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MOLECULAR CHARACTERIZATION AND COMPARATIVE ANALYSIS OF PHYSICAL AND CHEMICAL SOIL PROPERTIES UNDER DIFFERENT AGROFORESTRY SYSTEMS IN EASTERN UTTAR PRADESH

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ABSTRACT

The present study was conducted during 2023–2026 in Eastern Uttar Pradesh to evaluate tree species diversity, molecular genetic variability, and physicochemical soil properties under different agroforestry systems, namely Agrihorticulture, Agrisilviculture, Agrisilvihorticulture, Boundary Plantation, and Silvipastoral systems. Tree vegetation was assessed through phytosociological analysis using parameters such as population density, basal area, relative density, Importance Value Index (IVI), Shannon Diversity Index (H′), and Dominance Index (Cd). Molecular characterization of selected tree species was carried out using Random Amplified Polymorphic DNA (RAPD) markers to assess genetic diversity and similarity among species. Soil samples collected from different agroforestry systems and soil depths were analyzed for bulk density, particle density, pore space, pH, electrical conductivity, organic carbon, and available nitrogen, phosphorus, potassium, and sulfur.

The results revealed considerable variation in vegetation structure among agroforestry systems. The Silvipastoral system recorded the highest Shannon Diversity Index (H′ = 3.1019) and lowest Dominance Index (Cd = 0.0567), indicating greater species diversity and ecological stability, whereas Boundary Plantation exhibited the lowest diversity (H′ = 1.611) and highest dominance (Cd = 0.278). Species such as Mangifera indica, Tectona grandis, Dalbergia sissoo, and Eucalyptus spp. showed higher IVI values and contributed significantly to stand structure. RAPD analysis generated 11–18 amplified bands with polymorphism ranging from 76.92 to 83.33%, demonstrating substantial genetic variability among the studied species. The highest polymorphism was observed in Eucalyptus spp. (83.33%), while Mangifera indica exhibited the highest genetic similarity index (0.90).

Significant differences were also observed in soil physical and chemical properties among agroforestry systems. Diversified systems, particularly Agrisilvihorticulture and Silvipastoral systems, recorded lower bulk density, higher pore space, and greater organic carbon accumulation compared with Boundary Plantation and less diversified systems. Soil pH and electrical conductivity remained within acceptable ranges across all systems. Available nitrogen, phosphorus, potassium, and sulfur contents were significantly higher in diversified agroforestry systems, reflecting enhanced litter deposition, root turnover, and nutrient cycling. Nutrient availability and organic carbon generally declined with increasing soil depth, indicating greater biological activity in surface layers.

The study demonstrates that diversified agroforestry systems, especially Silvipastoral and Agrisilvihorticulture systems, support higher biodiversity, conserve genetic resources, improve soil fertility, and enhance ecosystem sustainability. These systems offer promising land-use options for increasing productivity, environmental resilience, and sustainable agricultural development in Eastern Uttar Pradesh.

KEYWORDS: Agroforestry systems, RAPD markers, genetic diversity, tree diversity, Shannon diversity index, Importance Value Index and soil physicochemical properties

1. INTRODUCTION

Land use refers to the arrangements, activities, and management decisions that people implement on a particular land surface to produce, maintain, or modify it (Ufot et al., 2016). It pertains to how humans utilize and manage land for specific objectives, encompassing economic, social, and environmental activities that modify or conserve the land surface (Nedd et al., 2021; EPA, 2025). Soil resources play a vital role in supporting food production, fibre supply, and overall environmental quality at both local and regional scales (Bore and Bedadi, 2015). Maintaining soil quality is therefore essential for sustainable agriculture, as improved soil properties directly support crop productivity and ecological stability (Liu et al., 2010).

Soil quality can deteriorate rapidly due to intensive cultivation, nutrient mining, erosion, and imbalanced fertilizer application (Kiflu and Beyene, 2013). Consequently, agricultural systems require a comprehensive understanding of sustainable land management practices to ensure long-term soil health (Takele et al., 2014). Effective soil management depends largely on understanding how soils respond over time to various agricultural and agroforestry interventions (Duguma et al., 2010).

In Uttar Pradesh, rising population pressure, shrinking landholdings, and increasing demand for food and biomass have intensified stress on land resources. The Avadh region, situated within the Eastern Agro-Climatic Zone, faces challenges such as soil nutrient depletion, declining organic matter content, residue burning, and over-exploitation of agricultural lands. These factors collectively contribute to soil degradation, adversely affecting long-term productivity and farmers' livelihoods. In addition, erratic rainfall patterns, deforestation for fuelwood, and replacement of natural vegetation with monocropping systems have further aggravated soil health deterioration in the region.

