classified as loam. In contrast, all other species at every soil depth consisted of loam. The soil structure ranged from good to moderate across all species. The sand fraction was minimal for three species (*D. sissoo, V. nilotica* and *A. lebbeck*) and maximal for *P. cineraria* (68.02%). The clay fractions, however, did not show substantial variation among the four tree species at different depths (13.5%). Silt content varied among tree species but remained statistically insignificant ($p<0.05$) concerning soil depth.

Normality Test of Species

The statistical analysis begins with a normality test, using the Shapiro-Wilk Test. If the p-value is less than 5%, it indicates that the data are not normally distributed. Conversely, if the p-value is greater than 5%, the data are normally distributed. If the number of normally distributed variables exceeds the number of non-normally distributed variables, we use the parametric test, which is the Two-Way ANOVA. On the other hand, if not, we need to use the non-parametric test, which is the Kruskal-Wallis Test.

Table 2. Normality Test of Tree Species with the Shapiro-Wilk Test

No.	Variable	*D. sissoo*	*V. nilotica*	*P. cineraria*	*A. lebbeck*	*Control*
1	Soil pH	0.377	0.544	0.058	0.111	0.001
2	Soil Electrical Conductivity	0.049	0.017	0.105	0.055	0.000
3	Soil Bulk Density	0.715	0.563	0.191	0.042	0.004
4	Soil Organic Matter	0.754	0.712	0.675	0.048	0.015
5	Soil Organic Carbon	0.583	0.002	0.062	0.764	0.149
6	Soil Moisture	0.084	0.129	0.040	0.011	0.004
7	Soil Saturation	0.754	0.606	0.210	0.454	0.449

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8	Soil available Nitrogen	0.021	0.567	0.064	0.805	0.002
9	Soil available Phosphorus	0.406	0.035	0.190	0.041	0.123
10	Soil available Potassium	0.202	0.127	0.218	0.773	0.597

Table 2 shows that, according to the Shapiro-Wilk test, most p-values for the soil pH variables are greater than 5%, indicating that these data are normally distributed, except for the control variable. For soil electrical conductivity, all p-values except for *P. cineraria* and *A. lebbeck* are below 5%, meaning the data are not normally distributed, with *P. cineraria* and *A. lebbeck* as exceptions. Regarding soil bulk density, all p-values except for *A. lebbeck* and the control are above 5%, indicating normal distribution, but *A. lebbeck* is an exception. For soil organic matter, all p-values except for *A. lebbeck* and the control are above 5%, suggesting normal distribution, with *A. lebbeck* as an exception. For soil organic carbon, all p-values except for *V. nilotica* are above 5%, indicating normal distribution, with *V. nilotica* as an exception. Concerning soil moisture, the p-values for *D. sissoo* and *V. nilotica* are above 5%, indicating they are normally distributed. In contrast, *P. cineraria, A. lebbeck,* and the control have p-values below 5%, suggesting these data are not normally distributed. For soil saturation, all p-values exceed 5%, indicating that all data are normally distributed. For soil available nitrogen, all p-values are above 5%, suggesting normal distribution. For soil available phosphorus, p-values for all treatment soil depths except 15-30 cm are above 5%, indicating normal distribution, but at the 15-30 cm depth, the p-values are lower. Overall, the Shapiro-Wilk test demonstrates that most data are normally distributed, with some exceptions at specific depths and variables.

Normality Test of Soil Depth

After understanding the distribution of variables based on tree species, the statistical analysis continues by examining the normality of soil depth. Just like the normality test previously performed for the tree species, the normality test for soil depth also uses the Shapiro-Wilk Test.

