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

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

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Abstract

This study evaluates the species-specific impacts of leguminous trees on soil fertility in arid and semi-arid climates, focusing on their influence on key soil physicochemical properties across multiple depths. A three-year field experiment assessed four native leguminous species *Dalbergia sissoo*, *Vachellia nilotica*, *Prosopis cineraria*, and *Albizzia lebbeck* using a randomized complete block design. Soil samples were collected beneath and outside the canopy at four depths (0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm) for laboratory analysis. Significant differences ($p < 0.05$) were found among tree species and depths for parameters such as pH, moisture, saturation, electrical conductivity, organic matter, and macronutrients. *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, boosting productivity, and supporting sustainable livelihoods in dryland farming systems.

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). Leguminous trees are especially important due to their nitrogen-fixing capabilities and litter decomposition (Diabate et al., 2005; 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 this study, we examine the effects of four native leguminous tree species; *Albizzia lebbeck*, *Dalbergia sissoo*, *Prosopis cineraria*, and *Vachellia nilotica* on soil physicochemical properties across four depths (0–60 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.

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 (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 (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). 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; 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., 2025). 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). This study evaluates their contributions to improving soil fertility across depths, aiming to guide species selection for sustainable agroforestry in arid and semi-arid climates.

Materials and Methods

The study was conducted in Bahawalpur District (27°48′–29°50′ N, 70°54′–72°50′ E), a semi-arid region in Punjab, Pakistan, characterized by sandy loam to loam soils with low organic matter

(<0.5%) and phosphorus (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 (GoP 2023). The climate is extreme, with summer temperatures reaching 40°C, winter averages of 22°C, and scant annual rainfall (<250 mm). Irrigation relies primarily on canal systems due to limited groundwater availability. The total cultivated area of Bahawalpur district is 372,324 hectares. The major crops of the district are cotton, wheat, rice and sugarcane. The weather in the summer and winter is extreme and the average temperature in summer is 40°C and 22°C in winter. 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. 2025).

Random soil samples were collected both beneath the tree canopy, and from bare or non-treed control plots entirely devoid of tree influence at four depth intervals (T1 = 0–15 cm, T2 = 15–30 cm, T3 = 30–45 cm, and T4 = 45–60 cm) along four transects during the study period from 2021 to 2023 for laboratory analysis. In addition to tree-associated sampling, control samples were also collected from nearby bare land areas with no tree cover to serve as a baseline for comparison. For each of the four tree species and the control group, 20 soil samples were collected at each of the four depths, resulting in a total of 320 samples (4 species × 4 depths × 20 samples). 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, as indicated by Oumarou (2016). 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). Various sizes of sieves were employed to assess soil texture. The hydrometer method was employed for particle size analysis. Soil pH was measured by a digital pH meter. Soil electrical conductivity meter was used to measure EC in a saturated paste extract following the procedure described by Houba et al. (1989). Core method was used for the determination of bulk density in soil (Rai, 2015). The percent soil organic matter (SOM) was calculated by multiplying the percent organic carbon by a factor of 1.724 (Nelson and Sommers, 1996). Soil organic carbon (SOC) was assessed using the wet-digestion technique according to Allison (1960). 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. Saturation percentage (SP) was determined as: -

$$SP = \text{(Loss in weight after oven drying (g))} / \text{(Total weight of soil after oven dry weight (g))} \times 100$$

Soil available nitrogen content was quantified via the Kjeldahl method as outlined by Jackson (1958). Available phosphorus was extracted and analyzed using the Olsen method (Olsen and

Sommers, 1982). Potassium (K) concentration in the extract was measured by flame photometry, following the protocol by Jackson (1958).

Statistical analysis

Each mean contains data from four tree species, with twenty samples corresponding to each soil depth. The collected data 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. 2025).

RESULTS

1. Soil Texture and Structure

At soil levels of 0-15 cm and 15-30 cm in *D. sissoo*, the texture was sandy loam, whereas at depths of 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, on the other hand, did not exhibit substantial variation among four tree species at different depths (13.5%). Silt content shown variability among tree species, although remained statistically insignificant ($p<0.05$) concerning soil depth.

2. Soil pH

Based on the results, there is a pattern for soil pH based on the treatment of soil depth (Figure 1). The first treatment with a soil depth of 0-15 cm has the highest pH, followed by the soil depths of 15-30 cm, 30-45 cm, and the lowest pH at a soil depth of 45-60 cm. This research indicates that the deepest soil depth, 45-60 cm, has the lowest pH, which approaches the neutral pH of 7. It can be estimated that a soil depth of 45-60 cm is the best option for plants that require neutral pH.

Table 1. Shapiro-Wilk test of soil pH based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	*Control*
P-value	0.3773	0.5445	0.05828	0.1113	0.001192

Based on **Table 1** with the Shapiro-Wilk test, all p-values, except for the control variable, are greater than 5%, indicating that all data are normally distributed, except for the control variable.

Table 2. Shapiro-Wilk test of soil pH based on soil depths

Depth	0-15cm	15-30cm	30-45cm	45-60cm
P-value	1.459E-05	0.002664	0.125	0.2285

Based on **Table 2** with the Shapiro-Wilk test, P-values for treatment soil depths of 0-15 cm and 15-30 cm are less than 5%, which means 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%, indicating that these two sets of data are normally distributed.

Table 3. Two-way ANOVA of soil pH with the tree species and soil depths

	Sum of sqrs	Df	Mean square	F	p (same)	Critical F
Species:	0.830067	4	0.207517	2.117	0.08355	2.456
Depth:	3.3236	3	1.10787	11.3	1.654E-06	2.689
Interaction:	0.174033	12	0.0145027	0.148	0.9996	1.843
Within:	10.5844	108	0.0980036			
Total:	14.9121	127				

Since it is established that almost all the data are normally distributed (**Table 3**), we use a parametric test, which is a two-way ANOVA test. The results indicate that the p-value for soil depth is less than 5%, which means that soil depth significantly affects the pH inside the tree canopy. Further analysis, a post-hoc test, will employ the Tukey HSD.

Table 4. Tukey's post-hoc (P-value) of soil pH with the tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D. sissoo		0.1764	0.09406	0.7132	0.5472
V. nilotica	0.1764		0.9985	0.8699	0.4835
P. cineraria	0.09406	0.9985		0.7199	0.2568
A. lebbeck	0.7132	0.8699	0.7199		0.999
Control	0.5472	0.4835	0.2568	0.999	

Based on **Table 4** with the post-hoc test using Tukey HSD, it is shown that all of the p-values from the four tree species and the control are greater than 5%, which means that there is no significant difference among the tree species for the soil pH inside the tree canopy.

Table 5. Tukey's post-hoc (P-value) of soil pH with the soil depths

Soil Depth	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm		0.1913	0.003429	8.889E-07
15-30cm	0.1913		0.4308	0.002561
30-45cm	0.003429	0.4308		0.1609
45-60cm	8.889E-07	0.002561	0.1609	

Based on **Table 5** with the post-hoc test using Tukey HSD, the results show that the p-values for the 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. In contrast, the p-values for the treatments of soil depths 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 is no significant difference in soil pH between them.

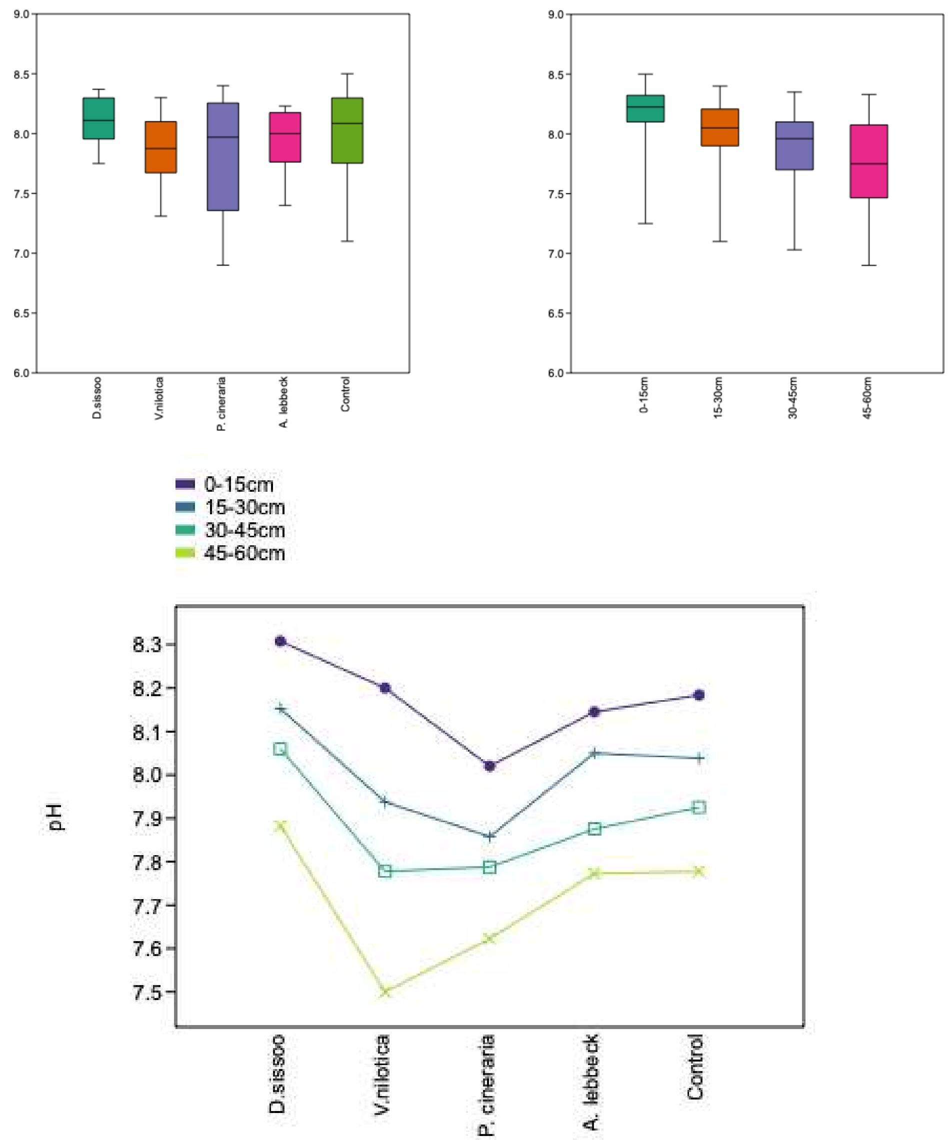


Figure 1. Boxplots and line charts of soil pH based on tree species and soil depths

3. Soil Electrical Conductivity EC

Based on the results, tree species *P. cineraria* and *A. lebbeck* have significantly lower amounts of soil electrical conductivity (Figure 2). *P. cineraria* has lower conductivity than *A. lebbeck*. This indicates that if we want to achieve low soil electrical conductivity, the tree species *P. cineraria* is the best option, followed by *A. lebbeck*.

