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Agroforestry: A Multifunctional Landuse System for Sustainable Agricultural Production under Climate Change Scenario

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

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ABSTRACT

Climate change is a serious issue for the entire world threatening the agricultural production systems. The sustainability of food production and other agricultural products is a big question for coming days and hence the survival of man and other organisms in future. Agroforestry, if properly implemented, is capable of providing solutions to many problems related to climate change. It is a resilient land-use system which mimics nature's design, contributes to 9 out of 17 UN's sustainable development goals (SDG). Its multifunctional ability makes agriculture climate-smart and provides

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enormous goods and services to society. It has potential to enhance overall productivity of agricultural land (10-100%), reduce the burden of carbon release from agricultural sector (1-25 Mg C ha^{-1} $year^{-1}$), improve physico-chemical properties of soil, improve nutritional security, reduce poverty, create resilient livelihood, improve water quality, enhance biodiversity, lower the use of agrochemical, support industrial growth, generate employment, provide healthy food, promote rural tourism, provide comfortable working environment, save natural forests, etc. For deriving maximum flow of agricultural benefits from lands and combat climate change issues, different agroforestry systems should be practiced as per the potential of land capability classes. Agroforestry has also many challenges for its wider adoptability. Suitable policies and actions should be taken at local, national and international level to promote agroforestry as a tool for sustainable agricultural production in the scenario of climate change.

Keywords: Agroforestry; climate change; sustainable agriculture; landuse; land capability class; resilience.

1. INTRODUCTION

Climate change stands as the most pressing global challenge, endangering human life and ecosystems alike. Its effects, now accelerating worldwide, include erratic rainfall patterns those lead to droughts, heat waves, and floods. As extreme weather events become more frequent and severe, farmers are increasingly affected, facing significant challenges in managing agricultural crops, livestock, soil, water resources, and rural communities. Currently, the Earth's surface temperature is approximately 1.2°C higher than it was in the late 1800s, prior to the industrial revolution. The last decade (2011-2020) was the warmest recorded, with each of the last four decades surpassing all previous ones since 1850. The adverse impacts of climate change pose considerable risks to agriculture, manifesting in unpredictable temperature fluctuations and varying water availability, leading to both excessive rainfall and drought.

Agricultural production systems are particularly sensitive to climate and weather changes, relying heavily on land, water, and other natural resources those are directly affected by these shifts. Additionally, the agriculture sector contributes significantly to greenhouse gas emissions, exacerbating climate change. The primary gases responsible for this include carbon dioxide and methane. Agricultural practices contribute to global warming through nitrous oxide emissions from fertilized soils, methane released by livestock, and carbon dioxide from burning fields. According to the UN Food and Agriculture Organization, agriculture accounts for about one-third of global greenhouse gas emissions. Food systems are the leading contributors to methane emissions and biodiversity loss while consuming around 70% of freshwater resources. Alarmingly, emissions from agriculture are rising in developing countries, a trend that must be reversed. Without substantial climate mitigation efforts within the agri-food sector, achieving the goals set by the Paris Agreement will be unattainable. Agriculture also plays a significant role in deforestation, particularly in pristine ecosystems like the Amazon and the Congo Basin. If no action is taken, emissions from food systems are expected to rise further as food production increases.

In the above scenario of global food production system, climate smart agriculture practices are required which simultaneously boost productivity, enhance resilience and reduce GHG emissions. One of the climate smart agricultural systems is Agroforestry. Agroforestry is a collective name for land use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same piece of land management unit as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economical interactions between the different components (Lundgren & Raintree, 1982). Its role for sustainable agricultural production under scenario of climate change is discussed here.

2. AGROFORESTRY AND SUSTAINABLE DEVELOPMENT GOALS

Sustainable solutions to both modern agriculture and forestry may lie within the multifunctionality of agroforestry systems (Wilson & Lovell, 2016)], that provides a broad range of sociocultural, economic and environmental benefits.

Agroforestry, a resilient land-use system that mimics nature's design, contributes to 9 out of 17 UN's sustainable development goals (SDG) (IISD, 2018). These goals concern poverty reduction (SDG1), hunger alleviation (SDG2), health and well-being (SDG3), gender equality (SDG5), access to clean water (SDG6), sustainable energy solutions (SDG7), responsible agriculture (SDG12), climate action (SDG13) and biodiversity conservation and sustainable land management (SDG15). Therefore, agroforestry is an important land use system for the entire world for sustainable development.

3. MULTIFUNCTIONALITY OF AGROFORESTRY LANDUSE SYSTEMS

Agroforestry performs multiple functions related to sustainable agricultural production in the scenario of climate change. The major functionalities of agroforestry are discussed below.

