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Toward a Greener Future: Scaling up Agroforestry for Global Sustainability

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Abstract: The current world faces several challenges, including climate change, an exponentially increasing population, the loss of biodiversity, and environmental concerns, which necessitate the adoption of sustainable nature-based solutions such as agroforestry. Agroforestry is the intricate integration of trees, crops, and livestock on the same piece of land management unit that helps to restore the ecosystem, improve soil health, and thus combat environmental degradation. Moreover, agroforestry has also emerged as a potential tool that bridges ecological preservation while increasing or at least maintaining the productivity of the whole agroecosystem. Agroforestry is a contemporary food system that relies primarily on natural inputs, leading to the creation of more sustainable and resilient landscapes. Simultaneously, agroforestry systems reduce soil erosion and increase the accumulation of organic matter, hence establishing a closed nutrient cycling that sustains the agricultural production for a longer duration. Simultaneously, agroforestry systems are effective in enhancing food security, diversifying farm income, and strengthening the resilience of the community to climate change, thus empowering the farmers and providing an opportunity to combat poverty. However, there are numerous constraints, including clear land tenure rights, market infrastructure and linkage, and lack of traditional knowledge, which influenced the adoption of agroforestry systems at the global level. This immediately needs to be addressed by implementing flexible legislation (such as the National Agroforestry Policy 2014 adopted by India), capacity building and community involvement, value chain development, and payment for ecosystem services. Overall, it is crucial to adopt low-carbon perennial agroecological practices like agroforestry in order to increase the CO_2 abatement rate, improve the food, nutritional, and livelihood security of smallholder farmers, and contribute to a more environmentally friendly and sustainable future.

Keywords: agroforestry, sustainability, climate change, biodiversity conservation, scaling up

1. Introduction

In recent decades, the impacts of climate change and deforestation have emerged as concerns affecting ecosystems, biodiversity, and human welfare. Concurrently, the rise in greenhouse gas emissions is contributing to shifts in climate patterns and extreme weather events that have effects on various environments [1]. The Inter-Governmental Panel on Climate Change (IPCC) underscores in its report the warming trend of the Earth's atmosphere and indicates that between 2011 and 2020, global surface temperatures have already increased by 1.09 °C compared to the industrial era (1850–1900). Additionally, the IPCC's projections through concentration pathways (RCPs) such as RCP 2.6 and RCP 8.5 indicate increases in global surface temperatures by 0.3–1.7 °C and sea levels by 0.26–0.54 m from 2081 to 2100 [2].

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Parallel to this, extensive forest clearing for agriculture exacerbates these difficulties, resulting in habitat loss, reduced emission sinks, and soil deterioration [3]. As a result, the goal for global sustainability and food security for growing populations worldwide has reignited interest in creative land-use techniques that encourage ecological resilience, carbon sequestration, and improved nutrition [4]. In this complicated environment, agroforestry appears as a bright beacon of hope, presenting a complete approach that incorporates perennial components within agricultural landscapes to handle numerous difficulties synergistically [5]. Agroforestry is the deliberate integration of the agricultural crops with livestock and perennial trees including forestry and horticulture on the same land management unit. Unlike traditional monoculture agriculture, which frequently involves the cultivation of a single crop, agroforestry uses a more exclusive approach, drawing inspiration from centuries-old Indigenous traditional knowledge (ITK). This intentional arrangement of the different components leads to both ecological and economic interactions that can provide

Figure 1
Contribution of agroforestry toward achieving relevant United Nations' Sustainable Development Goals

diversified products that otherwise can't be achieved in the sole cropping system. Globally, agroforestry is practiced by more than 1.2 billion people, spanning over 1 billion hectares of land [6], helping different nations to achieve at least nine of the United Nations' Sustainable Development Goals (SDGs) (Figure 1). However, there are several agroforestry practices, which can be classified into agri-silvicultural (agriculture crops and trees), silvopastoral (trees, grasses, and livestock), agro-silvopastoral systems (agriculture crops, trees, grasses, and livestock), and other specific systems (aqua-forestry, apiculture with trees) [7]. Overall, agroforestry provides a means to achieve a greener and more sustainable future by using the complementary interactions found in nature.

