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Agroforestry and Soil Health under Climate Change: A Review of Biological, Chemical, and Physical Indicators

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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Abstract

Agroforestry systems — intentional combinations of trees with crops and/or livestock — are increasingly recognised as multifunctional land-use strategies capable of sustaining agricultural productivity whilst mitigating the adverse effects of climate change on soil health. Soils represent the foundational resource underpinning global food security, and their biological, chemical, and physical integrity is vital to ecosystem functioning. Under conditions of accelerating climate change, conventional agriculture has demonstrated measurable deterioration in soil health indicators, prompting renewed interest in tree-based farming systems. This review critically examines the current state of knowledge regarding how agroforestry influences biological indicators (microbial biomass, enzyme activity, and soil fauna diversity), chemical indicators (soil organic carbon, nutrient availability, pH, and cation exchange capacity), and physical indicators (bulk density, aggregate stability, and water retention) of soil health. The review further explores how changing temperature and precipitation regimes modulate these indicator dynamics within agroforestry contexts. Evidence synthesised from peer-reviewed literature consistently demonstrates that well-designed agroforestry systems enhance soil biological activity, increase soil organic carbon stocks, improve soil structural stability, and confer greater resilience to climate-related stressors than their monocultural counterparts. However, the

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magnitude and direction of these effects are highly context-dependent, varying with agroforestry type, climatic zone, tree species composition, and management intensity. The review identifies critical research gaps, including the need for long-term observational studies, standardised soil health measurement frameworks, and mechanistic understanding of climate–agroforestry–soil interactions across diverse biomes. A more integrated and holistic approach to soil health assessment, incorporating minimum data sets tailored to agroforestry contexts, is advocated for future research and policy development.

Keywords: Agroforestry; climate change; biological soil indicators; microbial diversity; carbon sequestration.

1. Introduction

Soil health is the sustained ability of soil to function as a vital ecosystem that supports plants, animals, and humans. Conventional agricultural practices, such as intensive tillage and monocropping, degrade soils by depleting organic matter, causing erosion, and reducing biodiversity. Agroforestry systems, by contrast, mimic natural ecosystems and offer a viable solution to restore and protect this crucial resource. Agroforestry helps smallholder farmers adapt to extreme climate change and enhance food security by integrating trees into their farming systems. This practice provides multiple benefits that address challenges like extreme weather, soil degradation, and unreliable food sources (Manono, B. O., & Mwami, 2026). As the foundation of agricultural productivity, soil provides essential nutrients, supports biodiversity, and regulates water dynamics. However, intensive farming practices, land degradation, and climate change pose significant threats to soil quality, increasing the urgency for innovative and sustainable management strategies (Omer et al., 2026).

1.1 Background and Context

Global agricultural systems face an unprecedented convergence of pressures. Rapid population growth, escalating demand for food and fibre, and increasing anthropogenic climate change collectively threaten the ecological foundations upon which sustainable agriculture depends (Tilman et al., 2002). At the centre of this challenge lies soil health — a construct that encompasses the continued capacity of soils to function as vital living systems, sustaining plant and animal productivity, maintaining environmental quality, and promoting plant and animal health (Doran & Zeiss, 2000; Karlen et al., 1997). Soils harbour a remarkable diversity of biological communities, serve as repositories of carbon and nutrients, and provide the structural matrix through which water and gases move to support terrestrial life. When these functions are compromised, the consequences extend far beyond the field boundary, affecting water quality, atmospheric composition, and biodiversity at landscape and global scales (Kopittke et al., 2019).

The degradation of soils under conventional agricultural management is well-documented. Intensive tillage, monoculture cropping, excessive synthetic fertiliser application, and the removal of vegetative cover have collectively contributed to declining soil organic matter, reduced microbial diversity, compromised aggregate stability, and increased susceptibility to erosion (Pimentel et al., 1995; Tilman et al., 2002). These dynamics are further exacerbated under climate change, with altered precipitation patterns, elevated temperatures, and increased frequency of extreme weather events accelerating soil carbon losses, disrupting microbial communities, and intensifying erosion risk (IPCC, 2022). The Intergovernmental Panel on Climate Change has identified land use and land management as both significant contributors to greenhouse gas emissions and as critical levers for climate mitigation and adaptation, emphasising the necessity of sustainable land management practices that simultaneously protect soils and sequester atmospheric carbon (IPCC, 2022).

Agroforestry — the deliberate integration of trees and shrubs with crops and/or livestock — has attracted considerable scientific and policy attention as a land-use strategy that can reconcile agricultural production with ecosystem service provision (Jose, 2009). Unlike monoculture systems, agroforestry creates structural and functional complexity within the landscape that may confer significant advantages for soil health. Tree components contribute organic matter through leaf litter, root turnover, and exudate deposition; modulate microclimate by reducing temperature extremes and evapotranspiration losses; and enhance nutrient cycling through deep root systems that access subsoil nutrient pools unavailable to shallow-rooted crops (Nair et al., 2009). These attributes position agroforestry as a promising platform for restoring and maintaining soil health under both current and projected future climatic conditions. The Food and Agriculture Organization of the

United Nations has underscored that healthy soils are foundational not only to food production but also to ecosystem services including water purification, carbon storage, and climate regulation (FAO, 2015).

Despite a growing body of evidence attesting to the soil health benefits of agroforestry, substantial gaps remain in the scientific understanding of the mechanisms underpinning these benefits, the conditions under which they are most pronounced, and the extent to which they are sustained under climate change. The three principal categories of soil health indicators — biological, chemical, and physical — have been investigated in isolation far more frequently than in an integrated manner, limiting the capacity to draw holistic conclusions about agroforestry's influence on soil functioning. Moreover, most studies have been conducted at relatively short timescales and in limited geographic contexts, constraining the generalisability of findings to the diversity of agroforestry systems and soil types encountered globally. The increasing recognition of agroforestry's multifunctional role in sustainable land management (Nair, 2011; Sayer et al., 2013) makes a comprehensive synthesis of its soil health effects particularly timely.

1.2 Scope and Objectives

This review synthesises peer-reviewed evidence on the relationships between agroforestry systems and soil health indicators across the biological, chemical, and physical domains, with particular attention to how climate change modulates these relationships. The specific objectives are: to characterise the principal agroforestry system types and their mechanisms of influence on soil health; to critically evaluate evidence pertaining to biological, chemical, and physical indicators of soil health in agroforestry contexts; to examine how climate change interacts with agroforestry–soil health dynamics; to assess frameworks for integrated soil health assessment applicable to agroforestry systems; and to identify key research gaps and priorities for future investigation. The review does not seek to conduct a formal meta-analysis or systematic review; rather, it provides a narrative synthesis of current knowledge intended to inform both the scientific community and policy practitioners engaged in sustainable land management and climate adaptation.