3.1 Agroforestry Enhances Farm Productivity

Agroforestry significantly boosts farm productivity by integrating trees, crops, and/or animals within the same farming unit. This approach enhances resource use efficiency, leading to greater overall productivity and sustainability compared to traditional monoculture systems. The benefits of agroforestry are particularly evident in regions with high temperatures, where the interplay of temperature and humidity can hinder the optimal use of solar radiation by annual crops, unlike trees and forests. In agricultural settings, practices such as repeated plowing can deplete nutrients from the topsoil during monsoon seasons, resulting in reduced soil fertility due to accelerated decomposition of organic matter and denitrification. Additionally, soil erosion in monoculture farming can lead to significant nutrient loss. Conversely, trees effectively utilize solar radiation throughout the year, making forestry systems more productive than conventional agriculture. They also help maintain soil fertility by recycling nutrients, mitigating soil erosion, and preventing nutrient leaching. Certain leguminous tree species can fix atmospheric nitrogen, contributing to soil fertility through leaf litter that enriches the soil. The integration of crops with trees thus enhances land productivity. For instance, Bado et al. (2021) noted that in West Africa's Sahel region, smallholders who intercropped millet with Ziziphus trees at a density of 80 plants per hectare saw improved agricultural yields and incomes. Jiru (1998) documented grain yield increases of 101%, 67%, 40%, and 12% for sorghum, maize, wheat, and teff, respectively, when intercropped with *A. albida* in central Ethiopia.In Uttarakhand's terai region, taungya cultivators achieved higher yields of maize, wheat, and pulses in leased lands without fertilizers compared to traditional agricultural fields. Verinumbe (1987) found that dry matter yields, especially for maize and sorghum, were higher in forest-influenced soils in the Sahel than in conventional agricultural soils. In semi-arid Africa, intercropping with species such as *Leucaena leucocephala*, *Gliricidia sepium*, and *Cassia siamea* as hedgerows, combined with their prunings used as mulch and green manure, resulted in 30-40% higher maize yields (ICRAF, 2088). In Haryana and western Uttar Pradesh, agroforestry systems yielded approximately 20% more grains and wood compared to pure agricultural practices (Dwivedi & Sharma, 1989). Farmers in these regions planted Eucalyptus hybrids and *Populus deltoides* along field boundaries, and while crops near tree rows showed reduced growth, the overall yield of crops and wood combined exceeded that of conventional farming without trees. Research from IGFRI in Jhansi, India, indicated that integrating fodder grasses with fodder trees resulted in higher total yields than cultivating fodder grasses alone (Deb Roy, 1990). Additionally, *Leucaena leucocephala* intercropped with other agricultural crops and fodder grasses enhanced the total yield of food, fodder, and fuel (Pathak, 1989; Tiwari, 1970). Finally, integrating livestock with tree plantations has proven to be more profitable than traditional cropping methods (Fig. 2).

3.2 Agroforestry Makes Agriculture Climate-smart

Climate change is a significant environmental challenge stemming from unsustainable agricultural practices, including the excessive use of fertilizers, tillage, and deforestation. In recent years, the potential of agroforestry to mitigate and adapt to climate change has garnered considerable attention. The United Nations Framework Convention on Climate Change (UNFCCC) recognizes agroforestry as a key practice for climate mitigation, with 40% of developing nations incorporating it into their climate change strategies.

Fig. 1. Wheat cropping under Poplar plantation

Fig. 2. Poultry farming under Poplar plantation

Integrating trees into agricultural landscapes can reduce the impacts of climate change on farming while also minimizing agriculture's contribution to the problem. This can be achieved through several mechanisms:

a) **Sustainable Wood Production:** By sourcing wood products from on-farm trees, the need to harvest trees from natural forests is diminished, helping to lower deforestation rates—one of the primary drivers of climate change.
b) **Nutrient Management:** Improved management of soil nutrients can decrease reliance on chemical fertilizers, which are a significant source of greenhouse gas emissions.
c) **Carbon Sequestration:** Trees in agroforestry systems play a crucial role in capturing carbon dioxide from the atmosphere. Research indicates that various tree species are effective at sequestering greenhouse gases. For instance, a mature poplar tree can sequester approximately 266 kg of carbon, while green ash captures about 63 kg, white spruce approximately 143 kg, and caragana around 39 kg. When considering recommended spacing for shelterbelts, these amounts translate to 106 tonnes per kilometer (t/km) for poplar, 25 t/km for green ash, 41 t/km for white spruce, and 26 t/km for caragana. It is important to note that the carbon stored in the roots can equal roughly 50% of the above-ground sequestration figures.
d) **Carbon-Neutral Energy:** Utilizing wood fuel from agroforestry systems allows communities to meet their energy requirements in a manner that is carbon neutral.
e) **Microclimate Benefits:** Trees provide shade and cooler environments for sensitive crops and livestock, helping to maintain or even enhance yields despite the challenges posed by climate change, thereby increasing agricultural resilience.

The potential for carbon sequestration in various agroforestry systems in India is summarized in Table 1.

