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Role of Agroforestry for Sustainable Solutions to Climate Change in South Asia: A Comprehensive Review

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Abstract

Agroforestry, or the deliberate integration of trees with fruit crops or pastureland, is a sustainable land-use framework that supports ecosystem services, including climate change adaptation and mitigation. Agroforestry frameworks across South Asia have generally supported many small landholding farmers. In recent years, scientists have focused on agroforestry's potential as a carbon sink. Agroforestry's role in counterbalancing ozone-harming substances, achieving biodiversity targets, localizing sustainable development goals, and providing sustainable livelihoods has increased its importance. Agroforestry can support climate change adaptation by sheltering understory crops from rising temperatures while reducing transpiration, evaporation, and wind speeds through various measures. This review examines a range of agroforestry practices and their benefits for biodiversity and environmental change management in South Asia. This review investigates the key enabling and constraining conditions for mainstreaming agroforestry frameworks to achieve global environmental sustainability. However, deteriorating socio-economic conditions in South Asian countries, rapid population growth, poor planning, and limited access to domestic energy sources to replace fossil fuels have led to a significant decline in Himalayan forests (>60%) over the last three decades. Agroforestry practices have strong potential to mitigate climate change, support adaptation in South Asia, and increase forest cover for environmental management.

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Introduction

South Asia is one of the world's most vulnerable regions to climate-induced hazards. According to the Global Climate Risk Index 2021, most South Asian countries are among the most vulnerable, with low Climate Risk Index (CRI) scores (Fig. 1), adapted from Germanwatch [1]. The region faces various disasters, including intensifying heat waves, floods, cyclones, and droughts, which challenge governments, businesses, and citizens in South Asian countries. Over the last two decades, climate-related disasters have affected more than half of South Asians across eight countries (Bangladesh, Afghanistan, Bhutan, India, Sri Lanka, Maldives, Nepal and Pakistan). Climate change could affect the living conditions of up to 800 million Asians, the most vulnerable populations. South Asia is focusing on many climate-smart solutions, including scaling up renewable energy, innovative community approaches to coastal resilience, and encouraging regenerative forestry [2]. The region's distinctive geography and socioeconomic–demographic composition make it vulnerable to climate change risks. Human-induced climate change is already evident in rising sea levels, shifting monsoon patterns, and increasing extremes [3].

Agroforestry (AF) is a land-use system that combines plant types (trees, fruit plants, shrubs, palms, bamboos, etc.) with crops on the same land-management units, in a specific temporal sequence or spatial arrangement. Agroforestry systems (AFS) are dynamic and characterized by sustainable food production through efficient natural resource management without compromising the environment [4-6]. The economic and ecological interactions among AFS components strengthen ecosystem balance. Agroforestry integrates trees into farms and agricultural landscapes as a natural, dynamic resource management system based on ecological principles [7]. The system sustains and diversifies agricultural production, benefiting all stakeholders economically, socially, and environmentally. Combining trees and/or shrubs with crops and/or livestock maximizes benefits from biological interactions. Extreme weather events, including droughts, floods, and heatwaves, are becoming more common and pose risks to health, agriculture, and water resources [8]. Agroforestry can support climate change adaptation by sheltering understory crops from rising temperatures and reducing crop transpiration, soil evaporation, and wind speeds [9-10]. As a result, Pakistan launched the Green Pakistan Program, a five-year effort to plant 100 million trees to offset climate change impacts [11].

Status of agroforestry in South Asia

South Asia has wide ecological, physical, cultural, genetic, and human diversity. It is home to one-fifth of the global population and is among the region's most vulnerable to climate disasters. Agriculture and pastureland cover 33% of the region's total land. Feeding a rapidly growing population without changing land use is a major challenge, leading to severe food shortages. Intensified and expanded agriculture has driven deforestation and reduced regional biodiversity.

Competition for land resources is intensifying as environments change and the population grows. Agriculture and forest expansion are common types of land conversion, mainly to meet rising food demand. This transformation is expected to continue and will also influence how climate change affects agroforestry. Fig. 2 shows South Asia's future land use, divided into three major sectors: Forest, Agriculture, and arable land. Nepal has the highest forest cover at approximately 41.5%, while Afghanistan has the lowest at approximately 1.8%. Afghanistan has more agricultural land than forest, whereas Nepal has ideal land for both agriculture and forest, supporting sustainable agroforestry with significant potential to improve livelihoods with fewer inputs. Bangladesh (70%), Afghanistan (58%), Pakistan (47%), and Maldives (26%) show, respectively, the highest agricultural land, followed by forest, due to the expansion of croplands for food production to meet the needs of a growing population. The results show that uneven land use affects climate change by increasing GHG emissions from deforestation. Climate change will also affect future

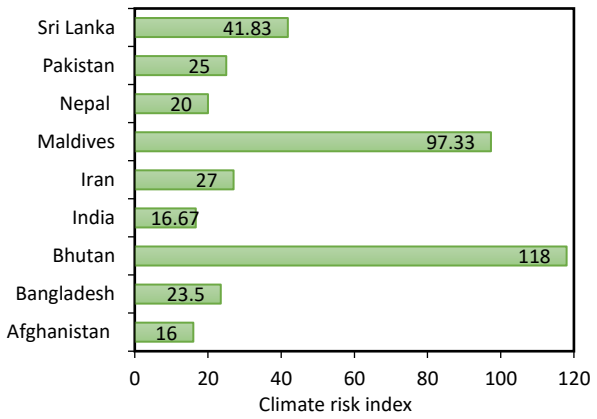


Fig. 1. Climate Risk Index of South Asian Countries [1].

land cover and land use, reducing agricultural productivity [10-11]. As a result, feeding a large population while preserving forest ecosystems and the services they provide is a major sustainability challenge, particularly in South Asian countries.

Afghanistan

Mountain locations provide vital ecosystem services to nearby towns. However, rising resource demands have steadily destroyed biodiverse mountain areas worldwide. Providing alternative, sustainable livelihoods, such as forestry, could support natural regeneration. Agroforestry, or the use of trees on farms, and integrating forestry and agriculture into multifunctional landscapes can bring a variety of economic, social, and environmental benefits. Farmers across the region have implemented various agroforestry systems and methods, boosting farmland production and helping provide food, income, and other basic needs in Afghanistan [13].

Sri Lanka

By providing diversified land-use practices, sustainable livelihoods, income streams, and enhanced forest and agricultural productivity, while reducing weather-related production losses, agroforestry plays a significant role in climate change adaptation in Sri Lanka. Sustainable agroforestry management is essential to helping Sri Lankans who depend on agriculture and forests adjust to the new conditions brought about by climate change. Other important strategies include raising awareness, strengthening technical capacity, and developing policies that support cross-sectoral and landscape approaches. Related sector agencies at the local, national, and international levels must help design and implement agroforestry activities on the ground for climate change adaptation [14].