2. Methods for Literature Selection

This article adopts the approach of a narrative literature review, which is appropriate for the breadth and interdisciplinary nature of the topic under consideration. Unlike systematic reviews, which are typically employed to address narrow, well-defined empirical questions and adhere to strict pre-specified protocols for study inclusion and exclusion, narrative reviews permit broader thematic synthesis across diverse methodological traditions and disciplinary perspectives (Snyder, 2019). Given that the subject matter spans soil science, ecology, agronomy, and climatology, and that the objective is to provide an integrative conceptual understanding rather than to calculate pooled effect sizes, a narrative approach was judged most fit for purpose. The conduct of this review was informed by recognised guidance for structured narrative reviews applicable to multi-disciplinary environmental science contexts (Snyder, 2019).

Literature searches were conducted using multiple academic databases, including Web of Science, Scopus, Google Scholar, PubMed, AGRIS (the Food and Agriculture Organization's International Information System for the Agricultural Sciences and Technology), CAB Direct, JSTOR, and the Directory of Open Access Journals. These databases were supplemented by targeted searches of the repositories of key international organisations — including the Food and Agriculture Organization of the United Nations, the Intergovernmental Panel on Climate Change, and the World Bank — for relevant institutional reports of official provenance. Subject-specific databases pertinent to the review topic included AGRICOLA (the United States National Agricultural Library catalogue), the Agroforestry Research Trust literature database, the Tropical Agriculture Platform knowledge hub, the CIFOR–ICRAF Forests, Trees and Agroforestry knowledge base, and the CIMMYT e-Publications digital repository. These specialist resources were consulted to ensure comprehensive coverage of agroforestry and soil science literature not always indexed in generalist databases.

Search terms were constructed using Boolean logic to identify literature at the intersection of agroforestry and soil health. Core search strings included combinations such as: "agroforestry AND soil health", "agroforestry AND soil organic carbon", "agroforestry AND microbial diversity", "agroforestry AND soil biological indicators", "agroforestry AND soil physical properties", "agroforestry AND climate change", "tree-based farming AND soil quality", "silvopastoral AND soil carbon", and "alley cropping AND soil fertility". The primary date range for searches spanned 2000 to 2026, with the intention of capturing recent developments in the field. Classic studies published prior to 2000 were also incorporated where they provided essential conceptual grounding, particularly for soil health indicator frameworks and foundational agroforestry definitions.

Screening proceeded in two stages. In the first stage, titles and abstracts were assessed for relevance to the review objectives, and duplicates identified across databases were removed. In the second stage, full texts of retained papers were evaluated against the following inclusion criteria: publication in a peer-reviewed scientific journal, or — in the case of institutional reports — availability as an officially verifiable document from a recognised international organisation; direct relevance to at least one of the three principal soil health indicator categories (biological, chemical, physical) in an agroforestry or comparable land-use context; and availability in the English language. Studies published exclusively as conference proceedings, theses, book chapters, or in non-peer-reviewed outlets were excluded. The final reference set was additionally supplemented through backward citation tracking — examination of reference lists of retrieved papers — to ensure that particularly influential work was not overlooked. Studies were classified as "influential" where they had accumulated a high citation count within their respective subject domains and where their findings had been independently corroborated. No statistical weighting of evidence was applied, consistent with the narrative review framework.

3. Agroforestry: Concepts, Classifications, and Global Significance

3.1 Defining Agroforestry

Agroforestry may be defined as a collective name for land-use systems and technologies in which woody perennials — trees, shrubs, palms, bamboos, and related plants — are deliberately used on the same land management unit as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence (Torquebiau, 2000). This definition encompasses an extraordinary diversity of practices, ranging from homegardens in tropical Asia to silvopastoral systems in temperate Europe and alley cropping arrangements across sub-Saharan Africa. The deliberate character of agroforestry distinguishes it from accidental or incidental tree presence in agricultural fields; the integration is managed with the expectation of ecological and/or economic interactions between the woody and non-woody components (Jose, 2009). Agroforestry thus represents not merely a cropping system but an approach to landscape management that recognises trees as integral components of agricultural production rather than competitors to be eliminated.

The conceptual evolution of agroforestry as a distinct scientific discipline dates from the late 1970s, when formal recognition of its potential for combining productivity and environmental sustainability stimulated the establishment of dedicated research institutions and the development of a systematic knowledge base (Jose, 2009; Nair, 2011). Since that time, the scientific literature on agroforestry has expanded substantially, encompassing physiological, ecological, biogeochemical, and social dimensions of tree–crop–animal interactions. Despite this breadth, soil health — the condition of the soil as a living system — has arguably received less systematic attention than above-ground productivity in much of the earlier agroforestry literature, a gap that subsequent research has increasingly moved to address.

3.2 Classification of Agroforestry Systems

The classification of agroforestry systems has been approached from multiple perspectives, including the nature of the components (agrosilvicultural, silvopastoral, or agrosilvopastoral), the spatial arrangement of components (mixed, zonal, or boundary plantings), the temporal sequence of interactions (simultaneous or sequential), and the ecological zone in which the system operates (Torquebiau, 2000). Among the most widely practised agroforestry systems globally are alley cropping, in which trees are planted in rows between which crops are cultivated; silvopastoral systems, in which trees are integrated with grasslands and livestock; homegardens, characterised by dense, multi-species mixtures of trees and crops around human dwellings; and improved fallows, in which fast-growing trees or shrubs are planted during the fallow period to restore soil fertility before the next cropping cycle (Jose, 2009; Nair, 2011). Windbreak and shelterbelt systems, riparian buffer strips, and forest farming represent additional categories of considerable ecological significance.

Each system type creates a distinctive above- and below-ground structural environment that influences soil health through partially distinct mechanisms. Alley cropping systems, for example, generate periodic lateral inputs of pruned biomass that are incorporated into the inter-row cropping zones, providing a concentrated pulse of organic matter and nutrient inputs that differ qualitatively from the more diffuse and continuous inputs characteristic of homegardens. Silvopastoral systems introduce additional complexity through the effects of livestock grazing on soil compaction, dung deposition, and vegetation structure. Riparian buffer strips are subject to periodic inundation that creates anaerobic conditions conducive to denitrification and methane production, adding further nuance to any assessment of their net effects on soil biological processes. It is important, therefore, that assessments of agroforestry's soil health effects account explicitly for the diversity of system types rather than treating agroforestry as a homogeneous category.

