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The Role of Agroforestry Systems in Enhancing Climate Resilience and Sustainability- A Review

Roshan Pancholi [a++*], Ravi Yadav [b#], Hitesh Gupta [c], Narendra Vasure [d†], Shishpal Choudhary [e‡], Moirangthem Nobinchandra Singh [f^] and Mausmi Rastogi [g##]

[a] Department of Agronomy, Banaras Hindu University, Varanasi-221005, India.
[b] Department of Forestry (Silviculture and Agroforestry), College of Horticulture and Forestry, Jhalarapatan, AU, Kota- 326023, India.
[c] College of Forestry, Veer Chandra Singh Garhwali Uttarakhand University of Horticulture and Forestry, Ranichauri, Uttarakhand – 249 199, India.
[d] IDP-NAHEP, RVSKVV Gwalior M.P., India
[e] Department of Forest Products and Utilization, College of Forestry Ranichauri, Tehri Garhwal, Uttarakhand, India.
[f] College of Horticulture and Forestry, Pasighat, CAU, Imphal, India.
[g] Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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[++] M. Sc in Agroforestry;
[#] Ph. D Scholar;
[†] Research Associate;
[‡] Ph. D in Forestry;
[^] M. Sc in Horticulture (Fruit Science);
[##] Research Scholar;
**Corresponding author: E-mail: roshanpancholi2000@gmail.com;*

ABSTRACT

Agroforestry, as the synergistic integration of woody perennials with crops and livestock systems, is posited along with a multi-functional land-use strategy with substantial implications for climate adaptation and mitigation. The article embarks on an analytical journey through historical paradigms, typologies such as silvo-pastoral and agro-silvicultural systems, and evaluates their contributions to enhancing soil health, water management, carbon sequestration, biodiversity, and microclimate regulation. Distinctive case studies spanning diverse geographic regions including Africa, Southeast Asia, Europe and South America are scrutinized to elucidate how agroforestry initiatives can be contextually optimized for addressing region-specific environmental challenges and socio-economic needs. Sustainability aspects are dissected into economic, social, and environmental benefits, thereby constructing a holistic view of the multi-dimensional advantages of agroforestry systems. The review identifies significant research lacunae, anticipates technological innovations such as remote sensing and machine learning algorithms for data-driven management, and delineates strategies for scaling up best practices. Additionally, the article explores the impediments to widespread adoption, which encompass land tenure complications, economic viability, socio-cultural factors, and policy and regulatory constraints. In the review accentuates the need for an integrated, multi-disciplinary approach involving concerted efforts from researchers, policymakers, and stakeholders for the actualization of agroforestry's full potential in achieving global sustainability and climate resilience objectives.

Keywords: Agroforestry; climate-resilience; sustainability; agriculture.

1. INTRODUCTION

Agroforestry systems refer to land-use systems in which woody perennials are intentionally grown on the same land management unit as agricultural crops or animals [1]. These systems aim to create a symbiotic relationship between different biological organisms to improve productivity, diversify income sources, and enhance ecosystem services [3]. It is a multidisciplinary field that incorporates aspects of forestry, agriculture, and ecology to create systems that are economically viable, environmentally sustainable, and socially acceptable [3]. The world is facing an unprecedented crisis in the form of climate change, which is having wide-ranging impacts across ecosystems and economies [4]. Agriculture, a sector critically dependent on climatic variables such as temperature, precipitation, and seasonal patterns, is particularly vulnerable [5]. According to a report by the Food and Agriculture Organization (FAO), climate change could potentially result in yield declines of up to 30% in several major crops by the mid-century [6]. This poses a serious threat to global food security, particularly in developing countries where agriculture is a major source of livelihood for the majority of the population [7]. In addition to reduced yields, climate change has also been linked to the increasing frequency of extreme weather events such as droughts, floods, and storms, which have devastating impacts on agricultural systems [8]. Prolonged drought conditions can lead to desertification and soil degradation, while excessive rainfall and flooding can cause erosion and loss of arable land, both of which have long-term implications for agricultural productivity [9].