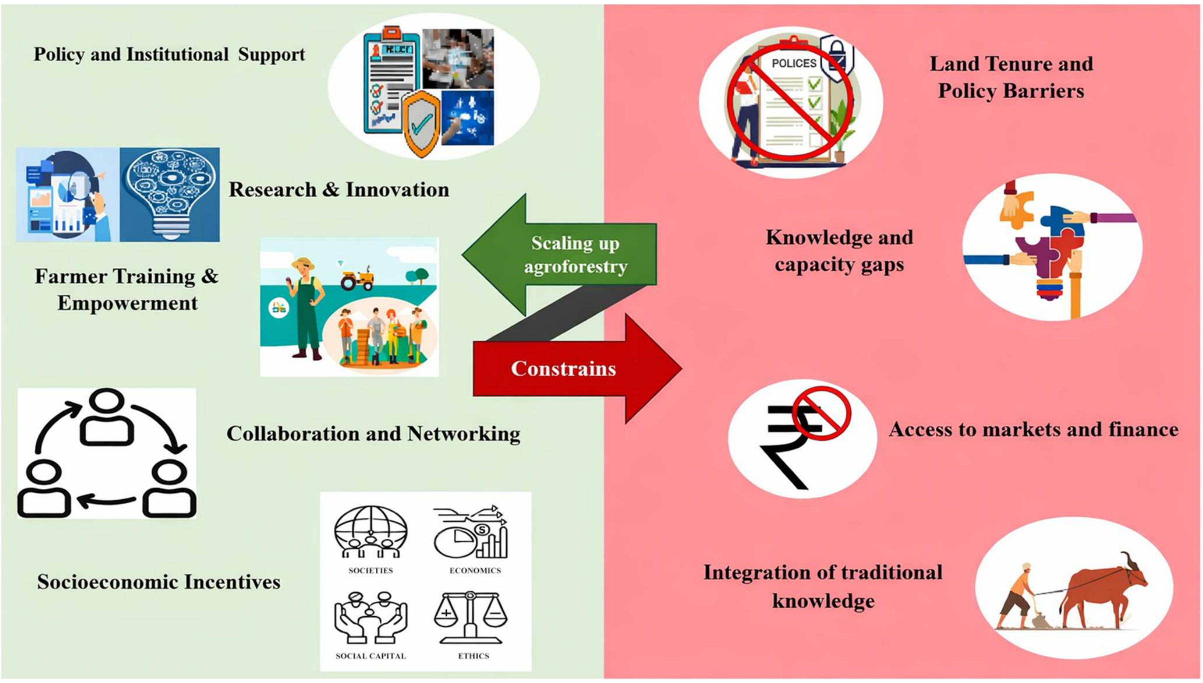
2. Agroforestry for Global Sustainability