3.3 Agroforestry Enriches Soil

Agroforestry significantly enhances and sustains long-term soil productivity through various mechanisms. In tropical systems, the integration of nitrogen-fixing trees alongside crops is common, but even non-nitrogen-fixing trees contribute by adding organic matter, which enhances soil properties and recycles nutrients. Key benefits include reduced soil and nutrient loss due to decreased runoff, carbon addition through organic matter, nitrogen enrichment, improved soil conditions (like water retention and drainage), and enhanced microbial activity (Dwivedi, 2012).

Tree density influences these effects; for example, tree canopies mitigate raindrop impact and create favorable microclimates. Vegetated watersheds experience less soil erosion compared to cultivated lands, with soil water infiltration rates in forests being three to five times higher than in agricultural areas (Sinha, 1975; Ghosh, 1974). Nitrogen fixation rates in some species range from 50 kg to 500 kg per hectare, and leaf litter contributes substantial nutrients between 150 kg to 300 kg of nitrogen, 10 to 20 kg of phosphorus, 75 to 150 kg of potassium, and 100 to 300 kg of calcium annually. This nutrient recycling can significantly reduce fertilizer requirements. Furthermore, mycorrhizal associations formed by tree roots aid in nutrient and water absorption while enhancing soil biochemical activity.

Forests can increase annual precipitation by 5 to 15 percent, enriching nutrient supply through rainfall (Ovington, 1965). Trees with deep roots recover nutrients lost to leaching and return them to the surface via litterfall, which also releases nutrients back into the soil. Although some nutrients are lost to water bodies, trees can absorb newly weathered minerals from lower soil layers, enhancing soil fertility (Vergara, 1982). Additionally, tree shade reduces evaporation, potentially decreasing irrigation needs by up to 30 percent (Sharma, 1988).

Table 1. Carbon sequestration in different agroforestry systems in India

S. No.	Agro-climatic zones	Agroforestry system	Carbon sequestration potential (Mg C ha^{-1} year-^{1})	References
1.	Western Himalayan Region	Agri-horticulture (*Prunus armeniaca*+ *Ocimum sanctum*)	1.80	Handa et al. (2020)
		(*Prunus persica*+ *Ocimum sanctum*)	2.0	
2.	Eastern Himalayan Region	Silvipasture (*Morus alba* + *Setaria anceps* grass)	1.55	Handa et al. (2020)
3.	Lower Gangetic Plains Region	Agrisilviculture (*Eucalyptus tereticornis*+ rice-wheat)	10.7	Sirohi & Bnagrawa (2017)
4.	Middle Gangetic Plains Region	Agrisilviculture (*Tectona grandis*+ sorghum/ groundnut)	2.32	Handa et al. (2020)
5.	Upper Gangetic Plains Region	Agrisilviculture (*Dalbergia sisso*+ mustard)	2.83	Newaj et al. (2012)
6.	Trans-Gangetic plains Region	Agrisilviculture (*Populus deltoides*+ wheat/potato/turmeric)	9.12	Chavan et al. (2022)
7.	Eastern Plateau & Hills Region	Agrisilviculture (*Albizia procera*+ wheat)	5.70	Newaj et al. (2012)
8.	Central Plateau & Hill Region	Agrisilviculture (Acacia + greengram-mustard)	3.70	Newaj et al. (2008)
9.	Western Plateau & Hills Region	Agrisilviculture (*Ailanthus excelsa*+ cowpea-mustard)	9.64	Handa et al. (2020); Handa et al. (2019)
10.	Southern Plateau and Hills Region	Silvipasture system (*Leucaena leucocephala* + *Gliricidia sepium* + *Stylosanthes hamata*)	23.2	Handa et al. (2019)
11.	East Coast plains & Hills region	Hortisilviculture (*Acacia mangium*+ pineapple)	5.51	Handa et al. (2019)
12.	Gujarat Plains & Hills Regions	Silvoaromatic (*Meliadubia*+ lemon grass)	20–25	Jinger et al. (2022)
13.	Western Dry Region	Silvipasture system (*Ailanthus* + *Cenchrus ciliaris/ Panicum antidotale*)	9.64	Handa et al. (2020)
14.	The Island Regions	Hortipasture (*Cocos nucifera* + *Calliandra calothyrsus*)	3.50	Joy et al. (2019)

3.4 Agroforestry Improves Food and Nutrition Security

Despite advancements in reducing hunger globally, approximately 800 million individuals still suffer from chronic undernourishment. A significant proportion of the world's impoverished population resides in rural areas, where, as of 2010, around 35% of rural inhabitants lived in extreme poverty-primarily in Africa and South Asia. Many of these individuals are subsistence farmers, pastoralists, or landless agricultural workers. When engaged in commercial activities, these farmers often focus on a single crop, leaving them vulnerable to market fluctuations. Additionally, low productivity levels in both land and labor hinder efforts to escape poverty.