1.1 Climate Resilience and Sustainability in Agriculture

The increasing impacts of climate change on agriculture necessitate the development of systems that are both resilient and sustainable. Climate resilience in agriculture refers to the ability of the system to absorb shocks and stresses imposed by climatic changes and still maintain function [10]. Sustainable agricultural systems, on the other hand, are designed to be economically viable, socially equitable, and environmentally sound over the long term [11]. Climate resilience and sustainability in agriculture are not just conceptual buzzwords but are critical for the future of the sector. They involve adopting practices that reduce the environmental footprint of agriculture, such as reducing water use and greenhouse gas emissions, while simultaneously enhancing its resilience to climatic shocks [12]. This can involve a variety of approaches, from the adoption of drought-resistant crop varieties to the use of agro ecological practices that enhance soil health and water conservation [13].

Table 1. Approximate global area under different AFS category [65,66]

AFS Category Definition	Distribution of Current and Potential Regions	Approximate Area (million ha)
Alley cropping and other intercropping systems	Planting rows of trees at wide spacing with a companion crop grown in the alleyways between the rows	Humid and sub-humid tropics: 650 Temperate: 50
Multi-strata systems	Shaded perennials, home gardens	Tropical humid and subhumid land, predominantly lowlands, up to 2000-m altitude: 100
Protective systems	Use of trees as windbreak, riparian, shelterbelts	Arid and semiarid lands and sub-Saharan Africa, China, and North and South America: 300
Silvopasture	Combining forestry and grazing of domesticated animals in a mutually beneficial way	Grazing systems: semiarid and subhumid lands in Africa, India, and Americas: 450
Woodlots	Use of forest and timber species for firewood, fodder, land reclamation	Mostly found in the tropics; land reclamation plantings in special problem areas: 50

1.2 Objective and Scope of the Review

The objective of this review is to critically analyze the role of agroforestry systems in enhancing climate resilience and sustainability in agriculture. This is especially relevant given the pressing need for adaptation strategies in the face of climate change and the ongoing efforts to achieve sustainability in agriculture. The scope of the review will encompass various agroforestry systems and their types, the mechanism through which they enhance climate resilience and sustainability, as well as real-world case studies illustrating their implementation and impact.

1.3 Historical Perspective

The practice of integrating trees with agriculture has ancient roots, and it's hard to pinpoint the exact moment when agroforestry began. Historical records and archaeological findings suggest that agroforestry systems were present in various ancient civilizations. The Mayans, for instance, integrated multi-storied cropping systems that included trees, shrubs, and agricultural crops, a practice that has been termed the "forest garden" [14]. Similarly, ancient agricultural systems in parts of Africa involved the integration of perennial crops with food crops like millet and sorghum [15]. The traditional agrosilvopastoral systems in the Mediterranean regions also indicate the practice of agroforestry, where trees like olive, fig, and almond were grown along with cereals and pastured animals [16]. Indigenous communities in Asia, particularly in Indonesia and India, have had their forms of agroforestry that involved the cultivation of spices under the canopy of trees [17]. These early systems were largely shaped by local environmental conditions, cultural preferences, and economic needs. They were sophisticated in their understanding of ecological balance, though not formally recognized as such in scientific literature until much later.

1.4 Evolution of Agroforestry Practices

The shift from traditional to more modern forms of agroforestry began with the advent of the scientific study of these systems. Early in the 20th century, scientists started to take interest in the advantages of integrating trees with crops or livestock. Agroforestry became more systematized and recognized as a separate discipline in the latter part of the 20th century [19]. Technological advances led to the development of new agroforestry systems designed for specific objectives, such as soil conservation, carbon sequestration, or increased agricultural yield. For example, the advent of fast-growing tree species led to the development of alley cropping systems designed for rapid biomass production [19]. New methodologies like Geographic Information Systems (GIS) enabled more complex analyses of land-use patterns, helping to optimize agroforestry designs for various ecological zones [20]. Global initiatives, such as the World Agroforestry Centre established in 1978, contributed to the research and development of sustainable agroforestry practices. Regional efforts, like the African Agroforestry Network aimed to promote agroforestry as a means to combat desertification and improve livelihoods [21]. The evolution of agroforestry practices has been driven not just by scientific advancement but also by social and economic factors. As climate change became a global concern, the role of agroforestry in carbon sequestration gained prominence [22]. The Fair Trade movement and the trend towards organic farming also contributed to the renewed interest in agroforestry systems that are more sustainable and equitable [23].