2.1. Carbon capture and microclimate amelioration

Agriculture covers 37% of the earth's area and is the most significant source of non-carbon dioxide greenhouse gas (GHGs) emissions. The principal gases emitted are methane and nitrous oxide, which are estimated to be between 5.2 and 5.8 billion tons carbon dioxide equivalents (CO_2 eq), or about 10–12% of overall global GHG emissions [8]. Agroforestry systems contain vast carbon sequestration possibilities; thus, they are critical international actors in the effort to mitigate climate change [9]. Agroforestry was officially accepted as a legitimate land management approach promoting greenhouse gas sequestration by the Kyoto Protocol in 2001, indicating that it has the potential to reduce climate change. Studies undertaken around the globe in different agroecosystems indicated that agroforestry systems can accumulate considerable carbon in both vegetative and soil. For instance, IPCC [10] reported that agroforestry systems had a technical abatement potential of 1.1–2.2 PgC. Simultaneously, IPCC [11] identified agroforestry systems as a landscape that could achieve the highest C sequestration by the year 2040 on the land. Rajput et al. [12] and Saleem et al. [13] evaluated different land-use options for their C storage and sequestration in the Northwestern Himalayas and concluded that after forestry land use, agroforestry could achieve the highest C content and sequestration. Niether et al. [14] also corroborate that agroforestry for cocoa is capable of sequestering 2.5 times more C in the cocoa system as compared to monoculture and cultivation. Thus, C sequestration in agroforestry is crucial for climate change adaptation and mitigation. Moreover, Kay et al. [15] showed that agroforestry systems in Europe possess 0.09–7.29 t C ha^{-1} $year^{-1}$ annually on aggregate; however, with an enhanced area, it could reach 2.1–63.9 million t C $year^{-1}$. This ability is attributed to the natural process of trees absorbing atmospheric carbon dioxide and then storing it in their biomass. However, the growth and behavior of different tree species within an agroforestry practice determine how well a given agroforestry system will sequester carbon [16]. Moreover, trees enhance additional carbon sequestration within the soil profile through the addition of leaf litter fall in agroforests, thereby promoting the sequestration of more carbon. Agroforestry also contributes to the reduction of GHG emissions in addition to offering carbon sequestration. Kim et al. [17] demonstrated that a shift from traditional cultivation to an agroforest mitigates a 27.2 t CO_2 eq ha^{-1} $year^{-1}$ in GHG emission. Furthermore, if the world's 630 million ha of unproductive agricultural lands are converted to agroforestry, there would be a worldwide net GHG reduction potential of 3.4 109 t CO_2 eq $year^{-1}$. Furthermore, the intricate relationships that exist between crops and trees also result in varied microclimates that impact soil temperature, moisture content, and microbial activity, which in turn influences methane and nitrous oxide emissions [18]. This domino effect emphasizes how agroforestry may sequester carbon and minimize the release of other significant greenhouse gases. Kuyah et al. [19] demonstrated that trees played an essential role in creating a more favorable microclimate in 61% of the assessed agroforestry systems in sub-Saharan Africa. Similarly, Niether et al. [14] reported that in cocoa agroforestry systems, shade trees in the canopy diminish solar radiation.

Compared to monoculture systems, the alteration in the microclimate provides an environment with greater stability that is characterized by lower mean temperatures and a buffering impact on the daily maximum and minimum temperatures. In addition, the organized arrangement of trees among agroforestry systems serves as a natural windbreak, hindering wind movement and holding onto soil particles [20]. This is particularly

Figure 2
Multifunctional benefits of agroforestry for global sustainability



pertinent in areas where strong winds or excessive rainfall can cause soil erosion. Furthermore, the interconnected system of tree roots maintains the soil's structure and lessens the susceptibility of topsoil to erosion. Muchane et al. [21] emphasized that agroforestry has a significant potential to improve soil health while reducing soil erosion (up to 50%) compared to conventional monocropping, which highlighted the importance of agroforestry in maintaining ecosystem services. Furthermore, besides reducing silt discharge into lakes and rivers, agroforestry also protects the soil resources and improves the water quality [18]. Thus, agroforestry practices alter microclimates, reduce temperature extremes, and improve crop conditions. Especially in regions prone to heat stress, the shade provided by trees reduces both soil and air temperatures during periods of high temperatures, thus enhancing agricultural productivity (Figure 2). In addition, agroforestry practices can also alter the wind patterns and increase humidity, which impacts the overall availability and distribution of moisture. These microclimatic alterations reduce water use and enhance tolerance to drought conditions [22].

2.2. Biodiversity conservation

The potential of agroforestry for carbon sequestration and CO_2 is scientifically well established; nevertheless, the real potential of agroforestry is in the ability to recover the ecosystem. Agroforestry combines intentionally various layers of vegetation, incorporating forestry trees and ground cover plants that form multifaceted ecosystems, which contain and release a diversity of dwelling organisms such as soil microbes and invertebrates, birds, pollinators, and others [23, 24]. The perennial component, that is, trees in the agroecosystem, provides additional services including nesting sites, food sources, and protective cover, hence promoting the survival and well-being of diverse species. On the other hand, the conventional monocropping system results in habitat loss and biodiversity decline. The previous literature [22, 25–27] has already confirmed that the diversity of species and their richness in association with the agroforestry is higher than in monocropping.