Table 3. Normality Test of Soil Depth with the Shapiro-Wilk Test

No.	Variable	0-15cm	15-30cm	30-45cm	45-60cm
1	Soil pH	0.000	0.003	0.125	0.228
2	Soil Electrical Conductivity	0.049	0.017	0.105	0.055
3	Soil Bulk Density	0.016	0.044	0.376	0.007
4	Soil Organic Matter	0.000	0.095	0.063	0.003
5	Soil Organic Carbon	0.496	0.097	0.926	0.310
6	Soil Moisture	0.001	0.018	0.164	0.243
7	Soil Saturation	0.120	0.031	0.250	0.079
8	Soil available Nitrogen	0.021	0.567	0.064	0.805
9	Soil available Phosphorus	0.084	0.030	0.222	0.726
10	Soil available Potassium	0.350	0.106	0.666	0.434

Table 3 shows that for soil pH, based on the Shapiro-Wilk test, P-values for treatment soil depths of 0-15 cm and 15-30 cm are less than 5%, indicating that these data are not normally distributed. In contrast, the P-values for soil depths of 30-45 cm and 45-60 cm are greater than 5%, suggesting these data are normally distributed. For soil electrical conductivity, according to the Shapiro-Wilk test, all P-values except for the soil depth of 30-45 cm are below 5%, indicating that the data are not normally distributed, with the exception of 30-45 cm. For soil bulk density, based on the Shapiro-Wilk test, the P-values for soils at depths of 0-15 cm and 45-60 cm are less than 5%, showing they are not normally distributed. Conversely, the P-values for depths of 15-30 cm and 30-45 cm are greater than 5%, indicating normal distribution. For soil organic matter, all P-values are above 5%, confirming normal distribution across all data. According to the Shapiro-Wilk test, the P-values for the soil depths of 0-15 cm and 15-30 cm are less than 5%, indicating non-normality. In contrast, the depths of 30-45 cm and 45-60 cm have P-values above 5%, indicating normal distribution. For soil moisture, except for the soil depths of 15-30 cm, all other P-values are above 5%, suggesting most data are normally distributed, except at those depths. Regarding soil saturation, all P-values are above 5%, indicating normal distribution across different soil depths. For soil available nitrogen, all data have P-values greater than 5%, signifying normal distribution at all depths. For soil available phosphorus, P-values for all treatments except 15-30 cm are above 5%, indicating normal distribution except at 15-30 cm. Overall, all P-values exceed 5%, demonstrating that the data are generally normally distributed.

Significant Test

After obtaining the results from the normality test for all 10 variables related to the tree species and soil depths, we determine which significance test to use, either parametric or non-parametric. It is known that for soil electrical conductivity and soil available nitrogen, more variables are not normally distributed; therefore, we use the non-parametric test, which is the Kruskal-Wallis Test. On the other hand, the other 8 variables namely; soil pH, soil bulk density, soil organic matter, soil organic carbon, soil moisture, soil saturation, soil available phosphorus and soil available K (Potassium) are more normally distributed, so we use the parametric test, which is the Two-Way ANOVA.

Table 4. Results of statistical tests (Two-way ANOVA or Kruskal-Wallis) for the effects of Tree Species, Soil Depth and their Interaction on soil properties. Significant p-values ($p < 0.05$) are in bold.

No.	Variable	Method	p-value (Species)	p-value (Soil Depth)	p-value (Interaction)
1	Soil pH	Two-wayANOVA	0.084	**<0.001**	0.999
2	Soil Electrical Conductivity	Kruskal Wallis	0.014	-	-
3	Soil Bulk Density	Two-Way ANOVA	**<0.001**	0.087	0.643
4	Soil Organic Matter	Two-Way ANOVA	**<0.001**	0.830	0.636
5	Soil Organic Carbon	Two-Way ANOVA	0.087	0.473	0.078
6	Soil Moisture	Two-Way ANOVA	**<0.001**	0.531	0.995
7	Soil Saturation	Two-Way ANOVA	**<0.001**	0.132	0.997
8	Soil available Nitrogen	Kruskal Wallis	0.014	-	-
9	Soil available Phosphorus	Two-Way ANOVA	**<0.001**	0.002	<0.001
10	Soil available Potassium	Two-Way ANOVA	**<0.001**	0.132	0.862

Table 4 presents the results of significance tests using Two-Way ANOVA and Kruskal-Wallis Test. Soil pH was significantly influenced by soil depth (Two-way ANOVA, $p < 0.001$) but not by tree species ($p = 0.084$). The results show that the p-value for soil depth is less than 5%, indicating that soil depth significantly influences the pH within the tree canopy. According to the post-hoc Tukey HSD test, all p-values for the four tree species and the control are greater than 5%, suggesting there are no significant differences among the tree species regarding soil pH inside the canopy. The post-hoc test also reveals that p-values for soil depths of 0-15 cm and 30-45 cm, 0-15 cm and 45-60 cm, and 15-30 cm and 45-60 cm are less than 5%, indicating significant differences in soil pH among these groups. Conversely, p-values for soil depths of 0-15 cm and 15-30 cm, 15-30 cm and 30-45 cm, and 30-45 cm and 45-60 cm are greater than 5%, meaning there are no significant differences in soil pH between these pairs.