3.3 Global Distribution and Importance

Agroforestry systems collectively occupy a substantial portion of the world's agricultural land. Zomer et al. (2016) estimated that approximately one billion hectares of agricultural land globally have at least ten per cent tree cover, with the proportion varying markedly by region. In sub-Saharan Africa, South and South-East Asia, and Latin America, agroforestry systems support the livelihoods of hundreds of millions of smallholder farmers and contribute substantially to household food security and income diversification (Kuyah et al., 2019). Beyond their productive functions, these systems deliver a suite of ecosystem services including carbon sequestration, watershed protection, biodiversity conservation, and soil health maintenance that have attracted increasing policy attention in the context of climate adaptation and mitigation (Sayer et al., 2013). The contribution of agroforestry to global carbon budgets has been estimated to be substantial, with tree biomass and soil carbon stocks on agricultural lands representing a significant and under-recognised component of terrestrial carbon cycling (Zomer et al., 2016). This growing recognition of agroforestry's multifunctional value has catalysed efforts to better understand and monitor its effects on soil health through robust and standardised indicator systems.

4. Biological Indicators of Soil Health in Agroforestry Systems

4.1 Microbial Biomass and Diversity

Soil biological activity is widely regarded as among the most sensitive and ecologically meaningful indicators of soil health, reflecting the integrated response of the soil community to changes in organic matter inputs, soil structure, and environmental conditions (Bardgett & van der Putten, 2014; Doran & Zeiss, 2000). Microbial biomass carbon (MBC) — the living component of soil organic matter represented by bacteria, fungi, and other microorganisms — serves as a dynamic measure of the size of the active microbial pool and is strongly responsive to changes in vegetation type and management (Lal, 2018). In agroforestry systems, microbial biomass tends to be substantially greater than in comparable monoculture systems, a pattern attributed to the greater continuity and diversity of organic matter inputs from tree litter, root turnover, and rhizodeposition (Muchane et al., 2020). The meta-analysis conducted by Muchane et al. (2020) across humid and sub-humid tropical systems found that agroforestry significantly enhanced microbial biomass carbon compared with monoculture controls, with the effect size increasing with system age, suggesting that the biological benefits of agroforestry accumulate progressively over time.

Microbial diversity — encompassing both species richness and functional diversity — is equally important from a soil health perspective, as ecologically diverse microbial communities are associated with greater functional redundancy, more robust nutrient cycling, and enhanced resistance and resilience to perturbation (Bardgett & van der Putten, 2014; Wardle et al., 2004). The structural heterogeneity characteristic of agroforestry systems, including variation in litter chemistry, rooting depth, microclimate, and substrate availability, creates a mosaic of microhabitats that supports greater microbial diversity than structurally simpler monocultures. Mycorrhizal fungi merit particular attention in this context; both arbuscular mycorrhizal and ectomycorrhizal associations are abundant in agroforestry soils and play critical roles in phosphorus acquisition, aggregate stabilisation, and the suppression of soil-borne pathogens (Wardle et al., 2004). The presence of diverse tree species in agroforestry systems is expected to support a greater diversity of mycorrhizal partners, with cascading benefits for soil nutrient cycling and structural integrity.

Advances in molecular ecology, including high-throughput sequencing of marker genes such as 16S rRNA for bacteria and ITS for fungi, have transformed the capacity to characterise soil microbial community composition in agroforestry and other land-use systems. Studies employing these methods have consistently reported higher alpha-diversity and greater evenness of microbial communities in agroforestry soils than in adjacent monoculture soils, particularly where the agroforestry systems involve multiple tree species and long-standing management (Bardgett & van der Putten, 2014). The functional implications of this diversity shift are significant: microbially diverse soils tend to exhibit more complete exploitation of available substrates, more efficient nutrient retention, and greater stability of biogeochemical cycling in the face of environmental perturbation. These characteristics translate directly into enhanced soil health, reduced nutrient leaching losses, and more sustained agricultural productivity under variable climatic conditions.

4.2 Soil Enzyme Activities

Soil enzyme activities represent functionally important biological indicators because enzymes mediate the biochemical transformations of organic matter that underpin nutrient cycling and carbon mineralisation. Key enzymes investigated in agroforestry contexts include urease (associated with nitrogen mineralisation from urea), phosphatase (catalysing the hydrolysis of organic phosphorus to plant-available inorganic phosphate), dehydrogenase (an index of overall microbial metabolic activity), and beta-glucosidase (involved in cellulose decomposition and carbon cycling). Evidence consistently indicates that agroforestry soils exhibit greater activities of these enzymes relative to monoculture soils, reflecting both the higher microbial biomass and the greater diversity of organic substrates available for enzymatic transformation (Muchane et al., 2020; Doran & Zeiss, 2000). The continuous input of chemically diverse leaf litter from multiple tree species in agroforestry systems contributes to the maintenance of enzyme activity even during periods of environmental stress, such as drought, when activity in monoculture systems may decline sharply.

Enzyme activities also provide temporally integrated information on soil biological functioning, as enzymes persist in the soil matrix for extended periods relative to the organisms that produce them. Lal (2018) emphasised that soil enzyme activity profiles can serve as early warning indicators of deterioration in soil health, potentially before changes in soil organic carbon or physical properties become detectable. In agroforestry systems, the sustained elevation of enzyme activities across seasons reflects the buffering capacity provided by the tree component, which moderates temperature and moisture fluctuations that would otherwise suppress microbial activity and enzyme production. This buffering effect is particularly relevant under climate change, as temperature and precipitation extremes become more frequent and severe (IPCC, 2022). The ratio of microbial biomass to total soil organic matter — the microbial quotient — represents an additional integrative indicator that is sensitive to changes in substrate quality and availability characteristic of transitions between monoculture and agroforestry management.

4.3 Soil Fauna Communities

The diversity and abundance of soil fauna — encompassing organisms spanning several orders of magnitude in body size, from protozoa and nematodes through mites and collembola to earthworms and termites — constitute a further critical dimension of soil biological health. Soil fauna perform essential ecosystem functions including litter fragmentation, bioturbation, decomposition regulation, and the physical redistribution of organic matter and mineral particles throughout the soil profile (Wardle et al., 2004). Earthworms, in particular, have long been recognised as ecosystem engineers whose burrowing and casting activities profoundly influence soil porosity, aggregate formation, and organic matter distribution. Studies in agroforestry systems have reported substantially greater earthworm density and biomass than in adjacent monoculture fields, attributable to the higher organic matter inputs and more favourable moisture and temperature conditions characteristic of tree-containing systems (Muchane et al., 2020).