In addition, agroforestry promotes biodiversity in the regions that would be mostly monotonous and thus function as the habitat of the native species [28]. Moreover, the presence of flowering trees can attract numerous pollinators, thus aiding in augmenting the pollination, crucial for sustainable crop productivity and ecosystem health. Varah et al. [29] reported that the agroforestry systems exhibited higher pollinator abundance and diversity in comparison to the monocropping system. This interaction between pollinators and plants is mutually advantageous, since it leads to enhanced crop yield and increased reproductive efficacy for both cultivated and wild flora. Moreover, it also promotes resilience that ensures its ability to recover its integrity after disturbances and maintain it in different states. Moreover, the presence of trees alone provides nesting facilities and attracts some insectivorous bird species, which, in turn, assists in pest management since predators, like these birds, lower the number of insects harassing crops [30]. Finally, establishing agroforestry buffer zones around the forest reserves also offers the creation of safe zones and guards to kill traps. Agroforestry farms function as ecological corridors where animals may migrate and even reproduce, searching and supplying gene flow for the preservation of numerous diverse species in forest reserves. As tropical landscapes become more and more fragmented, the conservation program for these diversified ecological communities should target agricultural lands, cooperating with farmers near forest reserves [31].

2.3. Soil health and nutrient cycling

Agroforestry practices play an important role in improving soil fertility and health by adding the organic matter content through leaf litter and plant material decomposition and root exudates [4]. Akinnifesi et al. [32] demonstrated that planting of the nitrogen-fixing trees in the agroecosystem can increase available nitrogen by over 60 kg per hectare while simultaneously reducing the demand for nitrogen fertilizers by about 75%. Previously, Sileshi et al. [33] reported that planting of the nitrogen-fixing trees considerably increased the yield of maize while ensuring stability in the face of droughts and extreme weather events. Similarly, in temperate agroforestry systems of Europe, the presence of the trees in the agroecosystem significantly increased the soil organic carbon [34]. In the Indian subcontinent, the soil fertility was higher under bamboo-based agroforestry systems in comparison to the sole cropping system, owing to enhanced soil organic matter and water holding capacity [35]. Moreover, agroforestry systems have a closed nutrient cycling, which maximizes the available nutrients while minimizing the nutrient losses. Simultaneously varied composition in these systems leads to accumulation and subsequent decomposition of litter inputs of different qualities, which supports a diverse microbial community and plays a crucial role in nutrient cycling. Researchers [4, 36–39] have shown that agroforestry systems have the potential to improve the availability of soil nutrients and, thereby, increase the nutrient uptake by agricultural crops. This may ultimately result in increased nutrient use efficiency, while the use of inorganic fertilizers may be reduced [40]. In addition, the extensive root systems of trees pump the nutrients from the deeper layer of the soil profile, thus minimizing nutrient stratification and ensuring their availability to crops.

