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Climate Change Mitigation and Adaptation in Agroforestry Systems: A Review of Strategies and Environmental Outcomes

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ABSTRACT: Agroforestry, which combines trees with crops and/or livestock within the same production system, has gained increasing attention as a sustainable land management approach capable of delivering multiple environmental benefits. This review synthesizes current evidence on the environmental performance of agroforestry, with particular emphasis on soil quality, biodiversity conservation, and ecosystem stability. The literature consistently shows that agroforestry improves soil health by increasing organic matter through leaf litter, root turnover, and biomass decomposition, thereby enhancing soil structure, water infiltration, and nutrient availability. Deep-rooted tree species play a key role in recycling nutrients from deeper soil horizons, while nitrogen-fixing trees enrich soil fertility and reduce the need for synthetic fertilizers. Their extensive root systems also stabilize soil and minimize erosion, especially in degraded or sloping landscapes. Beyond soil improvement, agroforestry creates structurally complex habitats that support diverse plant and animal communities, including pollinators, birds, beneficial insects, and soil microorganisms. This greater habitat diversity promotes species richness, strengthens ecological interactions, and improves landscape connectivity by facilitating species movement and genetic exchange. Agroforestry also enhances ecosystem resilience by increasing functional diversity and ecological redundancy, allowing production systems to better withstand disturbances such as drought, pest outbreaks, and extreme weather events. Collectively, these functions make agroforestry an effective nature-based solution for restoring ecosystem processes, strengthening climate resilience, and promoting environmentally sustainable agricultural landscapes.

KEYWORDS: Agroforestry; soil quality; biodiversity; ecosystem stability; climate resilience; sustainable agriculture.

1. Introduction

Climate change is widely recognized as one of the defining environmental challenges of the twenty-first century. Human activities particularly fossil fuel combustion, deforestation, and unsustainable land-use practices, have driven substantial increases in atmospheric concentrations of carbon dioxide, methane, and nitrous oxide. As a result, global temperatures continue to rise, precipitation patterns are becoming increasingly unpredictable, and extreme weather events such as droughts, floods, and heatwaves are occurring with greater frequency and intensity [1, 2]. These changes affect virtually every aspect of natural and human systems, influencing ecosystem functioning, agricultural productivity, water availability, and public well-being. Because land-use systems both release and absorb greenhouse gases, they occupy a central position in climate change mitigation and adaptation efforts. While deforestation, agricultural expansion, and land degradation contribute significantly to global emissions, well-managed landscapes can store carbon, enhance ecosystem resilience, and provide a wide range of environmental services. This dual role is particularly important in tropical and developing countries, where livelihoods depend heavily on natural resources and climate vulnerability remains high [3, 4].

Growing demands for food production, urban development, and natural resources continue to place unprecedented pressure on land-use systems. Conventional agricultural practices, especially those dominated by monocultures and intensive chemical inputs, often degrade soil quality, reduce biodiversity, and weaken ecosystem functions. Over time, these systems become less capable of storing carbon, regulating water, and maintaining long-term productivity. Climate change further amplifies these weaknesses by increasing the frequency of extreme weather events and accelerating land degradation, ultimately threatening food security and rural livelihoods. Smallholder farmers are particularly vulnerable because they often have limited capacity to adapt to changing environmental conditions. These challenges underscore the urgent need for land management strategies that simultaneously support agricultural productivity, environmental conservation, and climate resilience [5, 6].

Among the available approaches, agroforestry has emerged as one of the most promising nature-based solutions. By integrating trees with crops and, in many cases, livestock, agroforestry creates multifunctional production systems that combine economic and ecological benefits. Trees capture and store carbon in both biomass and soil while improving nutrient cycling, soil structure, and water retention. Their perennial canopy moderates local microclimates by reducing temperature extremes, lowering wind speed, and maintaining soil moisture, thereby improving crop performance under increasingly variable climatic conditions. At the same time, the structural complexity of agroforestry systems provides habitats for numerous plant and animal species, strengthening biodiversity and supporting essential ecosystem functions. These multiple benefits position agroforestry as an important strategy for climate-smart agriculture and sustainable landscape management [1–4].

Despite these well-recognized advantages, the environmental performance of agroforestry varies considerably depending on factors such as system design, tree species, climatic conditions, and management practices. Existing research is also highly fragmented. Many studies focus on individual aspects of agroforestry, including carbon sequestration, biodiversity conservation, climate adaptation, or socioeconomic outcomes, without examining how these components interact within an integrated land-use system. As a result, the broader environmental contributions of agroforestry remain difficult to assess. Differences in study design, evaluation methods, and reporting standards further complicate comparisons across regions and production systems. A comprehensive synthesis is therefore needed to consolidate current evidence, identify consistent patterns, and highlight priorities for future research [3–5].

This review addresses that need by critically examining the role of agroforestry in climate change mitigation and adaptation, with particular attention to the environmental mechanisms through which these systems enhance ecosystem performance. Specifically, the review synthesizes evidence on carbon sequestration, ecosystem service provision, biodiversity conservation, soil improvement, and resilience across a range of agroforestry systems and geographical settings. It also evaluates how differences in system design influence environmental outcomes and identifies knowledge gaps that may hinder broader implementation. By integrating findings from diverse studies, this review provides a comprehensive perspective on the contribution of agroforestry to sustainable land management under changing climatic conditions [1, 3, 6, 7].

A key contribution of this review is its integrated perspective. Rather than examining carbon storage, climate adaptation, biodiversity, or regional variation separately, it synthesizes these interconnected dimensions within a single PRISMA-guided systematic framework. Earlier reviews, including those by Abbas et al. [9] and Dhyani et al. [10], typically focused on individual themes or specific geographical regions. In contrast, the present review compares environmental outcomes across major agroforestry systems—including silvopastoral, agrosilvicultural, multistrata, and home garden systems—in both tropical and temperate environments. It also incorporates the latest studies published between 2023 and 2025, providing an updated assessment of recent advances in the field. This broader scope enables a more comprehensive understanding of agroforestry's role in addressing contemporary environmental challenges while offering practical insights for researchers, policymakers, and land managers.

Accordingly, this review addresses four key questions: (1) How do agroforestry systems contribute to climate change mitigation through carbon sequestration and greenhouse gas reduction? (2) In what ways do agroforestry practices strengthen climate adaptation and ecosystem resilience? (3) What environmental outcomes are associated with different agroforestry systems? (4) Which knowledge gaps should be prioritized to improve the effectiveness and wider adoption of agroforestry as a climate solution? By answering these questions, the review aims to provide an evidence-based foundation for developing sustainable, resilient, and environmentally sound land-use strategies.