In developing countries, integrating trees with crops or grazing lands can effectively address hunger and malnutrition. Trees provide food, fuel, and various non-wood products that can be consumed directly or sold for income. In agroforestry systems, the combination of food and forage from intercrops, along with supplemental food and fodder from trees, enhances overall productivity. Numerous trees, shrubs, herbs, and climbing plants offer substantial food resources that benefit rural communities, particularly among tribal populations. Recently, high-value and nutritious crops, such as mushrooms, have been successfully cultivated under the canopy of managed plantations and forest trees, further contributing to food security (Figs. 3, 4).

3.5 Agroforestry Helps Reduce Poverty

The economic potential of tree products can significantly aid agroforesters in overcoming poverty. First, agroforestry can lower agricultural input costs and enhance productivity, thereby increasing household incomes. Additionally, the production of higher-value agricultural and forest goods allows farmers and foresters to achieve better financial returns for their labor. The establishment of value chains for these new tree products can create opportunities for small-scale forest-based enterprises and generate employment. Furthermore, recognizing the environmental services provided by agroforestry through incentives can create a new income stream for both rural and urban populations.

3.6 Agroforestry Contributes to Create Resilient Livelihood

Integrating trees with crops and livestock can enhance resilience and improve recovery after natural disasters, hazards, or economic downturns. By diversifying production within agricultural systems, agroforestry reduces the risk of financial failure. The root systems of trees help strengthen soil structure, mitigating erosion and the potential for landslides. Additionally, tree plantations and windbreaks protect crops and livestock from strong winds and help prevent wind erosion. The water conservation capabilities of trees and forests combat desertification and its associated social and environmental issues.

3.7 Agroforestry Helps Solving Social Issues

Rural communities often face extreme poverty and marginalization, with limited opportunities for a decent livelihood driving migration to urban areas. Women, who typically have less access to resources than men, are particularly vulnerable to land degradation and natural disasters, especially in women-headed households. They are often tasked with gathering firewood, a time-consuming activity. Indigenous peoples, who comprise 5% of the global population but account for 15% of the world's poor, also face unique challenges.

Fig. 3. Paddy straw mushroom cultivation under coconut trees

Fig. 4. Paddy straw mushroom cultivation under sal trees

Agroforestry can help improve gender equality by empowering women, who constitute a significant portion of the agricultural and forestry labor force. When trees are easily accessible, women can save time and energy that would otherwise be spent collecting firewood or fodder. Selling fruits, fodder, or firewood from trees can increase their access to cash. Given that women often face barriers to resources, agroforestry presents a low-input method to restore soil fertility and boost agricultural output.

Additionally, agroforestry supports the sustainability of local communities and cultures. These systems often align with traditional land management practices and carry cultural significance. Collaborating with indigenous peoples and local communities can help ensure the long-term viability of these traditional systems while respecting local beliefs and customs. Preserving indigenous farming techniques and plant species safeguards humanity's agricultural heritage and contributes to cultural diversity. By providing stable livelihoods, agroforestry can help maintain vibrant rural communities, reinforcing local spiritual beliefs through the cultivation of culturally significant species.

3.8 Agroforestry Improves Water Quality and Water Cycle

Agroforestry practices are effective in enhancing water quality. Conventional agriculture often results in less than half of the nitrogen and phosphorus fertilizers being absorbed by crops, leading to excess fertilizer runoff that contaminates water sources and diminishes water quality (Cassman, 1999). For example, agricultural runoff can introduce excess sediments, nutrients, and pesticides into nearby water bodies, significantly contributing to issues like eutrophication, as seen in the Gulf of Mexico. Riparian buffers in agroforestry are proposed solutions to mitigate non-point source pollution from agricultural fields. These buffers improve runoff water quality by reducing flow velocity, promoting infiltration, sediment deposition, and nutrient retention, as well as minimizing nutrient transfer to groundwater. Several studies indicate that vegetative buffers in agroforestry systems can effectively reduce non-point source pollution from row crops. For instance, Lee et al. (2003) found that incorporating trees into a riparian buffer strip on Iowa farmland increased nutrient removal efficiency by 20% compared to a buffer composed solely of switchgrass (*Panicum virgatum*).

Trees with deep root systems in agroforestry can also enhance groundwater quality by acting as a safety net, absorbing excess nutrients that have leached beyond the root zones of agricultural crops. These nutrients are then recycled back into the ecosystem through root turnover and litter fall, improving nutrient use efficiency. Trees typically have longer growing seasons than most crops, allowing them to capture nutrients before and after the agricultural growing period. Studies in both tropical and temperate regions have confirmed this safety net function. For example, in a pecan-cotton alley cropping system in northwest Florida, Allen et al. (2004) reported a 72% reduction in nitrate-N at a depth of 0.9 meters compared to monoculture cotton. Similarly, Nair et al. (2007) monitored soil phosphorus levels in pastures with and without 20-year-old slash pine (*Pinuselliottii*) trees, concluding that agroforestry improved soil nutrient retention and decreased nutrient runoff. Overall, evidence suggests that agroforestry systems play a crucial role in addressing water quality challenges associated with intensive agricultural practices.