Pakistan

Pakistan has limited forest resources because its forest cover is small, accounting for only 4.8 percent (4.22 million hectares) of the country's total land area. Compared with state forests, trees grown on private agricultural lands (based on agroforestry/social forestry/community forestry) provide more than 90 percent of fuelwood and roughly 72% of timber requirements. On private farm holdings, trees must be grown alongside agricultural crops. Existing forest cover is insufficient to meet the growing demands of a country that is the world's seventh most populous and Asia's fourth largest. To increase production, increase economic output, enhance environmental outcomes, and maintain societal acceptability, effective food systems are necessary. One approach to achieve these goals is Pakistan's traditional land management system: agroforestry. When trees are planted on private farms, clear timber ownership and well-managed systems can support agriculture while reducing wood shortages. Coordinated extension efforts in Pakistan have developed innovative agroforestry techniques. With the right tree integration on farms, farmers can reduce land degradation, preserve food production, and generate extra revenue. Nonetheless, agroforestry systems and techniques vary and are complex, reflecting centuries of farmer knowledge, experience, and innovation [15].

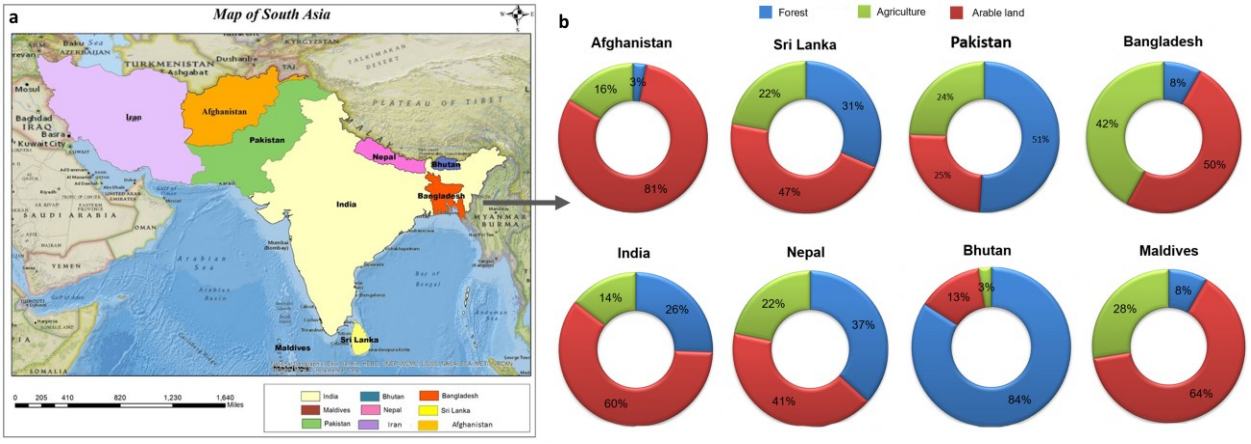


Fig. 2 GIS Mapping of covered land: (**a**) South Asia map; (**b**) major land cover sectors in South Asian countries. In terms of agroforestry, Nepal, Sri Lanka, and India have large forest and agricultural cover, supporting sustainable agroforestry [12].

Historically, traditional AFS have supported millions of small farmers in South Asia. Since 2007, global climate negotiations have debated AF for its potential as a carbon sink. Agroforestry is critical for reducing GHG emissions, ensuring sustainable livelihoods, meeting biodiversity objectives, and achieving SDGs at the regional scale [16]. Agroforestry is vital for improving whole-farm production, enriching soil, and delivering environmental services, including phytoremediation, watershed protection, carbon sequestration, and biodiversity conservation. On salt-affected soils in Pakistan, agroforestry systems (biosaline AFS) are a viable alternative land use. Several tree species are resilient to soil salinity or sodicity, and cultivating them can aid soil regeneration [17]. Many countries in both tropical and temperate zones are now seeing positive agroforestry transitions. During the 1990s, agroforestry cover increased in 38% of the world's countries, primarily in Europe, East Asia, North America, and South Asia [18].

Bangladesh

Farmers in Bangladesh are adopting agroforestry systems to address climate change. Agroforestry approaches based on fruit trees (Mangifera indica or Litchi chinensis) or forest trees (Eucalyptus camaldulensis or Swietenia mahagoni) can help meet a variety of livelihood needs. Agroforestry supports long-term livelihood viability by boosting farmers' knowledge and income, reducing crop-failure risk, maximizing natural resource use, and lowering risks associated with vulnerable livelihoods.

Nepal

Farmers in Nepal use two main agroforestry techniques, which offer more benefits than traditional farming. Although agroforestry has been encouraged to protect forests, traditional practices could be improved to reduce pressure on neighboring forests. Improved agroforestry can boost household income while protecting forests [19]. Agroforestry systems yield higher profits, boosting rural economic growth. Since 2016, Nepal has practiced package-based integrated agroforestry. It combines disaster mitigation, land and water management, and community development to strengthen agroforestry practices. Early results show that the package-based agroforestry initiative successfully builds community capacity. The program's major accomplishments include community sensitization and meaningful engagement in establishing and developing agroforestry methods. The program also encourages tree crop planting, soil and water conservation, and land management activities, positioning this system as a feasible way to expand local livelihood opportunities. Integrated agroforestry methods, which harness agroforestry's benefits and provide adequate opportunities for communities, are closely linked to sustainable land management and ecosystem resilience [20].

India

Government policy and farmers' choices largely shape agroforestry adoption in India, often driven by economic considerations. Agroforestry, in particular, and land use practices generally were affected by legal and policy tools in three ways: (1) direct support for plantation agriculture, which may include agroforestry; (2) indirect support for plantation agriculture, such as land tenure laws that restrict holding size under specific land use patterns; and (3) oblique support for plantation agriculture, such as land tenure laws that adopt commercial timber species like teak, rosewood, and sandal; and (4) market support, technical inputs, and subsidies to promote cashew, black pepper, coffee, rubber, and other cash/plantation crops [21].

Bhutan

Bhutan's agroforestry status is promising but difficult to quantify as a distinct sector. Trees and forests are integrated into rural livelihoods and farming practices in Bhutan, yet evidence on forest stewardship, mixed farming, and organic/low-input farming is much stronger than evidence on dedicated agroforestry adoption rates, programs, or outcomes. According to a 2024 study, Bhutan has 69.71% forest cover, 2.96% of national land is cultivated, and the average holding size is 1.38 ha, with smallholders practicing integrated farming [22]. The same study reports that traditional soil fertility practices include forest leaf litter, dung, crop residues, and farmyard manure or compost. Although these practices demonstrate tree-farm connections, they are not automatically considered formal agroforestry systems [23]. Bhutan's policy and development context strongly values sustainable natural resource management, and community forestry has established an institutional framework for forest management. A national study reported that Bhutan established its first community forest in 1997, and by the time of that study, 23 community forests had been approved. In addition to agriculture, forestry and livestock are considered part of the country's renewable natural resources sector [24].