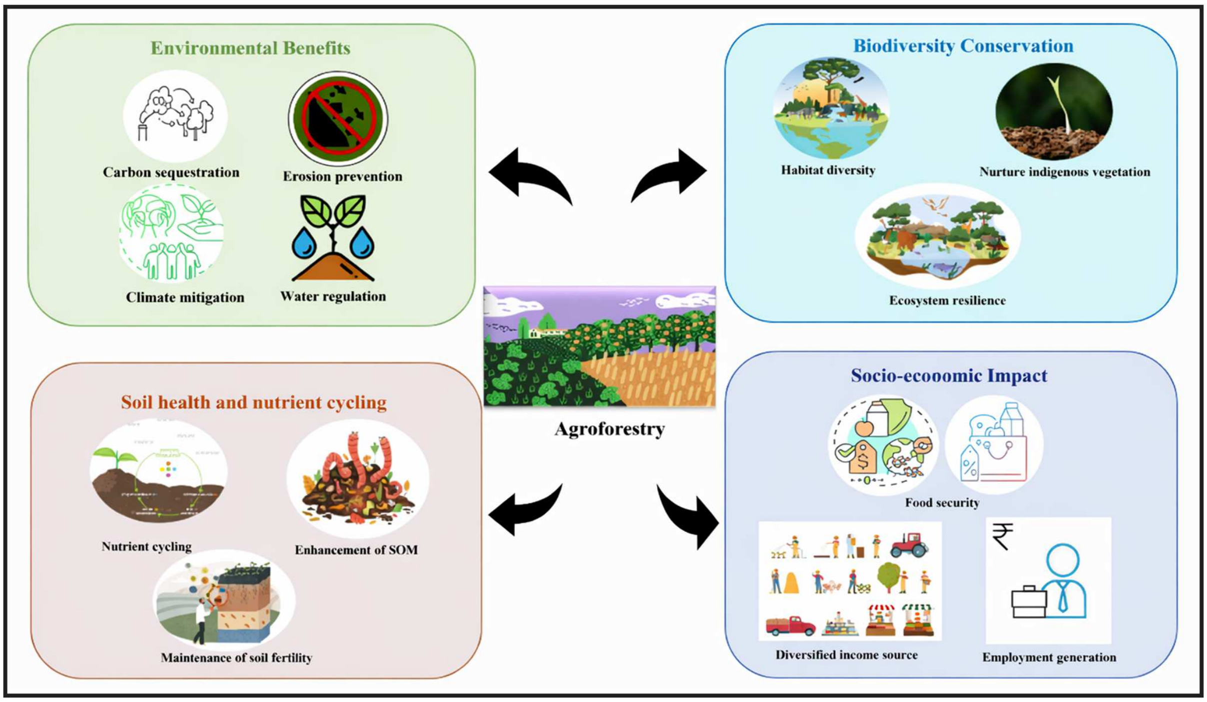
2.4. Socioeconomic impacts

Agroforestry systems provide diversity in terms of income streams as well as vegetation. Crops and trees work together to extend the variety of commodities that farmers may produce and trade. By limiting reliance on marketplace changes of particular crops, farmers' revenue instability is mitigated through diversification. Many research conducted worldwide [41–43] have shown that the availability of multiple sources of revenue contributes to the greater economic stability reported by households practicing agroforestry. Diverse products, which protect farmers from income shocks, such as timber, fodder, fruits, nuts, and non-timber forest products, have become sources of income in addition to traditional crops [44]. Agroforestry also helps to improve food security by combining many crops and products across a single landscape [45]. The diversity of plant species guarantees a steady and varied food source all year. Furthermore, the combination of basic crops, fruits, and vegetables provides a well-balanced diet, making people less vulnerable to malnutrition. Scholars such as Ghosh-Jerath et al. [46] and Soto-Pinto et al. [47] have offered evidence suggesting that households engaged in agroforestry practices have greater accessibility to a variety of food products. This diversity minimizes the demand for outside food sources and improves communities' general nutritional health, especially in areas with poor market accessibility [48]. Furthermore, the diversification of income sources and food supply Furthermore, diversifying sources of revenue and food supply acts as a buffer against failures in crops or market fluctuations caused by extreme weather events, making agroforestry a climate-resilient system that enhances the resilience of rural livelihoods in the face of climate variability and unexpected events. Agroforestry landscapes also provide shade and shelter for livestock, contributing to their well-being. Quandt et al. [49] indicated that communities engaged in agroforestry demonstrated greater resilience during droughts, heat stress, and storms compared to those relying solely on monoculture agriculture. Thus, the multilayered nature of agroforestry systems offers a safety net that ensures the continuity of livelihoods even in challenging climatic conditions [50]. Besides the immediate advantages of agroforestry systems, the carbon created by farmers can be sold in the carbon market, in the voluntary market, which is particularly prevalent in developing nations. Waldén et al. [51] showed that carbon revenue has the potential to boost the profitability of various agroforestry systems in Ethiopia by up to 70%. Similarly, Kumara et al. [16] emphasized that agroforestry systems can provide an additional carbon credit of 68.99–167.26 US dollars per hectare per year. In the meantime, the Uttar Pradesh government made public the launch of the Agroforestry Carbon Finance Project, which has the potential to yield around 4.5 million carbon credits. With an individual valuation of $6 per carbon credit, the overall revenue projection from this project is expected to be Rs 230 crore, which will be provided to farmers, assisting both the objectives of environmental conservation as well as supplementary revenue generation for the agricultural community.