The ecological linkages between above-ground plant diversity and below-ground faunal communities identified by Wardle et al. (2004) are particularly germane to agroforestry contexts. The diversity of plant species, litter types, and root architectures in agroforestry systems generates diverse niches and food web structures for soil fauna, sustaining communities that are both more diverse and more functionally complex than those found in monocultures. Nematode community indices — including the maturity index and the enrichment and structure indices derived from functional guild composition — have been used to characterise the state of soil food webs in agroforestry contexts, with evidence suggesting that more complex food webs, indicative of a more developed and stable soil ecosystem, occur under agroforestry management (Bardgett & van der Putten, 2014). Termites and ants, as additional important bioturbators, are particularly relevant in tropical agroforestry systems, where their nest construction and foraging activities can substantially alter soil physical properties including bulk density and macroporosity. These biological signals collectively argue for the routine inclusion of multiple fauna-based indicators alongside microbial metrics in any comprehensive assessment of soil health in agroforestry systems.

5. Chemical Indicators of Soil Health in Agroforestry Systems

5.1 Soil Organic Carbon and Organic Matter Fractions

Soil organic carbon (SOC) is arguably the most widely used single indicator of soil health, serving as a proxy for organic matter content, biological activity, nutrient supply capacity, and structural stability (Lehmann & Kleber, 2015; Lal, 2004). Globally, soils contain approximately three times more carbon than the atmosphere, and even modest increases in SOC stock have significant implications for atmospheric greenhouse gas concentrations (Minasny et al., 2017). The concept of "4 per mille" — proposed under the framework of the Paris Agreement — argues that an annual increase of 0.4 per cent in SOC stocks globally would be sufficient to offset current annual CO_2 emissions from fossil fuels, underscoring the centrality of SOC management to climate change mitigation strategies (Minasny et al., 2017).

Agroforestry systems are widely recognised for their capacity to maintain and augment SOC stocks relative to monoculture cropping systems, both in tropical and temperate contexts. The meta-analysis of Guo and Gifford (2002) demonstrated that land-use change from cropland to mixed systems including tree components consistently increased SOC stocks, with effects concentrated in surface horizons where litter inputs are greatest. Lorenz and Lal (2014) reviewed evidence from multiple continents and concluded that agroforestry systems accumulate significantly more SOC than adjacent monocultures, with the magnitude of accumulation dependent on tree species — particularly nitrogen-fixing species — stand age, climate, and soil texture. Oelbermann et al. (2004) provided comparative evidence from Costa Rica and Canada demonstrating that both tropical and temperate agroforestry systems sequester carbon in above- and below-ground pools, with below-ground stocks — including fine root biomass and rhizodeposits — often representing a substantial and underestimated fraction of total carbon sequestration. Nair et al. (2009) argued that agroforestry's capacity to channel photosynthetically fixed carbon into stable below-ground organic matter pools represents one of its most significant and enduring contributions to ecosystem carbon budgets.

The chemical character of soil organic matter is as important as its quantity. Lehmann and Kleber (2015) challenged the traditional view of soil organic matter as a defined set of compounds — humic acids, fulvic acids, and humins — and proposed instead that soil organic matter is a heterogeneous continuum of organic compounds of varying degrees of complexity, transformation, and mineral association. In agroforestry systems, the chemical diversity of organic inputs from multiple plant species is likely to produce a correspondingly diverse suite of organic matter compounds, with a proportion that is physically protected within aggregates or chemically stabilised through organo-mineral interactions, contributing to long-term carbon storage. The litter from leguminous tree species common in many agroforestry systems — such as Leucaena, Gliricidia, and Calliandra — is characteristically low in polyphenols and lignin relative to non-legume litter, promoting more rapid decomposition and nutrient release, while the roots of the same species contribute more recalcitrant organic compounds to subsoil carbon pools (FAO, 2015; Lorenz & Lal, 2014). The labile fractions of SOC — including particulate organic matter, dissolved organic carbon, and microbial biomass carbon — respond more rapidly to management change than total SOC and may serve as earlier indicators of agroforestry-induced soil health improvement, particularly in the first five to ten years following tree establishment.

5.2 Nutrient Availability and Cycling

Chemical indicators of soil nutrient status — encompassing total nitrogen, mineral nitrogen (ammonium and nitrate), available phosphorus, exchangeable cations (calcium, magnesium, potassium), and sulphur — provide critical information on the capacity of soils to supply plant nutritional requirements without recourse to external inputs. In agroforestry systems, nutrient cycling dynamics are strongly influenced by the presence of trees, which mediate biogeochemical processes through multiple pathways. Deep-rooted tree species can mine nutrients from subsoil horizons and return them to the surface through litterfall and root turnover, a process commonly described as the biogeochemical pump (Nair et al., 2009; Sanchez, 2002). This mechanism is particularly significant in highly weathered tropical soils, where surface nutrient depletion is a major constraint to agricultural productivity and where the capacity of tree roots to access subsoil nutrient pools may substantially alleviate surface nutrient limitation (Sanchez, 2002).

Nitrogen-fixing trees and shrubs integrated into agroforestry systems provide additional nitrogen inputs through biological nitrogen fixation, potentially reducing or replacing synthetic nitrogen fertiliser requirements (Jose, 2009; Nair, 2011). The magnitude of biological nitrogen fixation in agroforestry systems is highly variable, ranging from a few kilograms per hectare per year in less productive systems to more than 200 kg N ha^{-1} yr^{-1} in intensively managed alley cropping configurations with highly productive leguminous species. Phosphorus cycling in agroforestry systems is mediated by mycorrhizal fungi, phosphatase enzyme activity, and the exudation of organic acids and protons from tree roots that solubilise mineral phosphorus, all of which tend to be more active in agroforestry than in monoculture soils (Muchane et al., 2020; Wardle et al., 2004). The net effect of these processes is to maintain higher concentrations of plant-available nutrients, particularly nitrogen and phosphorus, in agroforestry soils relative to monoculture soils, reducing the risk of nutrient deficiency and supporting higher and more sustained crop productivity under varying climate conditions.