Table 6. Shapiro-Wilk test of soil electrical conductivity based on tree species

	D. Sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.0493	0.01705	0.1053	0.05544	2.122E-06

Based on **Table 6** with the Shapiro-Wilk test, all p-values, except for *P. cineraria* and *A. lebbeck*, are less than 5%, indicating that the data are not normally distributed, with the exception of *P. cineraria* and *A. lebbeck*.

Table 7. Shapiro-Wilk test of soil electrical conductivity based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.01547	0.04401	0.376	0.006882

According to **Table 7** with the Shapiro-Wilk test, all p-values, except for the treatment of soil depth 30-45 cm, are below 5%, indicating that the data are not normally distributed, with the exception of the soil depth 30-45 cm.

Table 8. Kruskal-Wallis test of soil electrical conductivity with tree species and soil depths

H (chi2):	35,03
Hc (tie corrected):	35,09
p (same):	0,01361

Since most of the data are not normally distributed (**Table 8**), we use a non-parametric test, specifically the Kruskal-Wallis test, to assess whether the medians are equal. The results indicate that the p-value is less than 5%, which means there is a significant difference between the sample medians. This indicates that there must be a variable that significantly affects soil electrical conductivity, which could be tree species or soil depth. Further analysis will utilize the Mann-Whitney test.

Table 9. Mann-Whitney Test of soil electrical conductivity with tree species and soil depths (*D.sissoo*)

	D.sissoo	*D.sissoo*	*D.sissoo*	*D.sissoo*
D.sissoo		0.665	1	0.7715
D.sissoo	0.665		0.665	0.8852
D.sissoo	1	0.665		0.4705
D.sissoo	0.7715	0.8852	0.4705	
V.nilotica	0.3836	0.1939	0.4705	0.3123
V.nilotica	0.4678	0.1913	0.6631	0.3094
V.nilotica	0.4705	0.1939	0.665	0.3123
V.nilotica	0.3123	0.1124	0.4705	0.3123
P. cineraria	0.8852	0.7715	0.665	1
P. cineraria	0.3005	0.7584	0.3005	0.3005
P. cineraria	0.3094	0.8824	0.3094	0.3807
P. cineraria	0.1939	0.8852	0.2454	0.3123
A. lebbeck	0.8845	0.7702	0.8824	0.4678
A. lebbeck	0.3094	0.8845	0.3094	0.3094
A. lebbeck	0.3094	0.8845	0.3094	0.3807
A. lebbeck	0.8845	0.6631	0.6631	1
Control	0.1855	0.05859	0.5386	0.1188
Control	0.3946	0.1297	0.813	0.2563
Control	0.7765	0.237	0.8499	0.4777
Control	0.7401	0.2961	0.9245	0.3935

Table 10. Mann-Whitney Test of soil electrical conductivity with tree species and soil depths (*V.nilotica*)

	V.nilotica	*V.nilotica*	*V.nilotica*	*V.nilotica*
D.sissoo	0.3836	0.4678	0.4705	0.3123
D.sissoo	0.1939	0.1913	0.1939	0.1124
D.sissoo	0.4705	0.6631	0.665	0.4705
D.sissoo	0.3123	0.3094	0.3123	0.3123
V.nilotica		0.8845	0.7715	1
V.nilotica	0.8845		0.8845	0.8845
V.nilotica	0.7715	0.8845		1
V.nilotica	1	0.8845	1	

P. cineraria	0.665	0.4678	0.665	0.3123
P. cineraria	0.3005	0.2975	0.3005	0.02652
P. cineraria	0.3094	0.3065	0.3094	0.05907
P. cineraria	0.1939	0.1913	0.1939	0.0606
A. lebbeck	0.6631	0.8839	0.6631	0.4678
A. lebbeck	0.3094	0.3065	0.3094	0.05907
A. lebbeck	0.3094	0.3065	0.3094	0.05907
A. lebbeck	0.6631	0.6552	0.6631	0.6631
Control	0.6029	0.7407	0.7052	0.7406
Control	0.4777	0.449	0.5074	0.4777
Control	0.3944	0.4198	0.3944	0.2763
Control	0.2177	0.217	0.2177	0.169

Table 11. Mann-Whitney Test of soil electrical conductivity with tree species and soil depths (*P. cineraria*)

	P. cineraria	*P. cineraria*	*P. cineraria*	*P. cineraria*
D.sissoo	0.8852	0.3005	0.3094	0.1939
D.sissoo	0.7715	0.7584	0.8824	0.8852
D.sissoo	0.665	0.3005	0.3094	0.2454
D.sissoo	1	0.3005	0.3807	0.3123
V.nilotica	0.665	0.3005	0.3094	0.1939
V.nilotica	0.4678	0.2975	0.3065	0.1913
V.nilotica	0.665	0.3005	0.3094	0.1939
V.nilotica	0.3123	0.02652	0.05907	0.0606
P. cineraria	***	0.1241	0.3719	0.3123
P. cineraria	0.1241	***	0.505	0.3719
P. cineraria	0.3719	0.505	***	1
P. cineraria	0.3123	0.3719	1	***
A. lebbeck	0.559	0.1215	0.1804	0.1913
A. lebbeck	0.4678	0.09508	0.6552	1
A. lebbeck	0.559	0.09508	0.5491	0.8824
A. lebbeck	0.559	0.02558	0.1416	0.05451
Control	0.1705	0.00923	0.00931	0.008103
Control	0.2563	0.01053	0.02037	0.02042
Control	0.449	0.01195	0.03706	0.04664
Control	0.3197	0.009046	0.01562	0.01566

Table 12. Mann-Whitney Test of soil electrical conductivity with tree species and soil depths (*A. lebbeck*)

	A. lebbeck	*A. lebbeck*	*A. lebbeck*	*A. lebbeck*
D.sissoo	0.8845	0.3094	0.3094	0.8845
D.sissoo	0.7702	0.8845	0.8845	0.6631
D.sissoo	0.8824	0.3094	0.3094	0.6631
D.sissoo	0.4678	0.3094	0.3807	1
V.nilotica	0.6631	0.3094	0.3094	0.6631
V.nilotica	0.8839	0.3065	0.3065	0.6552
V.nilotica	0.6631	0.3094	0.3094	0.6631
V.nilotica	0.4678	0.05907	0.05907	0.6631
P. cineraria	0.559	0.4678	0.559	0.559

P. cineraria	0.1215	0.09508	0.09508	0.02558
P. cineraria	0.1804	0.6552	0.5491	0.1416
P. cineraria	0.1913	1	0.8824	0.05451
A. lebbeck	***	0.3065	0.3065	0.6612
A. lebbeck	0.3065	***	1	0.05301
A. lebbeck	0.3065	1	***	0.1416
A. lebbeck	0.6612	0.05301	0.1416	***
Control	0.4492	0.00931	0.00931	0.1703
Control	0.67	0.01786	0.02298	0.4485
Control	0.9622	0.0367	0.04614	0.8495
Control	0.8868	0.01562	0.01562	0.5067

Table 13. Mann-Whitney Test of soil electrical conductivity with tree species and soil depths (control)

	Control	Control	Control	Control
D.sissoo	0.1855	0.3946	0.7765	0.7401
D.sissoo	0.05859	0.1297	0.237	0.2961
D.sissoo	0.5386	0.813	0.8499	0.9245
D.sissoo	0.1188	0.2563	0.4777	0.3935
V.nilotica	0.6029	0.4777	0.3944	0.2177
V.nilotica	0.7407	0.449	0.4198	0.217
V.nilotica	0.7052	0.5074	0.3944	0.2177
V.nilotica	0.7406	0.4777	0.2763	0.169
P. cineraria	0.1705	0.2563	0.449	0.3197
P. cineraria	0.00923	0.01053	0.01195	0.009046
P. cineraria	0.00931	0.02037	0.03706	0.01562
P. cineraria	0.008103	0.02042	0.04664	0.01566
A. lebbeck	0.4492	0.67	0.9622	0.8868
A. lebbeck	0.00931	0.01786	0.0367	0.01562
A. lebbeck	0.00931	0.02298	0.04614	0.01562
A. lebbeck	0.1703	0.4485	0.8495	0.5067
Control	***	0.4734	0.1313	0.08591
Control	0.4734	***	0.4618	0.3352
Control	0.1313	0.4618	***	0.8651
Control	0.08591	0.3352	0.8651	***

Based on the post-hoc test using the Mann-Whitney test (**Table 9, Table 10, Table 11, Table 12,** and **Table 13**), the table above shows all the variables from both tree species and soil depth that have a P-value less than 5% or are significantly different at the alpha level of 5%. From that table, it is clear that the species *P. cineraria* and *A. lebbeck* are significantly different from the control, indicating that these species may affect soil electrical conductivity. As for soil depth, it does not significantly affect soil electrical conductivity.