Trees also contribute to the water cycle by absorbing and releasing water, which helps maintain groundwater levels and regulate precipitation patterns.

3.9 Agroforestry Improves Biodiversity and Pollinators

Habitat destruction from modern development and intensive agriculture, characterized by extensive monoculture fields, has significantly displaced various species of birds, amphibians, insects, and mammals. Agroforestry practices offer critical shelter, food sources, and space for many beneficial species. Trees can function as ecological corridors, connecting fragmented habitats and facilitating the movement of wildlife. Recent studies underscore the vital role of agroforestry in global biodiversity conservation. For instance, coffee-shade systems have been shown to enhance biodiversity more effectively than traditional agricultural methods. Similarly, multistrata cacao agroforestry systems, which include timber, fruit, and native species, contribute to biodiversity by providing habitats for a variety of avian and mammalian species, enhancing landscape connectivity, and mitigating edge effects between forests and agricultural land.

Research by Harvey et al. (2007) indicated that agroforestry systems in Costa Rica supported bat assemblages that were as rich and diverse as those found in forests, with the added benefit of a higher abundance of nectar-feeding bats. Homegardens are particularly notable for their high floristic diversity; for example, Kumar & Nair (2004) documented species richness in tropical homegardens ranging from 27 species in Sri Lanka to 602 species in West Java. In regions where agricultural expansion has decimated forest cover, homegardens and similar agroforestry systems can serve as vital habitats for wildlife. In Bangladesh, where natural forest cover is below 10%, homegardens maintained by approximately 20 million households offer a strategy for biodiversity conservation (Kabir & Webb, 2009). A survey of 402 homegardens in southwestern Bangladesh revealed 419 species, 59% of which were native, including several species of conservation concern.

The diversity of tree-crop combinations and their spatial arrangements in agroforestry systems significantly influence insect population dynamics and species diversity. Research by Nair & Sreedharan (1986) and Bhol et al. (2015) highlighted the highly stratified and diverse homegardens in coastal Indian states like Kerala and Odisha. Brandle et al. (2004) reported increased insect density and diversity in windbreaks, attributing this to the varied microhabitats provided along edges, which support different life-cycle stages and offer a range of hosts, prey, and sources of pollen and nectar. Agroforestry practices also enhance wildlife habitats by increasing plant diversity in terms of both structure and composition. Windbreaks and riparian buffers often represent the only woody habitats in predominantly agricultural landscapes (Johnson & Beck, 1988). In a comparison of maize monoculture with riparian buffer plantings in Indiana, Gillespie et al. (1995) found that riparian strips supported greater bird density and diversity than monoculture fields. Similarly, Söderström et al. (2001) observed in Sweden that increasing the area of pasture covered by shrubs and trees positively impacted bird species richness, likely due to increased insect abundance and diversity.

Furthermore, agroforestry systems provide essential habitats for pollinators. Different flowering species offer food sources throughout various seasons, benefiting pollinators and ultimately enhancing the yield of agroforestry crops. By providing diverse floral resources, agroforestry supports the foraging activities of pollinators on seasonal crops, trees, and shrubs, reinforcing the interdependence between biodiversity and agricultural productivity.

3.10 Agroforestry Lowers Input of Agrochemicals

Agroforestry enhances soil quality, supplies nutrients, and modifies the microclimate in ways that naturally benefit various crop species and livestock. The shade provided by tree canopies helps suppress weed growth, while fallen leaves, branches, and bark create protective mulch in intercropping systems, promoting nutrient recycling. Certain tree species, such as Mesquite and Redbud, can fix nitrogen from the atmosphere, converting it into forms accessible to other plants. In some agroforestry practices, these nitrogen-fixing trees are strategically planted in alleys between crop rows or along contours to enrich soil nitrogen levels. This approach reduces the reliance on synthetic fertilizers, which helps lower chemical concentrations in agricultural runoff, thereby minimizing environmental pollution. Additionally, the introduction of perennial l trees into agricultural landscapes creates long-term habitats for beneficial insects and small wildlife, including birds. These organisms play a crucial role in controlling pest populations; estimates suggest that birds consume around 500 million tons of herbivorous insects annually. According to Staton (2022) agroforestry systems, which incorporate trees into arable fields, have led to a 25 percent reduction in insect pest populations, along with a nearly 30 percent increase in the numbers of insect predators compared to conventional agricultural settings. In silvipasture systems, the natural grazing behavior of livestock further aids in protecting fruit and nut trees from pests and diseases, showcasing the synergistic benefits of agroforestry practices.