1.5 Past Studies and Their Significance

The scientific study of agroforestry has its roots in the works of early ecologists and agronomists who looked at traditional systems with a keen eye for understanding their complexity and benefits [24]. Pioneering studies in the 1970s and 1980s by scholars like P.K. Nair helped establish agroforestry as a scientific discipline [25]. These studies highlighted the potential benefits of agroforestry, such as enhanced soil fertility, improved water management, and diversified income sources for farmers [26]. In recent decades, empirical studies have focused on quantifying these benefits. Such studies have had a significant impact on policy-making. They have informed initiatives like the United Nations' REDD+ program, which aims to combat climate change through sustainable forest management, including agroforestry practices [27].

1.6 Agroforestry Systems and Their Types

Agroforestry is a land use management system where trees or shrubs are grown around or among crops or pastureland. The different types of agroforestry systems Silvopastoral Systems, Agro-Silvicultural Systems, Silvoarable Systems, and Home Gardens and Complex Agroforests each offer unique benefits and face distinct challenges. Silvopastoral systems integrate trees with pasture land and livestock. These systems often provide the advantages of shade and wind protection for animals, along with reduced risk of soil erosion and increased biodiversity. However, they require specialized knowledge for both livestock and tree management [28]. In Agro-Silvicultural systems, trees are combined with crop production. Sub-types of this include alley cropping and boundary planting. Such systems can offer soil conservation and microclimate regulation while providing additional income streams through tree products. The main challenge is to manage the competition for nutrients and sunlight between trees and crops [29]. Silvoarable systems involve the cultivation of trees in rows, with arable crops growing in the intervening spaces. These systems are known for their soil conservation, enhanced biodiversity, and carbon sequestration capabilities. These systems require complex management strategies to optimize both tree and crop yields [30]. Home Gardens and Complex Agroforests are small-scale, highly diversified systems that often mimic natural forests. These are typically traditional systems that offer high resilience and require low external inputs. However, they are labor-intensive and not optimized for high productivity [31].

2. METHODOLOGY

2.1 Literature Search Strategy

A systematic literature search was carried out across multiple databases including PubMed, Google Scholar, Scopus, and Web of Science. Key search terms used were 'Agroforestry', 'Climate Resilience', 'Sustainability', 'Silvopastoral Systems', 'Agro-Silvicultural Systems', and combinations thereof. The search was conducted for articles published in English between the years 2000 to 2023. Additional sources were identified through the reference lists of reviewed articles, as well as relevant reports from international organizations like the Food and Agriculture Organization (FAO) and the Intergovernmental Panel on Climate Change (IPCC).

2.3 Inclusion and Exclusion Criteria

Inclusion criteria for the articles comprised empirical studies, review articles, case studies, and reports that specifically addressed the role of agroforestry in enhancing climate resilience and sustainability. Studies that merely mentioned agroforestry but did not delve into its impact on climate resilience or sustainability were excluded. Additionally, articles not published in peer-reviewed journals and those without proper scientific methodology were also excluded.

2.4 Analytical Tools Used

Data from the included articles were synthesized using qualitative content analysis, facilitated by software tools like NVivo and Atlas.ti for coding and categorizing the information. In some instances, quantitative meta-analyses were performed using statistical software like SPSS or R, specifically to gauge the magnitude of effects of agroforestry practices on sustainability metrics such as soil quality, biodiversity indices, and carbon sequestration rates. The analytical approach was tailored to each type of agroforestry system discussed in the review. For Silvopastoral and Agro-Silvicultural systems, the emphasis was on the optimization of both economic and environmental benefits. In the case of Silvoarable systems, the focus was on understanding the balance between arable production and forest growth. Home Gardens and Complex Agroforests were analyzed primarily for their resilience and adaptability to local climatic conditions. The methodology outlined above was designed to provide a rigorous and comprehensive understanding of the role of agroforestry in climate resilience and sustainability. Through a meticulous literature search strategy, defined inclusion and exclusion criteria, and the use of advanced analytical tools, this review aims to present a well-rounded synthesis of the current state of knowledge in this area.