2. Methodology

2.1. Study Design.

This review followed a systematic literature review design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. PRISMA was adopted to ensure a transparent, reproducible, and methodologically rigorous review process. Widely used in environmental and sustainability research, the framework provides a structured approach for identifying, screening, evaluating, and synthesizing relevant literature. In this study, it was applied throughout the review process, from the initial database search to the final synthesis of evidence on the role of agroforestry in climate change mitigation and adaptation. Following a systematic protocol helped reduce selection bias while ensuring that the findings were based on a comprehensive assessment of the available scientific literature across diverse geographical and agroecological settings.

2.2. Data Sources and Search Strategy.

The literature search was conducted using three major scientific databases: Scopus, Web of Science, and Google Scholar. These databases were selected because they provide broad coverage of peer-reviewed research in environmental science, forestry, agriculture, and climate change. A structured search strategy was developed using combinations of keywords and Boolean operators. The primary search terms included *agroforestry*, *climate change mitigation*, *climate adaptation*, *carbon sequestration*, *biodiversity conservation*, and *ecosystem services*. These terms were combined using AND and OR to refine the search and capture studies addressing different aspects of agroforestry. Representative search strings included: "agroforestry AND climate change mitigation," "agroforestry AND carbon sequestration," "agroforestry AND climate adaptation," "agroforestry AND biodiversity conservation," "agroforestry AND ecosystem services," and "agroforestry AND greenhouse gas emissions." The search covered publications published between 2000 and 2025, allowing the review to capture both foundational studies and recent advances in the field. The initial search identified 1,876 records (Scopus: 742; Web of Science: 683; Google Scholar: 351). After removing 412 duplicate records, 1,464 articles remained for title and abstract screening. Of these, 1,148 studies were excluded because they did not meet the review objectives. The remaining 316 full-text articles were assessed for eligibility. Following full-text evaluation, 276 studies were excluded because of not meeting inlcusson criteria, no full text available, published in languages other than English, and not directly related to agroforestry and climate change. Ultimately, 44 studies satisfied all eligibility criteria and were included in the final synthesis (Figure 1).

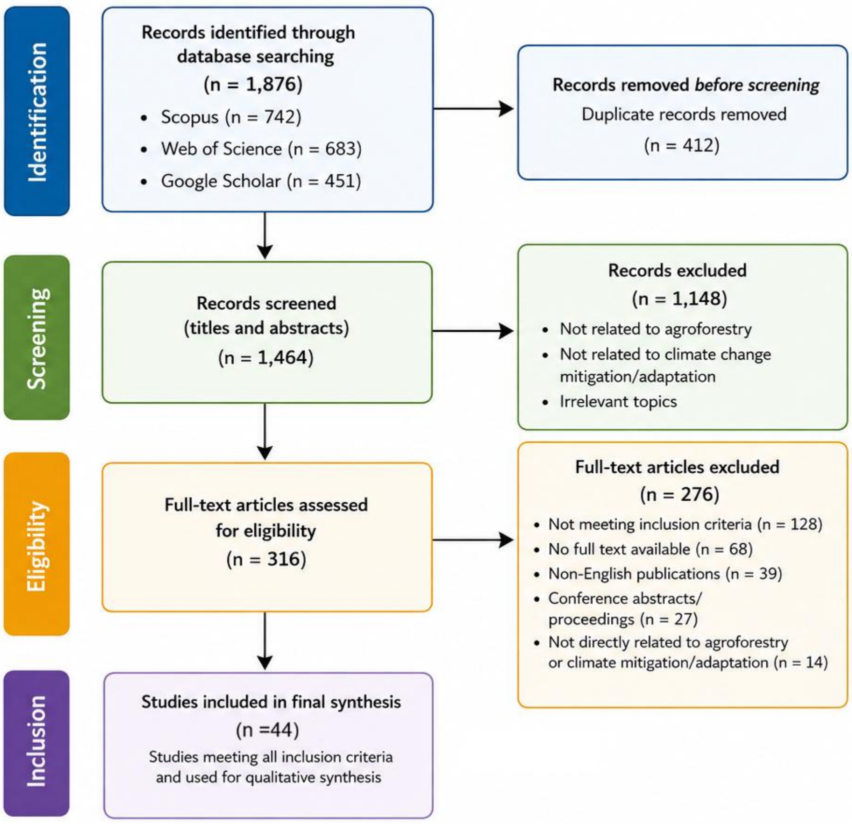

Figure 1. PRISMA flow diagram illustrating study identification, screening, eligibility assessment, and inclusion stages, including reasons for exclusion at the full-text review stage.

2.3. Eligibility Criteria.

2.3.1. Inclusion Criteria.

Studies were included in the review if they met the following criteria: (i) peer-reviewed journal articles, (ii) studies directly addressing agroforestry systems in relation to climate change mitigation or adaptation, and (iii) quantitative, qualitative, or mixed-methods research. Studies focusing on environmental outcomes such as carbon sequestration, soil improvement, biodiversity conservation, and ecosystem services were also included to ensure a comprehensive synthesis of ecological impacts.

2.3.2. Exclusion Criteria.

Studies were excluded if they were conference abstracts without full-text papers, editorials, opinion pieces, or other publications lacking sufficient methodological detail. Non-English publications and studies unrelated to agroforestry or climate change mitigation and adaptation were also excluded to maintain the relevance and consistency of the review.

2.4. Study Selection Process.

Study selection followed the four stages recommended by the PRISMA framework: identification, screening, eligibility, and inclusion. After records were retrieved from the selected databases, duplicate publications were removed. The remaining articles were screened based on their titles and abstracts to eliminate clearly irrelevant studies. Full-text articles that passed the initial screening were then evaluated against the predefined inclusion and exclusion criteria. Only studies meeting all requirements were retained for the final review. This systematic process ensured that study selection was transparent, reproducible, and consistent throughout the review.

2.5. Data Extraction.

Relevant information from each eligible study was extracted using a standardized data extraction form to ensure consistency across studies. The extracted variables included the authors, publication year, and study location, together with the type of agroforestry system investigated, such as silvopastoral, agrosilvicultural, or agrisilvopastoral systems. Environmental outcomes reported in each study were also recorded, including carbon sequestration, soil quality, biodiversity, ecosystem services, and climate change mitigation or adaptation benefits. Organizing the information in a standardized format facilitated comparison across studies and supported thematic analysis.

2.6. Quality Assessment.

The methodological quality of the included studies was evaluated to assess the reliability of the evidence. Each article was examined based on its research design, sampling approach, data collection procedures, analytical methods, and clarity of reporting. Greater weight was given to studies supported by robust experimental designs, long-term field observations, or well-validated modelling approaches. Differences in methodological quality were considered during the interpretation of findings to ensure that the conclusions reflected the strength of the available evidence.

