

Agroforestry Practices and Their Impact on Soil Health and Fertility : A Review

Abstract

The diverse applications and benefits of agroforestry, emphasizing its critical role in enhancing soil health and fertility. Agroforestry, the integration of trees, crops, and livestock within the same land management system, presents numerous advantages. These include improved soil structure, enhanced nutrient cycling, and increased carbon sequestration, contributing to overall ecosystem sustainability and resilience against climate change. Agroforestry systems have been shown to improve soil physical properties by enhancing soil structure and porosity, reducing erosion, and increasing water infiltration and retention. Furthermore, these systems boost soil chemical properties through increased organic matter, enhanced nutrient status and cycling, and favorable changes in soil pH and cation exchange capacity. Key findings from various case studies across tropical, temperate, and arid regions demonstrate the multifunctionality of agroforestry systems. For instance, in the Sahel region of Africa, the integration of *Faidherbia albida* significantly improved soil fertility and increased crop yields. Similarly, in the temperate regions of the United States, alley cropping with black walnut and corn improved soil structure and provided additional income through timber production. In arid regions like the Thar Desert of India, *Prosopis*-based agroforestry systems enhanced soil organic carbon and nutrient levels, leading to higher crop yields. Despite these benefits, the adoption of agroforestry practices faces significant challenges. Socio-economic barriers, such as the initial investment costs and land tenure insecurity, hinder widespread adoption. Additionally, a lack of knowledge and training among farmers and insufficient policy and institutional support further impede the implementation of agroforestry. Potential negative impacts, such as competition between trees and crops for resources, allelopathic effects, and management complexity, also need to be addressed through careful planning and management. Emerging trends in agroforestry research focus on integrating climate-smart agriculture principles and exploring the multifunctionality of these systems. Innovations such as precision agroforestry, biochar application, and the development of agroforestry-based bioproducts show promise in enhancing system efficiency and sustainability. However, research gaps remain, particularly in understanding the long-term impacts on soil health, the socio-economic benefits, and the integration of modern technologies. Addressing these gaps requires comprehensive, multidisciplinary approaches to fully realize the potential of agroforestry as a sustainable land management strategy.

Keywords: *Agroforestry, Soil health, Nutrient cycling, Carbon sequestration, Climate resilience*

1. Introduction

A. Definition and Scope of Agroforestry

Agroforestry is a sustainable land management practice that integrates trees and shrubs into agricultural landscapes. This system combines agricultural and forestry technologies to create more diverse, productive, profitable, healthy, and sustainable land-use systems. Agroforestry is characterized by the deliberate integration of trees with crops and/or livestock, which leads to multiple interactions and benefits from the different components of the system [1]. The primary types of agroforestry systems include agrisilviculture (combining trees and crops), silvopasture (integrating trees and livestock), agrosilvopasture (combining trees, crops, and livestock), alley cropping (growing crops between rows of

trees), windbreaks and shelterbelts (using trees to protect crops and livestock), and home gardens (diverse plantings around homes). The scope of agroforestry extends beyond simple tree planting; it encompasses a variety of practices adaptable to local environmental and socio-economic conditions. This flexibility makes agroforestry suitable for various climatic regions, including tropical, temperate, and arid zones. The integration of trees into agricultural landscapes can enhance biodiversity, improve water management, increase soil fertility, and provide economic benefits through the production of timber, fruit, fodder, and other non-timber forest products [2].

B. Importance of Soil Health and Fertility in Sustainable Agriculture

Soil health and fertility are crucial for sustainable agriculture as they directly affect plant growth, crop yields, and ecosystem stability. Soil health refers to the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Key indicators of soil health include soil structure, organic matter content, nutrient availability, and biological activity. Healthy soils support plant growth, regulate water supply, and filter pollutants, thereby maintaining ecological balance [3]. Soil fertility, a subset of soil health, pertains to the soil's ability to supply essential nutrients to plants in adequate amounts and proportions for growth. Fertile soils are rich in macronutrients (nitrogen, phosphorus, potassium) and micronutrients (zinc, copper, iron), which are vital for plant development. Maintaining soil fertility is essential for long-term agricultural productivity and sustainability. Practices that enhance soil fertility include organic matter addition, crop rotation, cover cropping, and the integration of agroforestry systems [4].

C. Objectives of the Review

The primary objectives of this review are to Examine the various agroforestry practices and their implementation across different regions. Analyze the impact of agroforestry on soil health and fertility. Identify the mechanisms through which agroforestry practices influence soil properties. Highlight successful case studies and regional variations in agroforestry practices. Discuss the challenges and limitations associated with agroforestry implementation. Explore future prospects and research needs in the field of agroforestry.

2. Background

A. History on Agroforestry

Agroforestry, though considered a modern practice by many, has its roots deeply embedded in ancient agricultural traditions. Historically, indigenous communities around the world have long recognized the benefits of integrating trees into their farming systems. In the tropics, for instance, shifting cultivation or slash-and-burn agriculture often involved leaving tree stumps intact to facilitate forest regrowth and improve soil fertility after cropping cycles [5]. Similarly, in Europe, the practice of "wood-pasture," where livestock grazed under the canopy of scattered trees, has been a part of traditional land use for centuries. The formal recognition and scientific study of agroforestry began in the mid-20th century. Early research laid the groundwork for understanding the ecological and socio-economic benefits of agroforestry. The establishment of the International Council for Research in Agroforestry (ICRAF), now known as the World Agroforestry Centre, marked a significant milestone in the institutionalization and promotion of agroforestry research and development.