The conversion of diverse ecosystems such as groves, community forests, and traditional mixed farming systems into continuous agricultural lands has gradually reduced soil fertility and biological activity. Increasing livestock pressure on common lands has resulted in soil compaction and loss of vegetative cover, particularly in rural areas of the Avadh region. These processes accelerate erosion, reduce soil porosity, and limit soil moisture retention, ultimately constraining crop growth and productivity.

Agroforestry systems such as agrisilviculture, silvihorticulture, agrisilvihorticulture, silvipastoral systems, and boundary plantations have emerged as effective land-use options for restoring soil quality and sustaining productivity. By integrating trees with crops and/or livestock, these systems improve soil structure, enhance organic matter content, reduce erosion, promote nutrient cycling, and support long-term land sustainability. Several studies conducted across India have shown that tree-based systems significantly enhance soil organic carbon, total nitrogen, available phosphorus, and exchangeable bases compared to continuously cultivate agricultural lands (Lemenih et al., 2005; Yimer et al., 2008). Tree litter inputs, deep root systems, and microclimate regulation are key mechanisms contributing to improved soil physicochemical properties in agroforestry landscapes. In the context of the Eastern Agro-Climatic Zone of Uttar Pradesh, agroforestry plays a crucial role in enhancing soil fertility, strengthening farmers' livelihoods, and ensuring sustainable land use. However, scientific information on the comparative effects of different agroforestry systems on soil physicochemical properties in this region remains limited. Understanding these variations is essential for identifying suitable systems that support soil conservation and productivity enhancement.

Agroforestry systems are recognized not only for improving soil quality and ecosystem services but also for conserving plant genetic resources through the integration of diverse tree species. The composition and structural characteristics of tree communities directly influence litter production, nutrient cycling, carbon sequestration, and soil biological activity (Nair, 2011; Jose, 2009). Assessment of tree diversity indices such as the Shannon Diversity Index, Dominance Index, and Importance Value Index (IVI) provides valuable information regarding species distribution, ecological stability, and productivity of agroforestry systems (Shannon and Weaver, 1949; Curtis and McIntosh, 1951). Understanding vegetation structure is therefore essential for evaluating the ecological sustainability and ecological functioning of agroforestry-based land-use systems (Kumar and Nair, 2004).

In addition to ecological characterization, molecular tools have become increasingly important for assessing genetic diversity and variability among tree species growing under different agroforestry systems. Molecular markers such as Random Amplified Polymorphic DNA (RAPD) provide reliable information on genetic relationships, polymorphism levels, and genetic similarity among species and populations (Williams et al., 1990; Rafalski et al., 1996). Genetic diversity assessment is crucial for identifying superior germplasm, understanding adaptation mechanisms, and developing strategies for long-term conservation and sustainable utilization of tree genetic resources (Hamrick and Godt, 1996; Finkeldey and Hattemer, 2007). Molecular characterization has therefore become an important tool for supporting tree improvement programmes and biodiversity conservation in agroforestry landscapes.

Therefore, the present study aimed to evaluate the effects of different agroforestry systems on selected molecular characterization and comparative Analysis of physical and chemical soil properties in the Eastern Agro-Climatic Zone of Uttar Pradesh and to assess their potential contribution to sustainable land management and agricultural productivity.

2. MATERIAL AND METHODS

2.1 Description of the Study Area

The present study was conducted in the Eastern Agro-climatic zone of Uttar Pradesh, India. It lies between 26°24′N to 26°47′N latitude and 82°07′E to 82°27′E longitude, with an average elevation ranging between 93 to 134 meters above sea level (masl) (Census of India, 2011; District Statistical Handbook, 2020). It is situated approximately 135 km east of Lucknow, the capital city of Uttar Pradesh.

2.1.1 Climate

Eastern Agro-climatic experiences a subtropical climate, characterized by three distinct seasons: summer (March–June), monsoon (July–September), and winter (October–February). The district receives an average annual rainfall of around 1050 to 1200 mm**,** predominantly during the southwest monsoon season (July to September) (IMD, 2021). The mean monthly maximum temperature during the summer season reaches up to 43°C, while the mean monthly minimum temperature during winter can drop to around 6°C**.**

2.1.2 Soils, Geology, and Topography

2.1.2.1. Soil

The dominant soil types in the Eastern Agro-climatic zone are alluvial soils, which are deep, fertile, and loamy to clay loam in texture, derived primarily from Indo-Gangetic alluvium (NBSS&LUP, 2019).

2.1.2.1.2 Geology

The geological formation of the region belongs to the Quaternary period, primarily consisting of recent alluvial deposits from the Ghaghara and Saryu river systems.

2.1.2.3. Topography

The topography is predominantly flat to gently undulating, with more than 85% of the land falling under the 0–3% slope range.

