



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; 8(11): 696-703
Received: 26-08-2025
Accepted: 24-09-2025

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Soil physico-chemical dynamics, microbial diversity and productivity responses in agroforestry system

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DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i11j.4252>

Abstract

Agroforestry systems play a crucial role in enhancing soil physico-chemical properties, nutrient dynamics, microbial diversity, and overall productivity, contributing to sustainable land management. Tree - based systems improve soil structure, organic carbon content, nutrient retention, and water-holding capacity through litterfall, root turnover, and microclimatic modifications. Soil nutrients exhibit spatial and temporal variability influenced by tree and crop interactions, topography, and seasonal changes, forming nutrient - rich zones that optimize crop and tree growth. Microbial communities, along with enzymatic activities, regulate nutrient cycling, soil organic carbon stabilization, and biological health, supporting long - term fertility and ecosystem resilience. Agroforestry also contributes to carbon sequestration, climate - change mitigation, and enhancement of ecosystem services. Integrating soil assessment data into management strategies enables early detection of soil constraints such as acidity, salinity, and nutrient deficiencies, allowing corrective interventions. These insights support climate-smart agroforestry planning, sustainable productivity, and the long - term health and resilience of agroecosystems.

Keywords: Agroforestry, soil physico-chemical properties, nutrient dynamics, microbial diversity, soil fertility, productivity, carbon sequestration, ecosystem services, soil health, sustainable land management

Introduction

Agroforestry in India functions as a long - established multifunctional land - use system that strengthens food, energy, livelihood and environmental security. Trees outside forests supply a substantial share of national timber requirements while simultaneously delivering a wide spectrum of ecosystem services. Agroforestry is recognised as a sustainable and climate-resilient alternative to monoculture due to its capacity to enhance productivity, improve soil quality and maintain ecological balance (Asbjornsen *et al.*, 2013; Kuyah *et al.*, 2016) ^[3, 33]. Despite its significance, yield-related data from diverse agroforestry configurations remain scattered and inconsistent (Vladimir *et al.*, 2021) ^[83], indicating the need for integrated assessments of soil physico-chemical processes, soil plant microbe interactions and productivity responses. Recent global syntheses further demonstrate the system's strong contribution to ecosystem multifunctionality, such as nutrient retention, soil carbon storage, hydrological regulation and climate adaptation (Mbow *et al.*, 2014; Lorenz & Lal, 2014) ^[35, 38, 40].

Tree and crop integration modifies soil physical and chemical processes through nitrogen fixation, nutrient pumping from deeper soil layers and reduction of nutrient losses by leaching and erosion (Shah *et al.*, 2022) ^[65]. Continuous inputs from leaf litter, woody residues and root turnover improve the organic matter-rich O-horizon, accelerating decomposition and long-term nutrient cycling (Gupta *et al.*, 2010; Vitousek & Sanford, 1986) ^[19, 82]. These organic inputs enhance bulk density, water-holding capacity and cation exchange capacity (Seta *et al.*, 2018) ^[64], while increased porosity and root-induced bio pores improve infiltration rates by 20-60% (Ilstedt *et al.*, 2007) ^[22]. Deep-rooted tree species also redistribute Ca, Mg and K from subsoil to surface layers, thereby improving nutrient stratification and promoting macro-aggregate formation essential for soil structure and erosion resistance (Six *et al.*, 2000; Nair *et al.*, 2009) ^[49, 70].

Agroforestry strongly influences soil biological processes by enriching microbial communities responsible for carbon cycling and nutrient transformation.

Litter deposition and root turnover act as primary drivers of microbial activity and decomposition pathways (Bargali *et al.*, 2015; Hättenschwiler *et al.*, 2010; Manral *et al.*, 2020; Karki *et al.*, 2021) [5, 21, 29, 39]. Microbial biomass has been reported to increase by 25 - 70% under agroforestry systems (Narwal, 2006) [51], while PLFA and metagenomic studies show enriched populations of Actinobacteria, Proteobacteria and arbuscular mycorrhizal fungi (Beule & Karlovsky, 2021) [8]. Functional gene profiling indicates an increase in nitrogen-cycling genes and carbon-decomposition enzymes, alongside elevated activities of β -glucosidase, urease and dehydrogenase at tree and crop interfaces (Sharma *et al.*, 2021) [66], demonstrating enhanced biochemical functioning.