3. Challenges and Opportunities

The constraints and opportunities associated with the adoption of agroforestry practices are closely linked to each other, creating a dynamic landscape for their growth and development. Agroforestry offers several advantages, but its widespread adoption faces several obstacles. Unfortunately, generally agriculture and forestry are considered under separate divisions; however, agroforestry is the combination of forestry and agriculture practices, making it difficult to get recognition as a separate division. One of the foremost challenges in the adoption of the agroforestry systems, especially in African countries, is the issue of land tenure and ownership (Figure 3). Clear land tenure rights are critical for farmers investing in long-term methods such as agroforestry. In many areas, ambiguous land tenure structures and conflicting ownership claims might impede the creation of agroforestry systems [52]. In Uganda, compensating farmers with compensation equal to the timber's value (USD 28 per hectare per year) for not cutting timber trees reduced deforestation by up to 9%. Nonetheless, the absence of legal acknowledgment of land and natural resource rights has hampered the establishment of payment for ecosystem services (PES) programs, mirroring the challenges faced by REDD$^+$ programs [53]. To overcome this, the government and local authorities need to make refinements in the current legislation and policy for defining clear and secure land tenure that recognizes and supports agroforestry practices. Concurrently, the establishment of legal safeguards for agroforestry land and the promotion of long-term land-use planning may establish the foundation for its expansion [54]. Moreover, the existing land-use management paradigm creates a division between agriculture and forestry, which generates doubt regarding agroforestry and establishes institutional barriers. This requires legislative reforms and collaboration among different sectors to incorporate agroforestry into extension activities [55]. Furthermore, effective implementation of agroforestry requires knowledge and skills from both experts to integrate trees and crops, while the inadequacy of extension services hinders the promotion of agroforestry systems at a wider scale. This knowledge gap needs to be bridged by conducting educational programs, on-field and on-farm trials, and extension services to promote the successful adoption of agroforestry practices. In addition, partnerships among research institutions, non-governmental organizations, and local communities can enhance the exchange of knowledge, thus enabling farmers to acquire new skills to design and manage agroforestry systems well suited to their region.

Figure 3
Challenges and opportunities for scaling up agroforestry for global sustainability



Establishing a link between the potential market and agroforestry products is also critical for generating income from these systems. Nevertheless, small-scale producers frequently face challenges in identifying a suitable market for their products, negotiating fair prices, and adhering to quality standards. Numerous nations have firmly established agricultural and forestry policies for their optimum development; however, there is a conspicuous lack of dedicated agroforestry policies, except in India and Nepal, implemented in 2014 and 2019, respectively. Furthermore, despite recognition and inclusion in policies, limited efforts have been made to align agroforestry with other policy frameworks, and no governmental entity has assumed a central role in its implementation. Consequently, this fragmented approach engenders legal, economic, and social impediments, constraining the realization of agroforestry's full potential [55]. Opportunities lie in developing value chains that link agroforestry products to local, regional, and global markets, especially for the high-end value species like sandalwood. With the exception of select products such as rubber, cocoa, and coffee, value chains for non-timber agroforestry products are generally underdeveloped, especially for the indigenous trees. Local cooperatives, farmer associations, and agribusinesses have the potential to provide farmers with microfinance and investment opportunities along with market infrastructure, which can enhance farmers' ability to negotiate for their products. Furthermore, agroforestry practices developed from the ITK and practices that have evolved over the generations [56]. Nevertheless, traditional practices may occasionally clash with contemporary conventional agriculture and forestry practices, resulting in conflicts and obstacles in the adoption of these practices. Fortunately, with the integration of ITK and scientific knowledge, the efficacy of the agroforestry practices can be increased. Simultaneously, effective collaboration among local communities, researchers, and practitioners needs to be established for the development of the novel solutions that consider traditional knowledge while implementing scientific techniques.