The stoichiometric relationships among carbon, nitrogen, and phosphorus in soil organic matter — expressed as the C:N, C:P, and N:P ratios — provide additional chemical indicators of soil health and microbial community functioning. In agroforestry systems, the incorporation of leguminous residues with low C:N ratios alongside woody litter with high C:N ratios tends to produce a more balanced stoichiometric environment for microbial mineralisation than monoculture residue inputs dominated by a single crop species. This balance is important for avoiding the nitrogen immobilisation that can occur when crop residues with very high C:N ratios are incorporated, temporarily suppressing plant-available nitrogen and reducing crop yields. The chemical diversity of litter inputs in agroforestry thus serves as a buffer against the extremes of nutrient immobilisation and leaching loss that can characterise monoculture systems, particularly under the heavy rainfall events projected to become more frequent under climate change (IPCC, 2022; Kopittke et al., 2019).

5.3 Soil Reaction, Cation Exchange Capacity, and Electrical Conductivity

Soil pH is a master variable governing the solubility and availability of mineral nutrients, the speciation of toxic elements such as aluminium and manganese, and the composition and activity of the soil microbial community. Agroforestry systems tend to buffer soil pH within ranges more favourable for crop growth and microbial activity than conventional monocultures, particularly in systems where leguminous trees release organic acids through root exudation and litter decomposition (Nair et al., 2009). Where acidic soils are ameliorated through liming, the presence of trees may help sustain the liming effect over longer periods by increasing the buffering capacity of the soil through additions of organic matter. Conversely, in semi-arid systems where secondary salinisation is a concern, certain agroforestry configurations that promote deep drainage may help prevent the capillary rise of salts that drives soil degradation (FAO, 2015).

Cation exchange capacity (CEC) — the ability of soils to retain and exchange cations — is strongly correlated with organic matter content and clay mineralogy. Because agroforestry systems generally accumulate greater quantities of soil organic matter than monocultures, their soils tend to exhibit higher CEC, enhancing their capacity to retain nutrient cations against leaching and to provide a sustained supply of nutrients to plant roots (Lorenz & Lal, 2014). This relationship is particularly important in coarse-textured or sandy soils, where CEC is primarily determined by organic matter rather than clay content, and where agroforestry-induced increases in organic matter may substantially improve the agronomic and environmental performance of soils. The percentage base saturation — the proportion of CEC occupied by basic cations (calcium, magnesium, potassium, and sodium) as opposed to acidic cations (hydrogen and aluminium) — represents a related chemical indicator of relevance in tropical soils where nutrient-poor conditions are commonplace. Electrical conductivity, as an indicator of soluble salt content, remains a relevant soil health metric in irrigated agroforestry systems where the risk of secondary salinisation requires active monitoring (FAO, 2015; Kopittke et al., 2019).

6. Physical Indicators of Soil Health in Agroforestry Systems

6.1 Bulk Density and Porosity

Soil bulk density — the mass of dry soil per unit total volume — provides a fundamental measure of soil compaction, pore space, and structural condition. High bulk density reflects a dense, poorly aerated soil structure that impedes root penetration, reduces water infiltration, and limits gas exchange between the soil and atmosphere (Bronick & Lal, 2005). In agricultural soils, bulk density is elevated by the compressive effects of heavy machinery, tillage-induced structural breakdown, and the loss of organic matter that would otherwise maintain an open, porous soil fabric. Agroforestry systems consistently exhibit lower bulk density values than adjacent monoculture or degraded soils, a pattern reflecting the cumulative effects of higher organic matter inputs, root biopore formation, and faunal bioturbation (Muchane et al., 2020; Bronick & Lal, 2005).

Tree roots in agroforestry systems create macropores — large soil channels that persist after root death and decay — providing pathways for preferential water flow, gas exchange, and root elongation into otherwise compact subsoil horizons (Bronick & Lal, 2005). The reduction in bulk density associated with agroforestry is not always uniform with depth; the most pronounced effects are often observed in the surface horizons where organic matter accumulation is greatest, but deeper effects are measurable in systems with deep-rooted tree species. Total porosity — the complement of bulk density expressed relative to particle density — responds accordingly, with higher porosity in agroforestry soils enabling greater water storage and improved aeration, both of which are critical for maintaining microbial activity and plant growth under both ambient and drought conditions. In systems where the canopy closure of trees reduces the surface impact of heavy rainfall, compaction of the soil surface layer is further diminished, contributing to the sustained low bulk density characteristic of mature agroforestry soils (IPCC, 2022).

6.2 Soil Aggregate Stability and Structural Integrity

Soil aggregate stability — the resistance of soil aggregates to disruption by water and mechanical forces — is a comprehensive physical indicator of soil structural health, integrating the effects of organic matter content, biological activity, clay mineralogy, and root and hyphal networks on the cohesion of soil particles (Bronick & Lal, 2005). Macro-aggregates (greater than 250 μm diameter) and micro-aggregates (less than 250 μm) differ in their mechanisms of formation and their sensitivity to management: macro-aggregates are formed and stabilised primarily by biological agents including fungal hyphae, roots, and earthworm casts, whilst micro-aggregates are stabilised by stronger organo-mineral associations and are consequently more persistent in the face of disturbance (Lehmann & Kleber, 2015; Bronick & Lal, 2005). The proportion of water-stable aggregates — those that do not disintegrate upon immersion in water — is among the most diagnostically useful physical indicators of soil health because it reflects the integration of biological, chemical, and physical determinants of soil structure.

Agroforestry systems promote aggregate stability through multiple reinforcing mechanisms. The mycorrhizal fungal networks that proliferate in the rhizospheres of tree roots produce glomalin-related soil proteins — glycoproteins that act as soil cements, binding mineral particles and organic fragments into water-stable aggregates (Wardle et al., 2004). The elevated earthworm populations characteristic of agroforestry soils contribute further to aggregate formation through the mixing and encapsulation of organic matter with mineral soil in earthworm casts, producing highly stable organo-mineral aggregates of extended persistence (Muchane et al., 2020). The net effect of these biological processes, reinforced by the chemical contribution of increased organic matter, is a soil with greater water-stable aggregate content, lower susceptibility to surface sealing and crusting, and greater resistance to water and wind erosion — all of which are increasingly important under the higher rainfall intensity events projected under climate change (IPCC, 2022; Pimentel et al., 1995). Improved aggregate stability also indirectly protects soil organic carbon through physical occlusion of organic matter within aggregates, thereby reducing its accessibility to decomposer organisms and extending its residence time in the soil (Lehmann & Kleber, 2015).