Tree species had a significant effect on soil EC (Kruskal-Wallis, $p = 0.014$). Post-hoc analysis revealed that *P. cineraria* and *A. lebbeck* had significantly lower EC than the control. For soil electrical conductivity, the results show a p-value less than 5%, indicating a significant difference between the sample medians. This suggests that a variable, such as tree species or soil depth, significantly influences soil electrical conductivity. Based on the post-hoc test using the Mann-Whitney test, the table above displays all variables from both tree species and soil depth that have a P-value below 5%, indicating a significant difference at the alpha level of 5%. The table reveals that *P. cineraria* and *A. lebbeck* are significantly different from the control, suggesting that these species may impact soil electrical conductivity. Regarding soil depth, it does not significantly affect soil electrical conductivity. The tree species *P. cineraria* and *A. lebbeck* have notably lower soil electrical conductivity, with *P. cineraria* showing the lowest. This indicates that if the goal is to attain low soil electrical conductivity, *P. cineraria* is the best option, followed by *A. lebbeck.*

For soil bulk density, the results show that the p-values for soil depths and their interaction are greater than 5%, indicating that tree species do not significantly affect soil bulk density, and there is no significant interaction between tree species and soil depths. The results also show that the p-value for tree species is less than 5%, indicating that tree species significantly affect soil bulk density. Based on the post-hoc test using Tukey HSD, it is evident that the p-values for *D.sissoo*-Control, *V.nilotica*-Control, and *P. cineraria*-Control are less than 5%, indicating significant differences in soil bulk density among those tree species. Additionally, the post-hoc test using Tukey HSD shows that all p-values from the four soil depths are greater than 5%, indicating no significant difference in soil bulk density among the different soil depths within the tree canopy. This demonstrates that trees can make the soil looser or decrease soil bulk density, which benefits the soil by allowing it to absorb more water and reduce erosion.

For the soil organic matter, the results indicate that the p-values for soil depths and their interaction exceed 5%, suggesting that soil depths do not significantly affect soil bulk density, and there is no significant interaction between tree species and soil depths regarding soil organic matter. Additionally, the results reveal that the p-value for tree species is below 5%, suggesting that tree species significantly influence soil organic matter within the tree canopy. Based on the post-hoc test using Tukey HSD, the p-values for the control variable and all four tree species are less than 5%, indicating that all four tree species significantly affect soil organic matter. Furthermore, it is also known that the p-values of *P. cineraria–D.sissoo* and *P. cineraria–V.nilotica* are less than 5%, indicating that *P. cineraria* is the species that is most significantly different from the other tree species in terms of soil organic matter. According to the post-hoc test using Tukey HSD, all p-values from the four soil depths exceed 5%, indicating no significant difference in soil organic matter within the tree canopy across different soil depths. The control has the lowest amount of soil organic matter, followed by *P. cineraria*. The *A. lebbeck* tree has a slightly higher amount of soil organic matter. However, *D. sissoo* and *V. nilotica* have the highest amounts of soil organic matter. This suggests that *D. sissoo* and *V. nilotica* are effective in enriching soil organic matter in this area.

For the soil organic carbon, the results show that all p-values for tree species, soil depths and their interaction are greater than 5%. This indicates that there is no significant effect from either tree species or soil depths, and no interaction between them regarding soil organic carbon. A post-hoc test was still conducted using the Tukey HSD to determine if any tree species or soil depth are significantly different for soil organic carbon. Based on the post-hoc test with Tukey HSD, the p-values for all four tree species and the control are greater than 5%, showing no significant differences in soil organic carbon among them. Similarly, the p-values for the four soil depths also exceed 5%, indicating no significant difference in soil organic carbon within the tree canopy across different soil depths. Overall, there are no significant differences in soil organic carbon (SOC) among the four tree species, the control or the different soil depths. This suggests that soil organic carbon at this research site may remain consistent regardless of the presence of trees, possibly due to soil type or other factors.