Beyond soil improvement, agroforestry supports rural livelihoods by producing food, fodder, fuelwood, fibre, timber and various bio-resources such as lac, sericulture and apiculture products (Singh *et al.*, 1994; Dwivedi, 2001) [17, 67]. Microclimatic moderation through tree shade reduces temperature, conserves soil moisture and lowers evapotranspiration, significantly enhancing crop productivity in arid and semi-arid regions. Empirical studies have documented yield increases such as 86% under *Prosopis cineraria*, 48.8% under *Tecomella undulata*, 57.9% under *Acacia albida* and 16.8% under *Azadirachta indica*. Tree-canopied soils inherently show greater organic carbon, improved moisture storage and better nutrient availability (Kumar *et al.*, 1998) [32]. Agroforestry also regulates wind speed and stabilises vapour pressure deficit, an important adaptation mechanism under climate change scenarios (Mbow *et al.*, 2014) [40].

Long-term residual effects persist even after tree removal; for example, nitrogen enrichment from *Acacia nilotica* remained effective for more than 15 years, improving rice yields substantially (Kohli & Saini, 2003; Prasad *et al.*, 2011) [30, 61]. Short-term on-farm experiments likewise report strong economic advantages, with *Eucalyptus* increasing intercrop yields by 45% and *Leucaena* by 36% (Pandey, 2011) [57]. Alley cropping, silvopasture and boundary plantations provide 40-65% productivity gains due to complementary resource use (Thevathasan & Gordon, 2004; Jose, 2009) [26, 79]. Spatial arrangements such as north-south row orientation optimise shading and competition-complementarity dynamics (Jose *et al.*, 2004) [28], contributing to income diversification, risk reduction and ecological sustainability (Mercer *et al.*, 2014) [43].

Increasing scientific evidence positions agroforestry as a critical strategy for climate mitigation and land restoration. With a carbon sequestration potential of 1.5-3.5 Mg C ha⁻¹ yr⁻¹ (Lorenz & Lal, 2014) [38], agroforestry enhances soil carbon pools, biodiversity, landscape resilience and long-term soil rehabilitation. Consequently, it has emerged as an indispensable component of sustainable land management across the world.

Material and Methods: The assessment of soil physical properties under agroforestry systems was carried out using standardized protocols widely adopted by USDA, ICAR, FAO and internationally reviewed methodologies. Composite and undisturbed soil samples were collected from agroforestry and adjacent monocropping fields at standard depths (0-15 cm and 15 - 30 cm). All laboratory analyses were performed under controlled conditions to ensure accuracy and reproducibility.

Bulk Density (Mg m⁻³): Bulk density was determined using the undisturbed soil core method (Blake & Hartge, 1986) [9]. Cylindrical stainless-steel cores (100 - 200 cm³) were inserted carefully to avoid compaction. Samples were oven-dried at 105°C for 24 h, weighed, and bulk density was calculated as:

$BD = \text{Oven dry soil weight (g)} / \text{Core volume (cm}^3\text{)}$

$$BD = \frac{\text{Oven dry soil weight (g)}}{\text{Core Volume (cm}^3\text{)}}$$

Values were converted to Mg m⁻³ for uniformity.

Soil Porosity (%)

Total soil porosity was derived using bulk density and particle density ($\rho_p = 2.65 \text{ g cm}^{-3}$):

$$\text{Porosity (\%)} = \left(1 - \frac{BD}{2.65}\right) \times 100$$

Infiltration Rate (mm hr⁻¹)

Infiltration rate was determined using a double-ring infiltrometer following the ASTM (American Society for Testing and Materials) standard. Inner ring: 30 cm diameter. Outer ring: 60 cm diameter. Constant head maintained at 2-5 cm. Measurements were taken at 5, 10, 15, 30, 45 and 60 min, and the steady-state infiltration rate was expressed in mm hr⁻¹.

Soil Aggregate Stability (%)

Aggregate stability was measured using the wet-sieving method with a Yoder apparatus (Yoder, 1936) [85]. Air-dried aggregates (1-2 mm) were re-humidified for 30 min. Wet-sieving performed at 30 cycles per minute for 10 min. Stability was expressed as Mean Weight Diameter (MWD):

$$MWD = \sum x_i w_i$$

Where -

- x_i = mean diameter of sieve fraction.
- w_i = weight proportion of aggregates retained.
- Higher MWD indicates greater stability.