6.3 Water Retention, Infiltration, and Hydraulic Conductivity

The capacity of soils to store and transmit water is fundamental to agricultural productivity, particularly under conditions of irregular or reduced rainfall. Water retention — quantified across the soil moisture characteristic curve from saturation to wilting point — is positively influenced by soil organic matter, which increases both total porosity and the proportion of fine pores that retain water against gravitational drainage (Bronick & Lal, 2005). Infiltration rate — the rate at which water enters the soil surface — is critically important for determining how much precipitation is captured by the soil versus lost as surface runoff, and it is strongly influenced by aggregate stability, surface roughness, and the presence of macropores. Agroforestry soils, with their higher aggregate stability, greater macroporosity, and more persistent surface litter layers, typically exhibit substantially higher infiltration rates than comparable monoculture or bare soils, enabling greater capture of rainfall and reduced surface runoff and erosion (Kopittke et al., 2019; Pimentel et al., 1995).

Saturated hydraulic conductivity — a measure of how rapidly water moves through a saturated soil — is enhanced in agroforestry soils through the macropore networks created by tree roots and soil fauna. This has implications not only for water availability to crops during dry periods but also for the capacity of soils to drain rapidly following heavy precipitation events, reducing the risk of waterlogging that damages crop roots and stimulates denitrification losses of soil nitrogen. Poeplau and Don (2015) demonstrated in their meta-analysis that increases in organic carbon in agricultural soils are associated with improved water storage capacity — a finding of direct relevance to agroforestry systems where organic carbon accumulation is a primary mechanism of soil health improvement. Plant-available water capacity — the water held between field capacity and permanent wilting point — increases with organic matter content in sandy soils, meaning that agroforestry-induced SOC accumulation directly augments the water reserve available to crops during inter-rainfall dry periods. Under conditions of climate change, where both drought frequency and extreme precipitation events are projected to increase (IPCC, 2022), the superior water management properties of agroforestry soils represent a critical adaptive advantage that is likely to become increasingly valued by farmers and land managers worldwide.

7. Climate Change Interactions with Agroforestry and Soil Health

7.1 Temperature-Mediated Shifts in Soil Processes

Rising mean temperatures and the increased frequency of heat extremes associated with anthropogenic climate change exert complex and often contradictory effects on soil biological, chemical, and physical processes. At the microbial level, elevated temperatures accelerate decomposition rates and enzyme kinetics in the short term, potentially stimulating nutrient mineralisation but also increasing soil respiration and the loss of soil organic carbon to the atmosphere as CO_2 (Lal, 2018). Over longer timescales, however, the thermal sensitivity of soil organic matter decomposition is modulated by the chemical recalcitrance of organic compounds, their physical protection within aggregates, and the temperature sensitivity of the microbial community itself, creating non-linear and context-dependent responses (Lehmann & Kleber, 2015). Higher temperatures may also shift the competitive balance among soil microbial taxa, altering community composition in ways that affect nutrient cycling stoichiometry and the relative proportions of carbon stabilised in organo-mineral associations versus mineralised to CO_2 (Bardgett & van der Putten, 2014).

In agroforestry systems, the tree canopy plays a crucial moderating role with respect to temperature effects on soils. Shade provision beneath tree canopies reduces soil surface temperatures, dampening the extremes of diurnal and seasonal temperature fluctuation experienced by the soil microbial community (Jose, 2009; Muchane et al., 2020). This thermal buffering is expected to become increasingly valuable under climate change, as more frequent and severe heat events threaten to suppress microbial activity and accelerate organic matter decomposition in unshaded agricultural soils. Zhao et al. (2017) demonstrated that even modest temperature increases significantly reduce global crop yields, underscoring the importance of thermal management strategies — including tree-based shading — in agricultural systems. Agroforestry's capacity to modulate soil temperature may thus partially compensate for the direct thermal stress on soil biological processes imposed by rising ambient temperatures, sustaining microbial community functioning and associated soil health services under conditions that would otherwise lead to their deterioration.

7.2 Precipitation Variability and Soil Moisture Dynamics

Climate change projections consistently indicate that precipitation regimes will become more variable, with more intense rainfall events interspersed with longer dry periods across many of the world's agricultural regions (IPCC, 2022). These changes have profound implications for soil health, as soil moisture is a primary regulator of virtually all soil biological and chemical processes. Drought stress suppresses microbial activity, reduces nutrient mineralisation, and can cause irreversible changes in microbial community composition; conversely, intense rainfall events on exposed or structurally degraded soils provoke surface sealing, runoff, and erosion that remove the biologically active topsoil horizon responsible for the majority of nutrient cycling and organic matter decomposition (Pimentel et al., 1995; Kopittke et al., 2019).

The multi-layered canopy structure of agroforestry systems modulates the hydrological cycle at multiple scales. Interception of rainfall by tree canopies reduces the kinetic energy of precipitation reaching the soil surface, diminishing the detachment and splash erosion of soil particles (Bronick & Lal, 2005). Soil infiltration capacity, enhanced by macropore networks and aggregate stability as described in the preceding section, increases the proportion of rainfall that enters the soil profile rather than running off the surface. During dry periods, tree roots accessing deep soil water reserves and contributing continuous litter inputs to the soil surface maintain sufficient moisture in surface horizons to sustain microbial communities through drought events that would effectively suppress biological activity in bare or thinly vegetated monoculture soils (Nair et al., 2009). The capacity of agroforestry to maintain more stable soil moisture conditions — neither too dry nor waterlogged — represents one of its most important contributions to soil health resilience in the face of precipitation variability.

7.3 Carbon Sequestration and Greenhouse Gas Mitigation Potential

Among agroforestry's most globally significant contributions to climate change mitigation is its potential for carbon sequestration in both above- and below-ground biomass and in the soil organic matter pool. Nair et al. (2009) estimated that agroforestry systems globally could sequester between 1.1 and 2.2 Pg C over the following 50 years if adopted at scale on degraded agricultural and marginal lands, representing a meaningful contribution to atmospheric carbon drawdown. Lorenz and Lal (2014) synthesised evidence suggesting that the transition from monoculture cropping to agroforestry can increase SOC stocks by between 25 and 50 per cent over decadal timescales, though the rate and magnitude of accumulation are strongly dependent on site-specific conditions. Schoeneberger (2009) similarly argued that agroforestry represents one of the most practical and cost-effective land management strategies for sequestering carbon on working agricultural lands, with co-benefits for soil health, water quality, and biodiversity that enhance its overall value as a climate response strategy.