B. Evolution of Agroforestry Practices Globally and Regionally

Agroforestry practices have evolved significantly over the past few decades, driven by both scientific advancements and the need for sustainable land management solutions. Globally, agroforestry systems have been adapted to suit diverse environmental conditions and cultural contexts. In Africa, agroforestry has been crucial in combating desertification and improving food security. The practice of integrating nitrogen-fixing trees such as *Faidherbia albida* into cropping systems has significantly enhanced soil fertility and crop yields in semi-arid regions [6]. In Latin America, the concept of "agroforestry landscapes" has gained prominence, where a mosaic of different land uses, including forests, agroforests, and agricultural fields, are managed in a way that enhances biodiversity and ecosystem services. In Asia, traditional agroforestry systems like the homegardens of Indonesia and Sri Lanka, where a diverse array of tree species, crops, and livestock are integrated, have been recognized for their high productivity and sustainability. Regionally, the evolution of agroforestry practices reflects local needs and priorities. In North America and Europe, the re-emergence of agroforestry is often linked to multifunctional agriculture, where the goal is to provide multiple ecosystem services, including carbon sequestration, biodiversity conservation, and landscape aesthetics, alongside food production [7].

C. Classification of Agroforestry Systems

Agroforestry systems can be broadly classified based on the components involved (trees, crops, and livestock) and their spatial and temporal arrangement. The main classifications include agrisilviculture, silvopasture, and agrosilvopasture.

1. Agrisilviculture

Agrisilviculture refers to the combination of trees and crops on the same land. This system can take various forms, such as alley cropping, where crops are grown between rows of trees, and taungya, where crops are planted alongside young forest trees until the canopy closes. Agrisilviculture systems are designed to optimize the use of sunlight, water, and nutrients, thereby enhancing overall productivity and sustainability [8]. For example, the integration of leguminous trees in agrisilviculture can improve soil nitrogen levels through biological nitrogen fixation, benefiting subsequent crop growth.

2. Silvopasture

Silvopasture integrates trees, forage, and livestock on the same land, creating a symbiotic relationship between these components. This system provides multiple benefits, including shade and shelter for livestock, improved forage quality, and diversified income sources from timber and non-timber forest products. In the southeastern United States, for instance, silvopasture systems incorporating loblolly pine (*Pinus taeda*) and cattle have demonstrated enhanced pasture productivity and animal performance compared to conventional pasture systems [9].

3. Agrosilvopasture

Agrosilvopasture combines trees, crops, and livestock in a single integrated system. This complex system maximizes the ecological interactions among the different components, leading to improved resource use efficiency and resilience against environmental stresses. In many traditional farming systems, agrosilvopasture has been practiced for generations. For example, in the Sahel region of Africa, farmers

maintain scattered trees in their fields to provide fodder, fuelwood, and food, while simultaneously growing crops and rearing livestock [10]. The classification and evolution of agroforestry practices underscore the adaptability and multifunctionality of these systems, making them valuable tools for sustainable land management and rural development across diverse environmental and socio-economic contexts.

3. Agroforestry Practices

A. Agrisilviculture: Combining Crops and Trees

Agrisilviculture, one of the most common forms of agroforestry, involves the deliberate integration of trees with crops on the same piece of land. This practice aims to optimize the use of sunlight, water, and nutrients by leveraging the complementary growth patterns and resource requirements of trees and crops. The inclusion of trees in agricultural fields can enhance biodiversity, improve soil structure, increase organic matter content, and reduce soil erosion [11]. For example, the integration of leguminous trees, such as *Gliricidia sepium*, in cropping systems can improve soil nitrogen levels through biological nitrogen fixation, which benefits subsequent crop growth. Moreover, the canopy of trees can provide shade, reducing heat stress on crops and contributing to microclimate regulation.

B. Silvopasture: Integrating Trees, Forage, and Livestock

Silvopasture is a practice that combines trees, forage, and livestock on the same land, creating a synergistic relationship between these components. This system offers multiple benefits, including providing shade and shelter for livestock, improving forage quality, and diversifying income sources through timber and non-timber forest products [12]. Silvopasture systems can enhance pasture productivity and animal performance by offering a more favorable microclimate and reducing heat stress on livestock. In the southeastern United States, for instance, silvopasture systems incorporating loblolly pine (*Pinus taeda*) and cattle have demonstrated enhanced pasture productivity and animal performance compared to conventional pasture systems. Additionally, the presence of trees can reduce soil erosion and improve water infiltration, contributing to overall land sustainability.

C. Agrosilvopasture: Combining Crops, Trees, and Livestock

Agrosilvopasture is an integrated agroforestry system that combines crops, trees, and livestock on the same land. This complex system maximizes the ecological interactions among the different components, leading to improved resource use efficiency and resilience against environmental stresses. In many traditional farming systems, agrosilvopasture has been practiced for generations. For example, in the Sahel region of Africa, farmers maintain scattered trees in their fields to provide fodder, fuelwood, and food, while simultaneously growing crops and rearing livestock [13]. This practice enhances soil fertility through litter fall and organic matter decomposition, improves water retention, and provides a diversified source of income for farmers.