2.7. Data Synthesis and Analysis.

Given the diversity of study designs, environmental settings, and outcome measures, the findings were synthesized using a narrative thematic approach rather than a statistical meta-analysis. A quantitative meta-analysis was not considered appropriate because of substantial differences in methodologies, measurement units, and analytical frameworks across the included studies. The evidence was organized into three broad themes: climate change mitigation, climate change adaptation, and the environmental outcomes of agroforestry systems. Within each theme, similarities, differences, and recurring patterns were identified and critically examined to provide an integrated understanding of agroforestry's contribution to carbon sequestration, ecosystem resilience, biodiversity conservation, and sustainable land management. The synthesis also highlights methodological limitations, identifies gaps in the current literature, and discusses emerging research directions to inform future studies and policy development.

3. Results

3.1. Overview of Selected Studies.

The systematic search identified 44 studies that satisfied the predefined inclusion criteria after a comprehensive screening of records retrieved from Scopus, Web of Science, and Google Scholar. These studies form a focused and methodologically robust body of evidence directly relevant to the objectives of this review. During the selection process, duplicate records, non-peer-reviewed publications, and studies with limited relevance to agroforestry and climate change were excluded. This rigorous screening ensured that only high-quality and thematically relevant studies were included in the final synthesis, providing a reliable basis for evaluating current knowledge and identifying emerging research trends.

The selected studies cover a wide range of geographical settings, although their distribution is uneven. Asia accounts for the largest share of the literature, with particularly strong representation from China, India, Indonesia, and Malaysia. This concentration reflects the region's growing investment in agroforestry research as a response to rapid land-use change, environmental degradation, and the need for more sustainable agricultural systems. Southeast Asia is especially well represented, where expanding agricultural production and industrial development have driven increasing interest in ecosystem conservation, environmental monitoring, and climate-resilient land management.

Europe and North America also make substantial contributions to the literature. Studies from countries such as the United Kingdom, Germany, Spain, the Netherlands, the United States, and Canada typically emphasize advanced analytical methods, environmental policy, biodiversity conservation, and climate mitigation strategies. By contrast, relatively few studies originate from Africa and South America, suggesting that important geographical gaps remain in the global evidence base. This imbalance highlights the need for additional research in underrepresented regions, where agroforestry has considerable potential to support both environmental sustainability and rural livelihoods.

The temporal distribution of the selected studies reveals a clear increase in research activity over the past decade. While earlier publications (2015–2018) primarily established methodological foundations and documented baseline environmental conditions, studies published from 2019 onward increasingly explored the role of agroforestry in addressing climate change and sustainable resource management. More recent work (2022–2025) has shifted toward interdisciplinary and technology-driven approaches, incorporating tools such as remote sensing, machine learning, molecular analysis, and spatial modelling to improve environmental assessment and decision-making. Overall, this progression reflects the rapid evolution of agroforestry research from descriptive investigations toward integrated, solution-oriented studies with stronger implications for policy and practice. The geographic and temporal characteristics of the selected literature are summarized in Table 1.

Table 1. Geographic and temporal distribution of the selected studies.

Aspect	Category/Region	Key Observations	Research Characteristics/Focus
Geographic Distribution	Asia	Largest proportion of selected studies originated from Asian countries such as China, Malaysia, Indonesia, and India.	Strong focus on environmental contamination, land-use change, sustainable agriculture, and ecosystem management.
	Southeast Asia	Well represented due to rapid industrialization and intensive agricultural development.	Emphasis on environmental monitoring, pollution assessment, and ecosystem impacts.
	Europe	Significant contributions from the United Kingdom, Germany, Spain, and the Netherlands.	Focus on advanced analytical methods, environmental policy frameworks, climate mitigation, and adaptation strategies.
	North America	Studies from the United States and Canada contributed substantially.	Research emphasized large-scale environmental modeling, technological innovation, and policy analysis.
	Africa and South America	Comparatively fewer studies were identified.	Indicates limited research representation and highlights potential regional research gaps.
	Overall Trend	Research distribution was globally diverse but unevenly concentrated.	Publication output and research capacity remain concentrated in specific regions.
Temporal Distribution	2015–2018	Earlier studies formed the foundational literature.	Focused on baseline assessments, methodological development, and preliminary environmental characterization.
	2019–2025	Majority of studies were published during this period.	Demonstrated increasing academic and policy interest in environmental sustainability and climate-related issues.
	2022–2025	Recent publications showed rapid growth and methodological advancement.	Increased use of remote sensing, machine learning, molecular analysis, and interdisciplinary approaches.
	Overall Trend	Publication frequency increased substantially over the last decade.	Reflects growing global concern regarding climate change, pollution, and sustainable resource management.
Research Evolution	Earlier Research Phase	Initial studies emphasized descriptive and monitoring-based approaches.	Concentrated on identifying environmental conditions and developing assessment methods.
	Recent Research Phase	More solution-oriented and technology-integrated studies emerged.	Greater emphasis on mitigation strategies, climate adaptation, and practical environmental applications.

Table 1 shows that research output remains concentrated in a relatively small number of countries despite the global relevance of agroforestry. Asia dominates the literature, particularly through studies examining environmental contamination, sustainable agriculture, ecosystem management, and land-use change. European and North American research tends to focus on technological innovation, environmental governance, and climate adaptation, whereas evidence from Africa and South America remains comparatively limited. Over time, the literature has evolved from baseline environmental assessments to more sophisticated investigations that combine emerging technologies with practical mitigation and adaptation strategies.

Table 2 provides a representative overview of the studies included in this review, highlighting their geographical distribution, agroforestry system types, research focus, and major quantitative findings. Collectively, the studies demonstrate that agroforestry consistently delivers positive environmental outcomes across diverse ecological settings. Reported benefits include greater soil carbon sequestration, improved soil moisture retention, enhanced biodiversity, stronger climate resilience, and a broader range of ecosystem services. For example, long-term agroforestry systems in India and Indonesia substantially increased soil organic carbon compared with conventional monoculture systems, while global meta-analyses reported significant improvements in crop productivity, biodiversity, and water regulation. Silvopastoral and multistrata systems also showed considerable potential for enhancing livestock productivity while strengthening ecosystem resilience.

Table 2. Summary of selected studies included in the review (representative sample of 40 studies).