Maldives

Agroforestry in the Maldives has deep traditional roots, particularly in polycultural home gardens where people cultivate coconut, breadfruit, banana, papaya, mango, vegetables, tubers, and spices together, supporting household nutrition, biodiversity, and livelihoods (Food and Agriculture Organization of the United Nations [25-26]). However, agroforestry remains relatively small-scale and constrained by limited cultivable land, soil and water salinity, climate change, and the country's dependence on food imports [27]. Importantly, the sector is now moving toward formalized, climate-resilient agroforestry development: in October 2026, the government initiated agroforestry farms on 10 islands, integrating long-term tree crops with short-term food crops under the Five Million Tree Planting Program. This transition presents an important opportunity to use agroforestry to advance food security, biodiversity conservation, ecosystem resilience, and sustainable land management in the highly climate-vulnerable Maldivian environment.

Agroforestry: a key strategy for climate change mitigation in South Asia

Mean annual temperature (MAT) in South Asia is expected to rise by 3.5-6°C due to global warming and higher GHG levels in the upper atmosphere. Projections indicate that the Himalayan highlands and western parts of the region will see greater temperature increases than the rest of South Asia [28]. The nation is seeing more droughts and floods, with major ramifications for water supplies, agriculture, and public health. With a population of almost 1.7 billion, South Asia is one of the regions least able to combat environmental change. It also contains four of the world's biodiversity regions of interest and a variety of biomes, from tropical in the south to serene in the north along the Himalayan border. These regions are characterized by high variation and endemism, but anthropogenic land use and environmental change threaten them. For example, rising CO_2-driven woody encroachment compromises South Asian savannas, and unchecked development in northeastern South Asia undermines biodiversity. This unchecked emissions increase has already raised the global average temperature by 1.1°C. IPCC (Intergovernmental Panel on Climate Change) scenarios predict 2.6°C to 4.8°C warming by the end of the 21st century, with most effects likely to occur on land surfaces [29]. Climate change is a major challenge Planet Earth faces today. The agriculture sector alone emits ~6 billion Mt of greenhouse gases [GHGs] annually [30]. Regional variability and uncertainty in climate-change projections, along with increasing vulnerability and limited adaptive capacity, make impacts more damaging and devastating [31-32]. Food security, ecosystem restoration, biodiversity conservation, and achieving sustainable development goals (SDGs) are among the major global challenges the Earth is facing. These issues are closely related to climate change mitigation and adaptation strategies [33]. As natural disasters and climate variability become more intense, frequent, and uncertain, climate adaptation and mitigation are becoming more important [34]. Land improvement and water management strategies are vital to strengthening overall climate resilience [35]. According to the Global Climate Risk Index 2019, Pakistan is projected to be among the countries most affected by climate change [36]. Integrating trees and crops offers several benefits, including carbon sequestration and improved soil fertility. However, carbon storage potential depends on species composition and ecological management systems. Agroforestry is a mutually beneficial approach that balances natural security and human needs. Particularly after the Kyoto Protocol, balancing CO_2 levels has drawn significant attention. Agroforestry is increasingly considered a feasible land-use option worldwide because of its environmental, economic, and social benefits. Consequently, building multi-layered information on agroforestry requires timely, open data on its carbon sequestration benefits and climate-change mitigation risks. Agroforestry can support climate change adaptation by sheltering understory crops from rising temperatures while lowering evapotranspiration, wind speeds, and crop water requirements. Fig. 3 shows the promising benefits and ecosystem services of agroforestry.

Shifts in climatic zone and forest type in South Asian countries

South Asia is one of the regions most vulnerable to climate change. Overall, rising air temperatures characterize past and current climatic trends and variability in South Asia. The intensity and frequency of extreme events in South Asia have increased over the previous century [37]. Climate change poses a major threat to crop yields in food-insecure regions such as South Asia. Expected changes in temperature

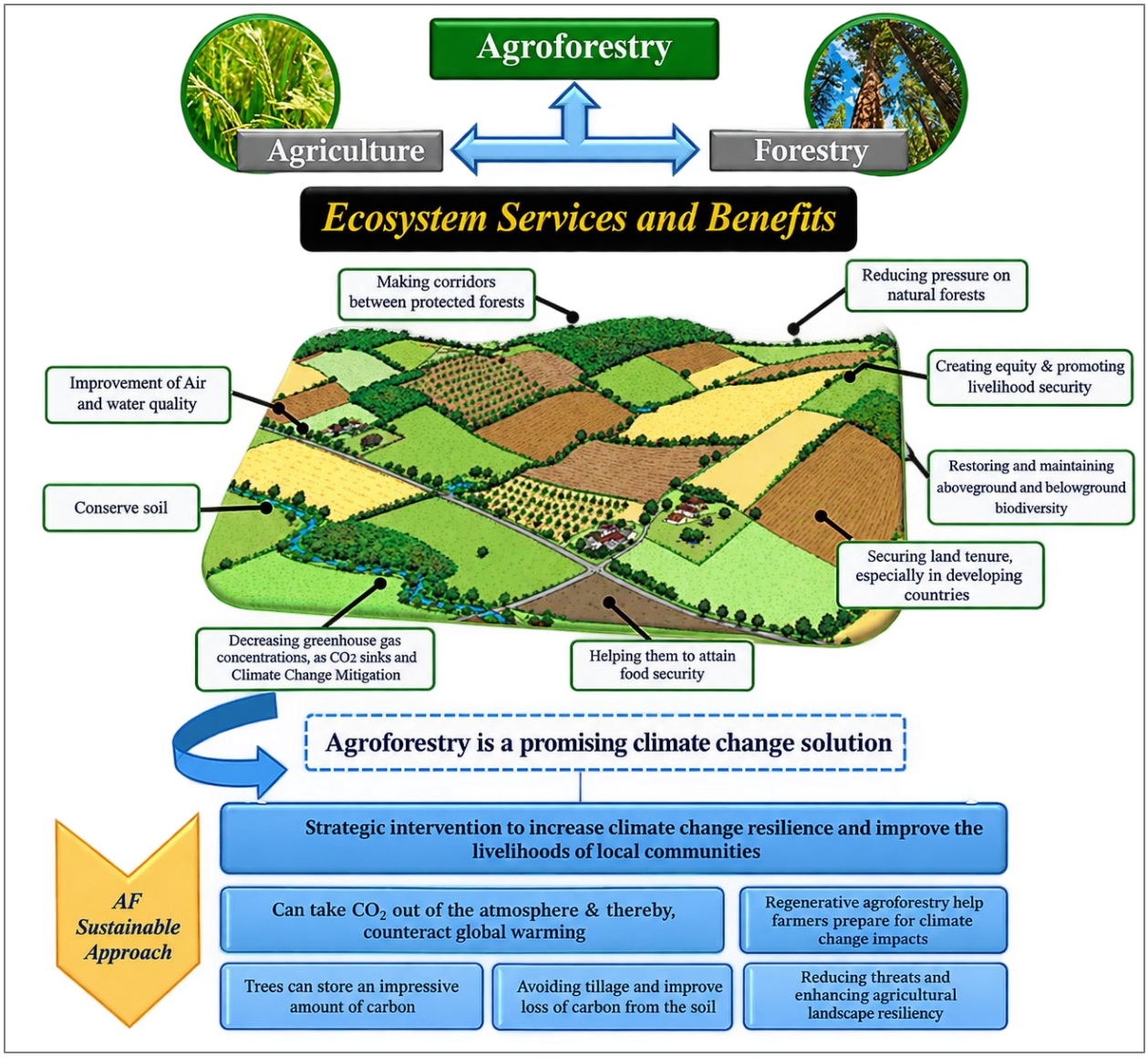


Fig. 3 Ecosystem services and benefits of Agroforestry System [AFS] for adaptation and mitigation of Climate Change Consequences. Agroforestry as a Regenerative System is one of the most promising solutions to counter global warming, help farmers achieve better yields, and address the climate change crisis. The authors created the figure using Microsoft PowerPoint.

and precipitation will shift current agro-ecological zones and significantly affect the feasibility of dryland and irrigated crop production [38-39]. Because climate is a major predictor of agronomic productivity, any alterations will affect crop growth and yield, water balances, input supply, and other aspects of agricultural management.