4. Scaling Up Agroforestry

Agroforestry symbolizes optimism, adaptability, and association, rather than just a land-use class. Agroforestry has enormous potential; however, to fully harness the potential, some comprehensive and coordinated initiatives need to be taken at the local, regional, and global scales. Efficient regulatory frameworks through incentives such as land tenure rights and tax breaks or subsidies can considerably increase the adoption of agroforestry (Figure 3). Simultaneously, the government can play a proactive role by formulating agroforestry-centric policies for the promotion and realization of future investments in this sector. Moreover, it is necessary to develop a strong Research and Development network by coordinating among research institutions, universities, and agricultural extension services to overcome the technological obstacles while improving the efficiency of agroforestry systems in different ecological and socioeconomic contexts.

Establishment of local institutions, community participation, and collaboration of social capital must be developed for the agroforestry business to thrive. This entails the establishment of agricultural cooperatives and producer organizations in which information can be exchanged between farmers and scientists. Formal science should supplement traditional ecological knowledge, organized training programs on cropping systems and associated topics such as tree management and sustainable practices provide farmers with the knowledge they need to establish and maintain such systems actively. Additionally, to engage in agroforestry, an investment must be made by a spectrum of stakeholders. There is a chance for economic incentives to greatly increase the adoption of agroforestry. Agroforestry participation among farmers can be promoted through PES models, which provide compensation in return for their efforts in carbon sequestration, biodiversity conservation, and watershed protection. In order to successfully expand agroforestry, a comprehensive strategy is needed that incorporates regulatory backing, advancements in research, empowerment of farmers, teamwork, and economic incentives. By harnessing the potential in all of these domains, agroforestry has the capacity to transition from a specialized solution to a global strategy that addresses climate change, safeguards biodiversity, enhances soil health, and empowers communities. By widely implementing agroforestry practices, the collaborative endeavors of governments, organizations, researchers, and farmers may pave the way for a future that is both environmentally aware and sustainable.

Furthermore, building local institutions, active involvement of the community, and establishing social capital are prerequisites for the successful implementation of the agroforestry systems in a particular region. This can be achieved by establishing agricultural cooperatives and farmer–producer organizations, facilitating the dissemination of information among farmers and scientists, and integrating scientific knowledge with ITK. Specifically, training programs based on crop integration, tree management, and sustainable practices need to be imparted to farmers for effective maintenance and management of the agroforestry system. Simultaneously, economic incentives to farmers such as PES models, which offer remuneration in return for their efforts in carbon sequestration, biodiversity conservation, and watershed protection, can boost the adoption of this system. Overall, scaling agroforestry needed a comprehensive strategy that combines policy support, advancement in research, empowerment of farmers, collaboration, and economic incentives. Agroforestry has the potential to transition from being a specialized solution to become a global strategy that can address climate change, declining biodiversity and soil health, and empower the community. The governments, organizations, policymakers, researchers, and farmers need to work together to create a future that is more sustainable and ecologically conscious by adopting agroforestry practices.

5. Conclusion

Agroforestry practices can help attain environmental and social sustainability by enhancing land-use effectiveness and increasing employment, as well as encouraging participation by the local community. Agroforestry is a multidimensional approach that is well placed to achieve the global environmental sustainability objective, which is evident from the reduction of soil erosion practices and microclimate alteration to carbon sequestration and, indeed, climate change mitigation. Simultaneously, in the current scenario of land degradation, imbalanced nutrient application, and growing concerns, agroforestry comes as a potential technology for building a greener future that aligns with SDGs and assures livelihood and food security especially to smallholder farmers. However, scaling up agroforestry practices needs to be effectively and efficiently achieved for the successful harnessing of the potential of this practice. Concurrently, it is necessary to optimize the policy assistance, including legislation, incentives, and regulatory frameworks, with advancements in technology and innovation, extension services, research, and social engagement strategies in agroforestry.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

Kamlesh Verma: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Supervision. **Prashant Sharma:** Conceptualization, Methodology, Software, Investigation, Writing – original draft, Project administration. **Daulat Ram Bhardwaj:** Validation, Data curation, Writing – review & editing, Supervision. **Vaishali Sharma:** Validation, Data curation, Writing – review & editing, Visualization. **Pankaj Thakur:** Formal analysis, Resources, Data curation, Writing – review & editing, Visualization.

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