Author(s)	Country/Region	AF System Type	Focus Area	Key Findings (with Quantitative Evidence)
[4]	India	Agrosilvicultural	Soil carbon	Long-term AF significantly increased soil organic C pools (by 34–67%) and deep soil C (>60 cm) in the Indian Himalayas, outperforming monoculture systems.
[2]	Global	Multiple types	Mitigation & adaptation	Smallholder AF systems store 1.1–228 Mg C ha−1; deliver economic benefits averaging USD 1,200 ha−1 yr−1; support NDCs across 40+ countries.
[3]	Indonesia	Multistrata	Carbon sequestration	AF in degraded West Java landscapes sequestered 49–96 Mg C ha−1, compared to <5 Mg C ha−1 in degraded monocultures.
[15]	Global	Multiple types	Multifunctionality	Global meta-analysis (n=287 studies): AF increased crop yield (+21%), soil C (+33%), biodiversity (+57%), and water regulation (+18%) compared to monocultures.
[14]	Mexico	Agrosilvicultural	Soil moisture/water	AF systems increased soil water infiltration by 38–62% and aquifer recharge by 29% vs. conventional farming in semi-arid conditions.
[25]	Europe	Various temperate	Biodiversity	AF systems support 2–4× more arthropod species richness and significantly higher bird diversity relative to open-field agroecosystems.
[11]	Pakistan (semi-arid)	Traditional AF	Carbon sequestration	Traditional AF stored 47.2 Mg C ha−1 in biomass + soil vs. 21.8 Mg C ha−1 in croplands; significant mitigation potential in dryland systems.
[33]	USA	Silvopastoral	Livestock & climate	Silvopasture reduced heat stress days by 30–50%, improved average daily weight gain by 0.18 kg head−1, and stored 30–50 Mg C ha−1 in biomass.
[6]	Global	Agricultural C sinks	Mitigation	Enhanced agricultural C sinks (including AF) could mitigate 1.5–3.6 Gt CO2-eq yr−1 globally while improving farmer income by 8–15%.
[27]	Tropical (global)	Tropical AF	Climate impacts on AF	Systematic review: 68% of tropical AF studies report positive adaptation outcomes; heat and drought tolerance improve under tree shade.
[7]	Global	Land-based systems	Mitigation feasibility	Land-based mitigation including AF could deliver 10.1–17.2 Gt CO2-eq yr−1 by 2050; AF among highest-potential nature-based solutions.
[8]	Argentina	Integrated AF	Sustainability	Integrated AF system with timber, forage, and livestock increased C stocks by 41 Mg C ha−1 over 12 years versus annual monocultures.

AF = Agroforestry; C = Carbon; Mg = Megagram; ha = hectare; yr = year; NDC = Nationally Determined Contribution.

Although the evidence spans both tropical and temperate regions, the majority of empirical studies have been conducted in Asia and Latin America, where agroforestry is widely adopted to support agricultural production, rural livelihoods, and environmental conservation. In comparison, studies from temperate and high-income countries are fewer in number but generally employ more advanced analytical techniques and tend to focus on biodiversity conservation, climate regulation, and ecosystem functioning. Together, these studies demonstrate the broad applicability of agroforestry while underscoring the importance of regional context in determining environmental outcomes. The representative studies summarized in Table 2 illustrate the diversity of agroforestry systems and the range of environmental benefits documented across different regions.

3.2. Agroforestry Strategies For Climate Change Mitigation.

Agroforestry has emerged as an effective strategy for mitigating climate change by integrating trees with crops and/or livestock within the same production system. This integrated approach enhances ecological functions while maintaining agricultural productivity, making it a practical example of climate-smart land management. Broadly, agroforestry contributes to climate change mitigation through three complementary mechanisms: increasing carbon storage in vegetation and soils, reducing greenhouse gas emissions associated with land-use change, and promoting sustainable land management practices that strengthen long-term ecosystem resilience [3,5].

Among these mechanisms, carbon sequestration is one of the most significant environmental benefits of agroforestry. Trees and other perennial species capture atmospheric carbon dioxide through photosynthesis and store it in aboveground biomass, including trunks, branches, and foliage, as well as in extensive root systems below ground. At the same time, agroforestry enhances soil organic carbon through continuous inputs of leaf litter, root turnover, and decomposing organic residues. Compared with conventional monoculture systems, agroforestry generally stores substantially more carbon because of its greater structural complexity and year-round biomass production. Deep-rooted tree species further increase carbon storage by transferring organic carbon to deeper soil layers, where it is less vulnerable to decomposition and disturbance. Together, these processes allow agroforestry systems to function as long-term carbon sinks and strengthen their role as a nature-based solution for climate change mitigation [4,5].

A second important contribution of agroforestry is its ability to reduce greenhouse gas emissions associated with land-use change. Deforestation and the conversion of natural ecosystems into agricultural land remain among the largest sources of global greenhouse gas emissions. By improving the productivity and resource-use efficiency of existing farmland, agroforestry reduces the need to expand cultivation into forested areas. This helps conserve natural ecosystems while meeting growing demands for food, fuel, and fiber. In addition, agroforestry often lowers reliance on synthetic fertilizers and other external inputs, whose production and application contribute to greenhouse gas emissions, particularly nitrous oxide. Nitrogen-fixing tree species naturally improve soil fertility, reducing fertilizer requirements while maintaining crop productivity. In degraded landscapes, agroforestry also supports ecological restoration by improving soil quality, reducing erosion, and restoring productive capacity, thereby limiting emissions associated with land degradation and abandonment [5,7].

Beyond carbon storage and emission reduction, agroforestry promotes sustainable land management practices that provide lasting environmental benefits (Table 3). Common practices include contour planting, alley cropping, silvopastoral systems, windbreaks, and multistrata cropping. These management approaches improve soil conservation, enhance water retention, regulate local microclimates, and promote efficient nutrient cycling. For example, windbreaks reduce wind speed and evapotranspiration, helping to conserve soil moisture and protect crops, while silvopastoral systems improve livestock productivity and reduce methane emissions per unit of production. The diversity of trees and crops within agroforestry systems also increases ecological stability, making agricultural landscapes more resilient to drought, pests, diseases, and other climate-related disturbances. By enhancing both productivity and ecosystem function, diversified agroforestry systems reduce pressure for agricultural expansion and contribute to more sustainable and climate-resilient land use [8–10].

Table 3. Agroforestry strategies for climate change mitigation.