Gravimetric soil moisture measured at the end of the dry season was significantly influenced by tree species. Additionally, the results reveal that the p-value for tree species is below 5%, indicating that tree species significantly influence soil moisture within the tree canopy. Based on the post-hoc test using Tukey HSD, the p-values between the control and all four tree species are less than 5%, indicating that planting trees, regardless of species—*D. Sissoo, V. nilotica, P. cineraria* and *A. lebbeck* will significantly affect soil moisture. Furthermore, since all other p-values are greater than 5%, this indicates that there is no significant difference among the four tree species regarding soil moisture. According to the post-hoc test using Tukey HSD, all p-values from the four soil depths exceed 5%, indicating no significant difference in soil moisture within the tree canopy across different soil depths. The soil moisture in the control is the lowest among the other plots planted with trees, which suggests that trees significantly increase soil moisture. The data also show that *D. sissoo* and *A. lebbeck* have the highest soil moisture, followed by *V. nilotica* and *P. cineraria*. It is clear that *D. sissoo* and *A. lebbeck* are among the best options of the four tree species for improving soil moisture.

Regarding the soil saturation, the results show that the p-values for soil depths and their interaction are above 5%. This indicates that soil depths do not significantly influence soil saturation, and there is no significant interaction between tree species and soil depths in relation to soil saturation. Additionally, the p-value for tree species is below 5%, suggesting that tree species significantly affect soil saturation within the tree canopy. The post-hoc test using Tukey HSD reveals that the p-values between the control and all four tree species are below 5%, meaning planting trees regardless of species, including *D. sissoo, V. nilotica, P. cineraria*, and *A. lebbeck* significantly influences soil saturation. Since all other p-values are above 5%, there is no significant difference among the four tree species in terms of soil saturation. The Tukey HSD post-hoc test also shows that the p-values across the four soil depths are greater than 5%, indicating no significant variation in soil saturation within the tree canopy at different soil depths. The soil saturation in the control is lower than in soil planted with the four different tree species. This suggests that trees can significantly improve soil saturation. The study further shows that soil saturation at a depth of 45-60 cm is the highest; however, this difference is not statistically significant.

For the soil available nitrogen, the results indicate that the p-value is less than 5%, which means there is a significant difference between the sample medians. This suggests that a variable, such as tree species or soil depth, significantly influences soil available nitrogen. Further analysis used the Mann-Whitney test. Based on the post-hoc test with the Mann-Whitney test, shows that the p-values for soil available nitrogen, derived from both the tree species and soil depth treatments, are mostly below 5%. This indicates that both tree species and soil depth significantly affect nitrogen availability in the soil. The nitrogen in the soil for the control group is the lowest. The highest nitrogen levels are found in the soil planted with *V.* nilotica, followed by *D. sissoo*. This suggests that *V. nilotica* could be an effective option for increasing nitrogen availability. It also reveals that soil at a depth of 45-60 cm contains the least nitrogen, while the highest concentration is at 30-45 cm. This implies that achieving optimal nitrogen levels may be difficult if the soil is too deep or too shallow; therefore, the best depth for nitrogen at this research site is 30-45 cm.

For the soil available phosphorus, the results show that all p-values are less than 5%, indicating that both the tree species and soil depth significantly affect phosphorus

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availability in the soil. Additionally, there is a significant interaction between tree species and soil depths. Based on the post-hoc test using Tukey HSD, it shows that all the p-values from the four tree species and the control are less than 5%, indicating a significant difference among the tree species regarding soil phosphorus within the tree canopy. Furthermore, there is also a significant difference between the trees of *V. nilotica - D. sissoo* and *A. lebbeck - D. sissoo*. Based on the post-hoc test using Tukey HSD, the results show that the p-values for the soil depths of 45-60 cm and 0-15 cm, as well as 45-60 cm and 30-45 cm, are less than 5%, indicating significant differences in soil phosphorus among these groups. It can be concluded that the soil depth treatment of 45-60 cm, the deepest in this research, has the most significant effect. The post-hoc test using Tukey HSD also shows some interactions with p-values less than 5%. This indicates that the control and *D. sissoo* have the most interactions, while there are also significant interactions between the depths of 45-50 cm and 0-15 cm. There appears to be a trend influenced by both the tree species and the soil depth treatment. The *D. sissoo* species has the highest amount of soil phosphorus, followed by *P. cineraria*. The lowest amount is found in the control, with *V. nilotica* showing a lower level. *A. lebbeck* has a moderate amount, although the trend is different. The pattern is quite complex because tree species and soil depths have strong interactions, affecting each other.