Future climate data analysis revealed significant changes in temperature and precipitation distribution, which will impact future farming techniques in South Asia. Agroforestry suitability and tree cover mapping would be vital to help agroforestry policymakers in various South Asian countries implement and expand it to new areas in a changing climate [40]. Over the past 40 years, South Asia has experienced a 0.6–1°C increase in mean annual temperature and ranks high on the climate risk index [36]. By the end of the century, temperatures are expected to rise by 2–5°C [according to IPCC projections], which may significantly affect the physiological development patterns of South Asia's forest ecosystems [41]. Climate change affects tree growth worldwide, and predicted climatic conditions are expected to exacerbate these effects [42]. Aridity-based agro-climatic categorization methods help distinguish aridity across diverse agro-climatic locations

worldwide, highlighting potentially significant consequences for the water and agriculture sectors under climate change. Aridity varies across time, space, and scale, and climate change has made it a major issue for the water and agriculture sectors worldwide.

Agriculture is the backbone of South Asian economies, and its increasing vulnerability to a changing climate may drive food insecurity. More intense precipitation, especially during the summer monsoon, can increase flooding. By contrast, drier summers in arid and semi-arid regions can lead to more severe droughts [43]. Delicate mountain ecosystems (Bhutan and Nepal), low-lying coastal areas (Bangladesh and Sri Lanka), and dryland farming (Pakistan and India) face various types of threats. The 2026 flash floods and landslides in Nepal show how vulnerable Himalayan landscapes and their farming communities are to climate-related hazards. The flash floods and landslides that followed a glacier collapse in late August 2026 killed more than 1,200 people and swept away entire villages [44]. UNDP estimated that the floods mobilized about 2.2 million tons of debris, including building materials, vegetation, rock, and sediment [45]. Further hazards followed. Heavy rainfall in late September triggered floods and landslides that killed at least 21 people. In October, a landslide in Gorkha District blocked the Budhi Gandaki River, causing a flash flood that destroyed houses and infrastructure [46-47]. Land management cannot prevent glacier collapse and high-altitude slope failure. However, the damage that floods and landslides cause to mid-hill farmland, settlements, and river corridors depends largely on land cover and land-use practices in the watersheds below. Agroforestry can reduce this vulnerability by maintaining multi-layered tree cover and deep-rooted vegetation on sloping farmland, improving soil stability, reducing surface runoff and erosion, and limiting sediment delivery to rivers. It can also diversify farm income and provide fodder, fuelwood, and timber, helping households recover when disasters destroy crops and assets. The 2026 events therefore highlight the need to integrate agroforestry into watershed management, disaster risk reduction, and climate adaptation planning in South Asia's mountain regions, together with early warning systems and sound land-use policies.

Response of climate change on forest management in South Asia

Climate change significantly affects biodiversity conservation and sustainable forest management, including climate-driven shifts in forest dynamics. To forecast agroforestry responses to global warming, we must better understand agroclimatic interactions and how forests respond. Socioeconomic challenges, supportive governance, and effective agroforestry management are among the most common indirect challenges in agroforestry today. Indirect climate effects on agroforestry include higher mortality rates, variation in growth, and regeneration success, which interact and ultimately affect species distributions. Climate-related disruptions, crop production, natural resource use, and environmental linkages are all direct problems. Environmental disturbances generally act as catalysts, triggering and facilitating processes that alter habitats and modify species and community composition in ecosystems. Direct impacts and indirect consequences seriously affect forest ecosystems. Moreover, delayed and unclear policymaking and management decisions further aggravate climate change impacts on forests [48-49]. Fig. 4 discusses factors that enhance, restrict, and are expected to further develop the adoption of Agroforestry frameworks and advancements.

Consequently, adaptive forest management (AFM) under changing climatic conditions is vital, and contemporary forest management research centers on it [50]. Intensively managed forests produce 10-15 times more trees than unmanaged forests. In the tropics, deforestation has increased afforestation. Improving high-yield plantations is never suitable on intensively managed land. Combined with short-rotation forestry, managed stands should be less vulnerable to the negative effects of climate change.

Climate change and disturbances affect carbon-flow dynamics and forest ecosystem productivity. However, researchers have debated the resilience of even-aged and multi-aged forests to disturbances for over 60 years because of technical measurement constraints [51]. Few studies have examined year-to-year variability and differences in climate sensitivity between canopy layers in uneven-aged temperate forests, even though understanding dominant and suppressed tree responses is essential to forest functioning [52]. Uneven-aged structures that allow the stand to retain high regeneration cover are predicted to make heterogeneous forests more robust to climate change [53]. Several direct and indirect interactions between species and climate change influence tree development in boreal forests. Forest stands are categorized as pure stands, mixed stands, heterogeneous stands, and single-species-dominating stands according to the dominant tree species [54].