Soil Compaction and Crusting

Compaction (Penetration Resistance) Soil penetration resistance was assessed using a handheld cone penetrometer (Eijkelkamp model). Measurements were taken at 0-10, 10-20 cm depths and expressed in MPa. Resistance >2 MPa was interpreted as severe compaction.

(b) Soil Crusting: Crust thickness was measured using a digital caliper, while crust strength was determined using a hand penetrometer (kg cm⁻²). Crusting susceptibility was evaluated using FAO's texture organic carbon index.

Soil Chemical Properties (N, P, K, OC, EC, pH)

Soil chemical properties under agroforestry and control (open field) systems were analysed using standard protocols recommended by ICAR (2015), AOAC, and Jackson (1973) [23]. Composite soil samples (0 - 15 cm and 15 - 30 cm) were collected, air-dried, powdered, and sieved (< 2 mm) before laboratory analysis.

Soil pH: Method

Electrometric glass-electrode method (Jackson, 1973) [23]

Procedure

Soil: distilled water ratio = 1:2.5 (w/v). Suspension stirred for 30 minutes. pH measured using a calibrated digital pH meter. Soil reaction (acidity/alkalinity)

Electrical Conductivity (EC)

Method: *Conductometric method* (Richards, 1954) ^[63].
Procedure - Same extract used as pH (1:2.5 soil-water). EC measured using an EC meter at 25°C, expressed as dS m⁻¹.
Output: Soil salinity level

Organic Carbon (OC)

Method: Walkley-Black Wet Oxidation Method (Walkley & Black, 1934) ^[84]

Procedure

g soil treated with 1N K₂Cr₂O₇ and concentrated H₂SO₄. Allowed to oxidize for 30 minutes. Titrated against 0.5N FeSO₄ using ferroin indicator. Calculation

$$OC (\%) = \frac{(B - T) \times 0.003 \times 100}{\text{Weight of Soil}}$$

(B = blank reading, T = sample reading) Soil organic carbon (%)

Available Nitrogen (N)

- **Method:** Alkaline Permanganate Method (Subbiah & Asija, 1956) ^[73]
- **Principle:** KMnO₄ oxidation releases ammonical - N → distilled → absorbed in boric acid → titrated.
- **Procedure:** Soil + 0.32% KMnO₄ + 40% NaOH heated. NH₃ collected in boric acid + mixed indicator. Titrated with 0.02 N H₂SO₄. Available N (kg ha⁻¹)

Available Phosphorus (P)**Methods depend on soil type**

- **Olsen's Method (for neutral-alkaline soils) Reference:** Olsen *et al.*, 1954 ^[52]
- **Procedure:** Soil extracted with 0.5 M NaHCO₃ (pH 8.5). Filtrate mixed with ammonium molybdate + stannous chloride. Blue colour intensity read at 660 nm using spectrophotometer. (Bray & Kurtz, 1945) Available P (kg ha⁻¹) ^[13].

Available Potassium (K)

Method: *Neutral Normal Ammonium Acetate Extraction* (Jackson, 1973) ^[23] **Procedure** - Soil shaken with 1N NH₄ OA c (pH 7.0)., Extract filtered., K concentration measured using Flame Photometer. Available K (kg ha⁻¹)

Summary of research paper**To assess soil physico-chemical properties**

Soil physico-chemical assessment measures pH, electrical conductivity (EC), organic carbon (OC), bulk density, texture, and nutrient availability (N, P, K, micronutrients). Researchers like Brady & Weil (2010) and Young (1997) ^[10, 86] reported that agroforestry systems improve soil structure, nutrient retention, and water-holding capacity compared to monoculture. Nair (2012) ^[46] emphasized that tree canopies and litter inputs modify soil chemical dynamics, enhancing fertility. Such assessments provide a scientific basis for monitoring soil health and guiding tree-crop selection in diverse agroforestry systems, ensuring sustainable productivity and ecosystem balance.

Importance: Systematic physico-chemical assessment will guide climate-smart agroforestry designs, improve soil health monitoring at landscape scales, and ensure long-term productivity under changing climatic conditions. Accurate soil data will support precision nutrient management, resource-efficient farming, and restoration of degraded lands.