D. Alley Cropping: Growing Crops Between Rows of Trees

Alley cropping involves growing crops between rows of trees or shrubs. This practice is designed to optimize the use of sunlight, water, and nutrients by taking advantage of the spatial and temporal complementarity of trees and crops. The trees can provide a range of benefits, including reducing wind

erosion, enhancing soil fertility through leaf litter, and improving microclimatic conditions for the crops. Alley cropping can also increase biodiversity and provide habitat for beneficial insects and wildlife. For example, in Nigeria, alley cropping systems with *Leucaena leucocephala* have been shown to improve soil fertility and increase maize yields [14].

E. Windbreaks and Shelterbelts: Using Trees to Protect Crops and Livestock

Windbreaks and shelterbelts are linear plantings of trees and shrubs designed to protect crops and livestock from wind damage. These agroforestry practices reduce wind speed, thereby minimizing soil erosion, protecting young plants, and reducing water loss from evaporation. Windbreaks can also improve microclimatic conditions by moderating temperature extremes and providing habitat for wildlife. In the Great Plains of the United States, windbreaks have been widely used to protect crops and reduce soil erosion, leading to improved agricultural productivity and sustainability [15]. Additionally, shelterbelts can serve as corridors for wildlife movement and enhance landscape aesthetics.

F. Home Gardens: Diverse Plantings Around Homes

Home gardens are traditional agroforestry systems characterized by diverse plantings around homes, often including a mix of trees, shrubs, herbs, vegetables, and sometimes livestock. These gardens provide a variety of products, such as fruits, vegetables, medicinal plants, and fuelwood, contributing to household food security and income. Home gardens are highly biodiverse and resilient, offering ecological benefits such as soil fertility enhancement, microclimate regulation, and habitat for beneficial organisms. In Indonesia and Sri Lanka, home gardens are integral to the rural landscape and are recognized for their high productivity and sustainability [16].

G. Case Studies Highlighting Successful Implementations

- 1. *Faidherbia albida* Agroforestry in Africa** In the Sahel region of Africa, the integration of *Faidherbia albida* trees into cropping systems has significantly improved soil fertility and crop yields. These nitrogen-fixing trees shed their leaves during the rainy season, providing organic matter to the soil and enhancing nutrient availability for crops. Studies have shown that fields with *Faidherbia albida* can yield up to four times more than fields without these trees, demonstrating the substantial benefits of this agroforestry practice [17].
- 2. Silvopasture in the Southeastern United States** In the southeastern United States, silvopasture systems incorporating loblolly pine and cattle have demonstrated significant benefits. Research found that these systems enhanced pasture productivity, improved animal performance, and provided additional income from timber production. The integration of trees also contributed to improved soil health and water quality, showcasing the multifunctional benefits of silvopasture [18].
- 3. Alley Cropping in Nigeria** In Nigeria, alley cropping systems with *Leucaena leucocephala* have been implemented to combat soil degradation and improve crop yields. Studies have shown that maize yields increased significantly in alley cropping systems compared to traditional monocropping. The trees' ability to fix nitrogen and provide organic matter to the soil played a crucial role in enhancing soil fertility and crop productivity [19].

4. **Windbreaks in the Great Plains, USA** In the Great Plains of the United States, windbreaks have been successfully used to protect crops from wind erosion and improve agricultural productivity. Research demonstrated that windbreaks reduced wind speed, minimized soil erosion, and created favorable microclimatic conditions for crop growth. These benefits contributed to increased yields and greater sustainability in agricultural landscapes.

4. Soil Health and Fertility Parameters

A. Physical Properties

1. Soil Structure

Soil structure refers to the arrangement of soil particles into aggregates or clusters, which significantly influences various soil functions, including water infiltration, root penetration, and aeration. Good soil structure is characterized by stable aggregates that resist erosion and compaction, thereby enhancing soil health and productivity [20]. Agroforestry practices can improve soil structure through the addition of organic matter from tree litter and root biomass, which act as binding agents to form and stabilize soil aggregates. For example, trees such as *Leucaena leucocephala* in alley cropping systems contribute to better soil aggregation and reduced erosion in tropical regions.

2. Texture

Soil texture, determined by the relative proportions of sand, silt, and clay particles, affects water retention, nutrient availability, and root growth. While agroforestry practices do not alter soil texture directly, they can influence soil physical properties that interact with texture. For instance, organic matter inputs from agroforestry systems can improve the water-holding capacity and nutrient retention of sandy soils and reduce the density and improve aeration in clayey soils [21]. This enhancement of soil texture-related properties is crucial for maintaining soil health and fertility in diverse agroecological zones.

3. Porosity

Porosity is the measure of the void spaces in soil and is crucial for water movement, root growth, and gas exchange. Agroforestry practices enhance soil porosity through the action of tree roots and the decomposition of organic matter, which create macropores and micropores in the soil matrix. Studies have shown that silvopasture systems, where trees are integrated with pasture, significantly increase soil porosity compared to conventional pastures, leading to better water infiltration and reduced surface runoff.

4. Bulk Density

Bulk density is the mass of soil per unit volume and is an indicator of soil compaction. High bulk density can impede root growth and water infiltration, while low bulk density indicates a well-structured soil with adequate pore space. Agroforestry systems typically reduce bulk density through the incorporation of organic matter and the bioturbation activities of soil fauna such as earthworms [22]. For example, the introduction of agroforestry practices in degraded lands has been shown to lower bulk density and improve soil physical health.