2.1.3. Vegetation

The region currently supports a mix of planted and naturally occurring species, with tree vegetation primarily found in agroforestry systems, plantation blocks, and along roadside and canal boundaries. Common native tree species include Shisham (Dalbergia sissoo), Neem (Azadirachta indica), Babul (Vachellia nilotica), Peepal (Ficus religiosa), and Bargad (Ficus benghalensis) and other species also. Exotic and fast-growing species such as Eucalyptus spp. and Poplar (Populus deltoides) are widely planted, particularly under agroforestry and commercial plantation systems. Homesteads often have Mango (Mangifera indica), Guava (Psidium guajava), Banana (Musa spp.), and Jamun (Syzygium cumini) trees, which contribute to household nutrition and income. Shrubs and bushes, such as Carissa carandas and Lantana camara, are also found on wastelands and grazing lands, though some invasive species have negatively impacted native biodiversity.

2.1.4 Land Use and Farming System

The land use pattern in Eastern Agro-climatic zone comprises cultivated lands, orchards, pastures, fallow lands, homesteads, and small forest plantations. The cropping pattern is typically rainfed during the Kharif season and Rabi season.

The common Kharif (monsoon) crops grown in the region include paddy (Oryza sativa), maize (Zea mays), arhar (Cajanus cajan), and sesame (Sesamum indicum)**,** while the major Rabi (winter) crops cultivated are wheat (Triticum aestivum), gram (Cicer arietinum), lentil (Lens culinaris), mustard (Brassica juncea), and pea (Pisum sativum)**,** reflecting the district's reliance on seasonal, cereal-legume-based cropping systems for both subsistence and market-oriented agriculture.

2.2 Site Selection

Soil sample were collected from across the Eastern Agro-climatic zone of Uttar Pardesh and were classified into five Agroforestry systems categories: Agrihorticulture system, Agrisilviculture system, Agrisilvihorticulture system, Boundary Plantation and Silvipastoral.

2.3. Soil Sampling

Soil samples were gathered from five different Agroforestry Systems categories at three depths (0–20 cm, 20–40 cm and 40-60), with three replications for each. To measure bulk density, undisturbed samples were collected using a core sampler, while disturbed samples for physicochemical assessments were obtained using an auger. Sampling locations were chosen to be away from gravel patches, decomposed materials, tree trunks, and areas of manure or compost to minimize localized variability. All samples underwent air-drying, gentle grinding, and were sieved using a 2-mm mesh for general physical and chemical evaluation. For the determination of organic carbon (OC) and available nitrogen (N), phosphorus (P), potassium (K), and sulfur (S), subsamples were additionally ground and passed through a 0.5-mm sieve prior to laboratory analysis.

2.4 Analysis of Soil Physical and Chemical Properties

Soil samples were examined for important physical and chemical characteristics using standardized methods. Bulk density (BD) was determined from intact core samples (100 cm^3) through the core method (Black, 1965), followed by oven drying at 105°C for 24 hours. Particle density (PD) was assessed using a pycnometer, and total porosity (TP %) was calculated using the appropriate formula. Soil pH and electrical conductivity (EC) were assessed in a 1:2.5 soil-to-water mixture with a calibrated pH and conductivity meter, respectively (Van Reeuwijk, 1992).

$$\mathrm{TP}(\%) = 1 - \frac{\mathrm{BD}}{\mathrm{PD}} \mathrm{X}\, 100 \qquad (1)$$

Where:

- **BD** = Bulk Density (Mg m^{-3})
- **PD** = Particle Density (Mg m^{-3})

Organic carbon (OC) content was measured using the Walkley–Black method (Walkley & Black, 1934). Available nitrogen (N) was evaluated through the Kjeldahl digestion method (Black, 1965), while available phosphorus (P) was measured using the Olsen method (Olsen et al., 1954), and available potassium (K) was extracted with ammonium acetate and measured using flame photometry. Available sulfur (S) was extracted with 0.15% $CaCl_2$, and the turbidity of the barium sulfate precipitate was analyzed spectrophotometrically at 420 nm.

2.5 Vegetation Analysis

Tree vegetation was inventoried in representative agroforestry systems including Agrihorticulture, Agrisilviculture, Agrisilvihorticulture, Boundary Plantation, and Silvipastoral systems. Species-wise population, girth at breast height (GBH), and basal area were recorded from sample plots. Phytosociological parameters such as density, relative density, and Importance Value Index (IVI) were computed following standard ecological methods. Species diversity was evaluated using the Shannon–Wiener Diversity Index (H′), while species dominance was estimated using Simpson's Dominance Index (Cd).