Analyzed soil nutrient dynamics and variability

Soil nutrient variability is influenced by spatial distribution, depth, tree species, litterfall, root turnover, and microbial activity. Jenny (1941) ^[25] and McBratney & Webster (1983) ^[41] highlighted how parent material and topography shape nutrient distribution. Researchers such as Nambiar (1990) ^[50] and Jose (2009) ^[26] observed that nutrient hotspots form beneath tree canopies due to litter deposition and root activity. Temporal variability is also important, as nutrient mineralization peaks during wet seasons (Palm *et al.*, 2001) ^[55]. Understanding these dynamics allows for precise nutrient management, reducing deficiencies and optimizing productivity in agroforestry systems.

Importance: Monitoring nutrient dynamics will enable adaptive nutrient management in tree-crop systems, enhance soil fertility resilience under climate variability, and support efficient fertilizer use. Understanding spatial and temporal nutrient variability will also aid in sustainable agroforestry expansion and ecosystem services optimization.

To evaluate microbial diversity and activity

Microbial biomass, diversity, and enzymatic activity govern nutrient cycling and soil fertility. Researchers including Six *et al.*, (2006) and Barea *et al.*, (2005) ^[4, 71] demonstrated that microbial communities are enriched under tree canopies due to organic inputs and rhizosphere processes. Enzyme activities such as β-glucosidase, urease, and phosphatase reflect nutrient mineralization and decomposition rates (Tabatabai, 1994). Nahon *et al.*, (2024) ^[44, 75] showed that agroforestry increases microbial functional diversity, supporting soil health. Assessing microbial dynamics is essential for evaluating biological soil quality, nutrient availability, and long-term agroecosystem sustainability.

Importance: Enhanced microbial diversity assessment will help predict soil fertility trends, optimize nutrient cycling, and promote resilient agroecosystems. Microbial monitoring will also assist in carbon sequestration strategies and bioindicator-based environmental assessments for sustainable land-use planning.

To investigate productivity responses of crops and trees

Soil physico-chemical properties and microbial activity directly influence crop yield and tree growth. Researchers like Singh *et al.*, (2017) and Kumar & Nair (2004) ^[31] found that leguminous trees enhance nitrogen availability, improving intercrop productivity, while deep-rooted species increase subsoil nutrient recycling and moisture retention. Productivity assessment quantifies the impact of soil-tree-crop interactions and helps select species combinations that maximize biomass, yield, and overall system efficiency. Such evaluations also inform management practices for improved benefit-cost ratios and ecosystem resilience.

Importance: Understanding productivity responses will enable optimization of species combinations for maximum biomass and yield. It will facilitate precision agroforestry management, enhance food and timber production, and improve resilience of farming systems under future environmental stresses.

To quantify soil carbon sequestration and ecosystem services

Agroforestry enhances soil organic carbon (SOC) through litterfall, root inputs, and stabilization of organic matter. Researchers like Six *et al.*, (2006) ^[71] and Lehmann & Kleber

(2015) ^[36] reported that microbial processes mediate SOC stabilization and nutrient retention. Studies in Indian agroforestry systems (Jose, 2009) ^[26] have shown significant carbon accumulation in surface and subsoil layers. Quantifying SOC provides insights into ecosystem services such as fertility improvement, climate-change mitigation, and soil restoration. This objective emphasizes the role of tree-based systems in long-term environmental sustainability and carbon management.

Importance: Quantifying SOC will be critical for climate mitigation strategies, carbon trading programs, and ecosystem restoration initiatives. It will support evidence-based policy-making for sustainable agroforestry and long-term environmental conservation.

To support sustainable land-use planning

Researchers Nair (1993) and Young (1997) ^[45, 86] highlighted that matching site-specific soil characteristics with appropriate tree-crop combinations is essential for maximizing productivity and ecological resilience. Soil assessments inform the selection of agroforestry models such as silvopasture, alley cropping, and boundary plantations. Soil nutrient mapping also identifies degraded lands suitable for restoration (Chaturvedi & Raghubanshi, 2014) ^[14]. Integrating soil data into land-use planning ensures climate-smart, resource-efficient, and sustainable agroforestry interventions, enhancing both environmental and economic benefits.