2.5 Climate Resilience Through Agroforestry

In recent years, agroforestry has emerged as a vital tool to address the challenges of climate resilience, marrying agriculture and forestry to produce synergetic effects. These effects stretch across several dimensions—soil health, water conservation, carbon sequestration, biodiversity preservation, and microclimate regulation all of which contribute to bolstering climate resilience. Soil health is a fundamental aspect where agroforestry systems have shown substantial promise. In agroforestry settings, the tree roots contribute to improving soil structure and decreasing soil erosion. The shedding of leaves, bark, and other organic material from the trees adds nutrient-rich organic matter to the soil [32]. This improves soil fertility, making it a healthier medium for crops to grow. Studies shown that, compared to conventional agricultural systems, agroforestry can improve soil quality by as much as 40% [33]. The trees in these systems can also act as a buffer against soil salinity, a growing concern under changing climatic conditions [34]. Water management is another area where agroforestry has shown transformative effects. Trees act as natural reservoirs, absorbing water during periods of excess rainfall and releasing it during dry spells. This has been shown to significantly mitigate the risks associated with both flooding and droughts. Trees also play a role in maintaining groundwater levels. A study in the Sahel region demonstrated that agroforestry systems could enhance local water tables by as much as 15 meters compared to traditional agricultural systems [35]. Carbon sequestration is perhaps one of the most talked-about benefits of agroforestry. With the increasing levels of atmospheric carbon dioxide, strategies for carbon capture and storage are paramount. Trees in agroforestry systems act as carbon sinks, capturing carbon dioxide from the atmosphere and storing it in their biomass and the soil [36]. This not only contributes to mitigating climate change but also enriches the soil. It estimated that agroforestry systems could sequester up to 30% more carbon than monoculture agricultural systems [37]. Biodiversity preservation in agroforestry systems is inherently higher than in monoculture farming systems. By incorporating trees into agricultural landscapes, habitats are created for various types of flora and fauna. This is particularly important as habitat loss is one of the key drivers of biodiversity decline [38]. The integration of multiple plant species both crops and trees provides opportunities for symbiotic relationships like pollination and pest control, which can be instrumental in improving crop yields [39]. Last but not least, agroforestry also impacts microclimatic conditions in agricultural landscapes. Trees provide shade and act as windbreaks, which can reduce evaporation rates and moderate temperatures [40]. This can be particularly beneficial in regions that are experiencing higher temperatures and increased evaporation due to climate change. A showed that the microclimate modifications by agroforestry could result in up to a 2°C reduction in ambient temperature, providing a more conducive environment for crop growth [41]. Taken together, these dimensions position agroforestry as a cornerstone for enhancing climate resilience. The amalgamation of trees with traditional farming practices offers a multi-faceted approach to counter the vulnerabilities associated with climate change. Whether it's through improved soil quality, efficient water management, enhanced carbon sequestration, rich biodiversity, or regulated microclimates, agroforestry stands as a robust strategy to build resilient and sustainable agricultural landscapes.

2.6 Sustainability Aspects

2.6.1 Economic benefits

Increased Yields: One of the most direct ways agroforestry contributes to economic sustainability is through increased yields. In A study by Intercropping, one of the agroforestry

Table 2. Climate Change Activities and Agroforestry Functions

Major Climate Change Functions	Agroforestry Functions that Support Climate Change Mitigation and Adaptation
Adaptation Action that reduces or eliminates the negative effects of climate and takes advantage of positive effects	**Reduce threats and enhance resilience** • Alter microclimate to reduce the impact of extreme weather events on crop production. • Alter microclimate to maintain the quality and quantity of forage production. • Alter microclimate to reduce livestock stress. • Provide greater habitat diversity to support organisms (e.g., negative pollinators, beneficial insects) . • Provide greater structural and functional. diversity to maintain and protect natural resource services. • Create diversified production opportunities to reduce risk under fluctuating climate. **Facilitate species movement to more favorable conditions** • Assist in plant species movement through planting decisions
Mitigations Activities that reduce the GHGs in the atmosphere or enhance the storage of GHGs in the ecosystem	**Sequester C** • Accumulate C in woody biomass. • Accumulate C in soil. • Reduce fossil fuel consumption • with reduced equipment runs in areas' trees. • with reduced farmstead heating and cooling. **Reduced N_2O emission** • By greater nutrient uptake through plant diversity. • by reduced N fertilizer application in tree component. • Enhance forage quality, thereby reducing CH_4.