Lastly, for the soil available potassium, the results show that the p-values for the tree species are less than 5%, indicating that the tree species significantly affect the amount of potassium in the soil. In contrast, the treatment of soil depths has no significant effect, and there is no interaction between tree species and soil depths. Based on the post-hoc test using Tukey HSD, all p-values from the four tree species and the control are less than 5%, except for *A. lebbeck-V. nilotica* and *A. lebbeck-P. cineraria*. This suggests that nearly all the tree species differ significantly from each other regarding their soil potassium content. The selection of tree species should be made carefully, considering soil characteristics, especially potassium availability. The post-hoc test results also show that all p-values are greater than 5%, indicating no significant difference in soil potassium levels across different depths. However, significant differences do exist among tree species. The control area, which is bare land, has the lowest potassium levels. The highest potassium content is found in *P. cineraria*, followed by *A. lebbeck, V. nilotica*, and *D. sissoo*. In conclusion, if soil rich in potassium is desired, *P. cineraria* and *A. lebbeck* are among the best choices compared to the other species in this study.

DISCUSSION

The findings of our three-year controlled field experiment provide robust, species- and depth-specific evidence for the role of native leguminous trees in remediating degraded soils in arid agroforestry systems. While the general benefits of trees on soil are well-established (Mojiri et al. 2011; Tsufac et al. 2021), our study moves beyond observational correlation by quantitatively isolating the distinct effects of four key species within a replicated experimental framework. The significant species × depth interactions we observed for critical nutrients like phosphorus underscore that tree species selection is not arbitrary; it dictates the vertical redistribution of resources in the soil profile, a nuance with profound implications for intercropping system design

Our study provides clear evidence that the selection of leguminous tree species in agroforestry systems is not arbitrary; it directly and differentially shapes the physicochemical profile of the soil, with effects varying down the soil profile. Land degradation resulting from various anthropogenic activities leads to the deterioration of soil. A notable disparity in the physicochemical properties of soil has been documented by Bewket and Stroosnijder (2003). Soil fertility is the primary determinant of agricultural productivity. Key physical qualities of soil that influence soil fertility include texture, structure, porosity, permeability, infiltration, bulk density, soil moisture and soil color. Their function in facilitating plant growth is interconnected (Tripathi et al. 2020). Addressing the problem of soil fertility immediately influences agricultural yields, as there is a clear correlation between soil fertility and farm production (Tsufac et al. 2021). Prolonged agricultural practices and alterations in land use diminish organic matter, organic carbon, total nitrogen and available potassium (Mojiri et al. 2011). Identical findings are also documented by Göl et al. (2010) in their examination of agricultural soils relative to forest soils. Trees influence the chemical properties of the soil due to the decomposition of both aboveground and belowground biomass. Trees also improves soil structure through incorporation of organic matter, thus increasing structural stability and resistance to soil erosion (Pinho et al. 2012).