B. Chemical Properties

1. Soil pH

Soil pH is a critical parameter that affects nutrient availability, microbial activity, and overall soil health. Agroforestry practices can influence soil pH through the decomposition of tree litter and root exudates, which release organic acids and other compounds into the soil. The incorporation of leguminous trees in agroforestry systems can help to neutralize soil acidity and enhance nutrient availability, thus improving soil fertility [23].

2. Nutrient Content (N, P, K, etc.)

Nutrient content, including macronutrients like nitrogen (N), phosphorus (P), and potassium (K), is essential for plant growth and soil fertility. Agroforestry practices can enhance soil nutrient content through biological nitrogen fixation by leguminous trees, the recycling of nutrients from deeper soil layers, and the addition of organic matter from tree litter and prunings. For instance, the integration of *Faidherbia albida* in cropping systems has been shown to increase soil nitrogen levels and improve crop yields in African agroecosystems [24].

3. Cation Exchange Capacity

Cation exchange capacity (CEC) is a measure of the soil's ability to hold and exchange cations (positively charged ions) such as calcium, magnesium, and potassium. Higher CEC indicates better nutrient retention and availability for plants. Agroforestry systems can enhance CEC through the addition of organic matter, which increases the number of exchange sites in the soil. The presence of trees in agroforestry systems contributes to the continuous supply of organic residues, thereby maintaining and enhancing soil CEC over time [25].

C. Biological Properties

1. Soil Microbial Biomass

Soil microbial biomass is the living component of soil organic matter, excluding plant roots and soil fauna. It plays a crucial role in nutrient cycling, organic matter decomposition, and soil health. Agroforestry practices can significantly increase soil microbial biomass by providing a continuous supply of organic substrates from tree litter and root exudates. Studies have shown that agroforestry systems have higher microbial biomass compared to monocropping systems, which contributes to improved soil fertility and plant health [26].

2. Diversity and Activity

Soil biological diversity, including bacteria, fungi, protozoa, and other microorganisms, is vital for ecosystem functioning and soil health. Agroforestry practices enhance soil biodiversity by creating a heterogeneous environment with varied microhabitats and nutrient sources. The presence of diverse plant species in agroforestry systems supports a wide range of soil organisms, leading to more robust and resilient soil ecosystems. Additionally, the activity of soil microorganisms, such as nutrient mineralization and organic matter decomposition, is often higher in agroforestry systems compared to conventional agriculture [27].

3. Earthworms and Other Soil Fauna

Earthworms and other soil fauna play a critical role in soil structure formation, organic matter decomposition, and nutrient cycling. Agroforestry practices enhance the abundance and diversity of soil fauna by providing habitat and food resources. Earthworms, in particular, are known to improve soil structure through their burrowing activities, which increase porosity and enhance root growth and water infiltration. The presence of trees and shrubs in agroforestry systems creates a favorable environment for soil fauna, contributing to overall soil health and fertility [28].

5. Impact of Agroforestry on Soil Health

A. Effects on Soil Physical Properties

1. Improvement in Soil Structure and Porosity

Agroforestry systems significantly improve soil structure and porosity, leading to enhanced soil health and productivity. The presence of trees in agricultural landscapes contributes organic matter through leaf litter, root exudates, and the decomposition of tree roots, which act as binding agents to form and stabilize soil aggregates. For example, studies have shown that the integration of leguminous trees such as *Gliricidia sepium* in alley cropping systems improves soil aggregation and porosity, thereby enhancing root penetration and water movement [29]. Additionally, the root systems of trees create macropores in the soil, which improve aeration and water infiltration, leading to better soil structure.

2. Reduction in Soil Erosion

One of the most significant benefits of agroforestry is its ability to reduce soil erosion. Trees and shrubs act as physical barriers that protect the soil from wind and water erosion by reducing the velocity of surface runoff and stabilizing the soil with their root systems. Agroforestry systems such as windbreaks and shelterbelts are particularly effective in preventing soil erosion in areas prone to high winds and heavy rains. In the Sahel region of Africa, the use of agroforestry techniques has been shown to reduce soil erosion significantly, thereby enhancing soil conservation and improving land productivity [30].

3. Enhancements in Water Infiltration and Retention

Agroforestry practices improve water infiltration and retention, which are critical for maintaining soil moisture and supporting crop growth, especially in arid and semi-arid regions. The presence of trees enhances soil organic matter content, which increases the soil's water-holding capacity. The root systems of trees and shrubs create channels in the soil that facilitate deeper water infiltration and reduce surface runoff. For instance, silvopasture systems, where trees are integrated with pasture, have been shown to improve water infiltration rates and reduce runoff, leading to better soil moisture conditions [31].

B. Effects on Soil Chemical Properties

1. Increase in Soil Organic Matter and Carbon Sequestration

Agroforestry systems play a crucial role in increasing soil organic matter and carbon sequestration, which are essential for maintaining soil fertility and mitigating climate change. The continuous addition of organic matter from tree litter, prunings, and root biomass enhances soil carbon stocks. Studies have shown that agroforestry systems can sequester significant amounts of carbon in both above-ground biomass and soil, contributing to the reduction of atmospheric CO₂ levels. For example, in tropical

regions, the integration of trees into agricultural systems has been shown to increase soil organic carbon levels, improving soil fertility and productivity [32].