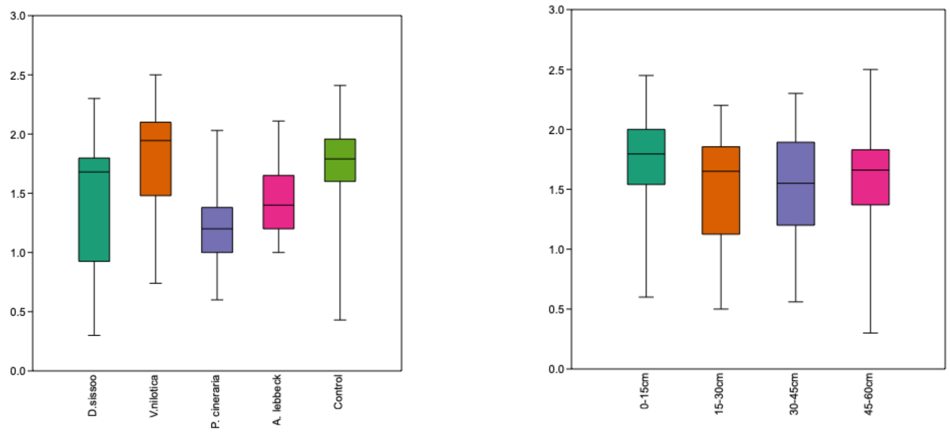


Figure 2. Boxplots of soil electrical conductivity with tree species and soil depths

4. Soil Bulk Density

Based on the results, control has a significantly higher soil bulk density compared to the areas with trees, especially for the three tree species: *D. sissoo, V. nilotica*, and *P. cineraria*. The boxplots indicate that *D. sissoo* and *V. nilotica* have the lowest soil bulk density, while *P. cineraria* has a slightly higher value. This result demonstrates that trees can make the soil looser or decrease the soil bulk density, which is beneficial for the soil as it can absorb more water and minimize erosion (Figure 3).

Table 14. Shapiro-Wilk Test of soil bulk density based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.7156	0.5627	0.191	0.0422	0.00437

According to **Table 14** with the Shapiro-Wilk test, all p-values, except for those of the A. lebbeck and control variables, are greater than 5%, indicating that the data are normally distributed, with the exception of the A. lebbeck control variable.

Table 15. Shapiro-Wilk Test of soil bulk density based on soil depths

Soil Depth	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.0004229	0.09488	0.06276	0.002797

Based on **Table 15** with the Shapiro-Wilk test, it is known that the p-values for the treatment of soil depths 0-15 cm and 45-60 cm are less than 5%, indicating that they are not normally distributed. In contrast, the treatment of soil depths 15-30 cm and 30-45 cm has p-values greater than 5%, indicating that they are normally distributed.

Table 16. Two-way ANOVA of soil bulk density with tree species and soil depths

	Sum of sqrs	Df	Mean square	F	p (same)	Critical F
Species:	0.51347	4	0.128367	5.69	0.0003408	2,456
Depth:	0.152121	3	0.050707	2.247	0.08693	2,689
Interaction:	0.218359	12	0.0181965	0.8065	0.6431	1,843
Within:	2.43667	108	0.0225617			
Total:	3.32062	127				

Since it has been established that all the data are normally distributed (**Table 16**), we use a parametric test, specifically a two-way ANOVA test. 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. Further post-hoc analysis will be done using Tukey HSD.

Table 17. Tukey's post-hoc (P-value) of soil bulk density with tree species

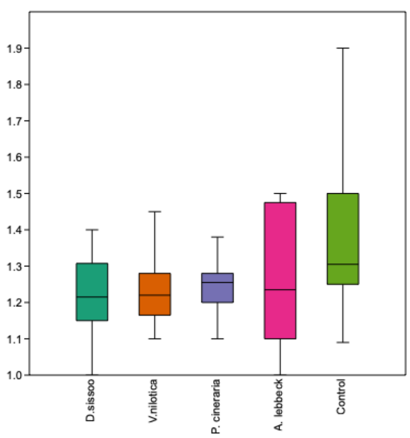
	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D. sissoo		0.9988	0.9748	0.8599	0.0013
V. nilotica	0.9988		0.9974	0.952	0.004826
P. cineraria	0.9748	0.9974		0.9951	0.02043
A. lebbeck	0.8599	0.952	0.9951		0.08719
Control	0.0013	0.004826	0.02043	0.08719	

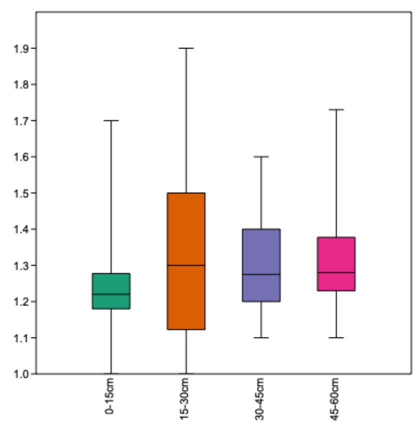
Based on **Table 17** with the post-hoc test using Tukey HSD, it is known that the p-values for *D.sissoo*-Control, *V.nilotica*-Control, and *P. cineraria*-Control are less than 5%, indicating that there are significant differences in soil bulk density among those tree species.

Table 18. Tukey's post-hoc (P-value) of soil bulk density with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm		0.05732	0.3565	0.4128
15-30cm	0.05732		0.8011	0.7457
30-45cm	0.3565	0.8011		0.9996
45-60cm	0.4128	0.7457	0.9996	

Based on **Table 18** with the post-hoc test using Tukey HSD, all p-values from the four soil depths are greater than 5%, indicating no significant difference among the four soil depths for soil bulk density inside the tree canopy.





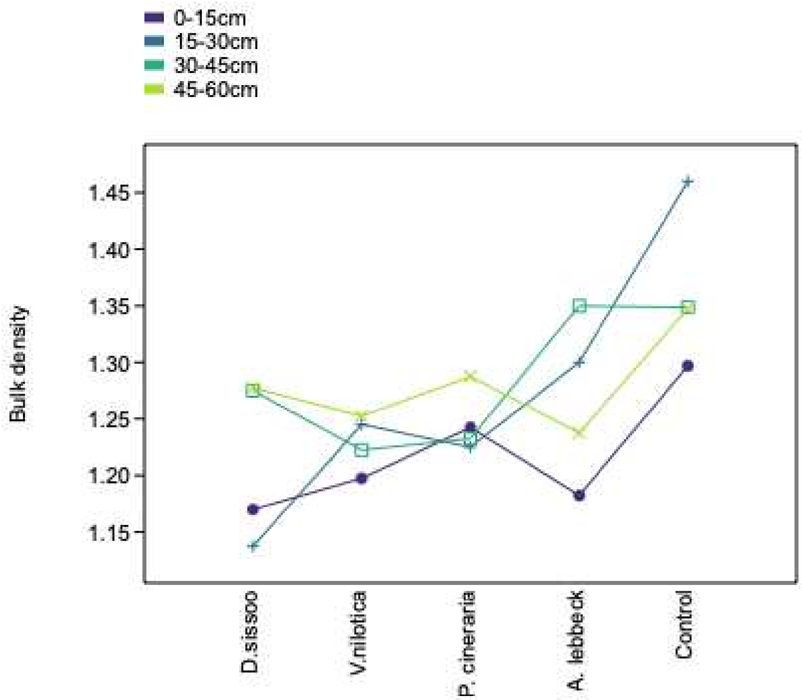


Figure 3. Boxplots and line charts of soil bulk density with tree species and soil depths

5. Soil Organic Matter

Based on the results, it is evident that 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 good plants for enriching the soil organic matter in this area (Figure 4).

Table 19. Shapiro-Wilk Test of soil organic matter based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.7536	0.7118	0.6752	0.04854	0.01527

According to **Table 19,** with the Shapiro-Wilk test, all p-values, except for those of the *A. lebbeck* and control variables, are greater than 5%, indicating that the data are normally distributed, except the *A. lebbeck* control variable.

Table 20. Shapiro-Wilk Test of soil organic matter based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.4956	0.09731	0.9265	0.3095

Based on **Table 20** with the Shapiro-Wilk test, all of the p-values are greater than 5%, which means that all of the data are normally distributed.

Table 21. Two-way ANOVA of soil organic matter with tree species and soil depths

	Sum of sqrs	Df	Mean square	F	p (same)	Critical F
Species:	1.49644	4	0.37411	30.8	4.208E-17	2.456
Depth:	0.0106773	3	0.00355911	0.293	0.8304	2.689
Interaction:	0.118665	12	0.00988874	0.8141	0.6355	1.843
Within:	1.31188	108	0.012147			
Total:	2.93766	127				

Since it has been established that almost all of the data are normally distributed (**Table 21**), we utilize a parametric test, specifically a two-way ANOVA test. 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. Further post-hoc analysis will be conducted using Tukey HSD.

Table 22. Tukey's post-hoc (P-value) of soil organic matter with tree species

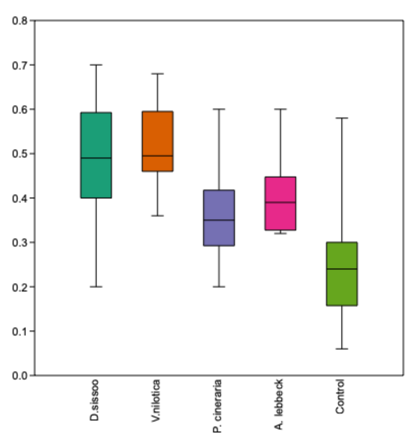
	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D.sissoo		0.9511	0.02847	0.3361	2.819E-13
V.nilotica	0.9511		0.003033	0.07777	0
P. cineraria	0.02847	0.003033		0.8027	0.000153
A. lebbeck	0.3361	0.07777	0.8027		1.795E-07
Control	2.819E-13	0	0.000153	1.795E-07	

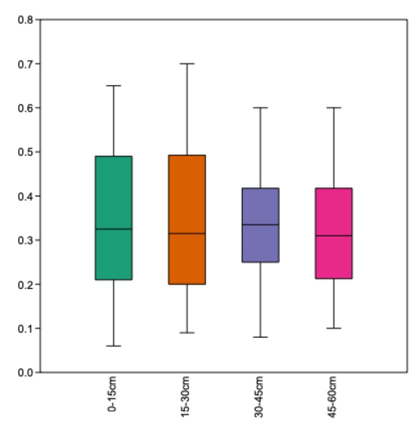
Based on **Table 22** with the post-hoc test using Tukey HSD, the p-values for the Control variable and all four tree species are less than 5%, indicating that all four tree species significantly affect soil organic matter. Furthermore, it is also known that the p-values of *P. cineraria- D.sissoo* and *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.