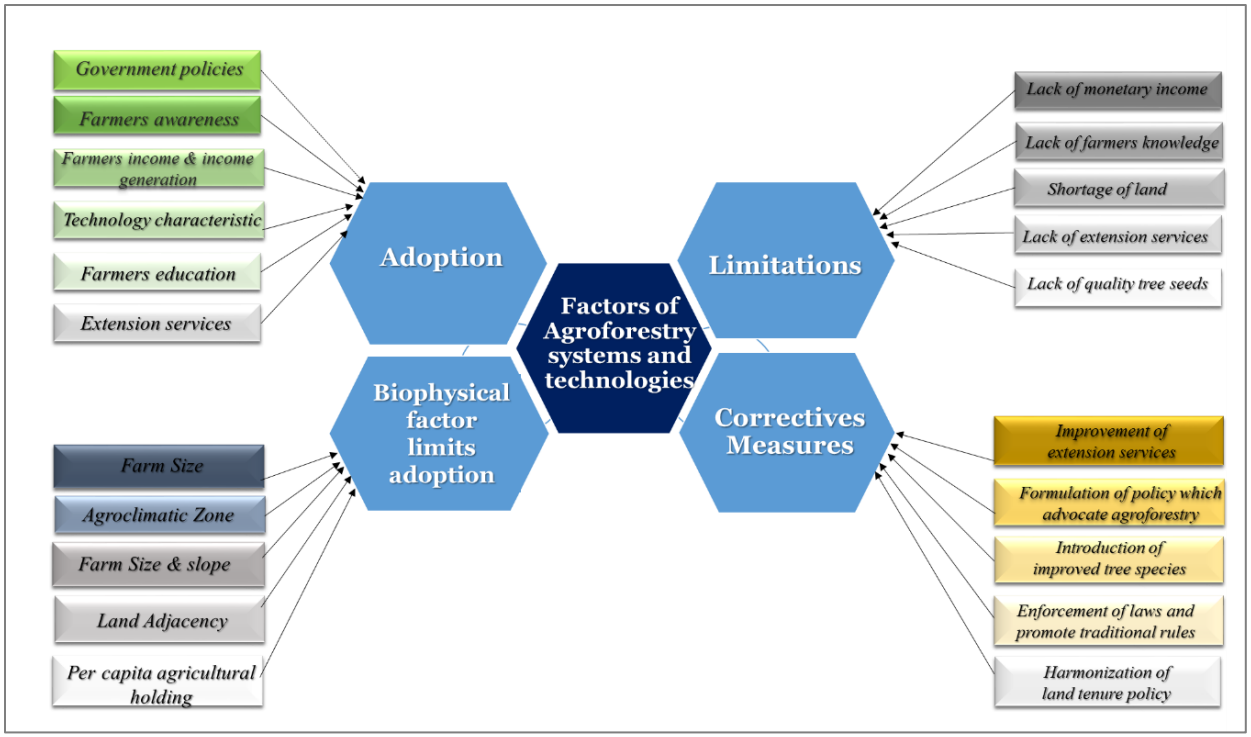


Fig. 4 Factors that enhance limits are required for improving adoption of Agroforestry systems and technologies. Various biophysical and socioeconomic factors affect the intensity of AF adoption and limit farmers' perceptions of its implementation. Corrective measures and long-term investment are needed to enhance adoption and overcome the barriers to spreading agroforestry as a sustainable practice. The authors created the figure using Microsoft PowerPoint.

Recent studies show that even a two-species stand can mitigate climate change effects by increasing and/or maintaining stand production. For example, Chavardes et al. [55] found that trembling aspen was less climate-sensitive than spruce and that black spruce was less vulnerable in mixed stands than in pure stands, with no differences in responses across stand mixtures [55-56]. According to Jourdan et al. [56], Tectona grandis, Shorea robusta, Michelia champaca, and Lagerstroemia parviflora should be the most significant commercial timbers in the Eastern Himalayan area of India, since they may help increase the C sink in agricultural and degraded environments. The species composition of mixed stands obtained through continuous optimization may help, but not entirely, minimize the economic effects of climate change [57]. Considering biophysical interactions between tree species, mixed stands of European beech (Fagus sylvatica L.) and Norway spruce (Picea abies L.) were more robust than block mixes. Intensive management includes controlling planting spacing, stand tending, one or more thinnings, and insect and disease protection and fertilization [58]. Agricultural land expansion and intensification in the humid tropics create strong pressure that drives up demand for forest land [59]. Proactive management techniques are needed to prevent climate change from harming the forest industry. For example, elite plantations can move more freely in the global environment. Instead of using simple inventory strategies and forecasting tools, intensive forest management usually relies on more sophisticated inventory and forecasting methods to plan and schedule forest interventions [59-61]. If managers don't harvest forests before they become overgrown, or if thinning isn't done properly, they become more vulnerable to climate change-induced decline [62]. Managed forests combined with agriculture are known as agroforestry. In most cases, combining livestock with trees planted for fuel, shelter, and shade, as well as fodder or fence posts, is an environmentally sound practice [63]. The American tropics have a long history of success. But in hilly areas, this can lead to serious soil erosion. Eucalyptus-related damage has been reported in East Africa and Ethiopia, and similar issues occur in South America's Andean countries and in South Asia. When crops complement each other, intercropping can substantially increase yields, according to research from the International Research Institute for the Semi-Arid Tropics (IRISAT) [64-65]. Farmers in the central highlands of South Asia benefit from

intercropping in several different ways. They grow fodder, browse, and fuelwood from tree branches [66], as well as coffee beans and seeds, for their cattle. Agbana [67] reports that "Alnus acuminata" has been successfully planted in Costa Rica's dairy region at elevations between 1300 and 2500 meters above sea level, with high rainfall (200 to 300 millimeters) and good soils, for at least 80 years. The trees are planted in pastures that are grazed or cut at wide spacing. There will be a greater need for integrated land-use planning as populations continue to grow so that agricultural and forestry crops can be produced on the same shared land base [68-69]. Root temperature affects carbon partitioning to shoots and roots. Trees in urban areas have grown for 50-100 years under increased warming from the 'urban heat island' effect, and they're still growing. So they differ from the same species in a natural forest because they've evolved in a changing climate. Today's urban forests can serve as useful observatories. Temperate climates favor ornamental species of Acer, Platanus, and Ginkgo because they can withstand urban stress [70].

Forests at high altitudes in North America, Europe, the Soviet Union, and elsewhere are also at the forest's age is determined by its characteristics. This has a greater impact on forests in the establishment and late-maturation phases. Moisture is essential for seedlings to form deep roots and endure future dry periods during establishment. Immature and young mature forests, as well as juvenile forests devoid of non-tree competitors, are more vigorous and thus more resistant to environmental stress. Species at the margins of their natural ranges, including temperate deciduous forests (North America), are also vulnerable. If specific forest components experience severe climate anomalies, an all-aged stand is more likely to retain continuity than an even-aged stand. In this regard, managed forests can serve as an additional risk [71, 72].

Major challenges of agroforestry in South Asia

Although agroforestry has advanced significantly in South Asia, several problems limit its widespread adoption. The following are some of South Asia's most pressing agroforestry challenges;

Farmers' responses to farm forestry

Farmers' responses to farm forestry are largely shaped by their assessment of the economic benefits of tree cultivation [73-74]. Millions of smallholder farmers in South Asia have been supported by traditional agroforestry systems. According to McGinty et al. [75], economic incentives are the most important factor in farmers planting trees on their farms. Similarly, Ali et al. [76] argued that the economic features of innovation directly affect its adoption rate. Farmers' decisions are also influenced by short-term economic and social rewards. According to Zubair and Chris [77], farmers are eager to cultivate trees on their farms even if trees negatively affect agricultural crops because of the large earnings and low costs associated with trees [78]. Farmers lack basic technical information on agroforestry systems and components. These systems are complex and unpredictable, and South Asia lacks locally verified agroforestry technologies. Farmers' limited knowledge about species selection affects agricultural output. Farmers need tree species that grow well alongside crops under realistic management levels, where agroforestry is currently practiced more intensively. However, financial measures must help thousands of smallholder farmers achieve biome restoration goals while supporting rural livelihoods and national food security.