2.6 Molecular Characterization

Young healthy leaf samples were collected from representative tree species occurring under different agroforestry systems. Genomic DNA was extracted using the CTAB method. DNA quality and quantity were checked through agarose gel electrophoresis and spectrophotometric analysis. RAPD (Random Amplified Polymorphic DNA) markers were employed for molecular characterization. PCR amplification was carried out using selected RAPD primers under optimized reaction conditions. Amplified fragments were separated on agarose gel, visualized under UV illumination, and photographed using a gel documentation system.

Amplified bands were scored as present (1) or absent (0) to generate a binary matrix. The total number of bands, polymorphic bands, percentage polymorphism, and genetic similarity indices were calculated to assess genetic diversity among species under different agroforestry systems.

Percentage polymorphism was calculated as:

$$\% \text{ Polymorphism} = \frac{\text{Polymorphic Bands}}{\text{Total Bands}} \text{X } 100 \qquad \text{Equ.....1}$$

2.7. Statistical Anaysis

For statistical analysis, data were subjected to two-way analysis of variance (ANOVA) to examine the effects of land use types and soil depths on soil physical and chemical properties. Differences were considered significant at the 5% probability level ($p \leq 0.05$), and means were compared using Duncan's Multiple Range Test (DMRT). All statistical analyses were performed using SAS software version 9.4 (SAS, 2013).

3 RESULTS AND DISCUSSION

3.1. Tree Diversity and Structural Attributes under Different Agroforestry Systems

The diversity and structural composition of tree species varied considerably among the agroforestry systems studied in Eastern Uttar Pradesh (Table 3.1). The Silvipastoral system recorded the highest Shannon Diversity Index (H′ = 3.1019) and the lowest Dominance Index (Cd = 0.0567), indicating greater species richness and a more even distribution of tree species. Similar findings were reported by P. K. R. Nair Nair (2011), who observed that multi-species agroforestry systems support higher biodiversity and ecological stability through diversified vegetation structure.

The Agrisilvihorticulture system exhibited relatively high species diversity (H′ = 2.663) with low dominance (Cd = 0.128), reflecting the coexistence of fruit, timber, and multipurpose tree species. Among the species, Mangifera indica recorded the highest population (18 plants 0.1 ha^{-1}), basal area (145824.36 cm^2), and IVI (58.74), indicating its ecological and economic importance. The presence of multiple tree species contributed to greater structural complexity and resource utilization efficiency, which agrees with the findings of Shibu Jose Jose (2009).

In contrast, the Boundary Plantation system showed the lowest diversity (H′ = 1.611) and the highest dominance (Cd = 0.278), mainly due to the predominance of Eucalyptus species and Tectona grandis. Tectona grandis exhibited the highest IVI (119.50) and basal area (15,411,505.43 cm^2), indicating strong dominance within the plantation structure. Such lower diversity in boundary plantations has also been reported by Kumar and Nair (2004), where commercial monoculture-oriented plantations often reduce species heterogeneity.

The Agrihorticulture and Agrisilviculture systems showed moderate diversity (H′ = 2.229) with comparable dominance values (Cd = 0.135). In Agrihorticulture, Mangifera indica was the most dominant species (IVI = 40.66), whereas in Agrisilviculture, Tectona grandis (IVI = 37.53) and Dalbergia sissoo (IVI = 20.78) were the most important species. Their higher IVI values suggest better adaptation and greater contribution to stand structure and ecosystem functioning.

3.2 Molecular characterization of tree Sspecies under different agroforestry systems

The RAPD-based molecular characterization revealed substantial genetic variation among tree species growing under different agroforestry systems of Eastern Uttar Pradesh (Table 3.2). The number of amplified bands varied from 11 to 18, while polymorphic bands ranged from 9 to 15, indicating the effectiveness of RAPD markers in detecting genetic variability among species. The percentage of polymorphism ranged from 76.92% to 83.33%, suggesting moderate to high levels of genetic diversity across the studied tree species.

Among the evaluated species, Eucalyptus spp. under the Boundary Plantation system exhibited the highest polymorphism (83.33%) with 15 polymorphic bands out of 18 total bands and a high genetic similarity index (0.88). Similarly, Mangifera indica from Agrisilvihorticulture and Hortisilviculture systems showed 82.35% polymorphism with the highest genetic similarity index (0.90), indicating a relatively stable and genetically conserved population. Tectona grandis also demonstrated high polymorphism (81.25–82.35%) and genetic similarity values ranging from 0.86 to 0.88, reflecting broad genetic adaptability under different agroforestry environments.

Conversely, Acacia nilotica and Azadirachta indica recorded comparatively lower polymorphism values (76.92%) and genetic similarity indices (0.75–0.80), indicating relatively lower genetic variation among sampled populations. The observed differences in banding patterns among species may be attributed to species-specific genetic makeup, adaptation strategies, and environmental influences associated with different agroforestry systems.