Table 23. Tukey's post-hoc (P-value) of soil organic matter with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm		1	0.9937	0.8411
15-30cm	1		0.9959	0.8571
30-45cm	0.9937	0.9959		0.9416
45-60cm	0.8411	0.8571	0.9416	

According to **Table 23** with 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 the different soil depths.





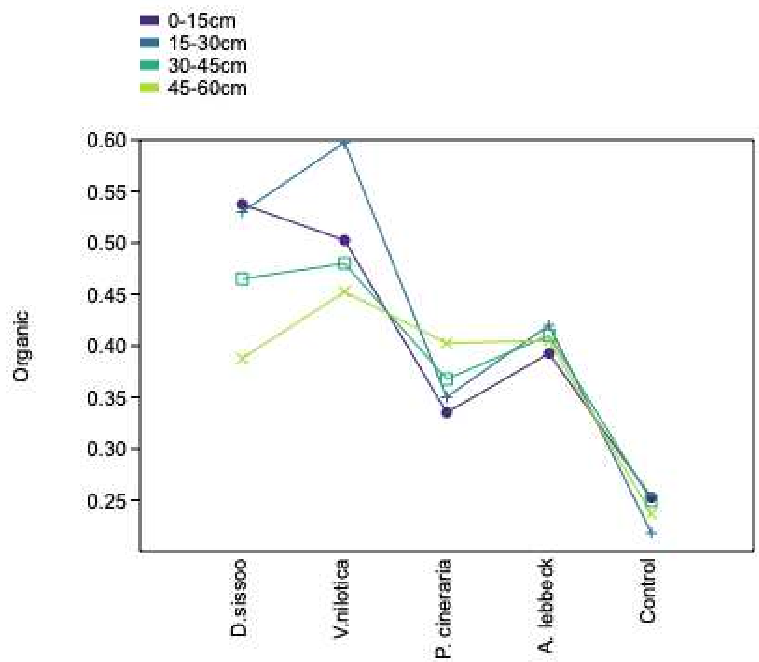


Figure 4. Boxplots and line charts of soil organic matter with tree species and soil depths

6. Soil Organic Carbon (SOC)

Based on the results, it shows that there are no significant differences in Soil Organic Carbon (SOC) among the four tree species and the control, as well as among all four different soil depths. This indicates that Soil Organic Carbon at this research site may remain the same, regardless of whether there are trees present, possibly due to the soil type or other factors (Figure 5).

Table 24. Shapiro-Wilk test of soil organic carbon based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.583	0.001747	0.06169	0.7645	0.1492

According to **Table 24** with the Shapiro-Wilk test, all p-values, except for those of the *V. nilotica*, are greater than 5%, indicating that the data are normally distributed, except for the *V. nilotica.*

Table 25. Shapiro-Wilk test of soil organic carbon based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.001489	0.01758	0.1639	0.2428

According to **Table 25** with the Shapiro-Wilk test, the p-values for the treatment of soil depths of 0-15 cm and 15-30 cm are less than 5%, indicating that they are not normally distributed. In contrast, the treatment for soil depths of 30-45 cm and 45-60 cm has p-values greater than 5%, indicating that they are normally distributed.

Table 26. Two-way ANOVA of soil organic carbon with tree species and soil depths

	Sum of sqrs	Df	Mean square	F	p (same)	Critical F
Species:	0.0766695	4	0.0191674	2.088	0.08737	2.456
Depth:	0.0232148	3	0.00773828	0.8429	0.4733	2.689
Interaction:	0.186415	12	0.0155346	1.692	0.07833	1.843
Within:	0.991556	108	0.00918108			
Total:	1.27786	127				

Since it has been established that almost all of the data are normally distributed (**Table 26**), we utilize a parametric test, specifically a two-way ANOVA. The results indicate that all p-values for Tree Species, Soil Depths, and their interaction are greater than 5%. This means 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 is still conducted using the Tukey HSD to see whether there might be a tree species or soil depth that is significantly different for Soil Organic Carbon.

Table 27. Tukey's post-hoc (P-value) of soil organic carbon with tree species

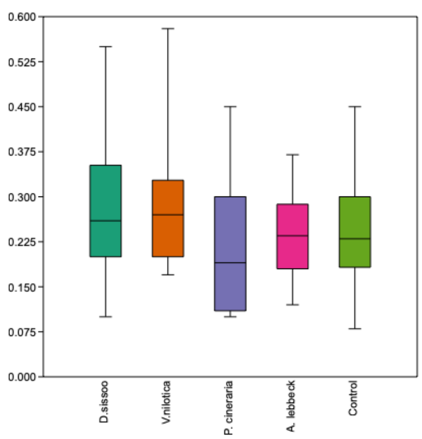
	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D.sissoo		0.9813	0.3639	0.7727	0.4528
V.nilotica	0.9813		0.1287	0.4287	0.1079
P. cineraria	0.3639	0.1287		0.9636	0.8938
A. lebbeck	0.7727	0.4287	0.9636		1
Control	0.4528	0.1079	0.8938	1	

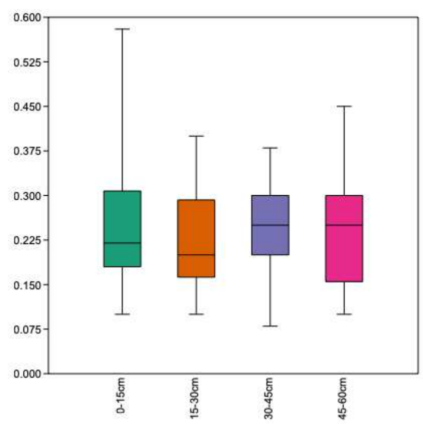
Based on **Table 27** with the post-hoc test using Tukey HSD, the p-values for all four tree species and the control are greater than 5%, indicating that there are no significant differences in Soil Organic Carbon among them.

Table 28. Tukey's post-hoc (P-value) of soil organic carbon with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm		0.4487	0.9917	0.9731
15-30cm	0.4487		0.6281	0.7165
30-45cm	0.9917	0.6281		0.9989
45-60cm	0.9731	0.7165	0.9989	

According to **Table 28** with the post-hoc test using Tukey HSD, all p-values from the four soil depths exceed 5%, indicating no significant difference in Soil Organic Carbon (SOC) within the tree canopy across the different soil depths.





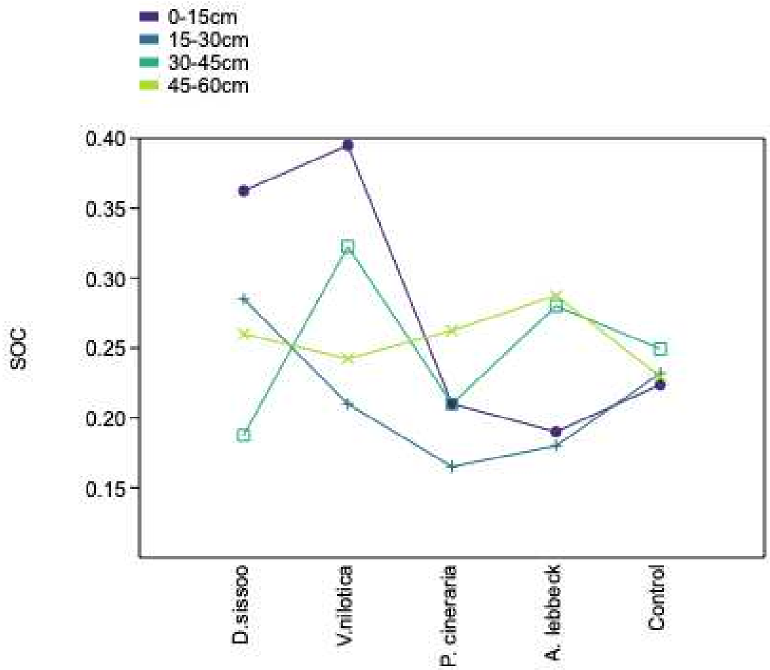


Figure 5. Boxplots and line charts of soil organic carbon with tree species and soil depths

7. Soil Moisture

Based on the results, it shows that the soil moisture in the control is the lowest among the other plots planted with trees. This indicates that the trees are significantly affecting the increase in soil moisture. The box plots also reveal that the trees *D. sissoo* and *A. lebbeck* have the highest soil moisture, followed by *V. nilotica* and *P. cineraria*. It is evident that *D. sissoo* and *A. lebbeck* are among the best options of the four tree species for improving soil moisture.

Table 29. Shapiro-Wilk test of soil moisture based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.08383	0.1288	0.04	0.01148	0.00445

According to **Table 29** with the Shapiro-Wilk test, the p-values of *D. sissoo* and *V. nilotica* are greater than 5%, indicating that they are normally distributed. On the other hand, *P. cineraria, A. lebbeck*, and Control have p-values less than 5%, indicating that these data are not normally distributed.

Table 30. Shapiro-Wilk test of soil moisture based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.1198	0.03134	0.2505	0.07918

According to **Table 30** with the Shapiro-Wilk test, all of the data, except for the soil depths of 15-30 cm, have p-values greater than 5%, indicating that all of the data are normally distributed, except for the soil depths of 15-30 cm.