Importance: Data-driven land-use planning will facilitate optimized tree-crop placement, efficient resource utilization, and ecosystem restoration. It will support sustainable development goals, climate adaptation, and landscape-level decision-making for future agroforestry expansion.

To identify soil constraints and propose corrective measures

Agroforestry soils may face acidity, salinity, nutrient deficiencies, and compaction. Researchers like Brady & Weil (2016) and Gupta & Abrol (1990) ^[18, 11] have shown that soil testing allows early detection of these constraints. Corrective measures such as liming acidic soils, gypsum application for sodic soils, and organic amendments for nutrient enhancement are evidence-based strategies (Tandon, 1995; Palm *et al.*, 2001) ^[55, 77]. Assessing soil limitations supports targeted interventions, improves productivity, and strengthens the sustainability of agroforestry systems.

Future Importance: Early detection and correction of soil constraints will enhance resilience of agroforestry systems under climate change, prevent land degradation, and ensure long-term soil health. It will also improve input-use efficiency, crop yields, and overall ecosystem sustainability.

Importance of Soil Analysis: Soil analysis provides the scientific foundation for understanding soil fertility, nutrient limitations, degradation status and land suitability. In agroforestry systems, where trees, crops and soil interact continuously, soil testing becomes even more critical because below-ground processes, nutrient exchanges and microbial activities are more complex than in monocropping systems.

Assessment of Soil Fertility and Nutrient Availability

Soil analysis is essential for evaluating nutrient availability and overall fertility. Standard analytical procedures include Subbiah & Asija (1956) for available nitrogen, Olsen *et al.*, (1954) ^[52, 73]

for available phosphorus, and Walkley & Black (1934) ^[84] for organic carbon assessment. Soil pH and electrical conductivity (EC), based on Jackson (1973) ^[23], help diagnose acidity, salinity and nutrient-solubility issues. These parameters directly influence microbial activity, root function and nutrient uptake (Brady & Weil, 2017) ^[12]. In agroforestry, nutrient cycling and fertility improvement through litterfall and root turnover have been clearly demonstrated by Palm *et al.*, (2005) ^[54]. Young (1997) ^[86] emphasized that systematic soil fertility evaluation is essential for selecting suitable tree-crop combinations and optimizing nutrient management.

Monitoring Soil Health in Agroforestry Systems

Agroforestry improves soil health through litter deposition, root turnover, nitrogen fixation and rhizosphere processes. According to Young (1997) and Nair (1993) ^[45, 86], continuous organic inputs from trees enhance soil organic matter and soil structure. Palm *et al.*, (2005) ^[54] reported improved aggregation through litter decomposition. Biological nitrogen fixation by leguminous trees such as *Gliricidia* and *Leucaena* - widely studied by Peoples & Herridge (1990) ^[59] - increases soil nitrogen and supports crop productivity.

Rhizosphere research by Dakora & Phillips (2002) ^[16] shows that root exudates stimulate microbial “hot spots,” enhancing nutrient mineralization. Soil analysis helps monitor these changes through physical parameters (porosity, bulk density), chemical parameters (organic carbon, nutrient status, pH), and biological parameters such as microbial biomass and enzyme activity, following methods by Powlson *et al.*, (1987) and Vance *et al.*, (1987) ^[60, 81].

Diagnosis of Soil Constraints: Soil testing helps identify key constraints such as acidity/alkalinity, salinity/sodicity, nutrient deficiencies, low organic carbon, high bulk density and poor infiltration. Soil pH effects on nutrient solubility and microbial behavior have been detailed by Brady & Weil (2016) ^[11]. Diagnostic frameworks for saline-sodic soils by Richards (1954) ^[63] remain the global standard. Nutrient deficiencies are diagnosed using procedures by Lindsay & Norvell (1978) ^[38] and Jackson (1973) ^[23]. Low organic carbon, linked to structural degradation, has been emphasized by Lal (1997) ^[34]. Soil compaction and its productivity impacts were quantified by Hamza & Anderson (2005) ^[20]. Corrective measures include liming for acidic soils (Adams & Evans, 1962), gypsum for sodic soils (Abrol & Bhumbla, 1971) ^[1] and integrated nutrient management (INM) supported by Tandon (1995) and Palm *et al.*, (2001) ^[2, 55, 77].