3.11 Agroforestry Aids Industrial Growth

Agroforestry plays a significant role in supporting various industries, including those based on food, animal products, and tree resources. As natural forest resources decline, agroforestry presents a promising opportunity for tree-based industries. In India, the cultivation of clones such as *Populus deltoides* and Eucalyptus hybrids demonstrates its viability. Agroforestry systems are adept at supplying raw materials for numerous agricultural and forest-related industries. For instance, industries like paper and pulp mills, sports equipment, and furniture manufacturing in states like Haryana, Punjab, and Uttar Pradesh are increasingly sourcing their raw materials from agroforestry produce. Eucalyptus hybrids cultivated by farmers on a large scale have found diverse applications, while poplar trees are extensively grown in the Terai region of Uttar Pradesh and Haryana for uses such as match splints, plywood, and packing cases. Some industries have implemented buy-back guarantee schemes for specific tree species, ensuring a steady supply of raw materials. A notable example is the Paper Industries Corporation of the Philippines (PICOP), which, in the 1970s, initiated a program to develop agriculture and tree plantations. This initiative aimed to secure a constant supply of raw materials for its paper mills while also enhancing the socio-economic conditions of local farmers (FAO, 1978).

3.12 Agroforestry Provides Employment Opportunity

Agroforestry offers greater employment potential compared to traditional monoculture farming. It provides jobs during the off-seasons of crop production, addressing the seasonal unemployment faced by farmers. The integration of trees into agricultural systems not only creates jobs for managing crops but also significantly increases employment opportunities related to tree management. Many forestry activities are labor-intensive, resulting in substantial employment generation through agroforestry initiatives. For example, tree plantations and nursery operations can generate between 200 to 500 man-days of labor per hectare. Ongoing care and maintenance of these plantations contribute an additional 50 to 75 man-days annually per hectare. Harvesting trees also requires considerable labor, averaging around 10 to 15 man-days for every cubic meter of wood collected. Beyond primary employment in agroforestry, secondary and tertiary sectors see a tenfold increase in job creation, particularly in industries related to pulp and paper, plywood, furniture, sports goods, and more. These industries encompass a wide array of products, including agricultural tools, musical instruments, and wood-based items, further amplifying the economic benefits of agroforestry.

3.13 Agroforestry Provides Support for Climbing Crops and Birds

Trees provide support to different climbers to grow on them. The climbers may be food plants, spices, medicinal plants, etc. For example, *Dioscorea* spp., *Piper* spp. and vanilla are grown on tree crops as overlapping system (Figs. 5, 6). This can be of significant economic value where tree stems are substituted for expensive poles or supports that need to be replaced periodically. Trees give support for perching of birds which help in control of insects and rodent pests.

3.14 Agroforestry Provides Comfortable Working Environment for Farmers

Presence of woody plants in farms makes working environment pleasant. It provides shade to workers and increases work efficiency. In the mid day, workers take rest under the tree canopy. It also provides partial protection against untimely rain. This is an invaluable aspect related to health of farmers in the scenario of consistent increasing of atmospheric temperature throughout the world. Further, green spaces with trees promote physical and mental well-being, encouraging outdoor activities and reducing stress.

Fig. 5. Black pepper on silveroak trees with tea plantation

Fig. 6. Betel vine cultivation on arecanut trees

Fig. 7. Pineapple and Turmeric crops under *Ziziphus mauritiana*

Fig. 8. Pineapple and Turmeric crops under *Eucalyptus europhylla*

3.15 Agroforestry Makes Positive Use of Shade

Some crops such as coffee, cacao, pine apple, turmeric, arrowroot, etc are benefitted from shade. This is particularly true under soil conditions those are not very favourable, when rainfall is excessive and when temperature are too extreme. Multistoried systems are used in many parts of the world to provide shade for plantation crops. The authors have observed better performance turmeric and pineapple crops under *Ziziphus mauritiana* based agroforestry system than open in Odisha, India (Fig. 7). Even these crops are performing satisfactorily under *Eucalyptus europhylla* plantations in costal Odisha (Fig. 8).

3.16 Agroforestry Reduces Microclimate Extremes

Temperature and moisture extremes are modified under tree canopies. The tree crowns shield the soil surface from solar radiation during day hours and serve to reduce heat losses at night, thereby narrowing the amplitude of daily temperature variation.

3.17 Agroforestry Produces Healthy Products

In agroforestry if different components can be integrated judiciously, then external inputs like chemical fertilizer, insecticides and pesticides will be less used and the product will be treated as organic. For this integration of dairy, fishery, poultry, honey, etc are very promising. The healthy products or organic products fetch higher price than the same products produced in intensive agricultural system. In eastern India, turmeric grown in tribal dominated areas without application of pesticide and chemical fertilizer where farming is agroforestry in nature has more demand in the market than turmeric of other areas.

3.18 Agroforestry Enhances Aesthetic Value of Locality and Rural Tourism

Agroforestry systems enhance aesthetic value of the locality as various multipurpose trees are grown. The phenophases of trees bring various scenic views to locality. The green foliage, different flower colours, fruits, assembling of various bird species, butter flies, honey bees, etc. make the area very pleasant and natural. This may create scope for development of rural tourism and other recreational avenues in an area and attract city people for recreation. The concept of landscaping, farm-house development, integrated farming, organic farming and sale of organic foods in the area can be further integrated to enhance the aesthetic value as well as economic benefit of agroforestry. In the farm houses people are integrating restaurant with local food, aquasilviculture, apisilviculture, birds and animals to attract tourists.