2. Enhancement of Soil Nutrient Status and Cycling

Agroforestry practices enhance soil nutrient status and cycling by increasing the availability of essential nutrients such as nitrogen, phosphorus, and potassium. Leguminous trees, in particular, play a vital role in biological nitrogen fixation, which adds nitrogen to the soil and improves the nutrient status for subsequent crops. Additionally, the deep root systems of trees can access nutrients from deeper soil layers and recycle them to the surface through leaf litter and root turnover. This nutrient recycling process enhances soil fertility and reduces the need for external fertilizer inputs. Research has shown that agroforestry systems improve nutrient cycling and increase the availability of nutrients in the soil, leading to higher crop yields [33].

3. Changes in Soil pH and Cation Exchange Capacity

Agroforestry practices can influence soil pH and cation exchange capacity (CEC), both of which are important for nutrient availability and soil fertility. The decomposition of organic matter from trees can produce organic acids that help to neutralize soil pH, making nutrients more available to plants. Additionally, the increased organic matter content in agroforestry systems enhances the soil's CEC, allowing it to hold and exchange more cations such as calcium, magnesium, and potassium. Studies have demonstrated that agroforestry systems can lead to more favorable soil pH levels and higher CEC, improving overall soil fertility [34].

C. Effects on Soil Biological Properties

1. Increase in Microbial Biomass and Activity

Soil microbial biomass and activity are crucial indicators of soil health, as microorganisms play a vital role in nutrient cycling, organic matter decomposition, and soil structure formation. Agroforestry practices enhance soil microbial biomass and activity by providing a continuous supply of organic substrates from tree litter, root exudates, and decomposing roots. Research has shown that agroforestry systems have higher microbial biomass and activity compared to monocropping systems, contributing to improved soil fertility and plant health [35].

2. Improvement in Soil Biodiversity

Agroforestry systems contribute to higher soil biodiversity by creating a heterogeneous environment with varied microhabitats and nutrient sources. The presence of diverse plant species in agroforestry systems supports a wide range of soil organisms, including bacteria, fungi, protozoa, and other microorganisms. This increased biodiversity enhances ecosystem resilience and stability, leading to healthier and more productive soils. Studies have shown that agroforestry systems harbor a greater diversity of soil organisms compared to conventional agricultural systems, which helps to maintain soil health and function [36].

3. Enhancement of Soil Fauna Populations

Soil fauna, such as earthworms and other invertebrates, play a critical role in soil structure formation, organic matter decomposition, and nutrient cycling. Agroforestry practices enhance the abundance and diversity of soil fauna by providing habitat and food resources. Earthworms, in particular, are known to improve soil structure through their burrowing activities, which increase porosity and enhance root growth and water infiltration. The presence of trees and shrubs in agroforestry systems creates a favorable environment for soil fauna, contributing to overall soil health and fertility [37].

6. Mechanisms of Impact

A. Influence of Tree Roots on Soil Structure and Nutrient Cycling

Tree roots play a crucial role in improving soil structure and enhancing nutrient cycling within agroforestry systems. The extensive and deep root systems of trees create channels and macropores in the soil, which enhance soil aeration, water infiltration, and root penetration. These macropores also facilitate the movement of soil fauna, such as earthworms and microarthropods, which contribute to the formation of stable soil aggregates and improve soil structure. In terms of nutrient cycling, tree roots access nutrients from deeper soil layers that are otherwise unavailable to shallow-rooted crops. This deep nutrient mining allows trees to uptake and translocate essential nutrients, such as nitrogen, phosphorus, and potassium, to the upper soil layers through leaf litter and root turnover [38]. The nutrient-rich litter from tree roots decomposes and releases these nutrients into the soil, enhancing the nutrient availability for crops and improving overall soil fertility. For example, in alley cropping systems, the deep-rooted *Gliricidia sepium* trees have been shown to enhance soil nutrient levels, benefiting subsequent crop yields.

B. Role of Litter Fall and Organic Matter Decomposition

Litter fall and the subsequent decomposition of organic matter are critical processes in agroforestry systems that significantly impact soil health and fertility. The litter fall from trees adds a substantial amount of organic material to the soil surface, which serves as a source of nutrients and organic carbon. This organic matter undergoes decomposition through the action of soil microorganisms and fauna, leading to the formation of humus, which improves soil structure and increases nutrient retention capacity. The decomposition process also releases essential nutrients back into the soil, making them available for plant uptake. For example, the decomposition of nitrogen-rich leaf litter from leguminous trees can significantly enhance soil nitrogen levels, promoting better crop growth and higher yields. Additionally, the continuous addition of organic matter through litter fall helps to maintain soil organic carbon levels, contributing to long-term soil fertility and stability [39].

C. Interaction Between Trees and Crops/Livestock in Nutrient Sharing

Agroforestry systems facilitate beneficial interactions between trees, crops, and livestock in nutrient sharing, leading to improved resource use efficiency and productivity. Trees and crops/livestock interact in various ways that enhance nutrient availability and distribution within the system. One key mechanism is the complementary use of different soil layers by the roots of trees and crops. While tree roots often explore deeper soil layers, crop roots mainly occupy the upper soil layers. This spatial separation reduces competition for nutrients and allows for more efficient nutrient use. Trees can enhance nutrient availability for crops through nutrient cycling. As trees uptake nutrients from deep soil layers and translocate them to their leaves, these nutrients are eventually returned to the soil surface through litter

fall and root turnover. This process enriches the topsoil with essential nutrients, benefiting shallow-rooted crops. Additionally, the presence of livestock in silvopasture systems contributes to nutrient cycling through manure deposition, which adds organic matter and nutrients to the soil, further enhancing soil fertility [40].