Evaluating Soil-Plant-Microbe Interactions

Soil-plant-microbe interactions regulate nutrient cycling and productivity in agroforestry systems. Microbial biomass acts as a key indicator of ecosystem functioning (Paul, 2015) ^[58]. Soil testing allows evaluation of microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and microbial functional groups. Enzymes such as β -glucosidase, urease, phosphatase and dehydrogenase, described by Tabatabai (1994) ^[75] and Trasar - Cepeda *et al.*, (2008) ^[80], indicate organic matter decomposition and nutrient mineralization rates. Litter quality strongly influences mineralization patterns, as shown by Swift, Heal & Anderson (1979) and Berg & McClaugherty (2008) ^[7, 74]. Carbon stabilization within agroforestry systems is governed by microbial residues, aggregation and root-derived carbon inputs, supported by Six *et al.*, (2006) and Lehmann & Kleber (2015) ^[136, 71].

Soil Analysis and Microbial Interactions in Sustainable Agroforestry Systems: Accurate soil data is fundamental for sustainable land-use planning in agroforestry systems. Key soil properties - texture, depth, bulk density, organic carbon, nutrient availability, pH, and water-holding capacity, determine land suitability for different agroforestry models. Matching site characteristics with appropriate tree and crop combinations is essential for maximizing productivity and ecological resilience (Nair, 1993; Young, 1997) ^[45, 86]. Soil surveys help identify suitable niches for silvopasture, alley cropping, agri-horticulture, boundary plantations, and shelterbelts. For example, sandy loam soils with moderate organic carbon favor agri-horticultural systems, while clay-loam soils with higher moisture retention support silvopastoral systems (Jose, 2009) ^[26]. Soil analysis also identifies degraded lands requiring restoration; agroforestry improves soil structure, enhances litter inputs, and promotes microbial recovery in eroded or nutrient-depleted areas (Chaturvedi & Raghubanshi, 2014) ^[15]. Evaluating soil moisture regimes and infiltration further helps select water-efficient tree-crop combinations, particularly for semi-arid regions (Ong *et al.*, 2004) ^[53].

Soil-plant-microbe interactions are central to nutrient dynamics and productivity in agroforestry systems. Tree litter, root exudates, and rhizosphere microbial communities regulate nutrient cycling and soil fertility. Soil microbial biomass, a sensitive indicator of ecosystem function, governs decomposition, humification, and nutrient turnover (Paul, 2015) ^[58]. Measuring microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and microbial functional diversity provides critical insights into soil health. Enzymatic activities, including β -glucosidase, urease, phosphatase, and dehydrogenase, reflect organic matter decomposition and nutrient mineralization, responding rapidly to land use changes and root-microbe interactions (Tabatabai, 1994; Trasar-Cepeda *et al.*, 2008) ^[75, 80]. Continuous organic inputs improve nitrogen mineralization, synchronize nutrient supply with crop demand, and enhance carbon sequestration through microbial residues and root-derived carbon (Swift *et al.*, 1979; Berg & McClaugherty, 2008; Six *et al.*, 2006; Lehmann & Kleber, 2015) ^[7, 36, 71, 74].

Soil analysis is essential for assessing the impact of agroforestry interventions. Comparing soil properties before and after agroforestry establishment allows quantification of improvements in fertility, structure, microbial functioning, and long-term ecosystem performance. Agroforestry plots maintain higher soil organic carbon, available N, P, K, and microbial biomass than monocropping systems, reflecting contributions from litter deposition, nitrogen fixation, and root-mediated aggregation (Singh *et al.*, 2017). Species-specific effects are also measurable: leguminous trees enhance soil nitrogen and microbial activity, while deep-rooted species improve subsoil nutrient recycling and moisture retention (Kumar & Nair, 2004) ^[31]. Long-term monitoring reveals progressive increases in organic carbon, reduced bulk density, improved infiltration, stabilized pH, and enhanced ecological resilience, demonstrating the sustainability of agroforestry systems (Jose, 2009) ^[26].