At the global scale, the analyses of Griscom et al. (2017) on natural climate solutions identified improved land stewardship — including agroforestry — as capable of providing up to 11.3 Pg CO_2-equivalent per year of cost-effective mitigation by 2030, representing a substantial proportion of the mitigation needed to keep global warming below 2°C. Bossio et al. (2020) further emphasised the role of soil carbon in natural climate solutions, arguing that soils represent the most underestimated component of the terrestrial carbon sink and that improved management of agricultural soils — with agroforestry as a leading strategy — could significantly expand global SOC stocks. The potential of cover crops as a complementary practice to agroforestry in carbon sequestration was demonstrated by Poeplau and Don (2015), whose meta-analysis found that cover crops increased SOC by an average of 0.32 Mg C ha^{-1} yr^{-1}, suggesting that combined use of agroforestry and cover crops could deliver synergistic carbon storage benefits. Smith et al. (2008) placed agroforestry within the broader landscape of greenhouse gas mitigation options for agriculture, noting its particular advantage in delivering mitigation simultaneously with adaptation, unlike many single-objective mitigation strategies that may compromise food security or ecosystem services. Lal (2004) established the foundational relationship between SOC sequestration and both global climate change mitigation and food security, a conceptual framework that remains central to understanding the value of agroforestry in the current climate context.

Despite this substantial evidence, the greenhouse gas accounting of agroforestry systems must also consider potential trade-offs. Some studies have reported elevated nitrous oxide emissions from highly fertile agroforestry soils, particularly those containing nitrogen-fixing species that contribute to elevated soil mineral nitrogen concentrations (Smith et al., 2008). Powlson et al. (2014) cautioned that the carbon sequestration potential of agricultural management changes, including those involving trees, can be overestimated if measurement protocols do not account for the full soil profile, spatial heterogeneity, and displacement of emissions to other land areas. These caveats notwithstanding, the weight of evidence supports agroforestry as a net contributor to climate change mitigation through soil carbon sequestration and biomass accumulation, particularly when implemented on degraded soils where the potential for carbon gain is greatest (Minasny et al., 2017; Lal, 2004). Global analyses of tree cover on agricultural lands, such as that of Zomer et al. (2016), underscore the scale of the potential contribution of existing and expanded agroforestry to national and global carbon budgets.

7.4 Resilience and Adaptive Capacity of Agroforestry Soils

The concept of soil health encompasses not only the current state of soil properties but also the capacity of the soil system to resist and recover from perturbation — its resilience in the face of stress. Climate change, with its attendant increases in temperature variability, precipitation extremes, and the likelihood of multi-year drought events, represents one of the most significant threats to agricultural soil resilience (IPCC, 2022). Agroforestry systems, by virtue of their structural complexity, higher organic matter stocks, and diverse biological communities, are expected to exhibit greater resilience than monoculture systems to these climate-imposed stressors.

The functional redundancy inherent in diverse microbial and faunal communities means that the loss of particular taxa to climate-driven perturbation is less likely to result in the collapse of critical ecosystem functions — such as decomposition and nutrient cycling — in agroforestry soils than in more species-poor monoculture soils (Bardgett & van der Putten, 2014). Higher SOC stocks serve as a buffer against the rapid depletion of soil nutrients during drought, maintaining a pool of slowly mineralising organic matter that sustains plant productivity and microbial activity even when fresh organic inputs are reduced (Lal, 2018). The physical characteristics of agroforestry soils — lower bulk density, higher aggregate stability, greater infiltration capacity — collectively contribute to a more resilient hydraulic system that moderates the effects of both drought and intense precipitation events. Kuyah et al. (2019) demonstrated across a meta-analysis of sub-Saharan African agroforestry systems that agroforestry delivered consistent ecosystem service benefits, including soil health maintenance, across a range of climatic and edaphic conditions, suggesting that its resilience-building attributes are robust rather than narrowly site-specific.

8. Integrated Soil Health Assessment Frameworks

The development of coherent frameworks for assessing soil health in agroforestry systems requires the selection of indicators that are sensitive to management-induced change, measurable with accessible and cost-effective methods, interpretable across a range of soil types and climatic contexts, and relevant to both the productive and ecological functions of soils. Karlen et al. (1997) proposed a foundational soil quality scoring approach in which indicators are selected based on their relevance to key soil functions — sustaining biological productivity, regulating and partitioning water and solute flow, filtering and buffering against pollutants, and cycling nutrients and energy — and their scores aggregated into a composite index. This framework has been widely applied and adapted in subsequent soil health assessment literature and provides a useful conceptual scaffold for agroforestry contexts (Doran & Zeiss, 2000).

The concept of a minimum data set (MDS) — a parsimonious but comprehensive suite of indicators sufficient to characterise the essential dimensions of soil health — has been advocated as a practical approach to soil health monitoring that is feasible for implementation at scale (Karlen et al., 1997). For agroforestry systems, an appropriate MDS would likely include at minimum: a biological indicator such as microbial biomass carbon or basal soil respiration; a chemical indicator such as total soil organic carbon and available nutrient concentrations; and physical indicators including bulk density, aggregate stability, and saturated hydraulic conductivity. The inclusion of multiple indicators from across the biological, chemical, and physical domains is essential because no single indicator is sufficient to characterise the multidimensional nature of soil health, and because changes in different indicator categories may not co-vary under all conditions of management change (Doran & Zeiss, 2000; Kopittke et al., 2019). The appropriate weighting of individual indicators within composite indices may also need to be adjusted to reflect the specific land-use functions and management objectives of different agroforestry systems.

Remote sensing and spatial modelling approaches offer promising complements to field-based indicator measurement for monitoring soil health across large agroforestry landscapes. Vagen and Winowiecki (2013) demonstrated the feasibility of spatially explicit SOC stock mapping as a tool for assessing climate change mitigation potential, and similar approaches could be extended to integrate additional soil health indicators accessible via proximal and remote sensing technologies. The integration of soil health assessments with ecosystem service valuation frameworks, as advocated by Sayer et al. (2013) in their landscape approach to sustainable land management, would further enable the trade-offs and synergies between agroforestry and other land uses to be evaluated comprehensively. Standardisation of measurement protocols across sites and studies remains a critical bottleneck; without such standardisation, the comparability of soil health data across the global diversity of agroforestry systems is severely limited, and the evidence base for policy development correspondingly weakened (Kopittke et al., 2019; FAO, 2015).

9. Research Gaps and Future Directions

Despite considerable advances in understanding agroforestry's effects on soil health indicators, several important gaps remain that constrain the development of evidence-based recommendations for policy and practice.

Perhaps the most significant is the relative scarcity of long-term observational and experimental studies that track the temporal trajectory of soil health indicator changes from the establishment of agroforestry systems through maturity and beyond. Most published studies are cross-sectional, comparing agroforestry and monoculture soils at a single point in time and inferring temporal dynamics from space-for-time substitution. Whilst this approach can be informative, it cannot capture the dynamic interactions between biological, chemical, and physical soil properties as they evolve over decades, particularly under changing climatic conditions (Lal, 2018; Minasny et al., 2017). The establishment and maintenance of replicated long-term agroforestry soil health monitoring sites across representative biomes represents an urgent research priority.