D. Role of Mycorrhizal Associations in Nutrient Uptake

Mycorrhizal associations play a vital role in enhancing nutrient uptake in agroforestry systems. Mycorrhizae are symbiotic relationships between certain soil fungi and plant roots, where the fungi colonize the roots and extend their hyphae into the soil, increasing the root surface area for nutrient and water absorption. These associations are particularly beneficial in agroforestry systems, where they enhance the nutrient uptake efficiency of both trees and crops. Mycorrhizal fungi improve the uptake of immobile nutrients, such as phosphorus, by accessing soil micropores that plant roots cannot reach. This enhanced nutrient uptake supports better plant growth and higher productivity. In agroforestry systems, mycorrhizal associations can create a nutrient-sharing network between trees and crops, facilitating the transfer of nutrients from the fungal hyphae to the host plants. This symbiotic relationship is especially important in nutrient-poor soils, where mycorrhizal fungi can significantly enhance plant nutrient acquisition and improve overall soil fertility [41]. Studies have shown that mycorrhizal inoculation in agroforestry systems with species such as *Glomus intraradices* can lead to higher phosphorus uptake and increased crop yields compared to non-mycorrhizal systems. This highlights the critical role of mycorrhizal associations in promoting nutrient uptake and improving soil health in agroforestry practices.

7. Case Studies and Regional Variations

A. Case Studies from Different Regions

Agroforestry practices vary widely across different regions due to variations in climate, soil types, and socio-economic conditions

1. Tropical Regions

In tropical regions, agroforestry systems have been extensively adopted to enhance soil fertility, increase crop yields, and provide sustainable livelihoods. One prominent example is the *Faidherbia albida*-based agroforestry system in the Sahel region of Africa. *Faidherbia albida* is a leguminous tree that sheds its leaves during the rainy season, providing organic matter and nutrients to the soil. Studies have shown that this system significantly improves soil fertility and increases cereal crop yields. Farmers practicing *Faidherbia* agroforestry reported up to four-fold increases in millet and sorghum yields compared to conventional practices [42]. Another notable case study from the tropics is the cocoa agroforestry systems in West Africa. Integrating shade trees with cocoa plantations has been shown to improve soil moisture retention, reduce soil erosion, and enhance biodiversity. Research conducted in Ghana demonstrated that cocoa yields were higher under shaded systems compared to full-sun monocultures. Additionally, the presence of shade trees improved soil organic matter content and nutrient cycling, contributing to long-term soil health.

2. Temperate Regions

In temperate regions, agroforestry practices such as alley cropping, silvopasture, and riparian buffer strips are commonly implemented. A significant case study from the United States involves the use of alley cropping with black walnut (*Juglans nigra*) and corn (*Zea mays*) in the Midwest. This system has shown improvements in soil structure, water infiltration, and reduced erosion. Moreover, the addition of black walnut trees provided an additional income source through timber production [43]. In Europe, silvopastoral systems combining livestock with tree species like oak (*Quercus* spp.) and chestnut (*Castanea* spp.) have been practiced for centuries. These systems have been shown to enhance soil organic matter, improve nutrient cycling, and provide habitat for diverse wildlife species. A study in Spain found that silvopastoral systems improved soil physical properties and increased pasture productivity compared to conventional grazing systems.

3. Arid Regions

In arid and semi-arid regions, agroforestry systems are crucial for combating desertification, improving soil fertility, and supporting sustainable agriculture. The use of *Prosopis* species in agroforestry systems in the Thar Desert of India is a notable example. *Prosopis* trees are drought-tolerant and can fix atmospheric nitrogen, improving soil fertility. Studies have shown that integrating *Prosopis* with crops such as millet and sorghum increased soil organic carbon and nutrient levels, leading to higher crop yields [44]. Another example from arid regions is the use of agroforestry systems in the Negev Desert of Israel. Farmers have successfully integrated date palms (*Phoenix dactylifera*) with vegetable crops and forages, utilizing limited water resources efficiently. This system has improved soil moisture retention, reduced soil erosion, and increased overall agricultural productivity.

B. Comparison of Agroforestry Impacts in Various Soil Types and Climates

Agroforestry systems exhibit varying impacts on soil health and productivity depending on soil types and climatic conditions. The following comparisons highlight these differences:

1. Soil Types

- **Sandy Soils:** In sandy soils, agroforestry systems help improve soil structure, increase organic matter content, and enhance nutrient retention. For example, alley cropping systems in sandy soils of Nigeria with *Leucaena leucocephala* have shown significant improvements in soil fertility and crop yields. The addition of organic matter from tree litter and root biomass enhances soil water-holding capacity and nutrient availability in sandy soils [45].
- **Clay Soils:** Agroforestry practices in clay soils focus on improving drainage, reducing compaction, and enhancing soil aeration. Silvopastoral systems in clayey soils of the southeastern United States have demonstrated increased soil porosity and reduced bulk density, leading to better root growth and water infiltration. The presence of trees helps to break up dense clay soils, improving their physical properties and overall productivity.
- **Loamy Soils:** Loamy soils, which are considered ideal for agriculture, benefit from agroforestry systems through enhanced nutrient cycling and organic matter addition. In loamy soils of temperate regions, alley cropping and riparian buffer strips have been shown to increase soil organic carbon, improve nutrient availability, and reduce soil erosion [46]. The balanced texture of loamy soils allows for efficient root growth and nutrient uptake in agroforestry systems.