Table 31. Two-way ANOVA of soil moisture with tree species and soil depths

	Sum of sqrs	df	Mean square	F	p (same)	Critical F
Species:	3372.55	4	843.138	18.02	2.321E-11	2.456
Depth:	103.664	3	34.5546	0.7384	0.5314	2.689
Interaction:	139.387	12	11.6156	0.2482	0.995	1.843
Within:	5054.05	108	46.7968	***	***	***
Total:	8669.66	127	***	***	***	***

Since it has been established that most of the data are normally distributed (**Table 31**), we utilize a parametric test, specifically a two-way ANOVA test. The results indicate that the p-values for soil depths and their interaction exceed 5%, suggesting that soil depths do not significantly affect soil moisture and that there is no significant interaction between tree species and soil depths regarding soil moisture. 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. Further post-hoc analysis will be conducted using Tukey HSD.

Table 32. Tukey's post-hoc (P-value) of soil moisture with tree species

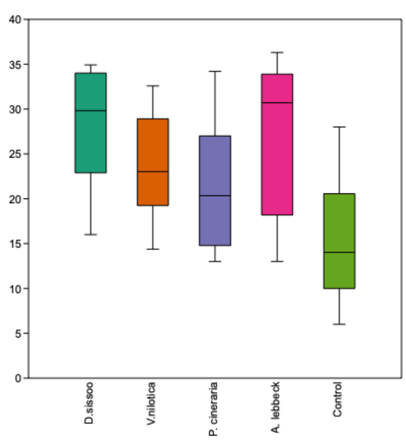
	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D.sissoo	***	0.3036	0.05693	0.9475	1.624E-10
V.nilotica	0.3036	***	0.9343	0.7503	5.208E-05
P. cineraria	0.05693	0.9343	***	0.2791	0.003324
A. lebbeck	0.9475	0.7503	0.2791	***	2.683E-08
Control	1.624E-10	5.208E-05	0.003324	2.683E-08	***

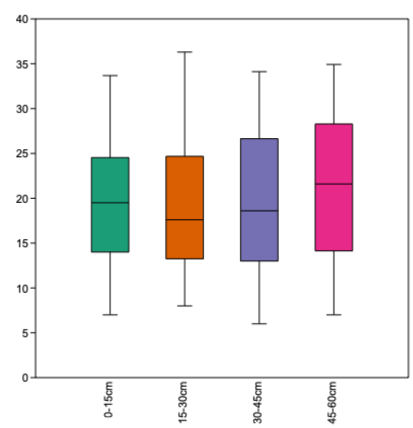
Based on **Table 32** with the post-hoc test using Tukey HSD, the p-values between the control and all four tree species are less than 5%, indicating that planting trees, regardless of the species, *D. sissoo, V. nilotica, P. cineraria*, and *A. lebbeck* will significantly affect soil moisture. Furthermore, 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.

Table 33. Tukey's post-hoc (P-value) of soil moisture with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm	***	0.9832	0.9999	0.7187
15-30cm	0.9832	***	0.9746	0.4904
30-45cm	0.9999	0.9746	***	0.7517
45-60cm	0.7187	0.4904	0.7517	***

According to **Table 33**, with 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 the different soil depths.





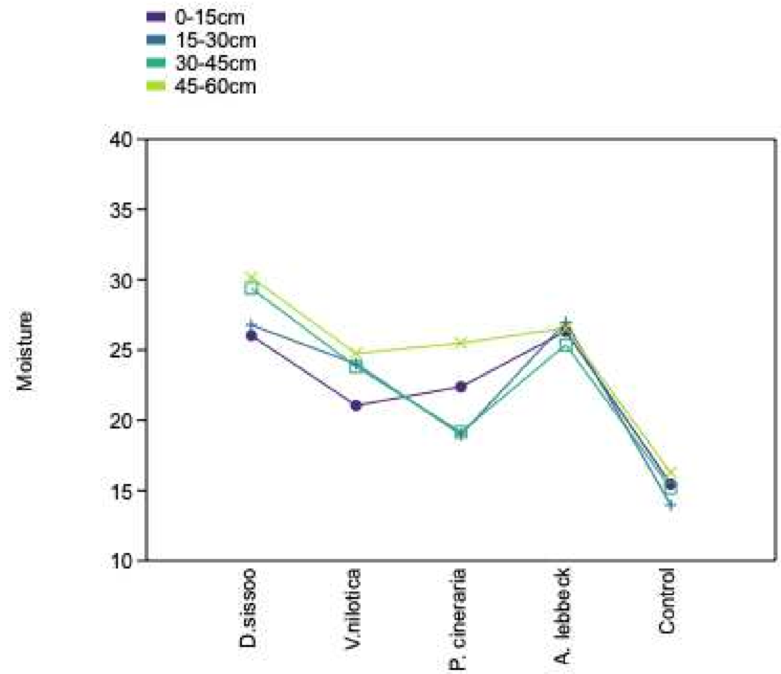


Figure 6. Boxplots and line charts of soil moisture with tree species and soil depths

8. Soil Saturation

Based on the results, it indicates that the soil saturation in the control has the lowest amount compared to the soil planted with four different tree species. This suggests that trees can significantly enhance soil saturation. The boxplots above also demonstrate that the soil saturation from the treatment at a depth of 45-60 cm has the highest soil saturation; however, it is not statistically significant (Figure 7).

Table 34. Shapiro-Wilk test of soil saturation based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.7542	0.6065	0.2095	0.4535	0.4491

According to **Table 34** with the Shapiro-Wilk test, all of the p-values are greater than 5%, indicating that all of the data are normally distributed.

Table 35. Shapiro-Wilk test of soil saturation based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.161	0.4491	0.7535	0.07463

According to **Table 35** with the Shapiro-Wilk test, all of the data have p-values greater than 5%. This means that all of the data regarding the saturation among the soil depths are normally distributed.

Table 36. Two-way ANOVA of soil saturation with tree species and soil depths

	Sum of sqrs	df	Mean square	F	p (same)	Critical F
Species:	723.686	4	180.921	6.916	5.39E-05	2.456
Depth:	150.241	3	50.0805	1.914	0.1316	2.689
Interaction:	71.5386	12	5.96155	0.2279	0.9967	1.843
Within:	2825.41	108	26.1612	***	***	***
Total:	3770.88	127	***	***	***	***

Since all the data is normally distributed, we use a parametric test (**Table 36**), specifically a two-way ANOVA test. The results indicate that the p-values for soil depths and their interaction exceed 5%, suggesting that soil depths do not significantly affect soil saturation and that there is no significant interaction between tree species and soil depths regarding soil saturation. Additionally, the results reveal that the p-value for tree species is below 5%, indicating that tree species have a significant impact on soil saturation within the tree canopy. Further post-hoc analysis will be conducted using the Tukey HSD test.

Table 37. Tukey's post-hoc (P-value) of soil saturation with tree species

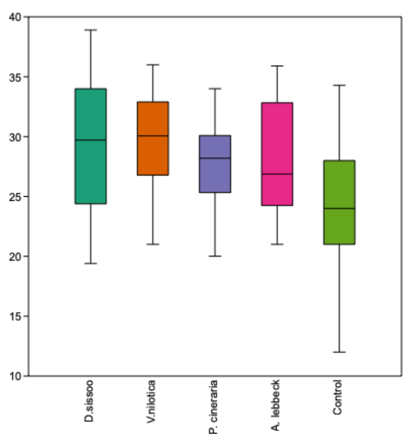
	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D.sissoo	***	1	0.8708	0.9654	0.0006108
V.nilotica	1	***	0.8335	0.9475	0.0003961
P. cineraria	0.8708	0.8335	***	0.998	0.04751
A. lebbeck	0.9654	0.9475	0.998	***	0.01387
Control	0.0006108	0.0003961	0.04751	0.01387	***

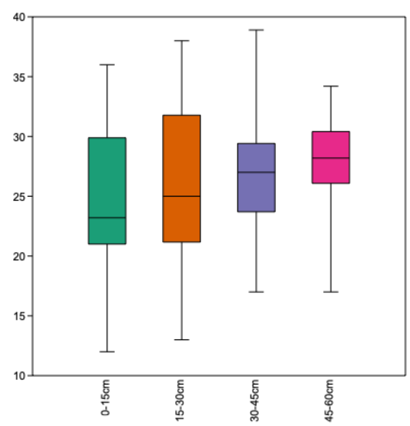
According to **Table** 37 with the post-hoc test using Tukey HSD, the p-values between the control and all four tree species are below 5%, indicating that planting trees regardless of the species, including *D. sissoo, V. nilotica, P. cineraria*, and *A. lebbeck* will significantly impact soil saturation. Moreover, since all other p-values exceed 5%, this suggests that there is no significant difference among the four tree species in terms of soil saturation.

Table 38. Tukey's post-hoc (P-value) of soil saturation with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm	***	0.7844	0.499	0.09316
15-30cm	0.7844	***	0.9662	0.4945
30-45cm	0.499	0.9662	***	0.7804
45-60cm	0.09316	0.4945	0.7804	***

According to **Table 38**, with the post-hoc test using Tukey HSD, all p-values from the four soil depths are greater than 5%, indicating no significant difference in soil saturation within the tree canopy across the various soil depths.