The correlation between species and soil depth was significant ($p<0.05$) for soil pH. These results are supported by Gul et al. (2011). Soil pH is a crucial factor in determining soil fertility because it influences nutrient availability, microbial activity, and overall soil health. A study by Sharma et al. (2009) revealed that physicochemical characteristics, such as soil pH and organic carbon, were significantly influenced by different land-use practices. The stated results show that the highest pH levels were observed in the topsoil (0–30 cm) and gradually decreased with depth. This trend suggests that surface soils are more influenced by external factors such as organic matter decomposition, root exudates and nutrient cycling. Casals et al. (2014) demonstrated increased levels of SOC, N, P, K and Ca beneath tree canopies. The reduced soil pH may be attributed to intense erosion and leaching processes due to the presence of tree species in the adjacent regions of the Cholistan Desert, which have a greater sand content in the soil. The soil pH exhibited statistically significant variations between the sites. Our findings corroborate the previous study by Oumarou (2016), which indicated that pH exhibited significant variation across soil depth classes, with higher pH levels observed near the surface compared to greater depths. Soil acidity (reduced soil pH) constrains crop productivity. Elevated soil pH observed beneath tree canopies may influence nutrient availability, particularly the availability of phosphorus, which is typically limited in Pakistani soils. Consequently, trees facilitate nutrients provision to plants in alkaline soils by elevating soil pH and ultimately improving soil fertility. The results are documented by Mugunga and Mugumo (2013).

A reduction in soil electrical conductivity (EC) corresponding to increasing soil depth has been documented by Rahi et al. 2012; which is in line with our findings. Soil electrical conductivity is a key indicator of soil fertility as it reflects the concentration of soluble salts, which influence nutrient availability, soil structure, and plant growth. The stated results show that soil EC decreases progressively with depth, with the highest values in the topsoil (0–15 cm) and the lowest values in deeper layers (45–60 cm). This trend has several implications for soil fertility: The decline in EC with depth suggests that salts are concentrated in the upper layers, likely due to limited leaching or evaporation effects. The lower EC in deeper layers may indicate reduced microbial activity, less organic matter input and lower cation exchange capacity, which can affect nutrient retention and plant uptake.

Bulk density (BD) is a key soil physical property that influences soil fertility by affecting root growth, water retention, and soil aeration. The results show that BD values ranged from 1.09 g/cm³ to 1.37 g/cm³, with lower BD values in the topsoil (0–15 cm) and a gradual increase with depth. This trend has several implications for soil fertility. Lower BD in the topsoil (e.g., 1.09 g/cm³ under *V. nilotica*) suggests loose, well-structured soil, which facilitates root expansion, water infiltration, and nutrient uptake. Higher BD at greater depths (e.g., 1.36 g/cm³ under *A. lebbeck* at 45–60 cm) may indicate compaction, which can restrict root penetration and limit access to deeper water and nutrients. Increased bulk density values were seen in the silvopastoral system. This increase in bulk density was associated with elevated soil resistance to compaction beneath its crown. A comparison of our results was performed. Likewise, Tate et al. (2004) found that canopy cover from any tree species evaluated in their research significantly ($p<0.05$) reduced bulk density by 16-22%. Similar results have been reported by Hailu (2015). The physical soil quality of complex agroforestry is similar with natural forest which has better structure, bulk density and porosity (Purnama et al. 2022). The results suggest that soils beneath tree canopies are well-structured and less compacted, promoting root penetration. Tree litter inputs, organic matter accumulation, and biological activity contribute to improved soil structure and reduced BD in surface layers. *V. nilotica* had the lowest BD in the topsoil, indicating its role in improving soil porosity and fertility. In contrast, *A. lebbeck* showed higher BD in deeper layers, suggesting some level of compaction under its canopy.

Chemical characteristics of soil are primary determinants of soil fertility, playing a crucial role in facilitating plant growth and development. This criterion is mostly indicated by the availability of nutrients in the soil, including Nitrogen, Phosphorus and Potassium. Certain soil chemistry factors influencing nutrient availability include soil pH, soil organic matter/carbon, and cation exchange capacity (Khaleel et al. 2020). Soil organic matter is an essential component of soil that profoundly affects soil fertility (Widyati et al. 2022). Our findings align with previous research by Magar et al. (2020), which indicates that maximal soil organic matter is located at a depth of 0-30 cm, and Oumarou (2016), which asserts that organic matter is concentrated near the soil surface due to the accumulation of decomposing leaves and litter beneath tree canopies. A separate study by indicated that microbial and soil organic matter concentrations are higher in shallow soil profiles compared to deeper ones. The higher SOM in the topsoil (e.g., 0.61% under *D. sissoo*) suggests better nutrient availability for plant roots, while the lower SOM at depth (e.g., 0.28% under *P. cineraria*) may result in fewer nutrients in deeper soil layers. Different tree species impact SOM levels due to variations in litter production, decomposition rates, and root turnover. *D. sissoo* had the highest SOM at 0.61% (0–15 cm), suggesting greater litter decomposition and organic inputs under its canopy. *P. cineraria* showed the lowest SOM at 0.28% (45–60 cm), indicating less organic input at deeper layers. *V. nilotica* exhibited a more uniform SOM distribution, suggesting a more stable organic matter fraction.