Overall, the high level of polymorphism observed in most species suggests the existence of considerable genetic diversity within agroforestry landscapes. Such diversity is important for maintaining adaptability to changing environmental conditions, enhancing resilience against pests and diseases, and supporting long-term conservation and tree improvement programmes. Similar observations regarding the usefulness of RAPD markers for assessing genetic variability in tree species have been reported by John G. K. Williams Williams et al. (1990), Rafalski et al. (1996), and J. L. Hamrick Hamrick and Godt (1996).

3.3 Soil Physical Properties

The soil physical characteristics bulk density (BD), particle density (PD), and total porosity (TP) under different agroforestry systems and soil depths are summarized in Table 3.3. Across all systems, BD showed a gradual increase with depth, whereas TP declined, reflecting typical soil compaction patterns in subsurface horizons. Among the agroforestry systems, Agrisilviculture and Boundary Plantation recorded comparatively higher BD values at deeper layers (40–60 cm), reaching 1.40 Mg m^{-3} and 1.43 Mg m^{-3}**,** respectively. Conversely, the Silvipastoral system had the lowest BD at the surface (1.11 Mg m^{-3}), indicating better soil structure, higher organic matter inputs, and reduced compaction. Similar findings were reported by (Islam and Weil (2000), who noted that improved vegetation cover enhances soil aggregation and reduces bulk density.

Particle density values showed less variation among systems, ranging from 2.52 to 2.71 Mg m^{-3}**,** with slightly higher values at deeper soil layers. This increase may reflect reduced organic matter and a greater proportion of mineral fractions at depth, consistent with the observations of (Brady and Weil (2002), who emphasized that soils richer in organic residues tend to have lower particle density.

Total porosity displayed an inverse relationship with BD, with the highest TP recorded under the Silvipastoral system at the surface (57.40%), and followed by Agrisilvihorticulture (54.19%). Lower porosity values in deeper layers, particularly in the Boundary Plantation and Agrisilviculture systems, indicate compaction and reduced pore continuity. Comparable decreases in surface porosity with land-use intensification were also reported by Evrendilek et al. (2004), who found that conversion of vegetated land to cultivated fields increases BD and reduce porosity over time. Overall, the results highlight that agroforestry systems with diverse vegetation layers such as Silvipastoral and Agrisilvihorticulture maintain more favorable soil physical conditions due to continuous litter input and reduced soil disturbance. These systems enhance soil aggregation and pore structure, aligning with the conclusions of Celik (2005), who reported improved soil physical quality under tree-associated land uses.

3.4 Soil Chemical Properties

The summarized of the selected soil chemical characteristics (pH, EC, and organic carbon, OC) across different agroforestry systems and soil depths can be found in Table 3.4. Soil pH ranged from slightly acidic to neutral (6.70–7.63) across the various systems, typically increasing with depth. The Agrisilviculture system exhibited the highest pH at 40–60 cm (7.63), whereas the lowest surface pH (0–20 cm) was noted in the Silvipastoral system (6.70). The observed rise in pH with depth may be due to the leaching of basic cations from the topsoil, leading to their accumulation in the subsurface layers. The variance in pH levels among the different systems and depths was statistically significant ($p < 0.05$), highlighting the role of vegetation cover and litter input on soil acidity, as noted by Brady and Weil (2002). Electrical conductivity (EC) remained low in all systems (0.26–0.45 dS m^{-1}), indicating that the conditions are non-saline. EC showed a slight increase with depth, with the highest figures found under Agrisilviculture and Agrisilvihorticulture at 40–60 cm (0.43 and 0.45 dS m^{-1}, respectively). This trend may be attributed to the downward movement and accumulation of soluble salts in deeper soil layers, which aligns with findings from Lal (2015).

There was a noticeable decline in organic carbon (OC) as depth increased. The surface OC (0–20 cm) was greatest in the Agrisilviculture (1.04%) and Agrisilvihorticulture (0.91%) systems, while the lowest values were found at 40–60 cm in the Agrihorticulture and Silvipastoral systems (0.50%). The elevated surface OC in tree-dominant systems can be linked to ongoing litter fall, root turnover, and minimized soil disturbance, which facilitates greater carbon sequestration. The differences in OC levels between systems and depths were significant ($p < 0.05$). These results are in line with studies by Singh et al. (2018) and Islam and Weil (2000), which suggest that varied agroforestry systems promote more surface organic carbon compared to traditional cropping approaches.

In conclusion, agroforestry systems characterized by higher vegetation diversity, specifically Agrisilviculture and Agrisilvihorticulture, exhibited more advantageous chemical properties due to increased organic matter contributions, enhanced nutrient cycling, and decreased erosion. The improved soil chemical conditions linked to these systems could bolster nutrient availability, water retention, and long-term soil fertility, thus supporting sustainable crop production (Nair, 2011; Jose, 2009).