Strategy	Description	Key Climate Mitigation Mechanisms	Main Environmental Benefits	References
Carbon sequestration in biomass and soil	Integration of trees and perennial vegetation into agricultural landscapes to store atmospheric carbon in biomass and soil organic matter.	Photosynthetic carbon uptake; aboveground biomass storage; belowground root carbon accumulation; enhanced soil organic carbon via litter decomposition; deep-soil carbon stabilization.	Higher carbon storage than monocropping systems; improved soil fertility; long-term carbon sink stability; increased ecosystem resilience.	[4, 5]
Reduced emissions from land-use change	Improving land-use efficiency to reduce deforestation and minimize external agricultural inputs.	Reduced deforestation pressure; decreased synthetic fertilizer use; nitrogen-fixing tree integration; restoration of degraded land.	Lower greenhouse gas emissions; reduced nitrous oxide release; prevention of land degradation; improved soil health.	[5, 7]
Sustainable land management practices	Use of diversified systems such as contour planting, alley cropping, silvopasture, windbreaks, and multistrata agroforestry.	Microclimate regulation; improved water retention; reduced erosion; enhanced nutrient cycling; increased system diversity.	Reduced evapotranspiration; improved livestock efficiency; lower methane intensity; greater resilience to climate extremes and biological stress.	[8–10]

3.3. Agroforestry contributions to climate adaptation and ecosystem stability.

Figure 2 summarizes agroforestry contributions to climate adaptation and ecosystem stability. Agroforestry systems not only mitigate climate change but also enhance climate adaptation by improving local environmental conditions and increasing ecosystem resilience. Three key adaptation mechanisms include microclimate regulation, improved soil moisture and water retention, and enhanced resilience to climate extremes. Agroforestry systems significantly influence local microclimates by modifying temperature, humidity, wind speed, and radiation balance within agricultural landscapes [10−12]. The presence of tree canopies provides shade, which reduces direct solar radiation on soil and understory crops, thereby lowering daytime surface temperatures. This shading effect helps minimize heat stress on crops, particularly in tropical and semi-arid regions where high temperatures can reduce photosynthetic efficiency and yield. Additionally, evapotranspiration from trees increases atmospheric humidity, creating a more stable and favorable microenvironment for crop growth. Windbreaks formed by strategically planted tree rows also reduce wind velocity, decreasing evapotranspiration losses and physical damage to crops. Collectively, these effects contribute to a buffered microclimate that enhances agricultural productivity under changing climatic conditions [12, 13].

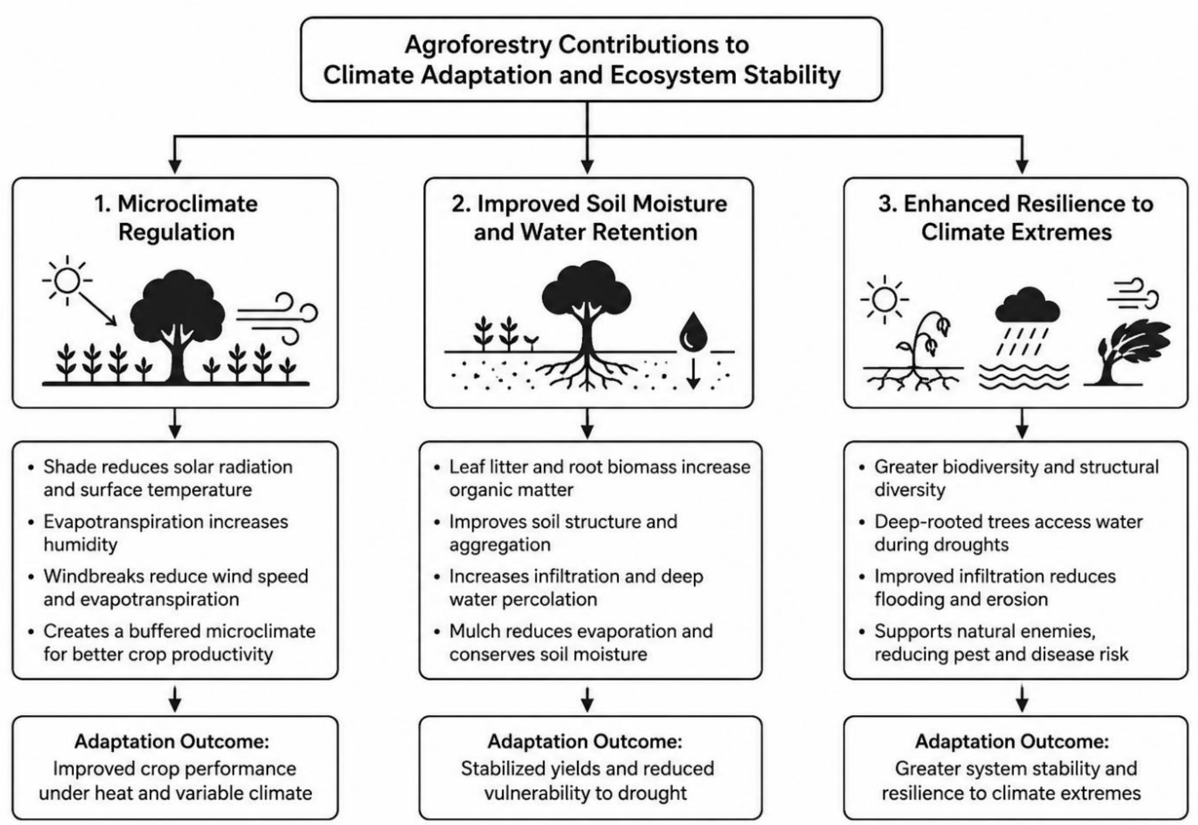

Figure 2. Agroforestry contributions to climate adaptation and ecosystem stability.

Agroforestry systems improve soil hydrological properties by increasing organic matter content and enhancing soil structure. The continuous input of leaf litter and root biomass promotes the formation of stable soil aggregates, which improves infiltration and water-holding capacity. Tree roots create macropores that facilitate deeper water percolation, reducing surface runoff and increasing groundwater recharge potential. In addition, mulch from decomposing plant material reduces evaporation from the soil surface, helping to maintain soil moisture during dry periods. These processes are particularly important in rainfed agricultural systems, where water availability is highly variable. By improving soil moisture retention, agroforestry systems help stabilize crop yields and reduce vulnerability to seasonal droughts [14, 15].

Agroforestry systems enhance resilience to climate extremes such as droughts, floods, storms, and temperature fluctuations by increasing biodiversity and system complexity. The structural diversity of trees, shrubs, and crops creates multiple functional layers that distribute environmental risk more effectively than monoculture systems. During drought conditions, deep-rooted trees can access water from deeper soil layers, maintaining partial productivity even when shallow-rooted crops are stressed. In flood-prone areas, improved soil structure and infiltration capacity reduce waterlogging and erosion risks. Agroforestry also reduces vulnerability to pest and disease outbreaks, which often intensify under climate stress, by promoting habitat diversity for natural predators and beneficial organisms. This ecological buffering capacity ensures greater system stability and long-term sustainability under increasingly unpredictable climatic conditions [16, 17].