3.19 Agroforestry Reduces Human Casualties

Climate change is increasing the frequency and intensity of lightning in tropical areas by which causalities of human beings is increasing day by day. Between 2000 and 2021, over 49,000 people have died from lightning strikes across India (Khan, 2023). Government of Odisha (India) has initiated a special planting of Palmyra palm (*Borassus flabellifer*) trees on farm bunds to check human causalities by lightning (Figs. 7, 8). It is believed that Palmyra palm attracts lightning due to its height and moisture content and saves people. This is an economic species found growing throughout the tropics and very compatible to agricultural crops on farm bunds. Bhol et al. (2022) have reported that *Borassus flabellifer* is the most resistant tree to extremely severe cyclone in east coast of India and is a climate resilient tree species. Trees like oaks, pines and maples have similar ability.

3.20 Agroforestry Saves Natural Forests

Agroforestry practices provide a diverse array of products that can reduce the pressure on natural forests, particularly in regions where wood is essential for cooking and other activities. Traditional practices like charcoal production, agricultural expansion, and livestock grazing often lead to rapid deforestation. In this context, agroforestry offers numerous benefits. By integrating trees with crops, farmers can sustainably harvest wood and non-wood products while cultivating other crops on the same land. This not only enhances soil fertility and crop yields but also allows farmers to access firewood directly from their property, reducing their need to enter forests for fuel. As a result, natural forests are better protected from human interference.

4. MAJOR CHALLENGES FOR WIDER ADOPTION OF AGROFORESTRY

Although the advantages of agroforestry are gaining attention internationally and a growing body of scientific literature provides evidence for them, it faces many challenges. The major challenges for agroforestry are as follow:

4.1 Delayed Returns on Investment

While agroforestry can eventually yield positive financial returns, the initial establishment costs can be high, and it may take years for profits to materialize (Jose & Dollinger, 2019). However, the return can be early by inclusion of suitable intercrops, fruit trees, short rotation clones, livestock, etc.

4.2 Underdeveloped Markets

The markets for tree products are often less efficient and less established compared to those for crops and livestock, leaving agroforestry value chains with limited support. The policy of Minimum Support Price (MSP) for forest products is very limited. Promotion of forest/ wood based industries can be helpful for market development.

4.3 Focus on Commercial Agriculture

Current agricultural policies frequently favour conventional models, such as monoculture systems, often providing incentives that overlook agroforestry practices. Support mechanisms like price controls and favorable credit terms typically do not extend to tree cultivation, making it harder for farmers to adopt agroforestry. Economic incentives in terms of bank loan at low rate of interest, deduction of income tax for tree farming, subsidies, supply of tree seedlings, free technical support and financial support to agroforestry entrepreneurs may be given for enhancing agroforestry adoption.

Fig. 9. *Borassus flabellifer* on paddy field

Fig. 10. Resiliency of *Borassus flabellifer* to extremely severe cyclone

4.4 Limited Awareness of Agroforestry Benefits

A reliance on traditional agricultural methods, combined with insufficient understanding of sustainable practices, diminishes policymakers' interest in agroforestry. This lack of awareness can lead to inadequate resource allocation for research, dissemination, and the provision of quality planting material, hindering agroforestry's adoption (Akinyemi & Odugbesan, 2020).

4.5 Unclear Land and Tree Resource Status

Uncertainty regarding land tenure can discourage long-term investments in agroforestry (Tschakert & Tutu, 2010). In many developing countries, unclear land rights may create confusion that deters farmers from implementing agroforestry systems. Additionally, stringent forest regulations may restrict tree cultivation on agricultural land.

4.6 Adverse Regulations

Policies that lack support for agroforestry can impede its adoption (Zomer et al., 2014). Growers face problem during cutting of trees and transit. Existing agricultural policies often favor large-scale, conventional production methods, which can create barriers for agroforestry initiatives. Even when supportive policies exist, bureaucratic hurdles can complicate implementation for potential users.

4.7 Competition for Resources

Trees can compete with annual crops for essential resources such as nutrients, light, and moisture, potentially impacting crop yields negatively (Ong & Huxley, 1996). However, selecting deep-rooted tree species can mitigate these challenges by minimizing competition with shallow-rooted crops.

4.8 Invasive Species and Pest Hosts

Choosing the right tree species is crucial for the success of agroforestry systems. Some trees may harbor pests or provide habitats for animals that damage crops, thus introducing new challenges to pest management.

4.9 Lack of Extension Services

Most countries lack specialized extension services focused on agroforestry, which limits farmers' access to technical knowledge and marketing support. While there are established extension services for agriculture, livestock, and forestry, agroforestry often lacks dedicated support.