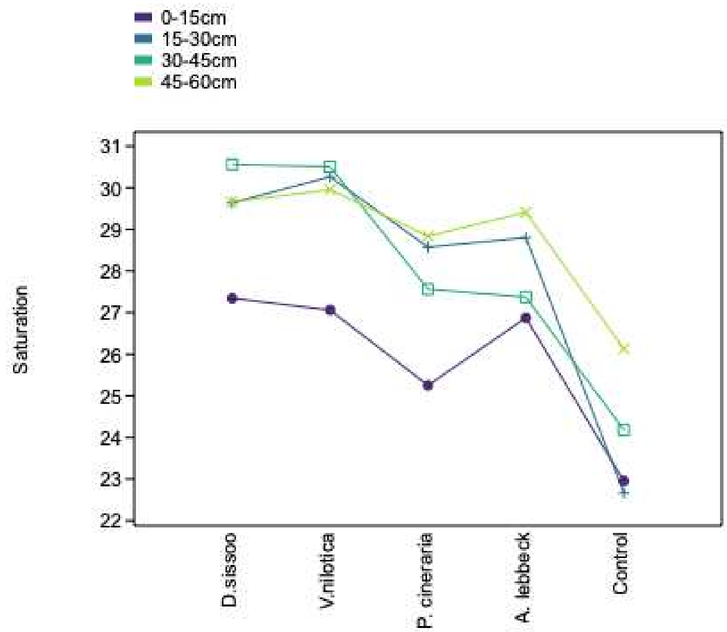


Figure 7. Boxplots and line charts of soil saturation with tree species and soil depths

9. Soil available Nitrogen

Based on the results, it indicates that the nitrogen available in the soil for the control group is the lowest. The highest nitrogen levels are found in the soil planted with the tree species *V. nilotica*, followed by *D. sissoo*. This suggests that *V. nilotica* could be an effective option for increasing nitrogen availability in the soil. The boxplots also reveal that the soil at a depth of 45-60 cm contains the least amount of nitrogen, while the highest concentration is found at a depth of 30-45 cm. This implies that achieving optimal nitrogen levels may be challenging if the soil is too deep or too shallow; therefore, the best depth for nitrogen in this research site is 30-45 cm (Figure 8).

Table 39. Shapiro-Wilk test of soil nitrogen based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.02065	0.5668	0.06375	0.8054	0.002368

According to **Table 39** with the Shapiro-Wilk test, all of the p-values are greater than 5%, indicating that all of the data are normally distributed.

Table 40. Shapiro-Wilk test of soil nitrogen based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.1821	0.02525	0.007285	0.0006793

According to **Table 40** with the Shapiro-Wilk test, all of the data have p-values greater than 5%. This means that all the data regarding the saturation at different soil depths are normally distributed.

Table 41. Kruskal-Wallis test of soil nitrogen with tree species and soil depths

H (chi2):	60.92
Hc (tie corrected):	35.09
p (same):	0.01361

Since most of the data are not normally distributed, we use a non-parametric test (**Table 41**), specifically the Kruskal-Wallis test, to assess whether the medians are equal. 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 there is likely a variable significantly influencing soil available nitrogen, which could be tree species or soil depth. Further analysis will utilize the Mann-Whitney test.

Table 42. Mann-Whitney test of soil nitrogen with tree species and soil depths (*D.sissoo*)

	D.sissoo	*D.sissoo*	*D.sissoo*	*D.sissoo*
D.sissoo	***	0.1832	0.8778	0.02107
D.sissoo	0.1832	***	0.01771	0.2684
D.sissoo	0.8778	0.01771	***	0.01312
D.sissoo	0.02107	0.2684	0.01312	***
V.nilotica	0.1465	0.02652	0.02107	0.02107
V.nilotica	0.559	0.2975	0.877	0.2784
V.nilotica	0.1102	0.02558	0.06675	0.02021
V.nilotica	0.665	0.6573	0.2817	0.06892
P. cineraria	0.0294	0.1016	0.02021	0.1859
P. cineraria	0.1913	0.2975	0.02021	0.02021
P. cineraria	0.7702	0.1804	0.02021	0.02021
P. cineraria	0.02107	0.2684	0.01312	1
A. lebbeck	0.05907	0.1804	0.02021	0.2784
A. lebbeck	0.3005	0.2881	0.01771	0.01771
A. lebbeck	0.8824	0.02558	0.2784	0.02021
A. lebbeck	0.02843	0.09942	0.01936	0.1814
Control	0.06499	0.3197	0.06398	0.6
Control	0.01195	0.09644	0.008838	0.5991
Control	0.05717	0.4184	0.06276	0.8857
Control	0.00279	0.01176	0.002687	0.1361

Table 43. Mann-Whitney test of soil nitrogen with tree species and soil depths (*V.nilotica*)

	V.nilotica	*V.nilotica*	*V.nilotica*	*V.nilotica*
D.sissoo	0.1465	0.559	0.1102	0.665
D.sissoo	0.02652	0.2975	0.02558	0.6573
D.sissoo	0.02107	0.877	0.06675	0.2817
D.sissoo	0.02107	0.2784	0.02021	0.06892
V.nilotica	***	0.0294	0.8845	0.1124
V.nilotica	0.0294	***	0.1081	0.8845
V.nilotica	0.8845	0.1081	***	0.05907
V.nilotica	0.1124	0.8845	0.05907	***
P. cineraria	0.0294	0.2396	0.02843	0.05451
P. cineraria	0.0294	0.3065	0.02843	0.7702
P. cineraria	0.0294	0.7688	0.02843	0.8845
P. cineraria	0.02107	0.2784	0.02021	0.06892
A. lebbeck	0.0294	0.1886	0.02843	0.07959
A. lebbeck	0.02652	0.2975	0.02558	0.7584
A. lebbeck	0.05907	0.8817	0.05755	0.8845
A. lebbeck	0.02843	0.1776	0.02747	0.05301
Control	0.005243	0.2543	0.009151	0.1294
Control	0.002811	0.05736	0.003804	0.05774
Control	0.002749	0.1804	0.006721	0.1533
Control	0.00279	0.03264	0.00278	0.008968

Table 44. Mann-Whitney test of soil nitrogen with tree species and soil depths (*P. cineraria*)

	P. cineraria	*P. cineraria*	*P. cineraria*	*P. cineraria*

D.sissoo	0.0294	0.1913	0.7702	0.02107
D.sissoo	0.1016	0.2975	0.1804	0.2684
D.sissoo	0.02021	0.02021	0.02021	0.01312
D.sissoo	0.1859	0.02021	0.02021	1
V.nilotica	0.0294	0.0294	0.0294	0.02107
V.nilotica	0.2396	0.3065	0.7688	0.2784
V.nilotica	0.02843	0.02843	0.02843	0.02021
V.nilotica	0.05451	0.7702	0.8845	0.06892
P. cineraria	***	0.02843	0.02843	0.1859
P. cineraria	0.02843	***	0.02843	0.02021
P. cineraria	0.02843	0.02843	***	0.02021
P. cineraria	0.1859	0.02021	0.02021	***
A. lebbeck	0.8839	0.07776	0.02843	0.2784
A. lebbeck	0.02558	0.7568	0.02558	0.01771
A. lebbeck	0.02843	0.02843	0.6489	0.02021
A. lebbeck	0.8744	0.02747	0.02747	0.1814
Control	0.9245	0.2361	0.09758	0.6
Control	0.8493	0.1174	0.03277	0.5991
Control	0.8119	0.4184	0.128	0.8857
Control	0.4182	0.006805	0.00278	0.1361

Table 45. Mann-Whitney test of soil nitrogen with tree species and soil depths (*A. lebbeck*)

	A. lebbeck	*A. lebbeck*	*A. lebbeck*	*A. lebbeck*
D.sissoo	0.05907	0.3005	0.8824	0.02843
D.sissoo	0.1804	0.2881	0.02558	0.09942
D.sissoo	0.02021	0.01771	0.2784	0.01936
D.sissoo	0.2784	0.01771	0.02021	0.1814
V.nilotica	0.0294	0.02652	0.05907	0.02843
V.nilotica	0.1886	0.2975	0.8817	0.1776
V.nilotica	0.02843	0.02558	0.05755	0.02747
V.nilotica	0.07959	0.7584	0.8845	0.05301
P. cineraria	0.8839	0.02558	0.02843	0.8744
P. cineraria	0.07776	0.7568	0.02843	0.02747
P. cineraria	0.02843	0.02558	0.6489	0.02747
P. cineraria	0.2784	0.01771	0.02021	0.1814
A. lebbeck	***	0.06317	0.02843	0.8831
A. lebbeck	0.06317	***	0.02558	0.02465
A. lebbeck	0.02843	0.02558	***	0.02747
A. lebbeck	0.8831	0.02465	0.02747	***
Control	0.9622	0.2335	0.06488	0.7397
Control	0.6694	0.06398	0.01554	0.8865
Control	0.8864	0.4157	0.06337	0.8118
Control	0.2352	0.002749	0.00278	0.6002

Table 46. Mann-Whitney test of soil nitrogen with tree species and soil depths (Control)

	Control	Control	Control	Control
D.sissoo	0.06499	0.01195	0.05717	0.00279
D.sissoo	0.3197	0.09644	0.4184	0.01176
D.sissoo	0.06398	0.008838	0.06276	0.002687
D.sissoo	0.6	0.5991	0.8857	0.1361
V.nilotica	0.005243	0.002811	0.002749	0.00279

V.nilotica	0.2543	0.05736	0.1804	0.03264
V.nilotica	0.009151	0.003804	0.006721	0.00278
V.nilotica	0.1294	0.05774	0.1533	0.008968
P. cineraria	0.9245	0.8493	0.8119	0.4182
P. cineraria	0.2361	0.1174	0.4184	0.006805
P. cineraria	0.09758	0.03277	0.128	0.00278
P. cineraria	0.6	0.5991	0.8857	0.1361
A. lebbeck	0.9622	0.6694	0.8864	0.2352
A. lebbeck	0.2335	0.06398	0.4157	0.002749
A. lebbeck	0.06488	0.01554	0.06337	0.00278
A. lebbeck	0.7397	0.8865	0.8118	0.6002
Control	***	0.3638	0.9849	0.168
Control	0.3638	***	0.2049	0.61
Control	0.9849	0.2049	***	0.03552
Control	0.168	0.61	0.03552	***

Based on the post-hoc test using the Mann-Whitney test (**Table 42, Table 43, Table 44, Table 45,** and **Table 46**), the table above indicates that the p-values for soil available nitrogen, derived from both the tree species and soil depth treatments, are mostly below 5%. This suggests that both the tree species and soil depth significantly impact the availability of nitrogen in the soil.