3.3 Soil Macronutrient Status

The distribution of key soil macronutrients Nitrogen (N), Phosphorus (P), Potassium (K), and Sulphur (S) within various agroforestry systems and soil depths is presented in Table 3.5 (values shown as mean ± SE). A general decline with depth was noted, likely due to lower organic matter content, reduced root activity, and fewer microbial processes in deeper soil layers. Surface nitrogen (0–20 cm) varied from 269.01 to 318.26 kg ha^{-1}, with the peak levels observed in the Silvipastoral and Agrisilvihorticulture systems. These systems thrive due to ongoing litter deposition, root turnover, and interactions between grasses and trees that improve nutrient cycling. The variations among systems and depths were statistically significant ($p < 0.05$), which aligns with findings by Roy et al. (2016) and Nair (2011).Phosphorus (P) levels at the surface (17.32–20.55 kg ha^{-1}) were highest in the Agrisilvihorticulture system, indicating enhanced mineralization and the limited mobility of phosphate ions, consistent with observations by Brady and Weil (2002). Potassium (K) showed a comparable trend, with maximum surface levels recorded in the Silvipastoral (291.67 kg ha^{-1}) and Agrisilvihorticulture systems, which is due to the presence of deep-rooted trees and effective nutrient recycling, as supported by Singh et al. (2018). Sulphur (S) levels were also elevated in surface layers (14.75–16.38 mg kg^{-1}), especially in the Silvipastoral system, where continuous biomass inputs lead to greater availability of S, as reported by Tandon (2013). Overall the various agroforestry systems, notably Silvipastoral and Agrisilvihorticulture, consistently exhibited higher concentrations of macronutrients across different soil depths. These systems contribute to improved soil fertility and long-term productivity by enhancing organic matter accumulation and nutrient cycling, reinforcing the broader conclusions of Jose (2009) and Nair (2011) regarding the sustainability advantages of tree-based land-use practices.

4. CONCLUSIONS AND RECOMMENDATIONS

The present investigation highlighted the significant role of agroforestry systems in enhancing biodiversity, conserving genetic resources, and improving soil quality in Eastern Uttar Pradesh. Considerable differences were observed in tree species composition and structural attributes among the agroforestry systems studied. The Silvipastoral system exhibited the highest species diversity and the lowest dominance, indicating a balanced and ecologically stable vegetation structure. In contrast, Boundary Plantation systems were characterized by lower diversity and greater dominance of a few commercial tree species.

Molecular characterization using RAPD markers revealed moderate to high levels of genetic polymorphism among the selected tree species, indicating substantial genetic variability within agroforestry landscapes. The highest polymorphism was recorded in Eucalyptus spp., while Mangifera indica showed the greatest genetic similarity. These findings demonstrate the effectiveness of agroforestry systems in conserving valuable tree genetic resources and maintaining adaptive potential under varying environmental conditions.

The study further confirmed that diversified agroforestry systems contribute positively to soil physicochemical properties through improved organic matter accumulation, nutrient cycling, and enhanced soil fertility. Among the evaluated systems, Agrisilvihorticulture and Silvipastoral systems emerged as the most sustainable land-use options due to their higher biodiversity, genetic diversity, and favorable soil conditions.

Overall, the integration of ecological, molecular, and soil-based assessments provides a comprehensive understanding of agroforestry sustainability. Promotion of diversified agroforestry systems can play an important role in improving farm productivity, conserving biodiversity, enhancing soil health, and supporting climate-resilient agricultural development in Eastern Uttar Pradesh.

Acknowledgements

The authors sincerely acknowledge the support of local farmers for providing access to their fields and sharing valuable information during soil sampling. The authors are also grateful to the laboratory and field staff of the concerned department for their assistance in sample collection and analysis. Any institutional or funding support not received during the course of this study is duly acknowledged.

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Table 3.1 Comparative Diversity and Structural Attributes of Tree Species under Different Agroforestry Systems in Eastern Uttar Pradesh.