Small landholdings contradictions

The average landholding size in South Asia is less than 3 hectares, although the national average is around 4-5 hectares. This land parcel is insufficient to support commercial forestry farming. Most farmers focus on food production, both for domestic consumption and as a source of revenue. Farmers often worry that tree development on fields harms annual agricultural production. Farmers worry about competition between trees and crops for light, soil, water, and labor. As a result, they are uninterested in planting trees on farmland. Most trees are cultivated on marginal sites unsuitable for annual crops [79].

Land tenure system variability

Land tenure largely determines the success or failure of agroforestry initiatives. Agroforestry on private farmland takes many forms, depending on the land tenure type. Farm forestry is more likely to succeed when the landowner cultivates the farmland himself. By contrast, farm forestry rarely succeeds when tenants cultivate farmland under crop-sharing arrangements because most such arrangements do not include tree benefit sharing with tenants. Approximately 45 % of all farms are administered by renters who are uninterested in tree maintenance and growth and occasionally acquire negative attitudes toward trees on farmland [80, 74].

Marketing strategies and managerial constraints

Tree product marketing is an important part of farm forestry. A lack of markets and access to marketing information has severely hampered the province's tree agriculture. However, this has allowed intermediaries to develop a monopoly in the wood trade and maximize their profits in the agricultural forestry business at the expense of tree growers. Growers have not earned the promised profits from selling trees because middlemen in the wood trade intervened. Social Forestry projects that focused on tree production overlooked the need for efficient marketing of the output. No industry formed to consume farmland timber. Eucalyptus, for example, was promoted primarily for pulp and paper manufacture, but no industry used this vast quantity of wood after the tree reached the harvestable stage. As a result, tree producers were discouraged, and they had no choice but to sell their products at very low rates as firewood. At the local and district levels, tree producers need a platform to access marketing information and contact industries directly to sell their products. Furthermore, the government's introduction of support prices for wood, as it does for agricultural commodities, will help encourage tree growth on farmland ([81-82]).

Shortage of planting material

Planting-material shortages throughout the planting season also hinder farmers. The province has no nursery network. Forest Department nurseries provide most seedlings, but most farmers cannot reach them. These nurseries are either located in wooded areas or lack the materials needed for planting. Farmers lack the knowledge and funding to start their own nurseries and produce planting stock. In social forestry circles, seedlings are rarely so scarce that they become a barrier to tree cultivation, but in Pakistan, nursery scarcity, combined with inadequate access, is a major barrier to farm forestry [83-85].

Lacking the support of public policy

Traditional AFS are sustainable and maintain site resources and biodiversity, but they are not yet underpinned by extensive government legislation [75]. In many parts of South Asia, commodity-centric agricultural and forest policies that promote exotic species have undermined agroforestry's potential as a land-management approach. Despite significant promotion, India has not widely implemented “modern” agroforestry technologies. Few case studies have examined how public policy affects agroforestry dynamics in tree farming. When rising wood demand and greater strain on natural forests emerged in 2001, it was suggested that existing or conflicting standards be updated and harmonized. Pakistan's forest plans (1955, 1962, and 1991) also reflected the importance of farm forestry. However, socioeconomic and technological constraints limited implementation [82]. Most government policies also ignore the environmental benefits provided by agroforestry or by farmers. Most attention focuses on the most profitable crops or trees, while domestic consumption and agro-biodiversity protection are often overlooked. Reorienting public policies on agroforestry is necessary in the global context of food security, climate change mitigation efforts, poverty alleviation efforts, and environmental and biodiversity preservation, as most small-scale farmers and marginal farmers in South Asia still depend on agroforestry for their livelihood

Urbanization

Urbanization is another major challenge for agroforestry in South Asia. Rapid population growth and expanding cities are converting productive farmland, including tree-based farming systems, into housing, roads, industrial zones, and commercial development. This conversion fragments landholdings and shrinks the area available for agroforestry. Rising land values near urban centers also push smallholders to sell or lease their land rather than invest in tree crops that take years to pay back. Rural-to-urban migration reduces the agricultural labor available for tree planting, pruning, and management. Urban growth also increases pressure on irrigation water and degrades soil and air quality through pollution and wastewater, which can lower tree survival and crop productivity. Together, these pressures weaken the long-term viability of agroforestry on peri-urban and fast-urbanizing farmland. To sustain its ecological and livelihood benefits, agroforestry needs to be integrated into land-use planning, productive tree-based farmland needs to be protected, and peri-urban agroforestry models need to be promoted [86].

Other considerations

Numerous factors influence tree cultivation on farms, including settlement location, the presence or absence of natural forest resources, and labor availability. When a settlement is close to a natural forest, farmers are less likely to plant trees on their farmland because they can use the natural forest for their wood needs.

Similarly, a village's proximity to a city reduces interest in farming, as most residents pursue non-farm income. Because labor is scarce, landowners choose permanent crops such as trees, which require less labor than annual crops [80, 87, 88]. Table 1 describes the major challenges and proposed solutions of AF for climate change adaptation and mitigation.

Opportunities for agroforestry in South Asia

Diversification of production, food and nutrition security, and economic viability

Agroforestry enhances food production directly or indirectly by integrating crops and woody perennials [89, 73]. For instance, South Asia's coconut gardens successfully intercrop cereals, tubers, vegetables, and forages to maximize yield. The stratified canopies in agroforestry systems (AFS) create varied light and humidity levels, supporting diverse species [90-91]. These systems supply green manure and livestock fodder, improving food security and diversity [92, 15, 21]. Agroforestry products also provide essential nutrients, supporting nutritional security, especially for vulnerable groups (Table 1). They also provide diverse foods, reduce hunger, and meet the rising demand for organic produce. Agroforestry also generates income and employment for rural communities while supporting food security [74, 93-94].

Carbon sequestration

The carbon sequestration potential of AFS varies widely with tree age, site, and tree/stand management. Agroforestry has great but unexplored potential as a CO_2 offset mechanism. In such environments, more than half of the carbon absorbed by woody perennials is transferred to the soil through root growth and organic matter turnover. According to Saha et al. [95], farmers who adopt agroforestry can sell carbon in addition to other commodities [96]. However, high transaction costs make agroforestry Carbon offset schemes hard to operate [97-99]. As a result, CDM (Clean Development Mechanism) programs dealing with afforestation and regeneration are currently concentrated in South Asia. At the time, only seven afforestation and reforestation CDM projects were registered in India. However, progress has been limited in the other 16 countries in the region for forest carbon, CDM, and Payment for Ecosystem Services (PES) [100].

Traditional agro-ecosystems to conserve biodiversity

Combining integrated, dynamic landscape mosaics with traditional land-use management can support a wide variety of species. Although many of these systems were destroyed during the "development era," South Asian agroforestry remains an excellent example of agro-biodiversity conservation. Outside natural and/or protected-area systems, home gardening systems are recognized as "refuges" for endangered and native species in Bangladesh [101]. However, contrary to some scientists' views, agroforestry may not prevent the extinction of every species in the future. Trees, grasses, livestock, and other living forms may serve as an effective buffer to reduce these losses, particularly in smallholder land-use systems where species packing is often higher than in larger ones [90, 97].