Digital Soil Mapping (DSM) Techniques and Analysis

Digital Soil Mapping (DSM) is a computer-assisted approach for predicting soil properties and classes by integrating quantitative models, geospatial data, environmental covariates, and field observations. Based on the SCORPAN framework (McBratney, Mendonça-Santos & Minasny, 2003) ^[42], DSM models soil as a function of soil, climate, organisms, relief, parent material, age,

and spatial position. By incorporating multi-source datasets - digital elevation models (DEM), satellite imagery, climate layers, land cover, and vegetation indices - DSM provides high-resolution, spatially explicit information on key soil attributes.

DSM enables precise mapping of soil physico-chemical properties such as pH, electrical conductivity, nitrogen (N), phosphorus (P), potassium (K), organic carbon (OC), bulk density, texture, moisture, infiltration, microbial biomass, and soil carbon stocks. These parameters are critical for assessing soil fertility, microbial activity, nutrient availability, and overall productivity in agroforestry systems. Environmental covariates are carefully selected using statistical methods like stepwise regression and variance inflation factor (VIF) analysis to capture topographic, climatic, and biological controls on soil formation. Geostatistical methods such as kriging, regression kriging, and co-kriging model the spatial variability of soil properties, while machine learning algorithms - including Random Forest, Gradient Boosting, Cubist, and Support Vector Machines - handle complex nonlinear soil - environment relationships. Model performance is validated using k-fold cross-validation, independent datasets, and accuracy metrics like R^2 , RMSE, and MAE, with uncertainty quantified through prediction intervals and ensemble variance propagation.

In agroforestry systems, DSM supports improved land - use planning, climate-smart tree -crop selection, mapping of nutrient - rich and degraded soils, prediction of soil organic carbon stocks, and assessment of root - zone moisture dynamics. By combining soil physico - chemical data with microbial indicators, DSM facilitates a better understanding of nutrient cycling, soil fertility enhancement, and productivity responses, ultimately guiding sustainable agroforestry design and management.

Soil Nutrient Assessment in Agroforestry Systems

Soil nutrient assessment is a systematic process of measuring and interpreting the availability and distribution of essential nutrients to evaluate soil fertility, diagnose constraints, and design site-specific nutrient-management strategies in agroforestry systems. Agroforestry alters soil nutrient dynamics through litterfall deposition, root turnover, nitrogen fixation, nutrient pumping from subsoil, and microbial activity, making nutrient assessment fundamental for monitoring system performance and guiding sustainable management (Sanchez *et al.*, 2003; Nair, 2012) ^[46].

Soil physico-chemical properties assessed include pH, electrical conductivity (EC), organic carbon (OC), and cation-exchange capacity (CEC), along with physical attributes such as bulk density, porosity, and soil moisture. These parameters regulate nutrient availability, root uptake, and microbial functioning (Brady & Weil, 2010; Young, 1997) ^[10, 86]. Macronutrients - nitrogen (N), phosphorus (P), and potassium (K) - are quantified using standardized laboratory methods, while micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) are analyzed through DTPA extraction. In agroforestry, leguminous trees enhance nitrogen availability through litter inputs (Palm *et al.*, 2001) ^[55], alley cropping systems improve phosphorus availability (Kang *et al.*, 1999), and tree canopies increase potassium and micronutrient retention (Jose, 2009; Schroth & Sinclair, 2003) ^[26].

Soil sampling strategies in agroforestry account for spatial heterogeneity by including tree-canopy zones, intercrop areas, and monocrop controls, often with depth-wise collections (0 - 15, 15 - 30, 30 - 60 cm). Geostatistical approaches capture landscape-level variability in nutrient distribution (McBratney *et*

et al., 2000) [42]. Laboratory analyses follow standardized procedures such as Walkley-Black for organic carbon, pH and EC measurements, Kjeldahl or alkaline methods for nitrogen, Olsen or Bray for phosphorus, flame photometry for potassium, and DTPA extraction for micronutrients. Interpreting results relies on established critical thresholds (ICAR, FAO, Landon, 1991; Sanchez, 2002) to inform balanced fertilizer application and nutrient management.

Agroforestry-driven nutrient dynamics include recycling via litterfall, deep-root nutrient retrieval (Ca, Mg, K), microbial decomposition enhancing N and P mineralization, and reduced nutrient leaching under tree cover (Muthuri *et al.*, 2005; Nair, 1993; Six *et al.*, 2006) [45, 71]. Soil nutrient assessment provides critical insights into soil fertility improvement, efficient fertilizer use, identification of constraints (acidity, salinity, compaction, nutrient deficiencies), and optimal tree - crop selection. Regular assessment enables comparison of baseline and post-intervention soil conditions, supporting enhanced productivity, improved tree growth, better benefit - cost ratios, and long-term sustainability of agroforestry systems.