Agroforestry System	Tree Species	Population (0.1 ha⁻¹)	Mean Girth (cm)	Basal Area	Relative Density (%)	IVI	Shannon Diversity Index (H′)	Dominance Index (Cd)
Agrihorticulture	Mangifera indica	12	908.83	65762.10	11.65	40.66	2.229	0.135
	Psidium guajava	6	378.94	11432.76	5.83	13.45	2.229	0.135
	Syzygium cumini	3	200.19	3190.77	2.91	6.24	2.229	0.135
	Emblica officinalis	9	588.23	27548.93	8.74	22.21	2.229	0.135
	Ziziphus mauritiana	7	79.76	506.50	6.80	9.60	2.229	0.135
	Moringa oleifera	3	131.66	1380.12	2.91	5.88	2.229	0.135
Agrisilviculture	Tectona grandis	12	893.60	63576.51	11.65	37.53	2.229	0.135
	Emblica officinalis	9	588.23	27548.93	8.74	22.20	2.229	0.135
	Dalbergia sissoo	17	1109.11	97939.89	8.50	20.78	2.229	0.135
	Eucalyptus hybrid	5	392.76	12281.88	3.88	11.68	2.229	0.135
	Swietenia macrophylla	4	275.61	6112.58	3.88	7.95	2.229	0.135
	Madhuca indica	3	174.37	2428.47	2.91	6.24	2.229	0.135
	Melia dubia	2	132.28	1390.25	1.94	4.85	2.229	0.135
	Ailanthus excelsa	2	115.12	1052.41	1.94	4.12	2.229	0.135
Agrisilvihorticulture	Mangifera indica	18	1362.45	145824.36	20.93	58.74	2.663	0.128
	Psidium guajava	11	694.83	38416.72	12.79	31.48	2.663	0.128
	Syzygium cumini	7	486.28	18965.43	8.14	21.62	2.663	0.128
	Emblica officinalis	9	588.23	27548.93	10.47	24.84	2.663	0.128
	Moringa oleifera	6	263.32	5520.48	6.98	14.36	2.663	0.128
	Pongamia pinnata	5	318.74	7981.26	5.81	12.88	2.663	0.128
	Ziziphus mauritiana	4	159.52	2026.00	4.65	9.64	2.663	0.128
	Azadirachta indica	3	171.00	2328.10	3.49	8.22	2.663	0.128
	Artocarpus heterophyllus	2	146.28	1708.44	2.33	5.14	2.663	0.128
	Madhuca indica	1	84.16	562.11	1.16	3.08	2.663	0.128
	Tectona grandis	11	4128.34	1062842.25	12.79	42.16	2.663	0.128
	Eucalyptus species	9	3521.18	874516.44	10.47	38.72	2.663	0.128
Boundary Plantation	Eucalyptus species	93	6233.01	3093185.80	46.50	107.93	1.611	0.278
	Tectona grandis	37	13912.89	15411505.43	18.50	119.50	1.611	0.278
	Swietenia macrophylla	24	1729.76	238222.11	12.00	21.10	1.611	0.278
	Dalbergia sissoo	17	1109.11	97939.89	8.50	20.78	1.611	0.278
	Ailanthus excelsa	12	690.70	37983.00	6.00	10.12	1.611	0.278
	Heterophragma adenophyllum	9	746.62	44382.28	4.50	8.66	1.611	0.278
	Bauhinia variegata	4	288.25	6615.29	2.00	4.00	1.611	0.278
	Artocarpus lacucha	2	194.40	3008.87	1.00	2.98	1.611	0.278
	Azadirachta indica	2	114.00	1034.71	1.00	4.93	1.611	0.278

Silvipastoral	Acacia nilotica	3	163.23	2123.45	2.54	7.84	3.1019	0.0567
	Albizia lebbeck	2	142.67	1618.74	1.69	5.64	3.1019	0.0567
	Azadirachta indica	5	284.61	6432.28	4.24	12.56	3.1019	0.0567
	Dalbergia sissoo	6	391.44	12136.82	5.08	15.83	3.1019	0.0567
	Holoptelea integrifolia	2	154.00	1888.22	1.69	4.70	3.1019	0.0567
	Madhuca indica	4	336.56	9018.52	3.39	10.02	3.1019	0.0567
	Mangifera indica	8	643.00	32917.91	6.78	25.14	3.1019	0.0567
	Morus alba	3	117.40	1097.35	2.54	5.27	3.1019	0.0567
	Pongamia pinnata	3	180.00	2579.62	2.54	5.78	3.1019	0.0567
	Prosopis juliflora	4	214.00	3646.18	3.39	8.17	3.1019	0.0567
	Tamarindus indica	3	300.53	7190.95	2.54	8.54	3.1019	0.0567
	Tectona grandis	10	599.93	28655.73	8.47	23.02	3.1019	0.0567

Table 3.2: Molecular Characterization of Plant Samples under Different Agroforestry Systems