Water quality improvement, reclamation of degraded sites, and soil fertility enhancement

Certain plant species can detoxify contaminated environments by removing or neutralizing pollutants like heavy metals (phytoremediation), offering potential to restore degraded, salt-affected soils. Agroforestry systems (AFS) with woody perennials reduce nitrogen leaching into water bodies [97-98] and minimize sediment loss and non-point source pollution in aquatic ecosystems more effectively than grass buffers [102-104]. Tree biomass (litter, roots, and green manure) enhances soil organic matter. Deep-rooted trees act as a "safety net," absorbing excess nutrients that would otherwise be lost to runoff and significantly reducing soil nutrient depletion compared with treeless areas. Additionally, trees aid in bio-drainage by extracting excess water, which is particularly beneficial in saline soils, and prevent wind erosion in arid regions [105]. Thus, agroforestry plays a vital role in rehabilitating wastelands, including deserts, ravines, and gullies.

Socioeconomic implications of climatic changes in the forest sector

Forest products mostly rely on roundwood production, a common industrial byproduct of forestry. The majority of this is used for paper and pulp (northern countries). However, in the tropics, high-quality lumber also competes for market share. Tropical nations extensively use teak/mahogany and other precious hardwoods [106]. Several researchers have examined the socioeconomic implications of

Table 1 Contribution and role of agroforestry in climate change mitigation and adaptation.

Functions	Role of Agroforestry in Mitigation and Adaptation	Reference
Carbon sequestration	Accumulate Carbon in woody biomass Accumulate Carbon in soil	[77] [139] [97] [144]
GHGs emission	Reduction in fossil fuel consumption Decreased emissions of GHGs like CO_2, N_2O, CH_4	
Increased resilience	Improved products [quantity and quality] Foster diversified production opportunities Increase structural and functional diversity Increase habitat diversity	
Reduced natural threats	Resilience against extreme weather events Stress reduction for local flora and fauna Serve as ecological corridors [for wildlife mobility]	
Species' migration	Provide travel corridors for species migration	[90-91]
Anthropogenic activities	Reduce CO_2 emissions through afforestation Proper forest management and regeneration Strong policies and legal protection against encroachment into forest reserves Sustainable urban development Extend and construct roads Reduce combustion of fossil fuels Reduce deforestation for fuelwood Increased plantations development Increase the amount of forested land	[9] [136] [137]
Agriculture	Improved farming practices Improved farming system sustainability Reducing farmers' vulnerability to climate Improving nitrogen fertilization Decreases the soil CH_4 sink	[9]
Tree plantations	Provide shade for companion crops Provide shade to the farmer against rising temperatures Shelter the crops against the harmful effects of raging storms Ensures income diversification Maintaining environmental services Accumulate CO_2 in their biomass	[81] [88]
Land use	Sustaining higher total yield through a combination of food crops Improved farm productivity Improved environmental sustainability Improved living standard Conservation of water and soil Ensure food security	[74] [81]
Role of Farmers	Increased yields Improved pollinator Improved Wildlife habitats Increased adaptation capacity against climate change Climate-resilient crop varieties Better crop management practices Rice-duck farming to mitigate GHG emissions Reduce dependence on agrochemicals	[73-74]

anticipated climatic change on forests and the forest sector. It would grow significantly, while growth rates in other forests would increase only slightly [107-109]. As industrial profitability rises, timber prices and harvest are expected to decline. New investments in production capacity would be directed there, increasing inventories in South Asian forests. This would reduce global timber prices. Generally, boreal forests would see a net increase in wood income, while lower prices and reduced harvest quantities would cause a net drop in timber income [110]. Natural (or semi-natural) ecosystems provide multifaceted ecological services, including environmental benefits, material provision, and psychological welfare [111-113]. As an important traditional land management practice AF on croplands, it provides diversified socio-economic, regulatory, and ecological advantages for climate

change adaptation [114-115]. Traditional AF systems in the South Asian subcontinent are designed to harness diverse benefits for human well-being [116]. In addition, a well-managed, multifunctional, sustainable AF supports diverse ecological functions. It is increasingly important to develop adaptation plans that consider regional and local environmental and cultural conditions. In low-income countries [Nepal, India, and Bangladesh], smallholder farmers are vulnerable to climate change because of poor infrastructure, physical isolation, low productivity, limited access to global markets, and a lack of official safety nets. Agriculture in these countries aims to be highly climate-resilient while also boosting yields to feed a growing population [117]. Although the need is significant, intensively managed forests can mitigate many of climate change's expected negative effects.

Global trend of agroforestry as a sustainable technique

Food security for the world's enormous and still-growing population and climate change mitigation are two major issues. To address these challenges, we need more varied, multifunctional agricultural systems. As a result, agroforestry has become a hotspot in scientific inquiry in recent decades as a sensible land management technique [118]. Researchers have studied agroforestry extensively worldwide as a sustainable production technique. However, because climates, geography, history, and economies vary widely, agroforestry research worldwide has become uneven, with distinct regional characteristics emerging. Agriculture, farming, and ecosystem health are in peril worldwide. Major planetary boundaries have already been exceeded as a result [119]. Agriculture and food systems will almost certainly need to transform to meet food production needs more sustainably in the coming decades. This is especially true worldwide, where climate change, population growth, local inequities, and developments in trade and industry create complex and often intractable challenges in rural landscapes. In this scenario, agroforestry and sustainable landscape management are key strategies for achieving the United Nations' Sustainable Development Goals in agricultural landscapes worldwide [120-121].

Agroforestry provides both tangible and intangible benefits to the Indian economy. On the one hand, it helps restore degraded fields; on the other, it boosts farm productivity. Agroforestry priorities are shifting toward biofuels, job creation, carbon sequestration, and optimizing farm productivity. Agroforestry is the only way to expand forest cover to 33% from less than 25% [16]. In underdeveloped nations like Nepal, agroforestry is often seen as a practice that gives farmers economic opportunities to meet subsistence needs [122-123] and benefits local agricultural communities in Bangladesh, Sri Lanka, the Philippines, and Kenya [124-126]. In Nepal's hills, widespread deforestation and more intensive land use to support a growing population have increased soil erosion, lowered soil fertility, and reduced agricultural output. This has raised concerns about the sustainability of the hill farming system. Growing evidence suggests agroforestry could help address these issues [127].

Climate change has already worsened water difficulties in some regions of Somalia and Kenya, and it is expected to worsen water shortages in new places, particularly in West Africa [128-129]. This could displace entire populations, straining the remaining land. Developing nations would bear the brunt of the consequences, particularly countries like Tanzania, where agriculture provides a living for over 80% of the people. Worldwide assessments estimate agricultural production will decrease by up to 10% by 2050 due to climate change. Tanzania's 2007 National Adaptation Program of Action Report predicts maize output reductions of up to 84% in the country's arid regions. These changes put agriculture at a crossroads, even though expanding agriculture in emerging areas is critical for poverty reduction and food security [130]. Despite these obstacles, agricultural technologies such as agroforestry offer ways to address them. Encouraging adoption of these agricultural technologies matters because they are typically low-cost, improve livelihoods, and reduce negative environmental impacts [131].