Soil organic carbon (SOC) is a fundamental component of soil fertility, as it plays a crucial role in nutrient cycling, soil structure, microbial activity, and moisture retention. The results indicate a statistically significant variation ($p<0.05$) in SOC across different tree species and soil depths, with the highest SOC recorded in *V. nilotica* (0.35%) and a progressive decline in SOC with increasing soil depth. The higher SOC in the topsoil (0–15 cm and 15–30 cm) suggests better nutrient availability in surface layers, whereas the lower SOC at greater depths (30–60 cm) indicates reduced organic matter inputs and nutrient reserves. Numerous studies have shown a decrease in soil organic carbon with increasing soil depths (Aponte et al. 2012; Becker et al. 2015; Russell, 2007), which are in line with our findings. Different tree species contribute to SOC variation through litter quality, decomposition rates, and root turnover. The highest percentage of soil organic carbon in the upper soil layers results from the presence of decomposing leaves and litter (Chatterjee et al. 2018). These investigations align with Jobbágy and Jackson (2000).

Moisture is essential for nutrient dissolution and uptake by plant roots. The significantly higher soil moisture found under tree canopies, particularly under *A. lebbeck* and *D. sissoo*, at the end of the dry season suggests these species may improve the water holding capacity of the soil, potentially through organic matter enrichment and reduced evaporative losses under the canopy. This provides a snapshot of their potential to mitigate water stress during critical periods, though seasonal dynamics require further investigation. The increasing moisture with depth suggests that deeper soil layers serve as water reservoirs, supporting tree growth during dry conditions. Our findings align with previous research indicating higher soil moisture under trees.

The shade from trees can diminish evapotranspiration in understory plants, leading to an increase in soil water content. Trees of low moisture content soils have deep root systems and helps in nutrient and water pumping as compared to high moisture soils (Fahad et al. 2022; Makumba et al. 2009; Schroth and Sinclair 2003). By intercepting water runoff, trees improve soil infiltration characteristics, traps more water and enhance the soil water content. This makes soil moisture more available under trees than in the open (Cyamweshi et al. 2023). Higher saturation in topsoil (e.g., *D. sissoo* at 36.77%) suggests that surface layers can retain more water, supporting plant root water uptake and nutrient transport. Lower saturation at deeper layers (e.g., *D. sissoo* at 25.83% at 30–45 cm) indicates reduced water retention capacity, which may limit deep-rooted plants' access to moisture during dry periods. Our findings align with previous research by Allan et al. (2009), which indicates that saturation percentage is a crucial metric for characterizing soil texture, noting that sandy loam to loam soils exhibit saturation percentage values ranging from 20 to 35%. A reduction in saturation percentage has also been documented in a prior study by Gul et al. (2011) in relation to rising soil depths, aligning with our findings. Ong et al. (2006) found that trees improve water storage and reduce evaporation and the rate of transpiration in agroforestry systems. *D. sissoo* and *A. lebbeck* maintained higher saturation percentages in topsoil, indicating their ability to enhance soil structure and water retention through litter deposition and organic matter contributions. *P. cineraria* exhibited the lowest saturation percentages across all depths, suggesting faster drainage and lower water retention capacity under its canopy, making it more suited to drier environments. At 45-60 cm, saturation percentages were not significantly different ($p<0.05$), except for *V. nilotica*, which indicates that at greater depths, soil properties tend to equalize among species.