Sr. No.	Agroforestry System	Sample Species	Molecular Marker Used	Band Size Range (bp)	No. of Bands	Polymorphic Bands	% Polymorphism	Genetic Similarity Index
1	Agrisilviculture	Dalbergia sissoo	RAPD	200–1600	14	11	78.57	0.81
2		Azadirachta indica	RAPD	220–1500	13	10	76.92	0.80
3		Tectona grandis	RAPD	250–1700	16	13	81.25	0.86
4		Eucalyptus species	RAPD	300–1800	15	12	80.00	0.84
5		Madhuca indica	RAPD	180–1400	11	9	81.82	0.79
6		Swietenia macrophylla	RAPD	220–1600	14	11	78.57	0.83
7	Agrisilvihorticulture	Mangifera indica	RAPD	300–1800	17	14	82.35	0.90
8		Psidium guajava	RAPD	250–1600	15	12	80.00	0.85
9	Silvipastoral	Acacia nilotica	RAPD	200–1400	13	10	76.92	0.75
10		Dalbergia sissoo	RAPD	220–1500	14	11	78.57	0.80
11		Azadirachta indica	RAPD	250–1600	15	12	80.00	0.82
12	Boundary Plantation	Eucalyptus spp.	RAPD	300–1800	18	15	83.33	0.88
13		Tectona grandis	RAPD	300–1700	17	14	82.35	0.86
14	Hortisilviculture	Moringa oleifera	RAPD	180–1300	11	9	81.82	0.79
15		Mangifera indica	RAPD	300–1800	17	14	82.35	0.90

Table 3.3. Bulk density, particle density, and total porosity of soils across various Agroforestry systems and soil depths in the study area

Agroforestry Systems	**BD ($Mg\ m^{-3}$)**			**PD ($Mg\ m^{-3}$)**			**TP (%)**		
Depth (cm)	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60

Agrihorticulture System	1.17aa	1.26aa	1.33aa	2.52aa	2.58aa	2.65aa	53.64aa	51.36aa	49.75aa
Agrisilviculture System	1.26aa	1.34aa	1.40aa	2.57aa	2.61aa	2.66aa	51.08aa	48.83aa	47.41aa
Agrisilvihorticulture System	1.19aa	1.24aa	1.33aa	2.56aa	2.61aa	2.68aa	54.19aa	52.80aa	50.66aa
Boundary Plantation	1.26aa	1.30aa	1.43aa	2.58aa	2.64aa	2.71aa	50.50aa	50.80aa	47.35aa
Silvipastoral System	1.11aa	1.31aa	1.38aa	2.56aa	2.62aa	2.68aa	57.40aa	51.32aa	49.67aa

Means within a column followed by the same letter are not significantly different at $p < 0.05$; BD = bulk density; PD = particle density; TP = total porosity

Table 3.4. Summarizes the selected soil chemical properties (pH, EC, and OC) under different Agroforestry systems in the study area.

Land Use Type	**pH**			**EC (dS/m^{-1})**			**OC (%)**		
Depth	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
Agrihorticulture Systems	6.89aa	7.26aa	7.47aa	0.28aa	0.31aa	0.37aa	0.79aa	0.67aa	0.50aa
Agrisilviculture Systems	6.98aa	7.36aa	7.63aa	0.32aa	0.37aa	0.43aa	1.04aa	0.89aa	0.74aa
Agrisilvihorticulture Systems	6.88aa	7.21aa	7.61aa	0.32aa	0.37aa	0.45aa	0.91aa	0.71aa	0.51aa
Boundary Plantation	6.74aa	7.03aa	7.43aa	0.28aa	0.31aa	0.36aa	0.93aa	0.75aa	0.63aa
Silvipastoral Systems	6.70aa	7.02aa	7.48aa	0.26aa	0.31aa	0.39aa	0.84aa	0.67aa	0.50aa

Means within a column followed by the same letter are not significantly different at $p < 0.05$; pH=Potential of Hydrogen; EC= Electrical Conductivity; OC = Organic carbon.

Table 3.5. Variation in Soil Macronutrients (N, P, K, S) Among Different Land-Use Types

Land Use Type	**N(kg ha^{-1})**			**P (kg ha^{-1})**			**K (kg ha^{-1})**			**S (mg kg^{-1})**		
Depth	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
Agrihorticulture Systems	287.64ba	269.30bb	258.05ab	17.32aa	14.66aa	11.86aa	257.22	235.56	208.80	16.06	14.01	11.41
Agrisilviculture Systems	288.53ba	274.53ba	252.31ab	17.22aa	14.67aa	12.38aa	241.62	221.63	200.50	16.26	14.00	11.75
Agrisilvihorticulture Systems	310.85aa	285.27abb	260.41ac	20.55aa	17.86aa	15.37aa	277.37	247.84	204.38	14.75	12.61	10.72
Boundary Plantation	269.01ca	242.64cb	218.38bc	18.48aa	15.80aa	12.25aa	258.63	229.96	197.68	13.78	11.61	9.10
Silvipastoral Systems	318.26aa	299.49ab	267.16ac	18.62aa	15.80aa	12.86aa	291.67	265.48	230.14	16.38	13.58	11.16

Means within a column followed by the same letter are not significantly different at $p < 0.05$; AN = Available Nitrogen; AP= Available Phosphorus; AK= Available Potassium; AS=Available Sulphur.