Variability of Soil Nutrients and Environmental Safety in Agroforestry Systems: Soil nutrient variability refers to the spatial and temporal differences in the availability of essential macro- and micronutrients - including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu) as well as soil pH, organic carbon (OC), and electrical conductivity (EC). This variability arises from inherent soil-forming processes, vegetation patterns, agroforestry interventions, land-use history, and climatic fluctuations (Jenny, 1941) [25].

Spatial variability occurs both horizontally and vertically due to differences in parent material, topography, runoff, erosion intensity, and vegetation cover. In agroforestry systems, tree canopies create nutrient-rich microsites through litter deposition and root turnover, forming hotspots of N, P, K, and OC (Nambiar, 1990; Jose, 2009; Schroth & Sinclair, 2003) [26, 50]. Temporal variability is driven by seasonal changes in temperature, moisture, microbial activity, and litter decomposition, with nutrient mineralization peaking during warm and wet periods (Palm *et al.*, 2001; Bray *et al.*, 2000; Dossa *et al.*, 2008) [55].

Tree-crop interactions further influence nutrient distribution. Deep-rooted species access subsoil nutrients and redistribute them to topsoil via litterfall and root turnover (nutrient pumping), enhancing soil fertility and reducing nutrient losses (Muthuri *et al.*, 2005; Kang *et al.*, 1999; Nair, 2012) [46]. Soil microbial communities, enzymatic activity, root exudates, and mycorrhizal associations mediate nutrient availability, stabilize soil organic matter, and regulate N and P cycling (Six *et al.*, 2006; Cardoso *et al.*, 2013; Barea *et al.*, 2005) [4, 71]. Management practices - including fertilizer use, irrigation, tillage, and organic amendments also contribute to heterogeneous nutrient distribution (Zingore *et al.*, 2007; Sanchez, 2002).

Environmental safety in agroforestry relies on soil analysis to detect potential hazards such as heavy metals, pesticide residues, salinity, and sodicity, which can affect crop health, soil biodiversity, and groundwater quality. Heavy metals (Pb, Cd, Cr, Ni) can accumulate in plants and food chains (Alloway, 1995; Adriano, 2001), while pesticide residues may reduce microbial diversity and persist in soils (Pimentel *et al.*, 1992). Salinity and sodicity degrade soil structure, reduce infiltration, and increase ion toxicity, compromising productivity (Gupta &

Abrol, 1990) [18]. Tree-soil interactions in agroforestry can influence the vertical distribution of contaminants, making regular soil monitoring essential. Early detection of chemical and biological stressors through soil analysis ensures safe and sustainable agroforestry practices, protects ecosystem functions, and supports long-term productivity.

Conclusion

The comprehensive review of soil physico-chemical dynamics, nutrient variability, microbial diversity, and productivity responses in agroforestry systems highlights the integral role of trees in enhancing soil health, fertility, and ecosystem sustainability. Demonstrate that agroforestry improves soil structure, water retention, and nutrient availability, while emphasizes its strategic importance for site-specific tree-crop selection and sustainable land-use planning. Nutrient cycling and spatial-temporal variability are influenced by parent material, topography, and tree-crop interactions and understanding these dynamics is essential for precise nutrient management and productivity optimization. Microbial diversity and enzymatic activity. Play a critical role in nutrient transformation, soil organic carbon stabilization, and overall soil biological health. Enhanced microbial functions under tree canopies support sustainable agroecosystem functioning and resilience. Agroforestry interventions also contribute significantly to soil carbon sequestration and climate-change mitigation, as evidenced. Furthermore, integrating soil assessment data into land-use planning enables the identification of constraints such as acidity, salinity, nutrient deficiencies, and compaction, allowing for corrective measures. This evidence-based approach ensures long-term productivity, ecosystem service enhancement, and environmental sustainability. Collectively, the studies underline that agroforestry systems not only optimize crop and tree productivity but also maintain soil health, biodiversity, and ecological balance, providing a robust framework for climate-smart and sustainable agricultural development.

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