3.4. Environmental outcomes of agroforestry systems.

Agroforestry systems generate a wide range of positive environmental outcomes by integrating woody perennials with agricultural crops and/or livestock. These outcomes extend beyond productivity gains and contribute substantially to ecosystem restoration, soil health improvement, and biodiversity conservation. Three major environmental outcomes include soil quality improvement, biodiversity enhancement, and increased ecosystem stability [18, 19].

One of the most well-documented environmental benefits of agroforestry is the improvement of soil quality. The integration of trees within agricultural landscapes enhances both physical and chemical soil properties over time. Tree litter fall, root turnover, and organic residue decomposition significantly increase soil organic matter content, which is a key indicator of soil fertility. Higher organic matter improves soil aggregation, porosity, and structure, thereby enhancing aeration and water infiltration capacity [20, 21].

In addition, agroforestry systems contribute to nutrient cycling efficiency. Deep-rooted tree species are able to access nutrients from deeper soil layers that are typically unavailable to shallow-rooted crops. These nutrients are then returned to the topsoil through leaf litter and decomposition processes, effectively recycling essential elements such as nitrogen, phosphorus, and potassium. In nitrogen-limited systems, the use of nitrogen-fixing tree species (such as *Acacia*, *Gliricidia*) further enhances soil fertility by biologically converting atmospheric nitrogen into plant-available forms. This reduces the need for synthetic fertilizers, which are often associated with soil acidification and long-term degradation [18, 22, 23].

Moreover, tree roots help stabilize soil particles, reducing erosion caused by wind and water. This is particularly important in sloped or degraded lands, where conventional agriculture often leads to rapid soil loss. Overall, agroforestry contributes to long-term soil restoration and maintains agricultural productivity in a more sustainable manner. Agroforestry systems play a critical role in enhancing biodiversity at multiple spatial scales. By introducing structural diversity into agricultural landscapes, agroforestry creates a variety of habitats that support a wide range of plant, animal, and microbial species. Unlike monoculture systems, which often lead to habitat simplification, agroforestry landscapes provide niches for pollinators, birds, insects, and soil organisms. Tree canopies offer nesting and foraging habitats for birds and arboreal species, while understory vegetation supports herbaceous plants and ground-dwelling organisms. This vertical stratification increases species richness and ecological interactions within the system. Pollinators such as bees and butterflies benefit from the continuous availability of flowering plants, which enhances pollination services for both crops and wild vegetation [22, 23].

Agroforestry systems also serve as ecological corridors that connect fragmented natural habitats, facilitating species movement and genetic exchange. This is particularly important in landscapes affected by deforestation and agricultural expansion. In addition, increased biodiversity contributes to natural pest control, as predatory insects and birds help regulate pest populations, reducing the need for chemical pesticides. Ecosystem stability in agroforestry systems is closely linked to their structural and functional diversity. The combination of multiple species with different growth forms and ecological roles enhances system resilience and reduces vulnerability to disturbances. This diversity ensures that ecosystem functions such as nutrient cycling, carbon storage, and water regulation are maintained even under changing environmental conditions. Agroforestry systems are more resilient to shocks such as droughts, pest outbreaks, and extreme weather events compared to conventional monocultures.

Functional redundancy—where multiple species perform similar ecological roles—ensures that if one species is affected, others can compensate, maintaining overall system performance. This buffering capacity stabilizes both ecological processes and agricultural outputs over time [24, 25].

Furthermore, agroforestry contributes to landscape-level stability by reducing land degradation and promoting long-term productivity. By maintaining vegetative cover and improving soil conditions, these systems prevent desertification and support the sustainable use of natural resources. In this way, agroforestry not only enhances farm-level sustainability but also contributes to broader ecosystem resilience and environmental health [2, 26]. Table 4 summarises the comparative climate mitigation and adaptation performance of major agroforestry system types.

Table 4. Comparative climate mitigation and adaptation performance of major agroforestry system types.

AF System Type	Carbon Seq. (Mg C ha⁻¹ yr⁻¹)	Biodiversity (vs. monoculture)	Soil Improvement	Climate Adaptation Strengths	Key Limitations
Silvopastoral	0.5–4.5 [33,34]	+30–60% species richness [25]	+25–40% soil organic matter [18]	Shade reduces heat stress; lower CH4 intensity per kg product; water infiltration	Forage competition; establishment cost; long payback
Agrosilvicultural (alley cropping)	0.3–3.2 [3,4]	+20–50% arthropod richness [25]	+20–55% soil N via N-fixers [18,22]	Wind buffering; microclimate cooling; drought resilience	Shading can cut crop yields if density mismanaged
Multistrata (tropical)	2.5–15.0 [3,29]	+57–150% species richness [15,25]	+33–67% soil C; strong erosion control [4,30]	High biodiversity; microclimate stability; multi-product food security	Pest pressure; nutrient leaching; skilled management required
Home gardens	0.8–5.0 [3]	High at local scale; pollinators and birds [25]	Continuous litter; maintains fertility with few inputs [18]	Crop diversity; localized food security; microclimate buffering	Small scale; limited scalability; variable management
Windbreaks / shelterbelts	0.3–2.0 [7]	Moderate; wildlife corridor function [25]	Reduced wind erosion; improved soil moisture [14]	Wind speed reduction up to 70%; crop protection; aquifer recharge	Narrow footprint; lower C stock vs. multistrata

AF = agroforestry; Mg C = megagram of carbon; ha = hectare; yr = year; CH_4 = methane; N = nitrogen. Ranges are indicative based on reviewed literature and may vary with climate zone, species composition, and management intensity.

3.5. Regional and System-Based Variations in Agroforestry Performance

Agroforestry systems vary significantly in their structure, function, and environmental performance depending on regional climatic conditions and the specific system design. These variations are commonly observed between tropical and temperate agroforestry systems, as well as between silvopastoral and agrosilvicultural arrangements. Understanding these differences is essential for optimizing agroforestry strategies for both climate mitigation and adaptation [27, 28].

Tropical agroforestry systems are generally characterized by high biodiversity, rapid biomass accumulation, and continuous growing seasons. These conditions enhance carbon sequestration potential due to year-round photosynthetic activity and fast decomposition rates that support continuous nutrient cycling. In tropical regions, agroforestry practices such as multistrata systems, home gardens, and shaded perennial crop systems (e.g., coffee and cacao under shade trees) are widely used. These systems are highly effective in stabilizing soils, reducing erosion from heavy rainfall, and maintaining microclimatic stability in warm, humid environments. However, tropical systems may face challenges such as high pest pressure and nutrient leaching due to intense rainfall, requiring careful species selection and management [29, 30].