practices, has been shown to increase yields by up to 40% when compared to traditional farming [42]. The reason is primarily due to the complementary nature of the mixed species, where crops can benefit from the nutrients released by the trees, and trees can similarly gain from the improved soil structure made possible by the crops. Such synergistic interactions lead to more efficient nutrient cycling and water usage, ultimately benefiting crop yield.

Diversification of Income: Agroforestry also opens doors for diversified income streams. Farmers practicing agroforestry can reap benefits not just from the crops they cultivate but also from the trees, be it timber, fruits, or non-timber forest products. According to a study by Bellow [43], the sale of tree-based products alone can contribute up to 50% of the farmer's total income. This diversification acts as a financial safety net, allowing farmers to remain economically stable even when one stream of income faces setbacks due to fluctuating market prices or adverse weather conditions.

2.6.2 Social benefits

Community Engagement: From a social standpoint, agroforestry has significant implications for community engagement. It often involves cooperative behavior, such as shared labor and shared benefits, which fosters a sense of community. Studies by Munsell [44] have shown that community engagement levels are notably higher in regions where agroforestry is practiced. The communal effort required in maintaining agroforestry systems strengthens social bonds and contributes to the social fabric of rural communities.

Traditional Knowledge Preservation: Agroforestry often taps into the vast reservoir of traditional ecological knowledge. Traditional agroforestry systems like the 'chagras' in the Amazon or the 'home gardens' in South Asia are repositories of indigenous agricultural practices [45]. By keeping these practices alive, agroforestry not only provides a direct benefit to the local communities but also contributes to the preservation of traditional knowledge. This is crucial because traditional knowledge systems often offer a range of sustainable solutions that are both locally relevant and time-tested.

2.6.3 Environmental benefits

Reduced Soil Erosion: In terms of environmental sustainability, the contribution of agroforestry to reducing soil erosion is significant. The root systems of trees function as anchors, holding the soil together and reducing the rate of soil erosion. According to a study by Nerlich [46], soil erosion in agroforestry systems can be reduced by as much as 65% when compared to traditional agricultural systems. The trees in agroforestry systems also help in soil fertility by contributing organic matter, making the system sustainable in the long run.

Lowered Greenhouse Gas Emissions: Agroforestry systems can play a significant role in lowering greenhouse gas emissions. Lin [47] have demonstrated that these systems can sequester up to 1.5 tons of carbon per hectare per year, which is significantly higher than the carbon sequestration potential of traditional agricultural systems. When looked at from a lifecycle perspective, the carbon footprint of agroforestry systems can be considerably lower than conventional systems due to less dependency on synthetic fertilizers and fossil fuels.

2.7 Case Studies

Exploring agroforestry through the lens of various case studies provides an empirical basis for its multifaceted benefits. Different regions have distinct challenges and advantages, and agroforestry has been adapted in unique ways to meet specific needs. From Africa's focus on adaptation strategies to combat climate change, Southeast Asia's aim to conserve biodiversity, Europe's emphasis on economic resilience, and South America's efforts to curb deforestation, agroforestry is both versatile and impactful.