The mechanistic understanding of how specific tree species and agroforestry configurations affect individual soil health indicators and their interactions remains insufficiently developed. Most studies have treated agroforestry as a generalised category rather than distinguishing among system types, tree species, management intensities, and spatial arrangements that may produce substantially different soil health outcomes. Greater investment in mechanistic studies that link specific biological processes — such as mycorrhizal network formation, litter decomposition stoichiometry, and root exudate chemistry — to changes in chemical and physical soil properties would substantially advance predictive capacity (Bardgett & van der Putten, 2014; Wardle et al., 2004). Similarly, the effects of climate change on agroforestry–soil interactions have been studied predominantly through observational approaches; experimental studies that manipulate temperature, precipitation, and elevated CO_2 in agroforestry contexts are urgently needed to separate the effects of individual climate drivers and to validate predictive models (IPCC, 2022).

Considerable geographic and socio-economic bias persists in the agroforestry soil health literature, with tropical systems in sub-Saharan Africa, South and South-East Asia, and Latin America receiving disproportionate attention relative to temperate and boreal systems. Smallholder agroforestry has received more attention than commercial-scale systems, and humid systems are better represented than dryland or semi-arid systems. The soil health dynamics of agroforestry in temperate Europe, North America, and East Asia under changing climate conditions represent a significant knowledge gap. Furthermore, the potential negative effects of agroforestry on soil health — including competition for water and nutrients between trees and crops in resource-limited environments, potential allelopathic effects of certain tree species, and the risk of elevated nitrous oxide emissions in highly productive nitrogen-fixing systems — deserve greater systematic attention than they have received in a literature that has sometimes been overly affirmative of agroforestry's benefits (Smith et al., 2008; Powlson et al., 2014). A more balanced appraisal of both the opportunities and limitations of agroforestry for soil health improvement across diverse contexts is necessary for the formulation of credible policy recommendations.

Advances in molecular ecology, including high-throughput DNA sequencing of soil microbial communities, metatranscriptomics, and stable isotope probing of microbial activity, offer transformative opportunities for understanding the biological dimension of soil health in agroforestry systems at unprecedented resolution and functional depth. Similarly, improvements in soil carbon measurement technology — including near-infrared spectroscopy, mid-infrared spectroscopy, and X-ray computed tomography of soil structure — are enabling more efficient, cost-effective, and spatially resolved characterisation of soil chemical and physical properties (Vagen & Winowiecki, 2013). The integration of these technological advances with long-term field experiments, remote sensing, and data-driven modelling approaches represents the most promising frontier for advancing agroforestry soil health science in the coming decades.

10. Conclusions

This review has synthesised evidence from a broad range of peer-reviewed literature to examine how agroforestry systems influence biological, chemical, and physical indicators of soil health, and how these relationships are modulated by climate change. The evidence is consistent in demonstrating that well-designed agroforestry systems confer substantial soil health benefits across all three indicator domains. Biologically, agroforestry enhances microbial biomass, promotes microbial diversity, elevates soil enzyme activities, and supports diverse and functionally complex soil faunal communities. Chemically, agroforestry increases soil organic carbon stocks, improves nutrient availability and cycling, buffers soil pH within favourable ranges, and enhances cation exchange capacity. Physically, agroforestry reduces bulk density, promotes aggregate stability, and improves water infiltration and retention capacity. These effects are not independent but are deeply interconnected, with biological processes driving chemical transformations that in turn influence physical properties through mechanisms of aggregate formation and organic matter stabilisation.

Under the conditions of accelerating climate change, these soil health benefits of agroforestry assume heightened significance. The thermal and hydrological buffering provided by tree canopies moderates the stress imposed by rising temperatures and precipitation variability on soil microbial communities. The greater organic carbon stocks of agroforestry soils confer resilience against drought-induced carbon losses and maintain soil biological activity through periods of environmental stress. The carbon sequestration potential of agroforestry represents a meaningful contribution to climate change mitigation that operates synergistically with the adaptation benefits of improved soil health and sustained agricultural productivity.

Policy instruments that incentivise the adoption of agroforestry as a component of sustainable land management strategies must be grounded in a realistic understanding of both the potential and the limitations of tree-based farming systems. Blanket prescriptions for agroforestry as a universal solution to soil degradation and climate change vulnerability would be both scientifically unjustified and practically counterproductive; rather, site-specific assessment of soil type, climate, tree species selection, and management objectives is essential to designing agroforestry systems that deliver the soil health benefits described in this review. Continued investment in long-term, mechanistically informed, and geographically diverse research is necessary to consolidate and extend the evidence base, close the identified knowledge gaps, and provide the scientific foundation for informed and effective land management decisions.

11. Limitations

This review is subject to a number of limitations that should be considered when interpreting its conclusions. As a narrative literature review, it is inherently susceptible to subjective judgements in the selection and interpretation of evidence, and it does not apply the stringent, pre-specified protocols for study inclusion and exclusion that characterise systematic reviews or meta-analyses. The possibility of confirmation bias — in which studies reporting beneficial effects of agroforestry on soil health are more frequently published and more prominently retrieved in literature searches than null or negative findings — cannot be eliminated and may influence the overall impression conveyed by the synthesis. The publication bias towards positive findings in agricultural and ecological sciences is a well-recognised problem that likely affects the evidence base presented in this review.

The exclusion of literature published in languages other than English represents a potential source of geographic bias, as important contributions from regions where agroforestry is widely practised — including parts of West Africa, Latin America, and South-East Asia — may be published predominantly in French, Spanish, Portuguese, or other languages. The quality and methodological rigour of individual studies included in the review are heterogeneous. Studies vary widely in the duration of observation, the breadth of indicators measured, the design of control treatments, and the degree to which potentially confounding factors such as soil type, climate, and prior land use have been accounted for. This heterogeneity limits the confidence with which general conclusions can be drawn from the synthesised evidence.

Furthermore, this review focuses primarily on soil health outcomes at the field scale and does not systematically address landscape-scale interactions, trade-offs with other land uses, or the socio-economic dimensions of agroforestry adoption — all of which are pertinent to the translation of soil health science into policy and practice. Future reviews incorporating quantitative meta-analysis where the primary literature permits, greater geographic scope including under-represented regions and climate zones, and explicit treatment of potential negative effects and trade-offs would complement and extend the present narrative synthesis.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Author has declared that no competing interests exist.

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