In contrast, temperate agroforestry systems operate under seasonal constraints, including winter dormancy and shorter growing periods. As a result, biomass accumulation and carbon sequestration rates are generally slower compared to tropical systems. Common temperate practices include alley cropping, riparian buffer strips, and windbreaks. Despite lower year-round productivity, temperate agroforestry systems are particularly effective in mitigating wind erosion, improving water quality through nutrient filtering, and enhancing soil organic carbon over longer time scales. Seasonal leaf litter accumulation also plays a key role in soil fertility enhancement. Thus, while tropical systems excel in rapid ecological productivity, temperate systems contribute strongly to long-term soil conservation and landscape stabilization [31, 32].

Silvopastoral systems integrate trees, forage plants, and livestock within a single land-use framework. These systems are highly effective in improving livestock productivity while reducing environmental impacts. Trees provide shade and shelter for animals, reducing heat stress and improving overall animal welfare, which in turn enhances feed efficiency and reduces methane emissions per unit of production. Additionally, tree roots improve soil structure and increase water infiltration, reducing erosion caused by grazing activities. Silvopastoral systems also support carbon sequestration in both woody biomass and pasture soils, making them important contributors to climate mitigation in livestock-dominated landscapes [33, 34].

Agrosilvicultural systems, on the other hand, combine trees with annual or perennial crops. These systems are primarily focused on crop production enhancement and soil conservation. Examples include alley cropping and intercropping systems where trees improve soil fertility, provide wind protection, and enhance water retention. Nitrogen-fixing trees are particularly valuable in these systems for improving soil nutrient availability and reducing dependence on synthetic fertilizers. Agrosilvicultural systems are often more crop-centric compared to silvopastoral systems, but both contribute significantly to diversified production and environmental sustainability [35, 36].

4. Discussion

4.1. Effectiveness of Agroforestry In Climate Mitigation.

The findings of this review demonstrate that agroforestry is an effective strategy for climate change mitigation due to its capacity to enhance carbon sequestration, reduce greenhouse gas emissions, and improve long-term ecosystem functioning. By integrating trees with crops and livestock systems, agroforestry increases aboveground and belowground biomass, allowing substantial carbon storage in vegetation and soils. Compared to conventional monoculture systems, agroforestry systems consistently exhibit higher soil organic carbon content and improved nutrient cycling. The inclusion of perennial tree species also contributes to long-term carbon stabilization, particularly through deep-root systems that store carbon in subsoil layers. Furthermore, agroforestry reduces pressure on natural forests by improving productivity within existing agricultural land, thereby minimizing deforestation and land-use conversion, which are major contributors to global carbon emissions [37, 38].

These findings align closely with and extend the conclusions of recent systematic reviews and meta-analyses. Mathieu et al. [15] conducted a global quantitative synthesis of 287 studies and reported that agroforestry increased soil carbon by an average of 33%, biodiversity by 57%, and water regulation by 18% relative to monocultures, providing strong meta-analytic validation for the directional findings reported in the present review. Barman et al. [4] demonstrated that long-term agroforestry in the Indian Himalayas increased soil organic carbon pools by 34–67% compared to monocultures, confirming that temporal duration of agroforestry practice is a critical determinant of carbon sequestration outcomes. Abbas et al. [2] further showed, across a global dataset of smallholder systems, that agroforestry carbon benefits range from 1.1 to 228 Mg C ha^{-1}, with tropical multistrata systems consistently outperforming temperate silvopastoral arrangements—an inconsistency that highlights the importance of system-specific and region-specific carbon accounting. By contrast, some earlier reviews (e.g., Scherer and Verburg, 2017 [40]) cautioned that agroforestry carbon benefits can be offset by management inefficiencies, a tension that persists in the more recent literature. These inconsistencies underscore the need for standardized long-term monitoring frameworks across agroforestry typologies and geographic contexts.

With respect to regional and system-specific variations, Watts et al. [27] systematically reviewed 120 tropical agroforestry studies and found that 68% reported positive adaptation outcomes but noted significant heterogeneity in effect size due to differences in species composition and management intensity. Poudel et al. [33] quantified that silvopastoral systems in the United States reduced heat stress days for livestock by 30–50% and improved average daily weight gain by 0.18 kg $head^{-1}$, illustrating the concrete adaptation potential of tree-livestock integration in temperate zones. Boinot et al. [25] reported that agroforestry systems support two to four times more arthropod species richness than open agroecosystems, confirming that biodiversity benefits are substantial and measurable. However, the magnitude of these benefits varies considerably: Philipp and Zander [22] noted that traditional orchard meadows in Germany, while culturally and ecologically valuable, provide lower carbon benefits than intensively managed multistrata systems, underscoring the trade-off between biodiversity and carbon yield that land managers must navigate. Taken together, these comparisons suggest that no single agroforestry system type is universally optimal, and that targeted deployment matched to local climate, land-use goals, and socio-economic context is essential.

A notable inconsistency across studies concerns the role of Africa and South America, which remain underrepresented in the reviewed literature despite housing significant agroforestry potential. Zerihun [19] and Miller et al. [20] both highlighted this evidence gap, noting that livelihood and environmental benefits of agroforestry in sub-Saharan Africa remain inadequately quantified relative to Asian and European systems. This geographic imbalance in the evidence base is a critical limitation of the current review and should motivate targeted field research in underrepresented regions. Future syntheses should prioritize rigorous primary data collection from African and Latin American contexts to enable more globally representative conclusions.

4.2. Role in Climate Adaptation and Resilience Building.

In addition to mitigation, agroforestry plays an essential role in climate adaptation and resilience building. The integration of trees modifies local microclimates by reducing temperature extremes, lowering wind speed, and improving humidity regulation. These microclimatic benefits are particularly important in regions vulnerable to drought and heat stress. Agroforestry systems also enhance soil moisture retention and improve infiltration rates due to increased organic matter and root penetration. Such improvements strengthen the resilience of farming systems during irregular rainfall events and prolonged dry seasons. Moreover, diversified agroforestry systems provide multiple sources of food, fuel, fodder, and income, reducing farmers' vulnerability to climate-related crop failure. Biodiversity enhancement within agroforestry landscapes further supports resilience by promoting ecological balance, natural pest control, and pollination services. The structural diversity of these systems allows them to recover more effectively from environmental disturbances compared to simplified agricultural systems [39, 40].