2. Climatic Conditions

- **Tropical Climates:** In tropical climates, agroforestry systems help mitigate the impacts of heavy rainfall and high temperatures on soil health. The shade provided by trees reduces soil temperature, enhances soil moisture retention, and protects soil from intense rainfall, reducing erosion. Additionally, the high biodiversity in tropical agroforestry systems supports robust nutrient cycling and organic matter decomposition.
- **Temperate Climates:** Agroforestry systems in temperate climates focus on improving soil fertility, enhancing water use efficiency, and providing additional income through timber and non-timber products. The integration of trees with crops and livestock in temperate regions has been shown to improve soil physical, chemical, and biological properties [47]. The seasonal leaf fall in temperate agroforestry systems adds organic matter to the soil, enhancing soil carbon and nutrient levels.
- **Arid Climates:** In arid climates, agroforestry systems are essential for conserving soil moisture, reducing erosion, and improving soil fertility. Drought-tolerant tree species such as Prosopis and date palms are commonly used to create microclimates that support crop growth. The addition of organic matter from tree litter improves soil structure and water-holding capacity, which is critical for agricultural productivity in arid regions [48].

8. Challenges and Limitations

A. Challenges in Implementing Agroforestry Practices

1. Socio-Economic Barriers

Implementing agroforestry practices often faces significant socio-economic barriers. One of the primary challenges is the initial investment required for establishing agroforestry systems, which can be prohibitively expensive for smallholder farmers. The costs associated with purchasing tree seedlings, labor for planting, and maintenance can deter adoption, especially in low-income regions where financial resources are limited. Additionally, the long-term nature of agroforestry benefits, which may take several years to materialize, can be a disincentive for farmers who need immediate returns to sustain their livelihoods. Another socio-economic barrier is land tenure insecurity. In many developing countries, farmers do not have secure land tenure, making them hesitant to invest in long-term agroforestry practices. Without guaranteed ownership or long-term access to land, farmers are unlikely to adopt practices that require significant time and resources. Furthermore, market access and the availability of markets for agroforestry products can be limited, reducing the potential economic benefits and discouraging adoption [49].

2. Lack of Knowledge and Training

A critical challenge in the implementation of agroforestry practices is the lack of knowledge and training among farmers. Many farmers are not aware of the benefits of agroforestry or the specific techniques required to implement these systems effectively. Extension services and agricultural training programs often focus on conventional farming practices, neglecting agroforestry, which limits farmers' access to essential information and skills. The complexity of agroforestry systems, which require an understanding

of ecological interactions and management practices, can be a barrier to adoption. Farmers may lack the technical expertise to design, establish, and maintain agroforestry systems, leading to suboptimal implementation and reduced effectiveness [50]. Effective training programs and extension services that provide comprehensive information and practical guidance on agroforestry practices are essential to overcome this barrier.

3. Policy and Institutional Constraints

Policy and institutional constraints are significant challenges in promoting agroforestry. In many countries, agricultural and forestry policies are not well-integrated, creating a dichotomy that hinders the implementation of agroforestry practices. Policies that favor monoculture or conventional farming practices over agroforestry can discourage adoption. For instance, subsidies and incentives for chemical fertilizers and monoculture crops can reduce the attractiveness of agroforestry systems [51]. Institutional support is also often lacking. Effective implementation of agroforestry requires coordinated efforts from various stakeholders, including government agencies, non-governmental organizations (NGOs), research institutions, and farmers' organizations. However, the absence of strong institutional frameworks and supportive policies can limit the promotion and adoption of agroforestry. Strengthening policy frameworks and creating institutional support mechanisms are crucial to overcoming these challenges.

B. Potential Negative Impacts

1. Competition Between Trees and Crops for Resources

One of the potential negative impacts of agroforestry is the competition between trees and crops for essential resources such as light, water, and nutrients. Trees with extensive root systems and large canopies can overshadow crops, reducing their access to sunlight and potentially decreasing crop yields [52]. Additionally, the roots of trees can compete with crops for water and nutrients, particularly in regions with limited rainfall and poor soil fertility. To mitigate these competitive interactions, careful planning and management are required. This includes selecting appropriate tree species, designing optimal spatial arrangements, and implementing practices such as root pruning and mulching to reduce competition. However, the complexity of managing these interactions can be a barrier for farmers without sufficient knowledge and resources.

2. Allelopathic Effects

Allelopathy refers to the chemical inhibition of one plant by another due to the release of toxic substances. In agroforestry systems, certain tree species can release allelopathic compounds that negatively affect the growth and development of adjacent crops [53]. For example, Eucalyptus species are known for their allelopathic effects, which can inhibit the germination and growth of understory crops. The allelopathic interactions between tree and crop species is essential for designing effective agroforestry systems. Selecting tree species with minimal allelopathic effects and implementing management practices such as spatial separation and mulching can help mitigate these negative impacts [54]. However, the complexity of allelopathic interactions can pose challenges for farmers, particularly in regions with diverse tree and crop species.