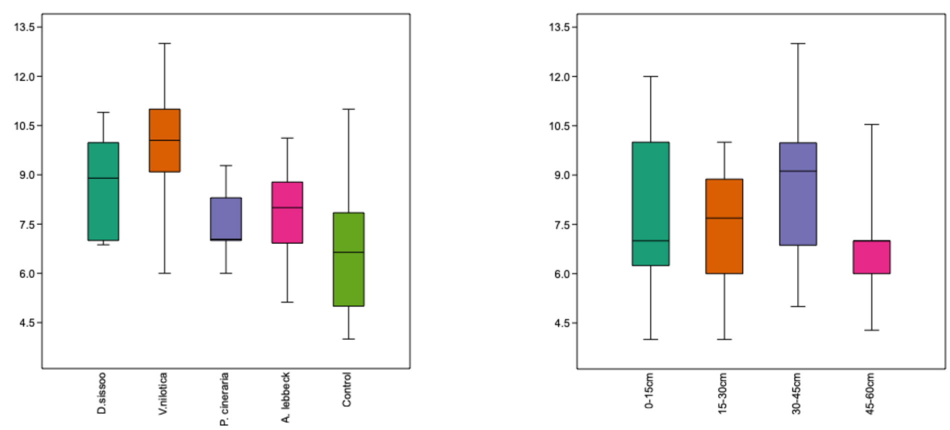


Figure 8. Boxplots of soil nitrogen with tree species and soil depths

10. Soil available Phosphorus

Based on results, it shows that there is a kind of trend that is affected by both the tree species and the treatment of soil depths. It can be seen that the *D. sissoo* tree species has the highest amount of phosphorus in the soil, followed by *P. cineraria*. The lowest amount is found in the control, followed by the tree species *V. nilotica*, *A. lebbeck* has a moderate amount of phosphorus, but the trend differs. The pattern is quite complicated because the tree species and soil depths have strong interactions, so they affect each other.

Table 47. Shapiro-Wilk test of soil phosphorus based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.4061	0.03513	0.1902	0.04138	0.1229

According to **Table 47** with the Shapiro-Wilk test, all p-values, except for *V. nilotica* and *A. lebbeck*, are greater than 5%, which indicates that all data are normally distributed, with the exception of *V. nilotica* and *A. lebbeck*.

Table 48. Shapiro-Wilk test of soil phosphorus based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.08414	0.03053	0.222	0.7266

According to **Table 48** with the Shapiro-Wilk test, P-values for all treatment soil depths except 15-30 cm are greater than 5%. This indicates that all data are normally distributed, except for the soil depth of 15-30 cm.

Table 49. Two-way ANOVA of soil phosphorus with tree species and soil depths

	Sum of sqrs	df	Mean square	F	p (same)	Critical F
Species:	96.6795	4	24.1699	23.46	5.629E-14	2.456
Depth:	15.7162	3	5.23874	5.085	0.002483	2.689
Interaction:	67.3953	12	5.61628	5.452	3.499E-07	1.843
Within:	111.259	108	1.03018	***	***	***
Total:	291.05	127	***	***	***	***

Since it is established that almost all of the data are normally distributed (**Table 49**), we use a parametric test, specifically a two-way ANOVA test. The results show that all p-values are less than 5%, indicating that both the tree species and soil depth significantly affect the availability of phosphorus in the soil. Additionally, there is a significant interaction between tree species and soil depths. Further analysis will include post-hoc analysis using Tukey HSD.

Table 50. Tukey's post-hoc (P-value) of soil phosphorus with tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D.sissoo		0.0002076	0.2553	0.009811	0
V.nilotica	0.0002076	***	0.1222	0.8076	0.01563
P. cineraria	0.2553	0.1222	***	0.6879	1.652E-08
A. lebbeck	0.009811	0.8076	0.6879	***	6.284E-05
Control	0	0.01563	1.652E-08	6.284E-05	***

Based on **Table 50** with 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 the 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*.

Table 51. Tukey's post-hoc (P-value) of soil phosphorus with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm	***	0.5096	0.8506	0.02905
15-30cm	0.5096	***	0.1309	0.4844
30-45cm	0.8506	0.1309	***	0.002469
45-60cm	0.02905	0.4844	0.002469	***

Based on **Table 51** with 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 treatment of soil depth 45-60 cm, the deepest soil depth in this research, has the most significant effect.

Table 52. Tukey's post-hoc (P-value) of soil phosphorus with the interaction of tree species and soil depths

Number	Variable 1	Variable 2	Q	P-value
7	*D.sissoo*-0-15cm	Control-0-15cm	11.2	1.50E-07
13	*D.sissoo*-15-30cm	Control-15-30cm	6.416	0.0008727
17	*D.sissoo*-30-45cm	*A. lebbeck*-30-45cm	5.212	0.01772
18	*D.sissoo*-30-45cm	Control-30-45cm	6.329	0.001105
25	*V.nilotica*-0-15cm	*V.nilotica*-45-60cm	6.522	0.0006527
28	*V.nilotica*-0-15cm	Control-0-15cm	8.371	2.50E-06
34	*V.nilotica*-30-45cm	*V.nilotica*-45-60cm	5.222	0.01733
43	*P. cineraria*-0-15cm	*P. cineraria*-45-60cm	5.862	0.003742

45	*P. cineraria*-0-15cm	Control-0-15cm	11.34	9.09E-08
58	*A. lebbeck*-0-15cm	Control-0-15cm	8.064	6.66E-03
61	*A. lebbeck*-15-30cm	Control-15-30cm	5.95	0.002997
66	Control-0-15cm	Control-30-45cm	5.783	0.004561

Based on **Table 52** with the post-hoc test using Tukey HSD shows that there are some interactions with p-values less than 5%. It indicates that the control and D.sissoo have the largest number of interactions, while for the depths of 45-50 cm and 0-15 cm, there is also a significant number of interactions

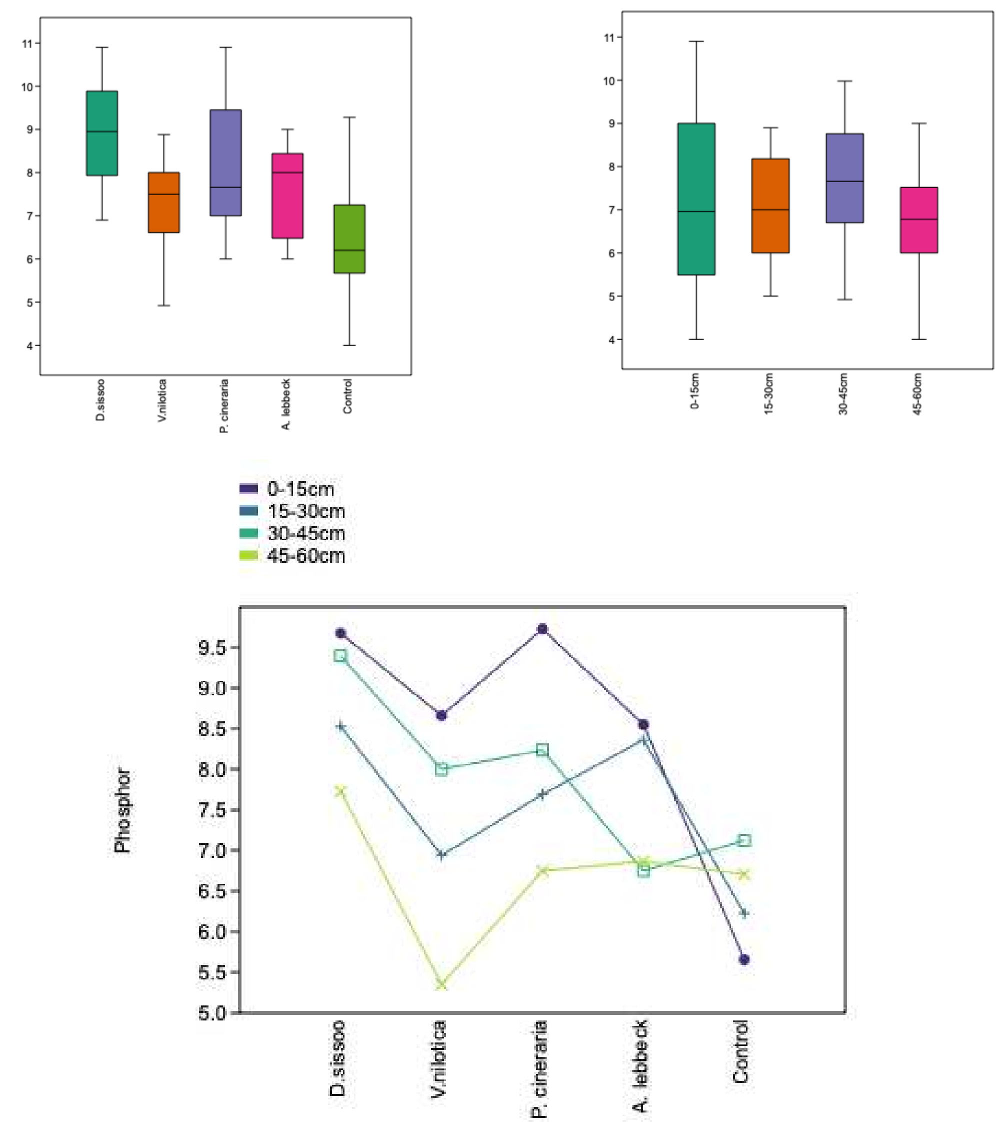


Figure 9. Boxplots and line charts of soil phosphorus with tree species and soil depths

11. Soil available K (Potassium)

Based on the results, it shows that there is no significant difference in potassium levels in soil based on their soil depths. However, it is evident that there are significant differences in potassium amounts based on tree species. The control area, which is bare land, has the lowest potassium levels. The highest potassium content is found in the tree species *P. cineraria*, followed by *A. lebbeck, V. nilotica*, and *D. sissoo*. It can be concluded that if we want soil rich in potassium, *P. cineraria* and *A. lebbeck* are among the best options compared to the other tree species in this research (Figure 9).