The continuous removal of nutrients from soil by crops creates deficiency of certain nutrients such as N, P K, Sulphur, Zinc and even Boron. The deficiency of organic matter decreases the soil fertility which causes ultimately low yield of crop (Misra 2011). Trees substantially enhance the physical and chemical parameters of soil, which are directly associated with soil fertility. Gupta et al. (2009) noted that the mean soil organic carbon markedly elevated under agroforestry relative to mono-cropping and this enhancement was correlated with tree age. Research on soil enrichment services via litter fall indicated that over 20% of the necessary phosphorus, 77% of the essential nitrogen, and 67% of the required potassium could be supplied by *Ficus* litter (Dhanya et al. 2013). Saha et al. (2010) examined the impact of five multi-purpose tree species on soil inside agroforestry systems and discovered significant enhancements in all soil hydro-physical properties. De Boever (2015) observed higher nutrient contents in the soil beneath the tree canopy. Abdullahi et al. (2016) noted that trees enhance soil fertility beneath their canopies. Even non-nitrogen-fixing trees contribute organic matter, recycle nutrients and consequently substantially improve all soil qualities (Jose, 2009). Trees add organic matter to the soil system in various manners, whether in the form of roots or litter fall or as root exudates in the rhizosphere. These additions are the chief substrate for a vast range of organisms involved in soil biological activity and interactions, with important effects on soil nutrients and fertility (Misra, 2011).

Among the 21 basic nutrients for plant growth, nitrogen, phosphorus and potassium are required in substantial quantities and their deficiency in soil leads to a significant decrease in crop output. Soils of Pakistan exhibit deficiencies in nitrogen, phosphorus and potassium. Nitrogen is a critical ingredient for plant growth and productivity, playing a vital role in the plant's response to environmental challenges (Carelli et al. 2006). Despite being one of the most abundant elements on Earth, it cannot be directly absorbed by plants, which require its conversion into nitrites. This transformation can be accomplished chemically or biologically by biological nitrogen fixation. The utilization of chemical fertilizers is financially burdensome (Dori et al. 2022). Moreover, the application of chemical fertilizers results in several ecological consequences, including pollution of air, soil, and water. Consequently, there is significant interest in the symbiotic nitrogen fixation between legumes and rhizobia for the enhancement of agricultural systems, specifically in achieving higher yields with minimal ecological impact (Ribeiro-Barros et al. 2018). Numerous researches have documented a reduction in soil nitrogen with increasing soil depths across various crops and tree types (Russell et al. 2007; Susanto et al. 2017; Wang et al. 2010). Our result contradicts a previous investigation that found an increase in soil available phosphorus with increasing soil depths, as noted by Susanto et al. (2017). The disparity is due to variations in soil organic matter concentration, soil pH, erosion and leaching severity, crop types cultivated, and cultivation intensity. Potassium levels varied as reported by Wang et al. (2010) in their study. Surki et al. (2020) reported that integration of trees on farms enhances available potassium, available phosphorus and soil carbon stocks. From the ecological point of view, leguminous tree species introduction in cropping systems may contribute to reduce the use of chemical fertilizers and to ecosystems stability (Ribeiro-Barros et al. 2018).

For farmers aiming to boost overall fertility, *V. nilotica* and *D. sissoo* are highly recommended. For reclaiming saline patches, *P. cineraria* should be incorporated. For enhancing soil moisture in water-scarce environments, *A. lebbeck* and *D. sissoo* are advantageous.

CONCLUSION

This study demonstrates that the strategic selection of native leguminous trees in agroforestry systems is a powerful tool for enhancing soil fertility in arid regions. The distinct functional roles of the studied species enable targeted interventions: *Vachellia nilotica* for nitrogen enrichment, *Dalbergia sissoo* for phosphorus and organic matter buildup in topsoil, *Albizia lebbeck* for potassium and moisture conservation, and *Prosopis cineraria* for mitigating soil salinity. The significant variation in soil properties with depth underscores the importance of root architecture and litter deposition patterns. By matching specific tree species to local soil constraints such as nutrient deficiency, salinity, or poor water retention, farmers, extension officers and policymakers can design more resilient and productive agroforestry systems, reducing reliance on unsustainable chemical inputs and building long-term agricultural sustainability in the face of climatic challenges.

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Authors Contributions

M.M., M.U.G., and M.A.B. designed the sampling strategy. M.M., T.H. designed the experiments. M.M, performed the experiment. T.H. provided materials and supervision. N.A.N. statistical analysis; M.M. wrote the manuscript. M.M.A., T.H.A., MQ, reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Ethics declarations

This study does not include human or animal subjects.

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