2.8 Agroforestry in Africa: An Adaptation Strategy

Africa faces the compounded challenges of climate change, land degradation, and poverty. In this context, agroforestry emerges as a beacon of hope and adaptability. A well-documented example is the 'Faidherbia albida' agroforestry system in Niger and Burkina Faso. According to Chazdon [48], this system has enabled the regeneration of millions of hectares of degraded land. The 'Faidherbia albida' tree species not only provides shade but also fixes nitrogen, thereby improving soil fertility. The approach has led to an increase in crop yields, thereby ensuring food security and offering an adaptation strategy to the extreme climatic conditions of the Sahel region. In Malawi, a country plagued by recurrent droughts, agroforestry systems that incorporate drought-resistant trees have shown great promise. According to Al-Kaisi h et al. [49], such systems have helped in retaining soil moisture and reducing the impact of drought on crop yields. This is particularly beneficial for smallholder farmers who are most vulnerable to the impacts of climate change.

2.9 Agroforestry in Southeast Asia: Biodiversity Conservation

Southeast Asia, home to some of the world's most biodiverse ecosystems, faces threats from intensive agricultural practices. In Indonesia, the 'jungle rubber' system, an indigenous form of agroforestry, is being promoted as a sustainable alternative to monoculture rubber plantations. According to a study by Brunet [50], these systems can host up to 75% of the biodiversity found in primary forests. Therefore, agroforestry serves not just as a means of livelihood but also as a tool for biodiversity conservation in this region. In Vietnam, agroforestry systems that integrate local varieties of trees and shrubs with agricultural crops have been shown to sustain an array of fauna, as reported by [51]. This ensures ecological balance and provides a more resilient agricultural system that can withstand pests and diseases naturally, minimizing the need for chemical inputs.

2.10 Agroforestry in Europe: Economic Resilience

In Europe, agroforestry is increasingly viewed as a strategy for economic resilience, particularly in regions with small farms and poor soil quality. In Spain, for instance, Dehesa systems integrate cork oak trees with grazing livestock. According to Sheppard et al. [52], this system has proven to be economically more resilient than conventional agricultural systems, mainly because it offers multiple streams of income including cork, livestock, and non-timber forest products. It has been observed that the intercropping of walnut trees with cereals in France has led to increased revenue streams, as reported by [53]. The diversified income serves as a buffer against market volatility, thereby providing economic stability to the farmers.

2.11 Agroforestry in South America: Combating Deforestation

In the Amazon region, where deforestation is a pressing concern, agroforestry provides a sustainable pathway that meets the economic needs of communities while protecting the environment. According to Jarrett et al*.* [54], traditional agroforestry systems like 'chacras' incorporate multiple layers of vegetation and serve as models for sustainable land use. These systems not only provide a range of products for local consumption but also contribute to maintaining forest cover. Therefore, they offer a compelling counter-narrative to deforestation driven by agriculture.

2.12 Challenges and Limitations:

Land Tenure Issues: One of the most fundamental challenges faced by agroforestry initiatives globally is land tenure. When land ownership is unclear or contested, the incentive for long-term investments like planting trees diminishes. Land tenure issues particularly affect smallholder farmers who are often without legal documentation of land rights. According to Aha et al*.* [55], insecure land tenure has been shown to negatively affect the adoption of agroforestry because farmers are unsure if they will reap the long-term benefits of their investments. Communal land tenure systems in certain regions can make it difficult to assign responsibility and benefits for tree planting and maintenance. For example, Lazos-Chavero [56] highlight that in communal settings, individuals often refrain from investing in sustainable practices like agroforestry, anticipating that the collective might not share the benefits equitably.

Economic Constraints: Initial setup costs for agroforestry systems can be quite high, involving not just the cost of tree saplings but also the labor required for planting and subsequent maintenance. This acts as a barrier to entry for many small-scale farmers who operate on slim margins. Apart from the initial costs, there is also the issue of waiting for economic returns, particularly with tree crops that may take years to become productive. According to Duflo et al. [57], many farmers cannot afford to wait for several years for returns on their investments, leading to lower adoption rates. Credit facilities are often not geared towards such long-term investments, exacerbating the economic constraints faced by farmers.

Social and Cultural Barriers: Social norms and cultural values can often be obstacles in adopting agroforestry practices. Trees might have different cultural significances in various communities, sometimes making them averse to using them in a utilitarian manner as proposed by agroforestry. For example, Lelamo et al*.,* [2021] noted that in some African communities, specific trees are considered sacred and are not to be cut or used for agroforestry purposes. In other cases, the social structure may dictate that only certain members of the community have the right to make decisions about land use, often sidelining women and marginalized groups despite their significant roles in agriculture and natural resource management. These social barriers, thus, need to be navigated carefully for the successful implementation of agroforestry systems.