Table 53. Shapiro-Wilk test of soil potassium based on tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
P-value	0.2015	0.1272	0.218	0.7726	0.5972

According to **Table 53** with the Shapiro-Wilk test, all p-values are greater than 5%, which indicates that all of the data are normally distributed.

Table 54. Shapiro-Wilk test of soil potassium based on soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
P-value	0.3497	0.1061	0.6662	0.4339

According to **Table 54** with the Shapiro-Wilk test, all p-values are greater than 5%, which indicates that all of the data are normally distributed.

Table 55. Two-way ANOVA of soil potassium with tree species and soil depths

	Sum of sqrs	df	Mean square	F	p (same)	Critical F
Species:	29778	4	7444.5	54.96	3.387E-25	2.456
Depth:	297.797	3	99.2656	0.7328	0.5346	2.689
Interaction:	899.726	12	74.9771	0.5535	0.8743	1.843
Within:	14628.9	108	135.453	***	***	***
Total:	45604.4	127	***	***	***	***

Since it has been established that all the data are normally distributed (**Table 55**), we use a parametric test, specifically a two-way ANOVA test. 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 K (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.

Table 56. Tukey's post-hoc (P-value) of soil potassium with tree species

	D. sissoo	*V. nilotica*	*P. cineraria*	*A. lebbeck*	Control
D.sissoo		6.419E-05	9.382E-12	1.33E-09	0.649
V.nilotica	6.419E-05	***	0.009501	0.1315	1.059E-11
P. cineraria	9.382E-12	0.009501	***	0.8619	0
A. lebbeck	1.33E-09	0.1315	0.8619	***	0
Control	0.649	1.059E-11	0	0	***

Based on **Table 56** with 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%, except for the *A. lebbeck-V. nilotica* and *A. lebbeck-P. cineraria*. This indicates that almost all of the tree species are significantly different from each other regarding their potassium content in the soil. The selection of tree species needs to be done carefully based on the characteristics of the soil, especially regarding its potassium availability.

Table 57. Tukey's post-hoc (P-value) of soil potassium with soil depths

	0-15cm	15-30cm	30-45cm	45-60cm
0-15cm	***	0.7796	0.9718	0.5068
15-30cm	0.7796	***	0.9567	0.9704
30-45cm	0.9718	0.9567	***	0.7752
45-60cm	0.5068	0.9704	0.7752	***

Based on **Table 57** with the post-hoc test using Tukey HSD, the results show that all p-values are greater than 5%, indicating that there is no significant difference in potassium (K) levels in soil based on their depths.

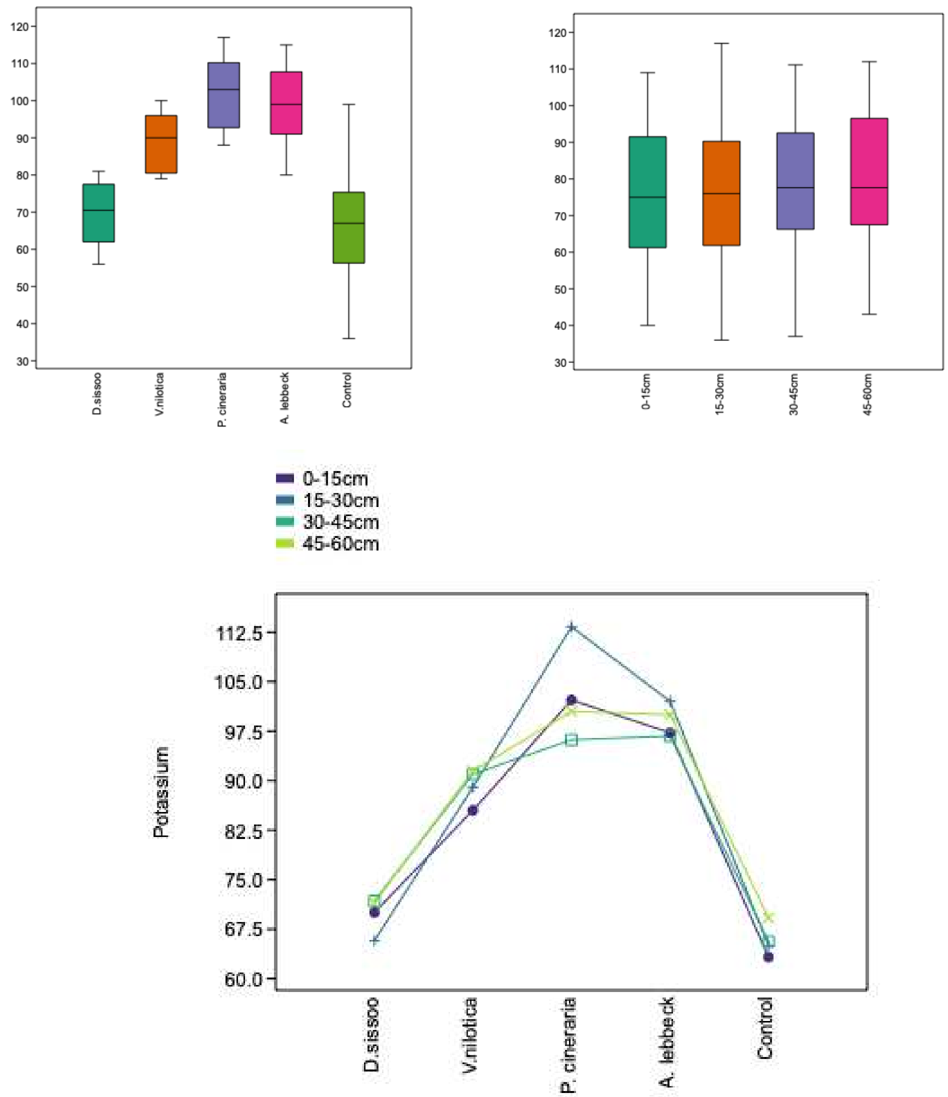


Figure 9. Boxplots and line charts of soil potassium with tree species and soil depths

Discussion

Almost all assessed indicators showed significant disparities ($p < 0.05$) among species, and some were significantly affected by soil depth or both indicators. Land degradation resulting from various anthropogenic activities leads to the deterioration of soil (Nurrochmat et al. 2023; Nurrochmat et al. 2024). 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 improve soil structure through incorporation of organic matter, thus increasing structural stability and resistance to soil erosion (Pinho et al. 2012).

The results show that the three species do not significantly affect the soil pH, but the soil depth significantly affects ($p<0.05$) the 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 (**Figure 1**) 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 nutrient 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 (**Figure 2**) 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/cm^3 to 1.37 g/cm^3, 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/cm^3 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 to that of 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. Comparable results have also been documented by a separate study, which 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 (**Table 26**) indicate a statistically insignificant variation in SOC across different tree species and soil depths. However, as shown in **Figure 5**, the highest SOC was recorded in V. nilotica (0.35%), with a progressive decline in SOC observed 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), 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 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 help in nutrient and water pumping (**Figure 6**) 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, trap 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 ($p<0.05$). **Table 37** shows that although there is no significant difference among the four tree species, the control has a significant difference compared to the other four tree species. This means that trees have a significant impact on improving soil saturation.

The continuous removal of nutrients from soil by crops creates a deficiency of certain nutrients such as N, P, K, sulfur, Zinc, and even Boron. The deficiency of organic matter decreases the soil fertility, which ultimately causes a low yield of crop (Misra 2011). Trees substantially enhance the physical and chemical parameters of soil, which are directly associated with soil fertility (Figure 11). Gupta et al. (2009) noted that the mean soil organic carbon was markedly elevated under agroforestry relative to monocropping, 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) and Kidane et al. 2025 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 ways, whether in the form of roots, 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 through 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 (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 reducing the use of chemical fertilizers and ecosystem stability (Ribeiro-Barros et al. 2018). Taken together, our findings affirm that tree species differ in their capacity to enrich soil and mitigate degradation. Tree selection should, therefore, be tailored based on specific soil deficiencies and site conditions to maximize benefits. Integrating leguminous and native tree species in agroecosystems can help reduce dependence on chemical fertilizers and promote sustainability. These results provide valuable insights for designing climate-resilient, cost-effective land use strategies in arid and semi-arid environments.

Conclusion

Due to adverse climatic and economic circumstances, farmers cannot satisfy the rising demand for food, fiber, and shelter by conventional soil fertility enhancement methods. The extensive use of chemical fertilizers aggravates soil fertility problems and entails significant expenses. Incorporating indigenous tree species into agricultural systems can enhance soil fertility. Trees, by their Phyto-remedial actions and alterations in soil parameters, significantly enhance soil fertility; hence, a well-planned integration of trees with crops can yield increased agricultural production. The variation in pH across different tree species influences nutrient availability, with higher pH levels potentially limiting phosphorus uptake while benefiting nitrogen fixation. Organic matter accumulation under tree canopies enhances soil structure, moisture retention, and microbial activity, which are essential for sustaining soil fertility. The depth-wise distribution of nutrients such as nitrogen, phosphorus, and potassium indicates how effectively different species contribute to nutrient cycling and replenishment (**Figure 8, Figure**

9, and **Figure 10**). A better understanding of these soil fertility dynamics will enable policymakers and farmers to adopt tree species that maximize soil health benefits, ensuring long-term agricultural resilience in challenging climatic conditions.

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Conceptualization MM; methodology, TH and MM; software, NAN; validation, MAS, MA and MM; formal analysis, MK and HAM; investigation, MM; resources, TH; data curation, MM writing—original draft preparation, MM; writing—review and editing, visualization, MA and THA; supervision, TH; project administration, TH. All authors have read and agreed to the published version of the manuscript.

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Ethics declarations

Ethics approval and consent to participate

This study does not include human or animal subjects.

Consent for publication

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Statement on guidelines

All experimental studies and experimental materials involved in this research are in full compliance with relevant institutional, national and international guidelines and legislation.

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