4.10 Coordination Challenges among Sectors

Agroforestry intersects multiple sectors, including agriculture, forestry, livestock, and rural development. This complexity can lead to policy conflicts and gaps, as different departments may not coordinate effectively, hindering agroforestry's progress.

These challenges underline the complexities of implementing agroforestry systems and highlight the need for integrated, multidisciplinary strategies to address them.

Table 2. Agroforestry systems in different land capability classes

Land capability class	Important feature of land	Suitable agroforestry systems
Class I: Excellent Agricultural Land	These areas have deep, fertile soils with minimal limitations for agriculture	Food based alley cropping, Multipurpose trees & shrubs on farm lands, Integrated farming system and Homegardens should be preferred. However, these lands are capable for all forms of agroforestry.
Class II: Good Agricultural Land	Land that is suitable for most crops but may have some limitations like drainage issues	Food based alley cropping, Multipurpose trees & shrubs on farm lands, Integrated farming system and Homegardens can be practiced with proper drainage measures.
Class III: Moderately Good Agricultural Land	Land with moderate limitations that require careful management, such as erosion risk or poor drainage.	Multipurpose trees and shrubs on farm lands, Fruit tree based alley cropping systems, Short rotation tree based alley cropping systems, Hedgerow intercropping systems, Windbreaks and Crop combinations with plantation crops in suitable agroclimate can be adopted with adequate soil conservation measures.

Land capability class	Important feature of land	Suitable agroforestry systems
Class IV: Marginal Agricultural Land	• Land that can be cultivated, but has significant limitations such as steep slopes or shallow soils.	Silvipastoral systems, Multipurpose trees and shrubs on farm lands, Windbreaks, Hedgerow intercropping, Fallow improvement systems and Crop combinations with plantation crops can be practiced with minimum tillage and adequate soil and water conservation measures.
Class V: Non-Agricultural Land	• Land not suited for regular agricultural practices due to severe limitations such as wetlands or rocky terrain.	Silvipastoral system, Aquasilviculture, Multipurpose trees on farm lands and Riparian buffers can be adopted with suitable land development.
Class VI: Land with Severe Limitations	• Land that is very limited in agricultural potential, often steep, erodible or with poor drainage.	Protein bank system, Controlled forest grazing, Multispecies tree gardens, Agroforestry for fuelwood production and Soil conservation hedges can be practised with suitable soil and water conservation treatments.
Class VII: Land unsuitable for agriculture	• Land that cannot be cultivated but can be used for forest production or other non-agricultural purposes.	Less remunerative agroforestry systems such as Limited forest grazing, Agroforestry for NTFP production and Soil conservation hedges can be adopted in limited scale.
Land Class VIII: Very fragile Land	Land cannot be cultivated and should be conserved for ecosystem services.	No agroforestry practices can be adopted.

5. AGROFORESTRY IN DIFFERENT LAND CAPABILITY CLASSES

For sustainable agricultural production under the scenario of climate change, the land resource should be holistically used as per its capability class. Agroforestry systems can be tailored to various land capability classes, each defined by its physical characteristics, potential productivity, and limitations for agricultural use. Here’s an overview of agroforestry systems suited to different land capability classes (Table 2).

Table 2 highlights the diversity of agroforestry systems and their adaptation to various land capability classes, promoting sustainable land management and ecological resilience.

6. CALL FOR FUTURE RESEARCH

The literature of agroforestry is increasing rapidly every day. However, for wider adoption of agroforestry the future research should give priority to following aspects.

(i) Development of remunerative agroforestry models for particular agro-climatic zone and particular land capability class.
(ii) Development of high yielding and fast growing clones of tree species having high marketability.
(iii) Quantification of ecosystem services of remunerative agroforestry systems.
(iv) Development of mechanized agroforestry systems for highly remunerative crop combinations.
(v) Integration of commercial enterprises like mushroom, poultry, diary, apiculture, fishery, fruit trees, short rotation tree clones, etc. of improved varieties in agroforestry landuse.
(vi) Standardization of management techniques of woody and non-woody components of agroforestry for enhancing productivity.
(vii) Improvement of soil health under remunerative agroforestry systems.

(viii) Development of market oriented and value added products of agroforestry

7. CONCLUSION

Climate change is the most dangerous issue for the present and future world questioning the survival of man and other organisms on earth. Agroforestry contributes to addressing many problems the world is facing today. From an environmental standpoint, it helps to reduce agriculture's contribution and vulnerability to climate change, while also improves soil health and water quality and availability, among other services. In terms of economic well-being, agroforestry can increase farm income and diversify farmers' incomes and allow them to have access to more nutritious food. As to the social benefits, agroforestry can empower women, validate indigenous knowledge and improve rural livelihoods. If properly implemented, agroforestry will make agriculture climate-smart.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO AI technologies such as Large Language Models (ChatGPT, COPILT, etc.) and text –to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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