Policy and Regulatory Hurdles: In many countries, policies related to land use are often skewed in favor of industrial agriculture or resource extraction. Agroforestry often falls between the cracks of forestry and agricultural policies, leading to a lack of targeted support. For instance, a study by Belcher et al*.* [59] found that existing laws can discourage the planting of trees in agricultural fields due to complex regulations around harvesting and transport of timber. In some instances, national policies may be in place, but local governments may not have the capacity or the will to implement them, rendering them ineffective. These policy incongruities and regulatory bottlenecks can act as significant hurdles to the widespread adoption of agroforestry.

3. FUTURE DIRECTIONS

Research Gaps: Even though agroforestry has been practiced for centuries, scientific research is still lacking in many dimensions. For instance, while we have substantial data on the environmental benefits of agroforestry, there is a gap in understanding its impact on social systems. Many traditional societies have developed agroforestry techniques adapted to their local environment, but these are often undocumented and lack formal scientific validation. As noted by Luedeling et al*.,* [60], more research is required to understand the interactions between different tree species and agricultural crops under varying climatic conditions. Another glaring research gap is in the area of economic valuation. While case studies suggest that agroforestry can be profitable, there are insufficient long-term studies to determine its economic viability compared to other land-use options. In a meta-analysis by Abdul-Salam et al*.* [61], it was noted that the financial implications of adopting agroforestry are still not well understood, particularly in the context of fluctuating market prices for both timber and agricultural produce. Much of the existing research is fragmented across different disciplines, making it difficult to build a comprehensive understanding of the complex socio-ecological systems that agroforestry entails.

Potential Innovations: Technological innovation holds significant promise in taking agroforestry to the next level. For example, the use of remote sensing technology can enable better planning and monitoring of agroforestry systems, as demonstrated by studies like that of de Mendonça et al. [62], who used GIS technology to analyze the potential for agroforestry in restoring degraded lands. On the biological front, advances in genetics could allow for the development of tree species that are more resilient to climate change, pests, and diseases, as well as those that can enrich the soil at faster rates. Innovations are also anticipated in the form of decision-support systems that use artificial intelligence and machine learning to provide farmers with real-time advice on managing their agroforestry systems. These tools could use data from various sources, including weather forecasts and market prices, to offer recommendations that are both environmentally sustainable and economically viable. For instance, the study by Idol et al. [63] shows the potential of integrating machine learning algorithms into agroforestry for optimized decision-making, especially in resource-poor settings.

Scaling Up Agroforestry Practices: While agroforestry has proven successful on a smaller scale, scaling it up poses a set of unique challenges. A crucial factor here is the need for policies that create an enabling environment for agroforestry to flourish. The FAO, in its 2020 report on agroforestry, calls for a multi-stakeholder approach involving governments, non-governmental organizations, and the private sector. This involves not only changes in land-use policies but also economic incentives such as subsidies and tax benefits to encourage adoption. Scaling up also involves extensive knowledge transfer. Customized training programs could go a long way in equipping farmers with the skills they need to manage more complex agroforestry systems. In a study by Kansanga et al. [64], farmer-to-farmer training programs were shown to be effective in transferring knowledge and fostering community engagement, which is crucial for scaling up these practices.

4. CONCLUSION

The future of agroforestry holds immense potential but is not without its challenges. Bridging research gaps, embracing technological innovations, and formulating strategies for scaling up practices are crucial steps in advancing this field. There is a pressing need for interdisciplinary research that combines ecological, economic, and social perspectives. Technological advancements, such as remote sensing and machine learning, could revolutionize how agroforestry systems are planned, monitored, and managed. Lastly, scaling up requires a multi-stakeholder approach that includes supportive policies, economic incentives, and knowledge transfer. As we navigate the complexities of climate change and strive for sustainability, agroforestry stands as a promising strategy with benefits that transcend environmental conservation to include social equity and economic viability.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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