4.3. Trade-offs and Limitations.

Despite its numerous benefits, agroforestry also presents several trade-offs and limitations. One major challenge is the competition between trees and crops for sunlight, nutrients, and water, particularly when species selection and spatial arrangement are poorly managed. In some cases, excessive tree density can reduce crop yields due to shading effects. The establishment phase of agroforestry systems may also require significant financial investment, labor, and technical knowledge, which can limit adoption among smallholder farmers. Another limitation is the delayed economic return associated with tree-based systems. Unlike annual crops that provide immediate income, many agroforestry components require several years before generating economic benefits. Additionally, measuring carbon sequestration and ecosystem services in agroforestry systems remains methodologically complex due to variations in climate, species composition, and management practices. These uncertainties may hinder the inclusion of agroforestry within formal carbon credit and climate financing mechanisms. Land tenure insecurity is another important constraint in many developing countries. Farmers may hesitate to invest in long-term tree planting if land ownership or resource rights are unclear. Therefore, while agroforestry offers substantial environmental advantages, its implementation requires context-specific management and institutional support [41, 42].

4.4. Policy and Land Management Implications.

The review highlights the importance of supportive policies and integrated land management strategies for expanding agroforestry adoption. Governments and environmental agencies should develop policies that incentivize tree planting and sustainable land-use practices through subsidies, technical assistance, and payment for ecosystem services schemes. Agroforestry should also be incorporated into national climate adaptation and land restoration programs, particularly in regions experiencing severe land degradation and biodiversity loss. Capacity-building initiatives are equally important to improve farmer awareness and technical skills related to species selection, system design, and long-term management. In addition, stronger collaboration between policymakers, researchers, and local communities is necessary to ensure that agroforestry interventions are socially acceptable and economically viable. Integrating agroforestry into broader landscape management approaches can also improve watershed protection, reduce erosion, and strengthen ecosystem resilience at regional scales [43, 44].

4.5. Integration with Global Climate Strategies.

Agroforestry strongly aligns with global climate and sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement.

Agroforestry contributes directly to SDG 13 (Climate Action) through carbon sequestration and climate adaptation measures. It also supports SDG 15 (Life on Land) by promoting biodiversity conservation, ecosystem restoration, and sustainable land management. In addition, agroforestry contributes to SDG 2 (Zero Hunger) by enhancing food security and improving agricultural productivity under changing climatic conditions. Its multifunctional nature also supports poverty reduction and rural livelihood improvement, aligning with SDG 1 (No Poverty). Within the framework of the Paris Agreement, agroforestry is increasingly recognized as a nature-based solution capable of supporting Nationally Determined Contributions (NDCs) through emission reduction and ecosystem restoration targets. As global attention toward sustainable agriculture increases, agroforestry has become an important strategy for achieving climate neutrality and long-term environmental sustainability [2, 9, 10].

4.6. Comparison with Conventional Agricultural Systems.

Compared to conventional agricultural systems, agroforestry provides significantly greater environmental and ecological benefits. Conventional monoculture farming often relies heavily on synthetic fertilizers, pesticides, and intensive land clearing, which contribute to soil degradation, biodiversity loss, and greenhouse gas emissions. In contrast, agroforestry systems promote ecological interactions that naturally improve soil fertility, regulate pests, and conserve water resources. Agroforestry systems are generally more resilient to climate variability because they contain greater structural and biological diversity. While conventional systems may achieve high short-term yields, they are often vulnerable to environmental shocks such as droughts, floods, and pest outbreaks. Agroforestry, however, supports long-term sustainability by balancing productivity with ecosystem conservation. Although management complexity may be higher, the long-term environmental, economic, and social benefits of agroforestry make it a more sustainable alternative to conventional agricultural practices [9, 24]. Summary of the effectiveness, challenges, and policy relevance of agroforestry systems in climate mitigation and adaptation is summarized in Table 5.

Table 5. Synthesis of Agroforestry Effectiveness for Climate Change Mitigation and Adaptation.

Theme	Summary	Ref
Climate mitigation	Increases biomass and soil carbon, improves nutrient cycling, and reduces deforestation pressure, contributing to greenhouse gas mitigation.	[37,38]
Climate adaptation	Regulates microclimate, enhances soil moisture and water infiltration, and improves resilience to drought, heat, and climate variability.	[39,40]
Trade-offs	Adoption is constrained by resource competition, establishment costs, delayed returns, carbon measurement challenges, and insecure land tenure.	[41,42]
Policy implications	Financial incentives, technical support, and integration into national climate and restoration policies can accelerate adoption.	[43,44]
Global relevance	Supports the SDGs and Paris Agreement while providing greater long-term environmental benefits than conventional monoculture systems.	[2,9,10,24]

5. Conclusions

This review demonstrates that agroforestry systems provide substantial environmental, ecological, and climate-related benefits through the integration of trees with agricultural crops and livestock. The reviewed studies consistently showed that agroforestry enhances carbon sequestration in both biomass and soil, improves soil fertility and water retention, supports biodiversity conservation, and strengthens ecosystem stability. Agroforestry systems also contribute to climate adaptation by regulating microclimates, reducing soil erosion, and improving resilience against droughts, floods, and other climate extremes. Variations in system performance were observed across tropical and temperate regions as well as between silvopastoral and agrosilvicultural systems, indicating the importance of site-specific management approaches. Overall, agroforestry is an effective nature-based solution for addressing climate change mitigation and adaptation simultaneously. Compared to conventional agricultural systems, agroforestry offers greater long-term sustainability due to its multifunctional ecological benefits and capacity to maintain agricultural productivity while conserving natural resources. The integration of trees within farming landscapes reduces greenhouse gas emissions, supports carbon storage, and promotes resilient food production systems. In addition, agroforestry aligns strongly with global sustainability frameworks such as the Sustainable Development Goals (SDGs) and the Paris Agreement, reinforcing its role in achieving international climate and environmental targets. To maximize the benefits of agroforestry, stronger policy support, financial incentives, and technical assistance are required to encourage wider adoption among farmers and land managers. Governments and stakeholders should integrate agroforestry into national climate action plans, land restoration initiatives, and sustainable agricultural policies. Future research should focus on long-term empirical monitoring, standardized carbon assessment methods, and the integration of advanced technologies such as GIS, remote sensing, and artificial intelligence. Strengthening interdisciplinary collaboration between researchers, policymakers, and local communities will be essential for promoting sustainable agroforestry practices and enhancing global climate resilience.

Author Contributions

All authors contributed equally to the conception, writing, analysis, and revision of the manuscript. All authors read and approved the final version of the manuscript.

Data Availability Statement

All data used in this review are derived from published literature and are fully available within the cited references. No new datasets were generated or analyzed during the current study.

Competing Interests

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this manuscript.

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