Climate change mitigation/ adaptation potential of agroforestry

Climate variables largely determine carbon sink productivity and can disrupt biological processes such as forest structure, phenology, nutrient cycling, carbon storage potential, and species development rates and distributions [132]. Forest biomes provide enormous ecosystem functions for carbon sequestration, helping mitigate climate change. Because of their distinct characteristics, primary forest biomes (tropical, temperate, and boreal) respond differently to changing climatic conditions and differ in mitigation potential [133-134].

Table 2 Major challenges to agroforestry and their potential solution reported by various scientific studies.

Category	Challenges	Solution	References
Indirect (challenges and solutions to Agroforestry)	Socio-economic viability	Promote cooperative management Develop "safe economic routes" for profitable AFSs. Diversification and value addition of AF marketable products. Introduction of strategies to ensure income generation Promote the social value of AFS for local communities. Establish and strengthen coordination and networking among farmers, markets, and end-users Highlight success stories and local innovations to change farmers' perception of AF Establishment of local markets for AF products. Branding of AF Products and trademark improvement Introduction of incentives and payment schemes for ecosystem services.	[139-141] [95]
	Supportive governance	Launch of public subsidies and increased access at spatiotemporal scales. Provision of better and flexible payment strategies Introduce better incentives for high performers. Launch of awareness campaigns and improved communication regarding AF benefits to all stakeholders Improved government employees' assistance in the field Improved land ownership schemes Clarification and flexibility of regulations (e.g. matching permits for tree and crop management) Improved eligibility criteria for AFS in the CAP Pillar I. Legal recognition of diverse AFSs	[96] [35] [41]
	Adequate management	Description of best practices and collection of data for benchmarking. Establish demonstration farms to evaluate and showcase innovations and achievements. Prepare manuals and brochures on AFS establishment and relevant technical guidelines Form training programs for AF managers aimed at capacity building, training and information exchange Develop and design a web portal to collect and disseminate information, knowledge, experiences, and success stories. Design and conduct evaluation trials to select suitable species at the regional level, incorporate them into existing cropping systems, assess the potential of intercropping and crop rotations, and meet regional food, feed, and industrial requirements. Design and conduct research activities to select suitable management practices and species for non-chemical and biological management of diseases, pests, and wildlife. Model and simulate ideal planting geometry to maximize financial output without compromising the natural environment. Research to use technologies to develop appropriate farm machinery that can fulfill AFS's various needs. Improved strategies for tree protection against various abiotic and biotic stresses Incorporation of legume species as intercrops Development of multipurpose hedgerows.	[41]
Direct challenges and solutions to Agroforestry	Climate change	Adoption of management strategies to improve soil organic carbon SOC. Develop simulations, models, and other advanced technologies to better understand and maximize C sequestration potential and wood production from AFS. Intercropping with leguminous plants. Innovative practices to use tree species acclimatized to diverse climatic conditions, with increased tolerance to diseases and livestock. Introduce adapted tree varieties with the potential to produce high-quality timber.	[74] [15] [92][21]
	Crop production	Select suitable species and design optimal crop rotation and intercropping options to maximize yields and livestock capacity, adaptable to a wide range of climatic conditions. Develop and maintain multifunctional windbreaks and hedgerows with trees and shrubs. Development of models to integrate diverse marketable products.	

Natural resource use	Introduce grass mixes that tolerate shade and support foraging in low-competition combinations. Improved pastoral management and precision grazing. Trees have a vital role in nutrient cycling and N fixation. Comparison of nutrient cycling capacity of different rotations of main and cover crops having different rooting depths. It will slow nutrient depletion. Multi-story AFS intercept and harvest solar radiation at different levels, maximizing radiation use efficiency AFSs increase soil water-holding capacity and water infiltration and reduce runoff, hence improving water use efficiency.	[142]
Environment for sustained Production	The microclimate developed in AFSs reduces light penetration to the soil, inhibits water losses such as evaporation and transpiration, and conserves moisture, keeping conditions optimum for diverse aboveground and belowground biota. Tree plantations as windbreaks provide favorable conditions for crops, increasing yield quantity and quality. Windbreaks protect crops from abiotic stresses [damaging winds, extreme heat and cold, soil erosion, soil drying] and biotic stresses [pests, diseases]. Roots of undisturbed trees, crop and cover crops, and mycorrhizal systems improve soil physical and chemical properties, reduce nutrient leaching, bind soil, and inhibit erosion. AFSs host diverse biota and enhance biodiversity, providing ecological services and maintaining a delicate balance across trophic levels (autotrophs, pests, predators) in the ecosystem.	[59]
Environmental improvement	AFS reduces pressure for forest products. Agroforestry extends habitat and supports biodiversity for flora and fauna (macro and micro) Agroforestry improves nutrient, soil, and water conservation AFS reduces GHG emissions by increasing carbon sequestration. Enhanced nutrient cycling increases nutrient availability and reduces nutrient losses, lowering the need for nutrient supplementation through inorganic fertilizers.	[143]

Mangrove extent, variability, and richness in South Asian countries are unparalleled. The Sundarbans, one of the world's largest mangrove ecosystems, is located in this region. South Asian countries are also vulnerable to tsunamis and tropical cyclones, and mangrove forests serve as the primary protective barrier against these hazards [135]. In agricultural lands, forests can provide benefits by planting trees along crop peripheries. In Pakistan, 22.15 mha is under agricultural production; 10% of this area can be utilized for tree plantation without compromising agricultural production. A viable approach to preventing deforestation is to promote AF by raising farmer awareness. Trees play an important role in managing erosion and pollution. Trees also provide vital resources for human needs (food, feed, medicines, wood, etc.), environmental services (enhanced soil fertility, soil and water conservation, shade), and income for farmers [136-138]. Farmers in Pakistan have long regarded trees as a crop for desolate terrain. However, the current state of AF and the challenges farmers encounter in implementing it at the grassroots level can be improved. Table 2 presents the valuable contributions to climate change adaptation and mitigation extensively reviewed in various studies.

Conclusions and Recommendations

Agroforestry systems offer secondary environmental benefits, including supporting food security and secure land tenure, increasing monetary benefits, and restoring and maintaining biodiversity and carbon sinks, making them a preferred approach for climate change adaptation and mitigation in South Asia. Agroforestry reduces demand for wood and protects natural forests. South Asia has significant potential for agroforestry development, despite many obstacles and challenges. Plantations on farmland are a practical option to increase wood production and reduce pressure on natural forests. As the population grows, so does the need for fuel, wood, and lumber. Foresters are now getting better returns on their trees because of improved wood marketing. Collaboration among forestry and agriculture departments, along with other stakeholders, can increase agroforestry adoption. Farmers should adopt advanced agronomic techniques, such as regenerative agroforestry and adjusted planting geometry. Select and regenerate tree species that play a key role in mitigating climate change. South Asian countries should promote and share emerging techniques in the forest and agriculture sectors.

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Conflicts of Interests

The authors share no competing interests in the preparation of this manuscript.

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