3. Management Complexity

Agroforestry systems are inherently complex due to the integration of multiple species and the interactions between them. Managing these systems requires a higher level of knowledge and skill compared to conventional farming practices. Farmers need to understand the ecological interactions between trees, crops, and livestock, as well as the specific management practices required for each component. The complexity of agroforestry management can be a significant barrier, particularly for smallholder farmers with limited resources and access to technical support [55]. Effective management requires regular monitoring and adaptive management to address issues such as pest and disease control, nutrient management, and spatial arrangement. Providing farmers with the necessary training, resources, and technical support is essential to address the challenges associated with managing agroforestry systems.

9. Future Prospects and Research Needs

A. Emerging Trends in Agroforestry Research

Agroforestry research is continually evolving, with new trends focusing on integrating ecological sustainability with socio-economic benefits. One of the emerging trends is the emphasis on climate-smart agriculture (CSA), where agroforestry is recognized for its potential to enhance climate resilience, mitigate greenhouse gas emissions, and improve carbon sequestration [56]. Studies are increasingly examining the role of agroforestry in reducing the vulnerability of farming systems to climate change by enhancing biodiversity, improving soil health, and increasing water use efficiency. Another trend is the growing interest in the multifunctionality of agroforestry systems. Researchers are exploring how agroforestry can simultaneously provide multiple ecosystem services, such as biodiversity conservation, soil fertility enhancement, and water quality improvement, alongside agricultural production. This holistic approach is gaining traction as it aligns with the principles of sustainable land management and addresses the interconnected challenges of food security, environmental degradation, and climate change [57].

B. Innovations in Agroforestry Practices

Innovations in agroforestry practices are crucial for improving system efficiency, productivity, and sustainability. One such innovation is the development of improved tree-crop-livestock integration models that optimize resource use and enhance synergies among system components. For example, precision agroforestry integrates modern precision agriculture techniques with traditional agroforestry practices to monitor and manage tree-crop interactions more effectively, thus maximizing yields and environmental benefits. Another significant innovation is the use of biochar in agroforestry systems. Biochar, a stable form of charcoal produced from organic matter, can improve soil fertility, enhance carbon sequestration, and increase crop yields when incorporated into agroforestry systems [58]. Research has shown that biochar-amended soils exhibit improved nutrient retention, water-holding capacity, and microbial activity, making it a promising tool for sustainable agroforestry practices. The development of agroforestry-based bioproducts, such as medicinal plants, essential oils, and biofuels, is another area of innovation. These bioproducts not only provide additional income streams for farmers but also contribute to the diversification and resilience of agroforestry systems. For instance, the cultivation of high-value medicinal plants in agroforestry systems in India has shown economic benefits for farmers and improved conservation of medicinal plant species [59].

C. Research Gaps and Future Directions

Despite the progress in agroforestry research and practice, several gaps remain that need to be addressed to fully realize the potential of agroforestry systems.

1. Long-Term Studies on Soil Health Impacts

Long-term studies on the impacts of agroforestry on soil health are essential to understand the sustainability and resilience of these systems. While numerous short-term studies have demonstrated the benefits of agroforestry on soil structure, nutrient cycling, and organic matter content, long-term data are needed to assess the persistence of these benefits and their cumulative effects. Future research should focus on long-term monitoring of soil health parameters, such as soil organic carbon, microbial biomass, and nutrient dynamics, to provide comprehensive insights into the ecological sustainability of agroforestry systems [60].

2. Socio-Economic Impacts of Agroforestry

There is a need for more research on the socio-economic impacts of agroforestry, particularly in terms of livelihoods, food security, and poverty alleviation. While agroforestry is recognized for its potential to improve farmers' incomes and resilience, empirical data on the economic benefits and social outcomes of agroforestry adoption are limited. Future research should investigate the economic viability of different agroforestry models, the impact on household income and food security, and the social dynamics that influence the adoption and scaling of agroforestry practices. Understanding these socio-economic aspects is crucial for designing policies and programs that effectively support agroforestry adoption.

3. Integration of Modern Technologies in Agroforestry

The integration of modern technologies, such as remote sensing, geographic information systems (GIS), and digital agriculture tools, holds significant potential for advancing agroforestry research and practice. Remote sensing and GIS can be used to map and monitor agroforestry systems, assess land suitability, and evaluate the impacts of agroforestry on landscape-scale ecosystem services [61]. Digital agriculture tools, such as mobile apps and decision support systems, can provide farmers with real-time information on tree-crop interactions, pest and disease management, and optimal planting configurations. Future research should explore the application of these technologies in agroforestry, focusing on their potential to enhance system management, increase productivity, and improve environmental outcomes. Additionally, the development of participatory tools and platforms that engage farmers in the co-design and implementation of agroforestry innovations is essential for ensuring the relevance and scalability of these technologies [62].

Conclusion

The future of agroforestry research and practice is promising, with emerging trends emphasizing climate resilience, multifunctionality, and the integration of modern technologies. Innovations such as precision agroforestry, biochar application, and the development of agroforestry-based bioproducts enhance system efficiency and sustainability. However, significant research gaps remain, particularly in long-term soil health impacts, socio-economic benefits, and the integration of digital tools. Addressing these gaps requires comprehensive, long-term studies and a multidisciplinary approach that includes socio-economic evaluations and technological advancements. By focusing on these areas, agroforestry can continue to evolve as a vital strategy for sustainable land management, offering substantial ecological, economic, and

social benefits while addressing the pressing challenges of food security, climate change, and environmental degradation.

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