**Carbon Sequestration Potential and Co-benefits of Agroforestry Systems: A Comprehensive Review**

**Abstract**

Agroforestry, characterized by the integration of trees and crops on the same land, has emerged as a viable strategy to address environmental and socio-economic challenges in India. This comprehensive review evaluates the carbon sequestration potential of diverse agroforestry systems and their associated co-benefits. These systems efficiently sequester atmospheric CO2 in both above ground biomass and soil thus playing a role in climate change. Carbon sequestration potential varies with agroforestry practices because of differences in tree species, management practices, and site conditions. Some of these systems include alley cropping, silvopasture, home gardens, windbreaks and riparian buffers, has ability to sequester carbon.
Besides carbon sequestration, agroforestry systems provide other numerous ecosystem services including soil protection, species conservation, water control, food production, income diversification and vulnerability reduction to climatic fluctuations. Economic analyses suggest that it has the capacity to produce income through carbon offset markets, wood, and other non-wood products. Examples include the Subabul Agroforestry System in Haryana, Agri-Horti-Silviculture Systems in the North Eastern Hill areas and Wadi Model in Gujarat to capture carbon and store and this helps to earn additional income and empower the society.
However, constraint like low technical know-how, poor policies and legislations on land tenure systems act as a barrier to the adoption of agroforestry. Future research efforts should focus on the following; estimation of sequestration capacity per region, examination of co-benefits, duplication of successful strategies by other regions, and incorporation of agroforestry into existing frameworks of agriculture. This means that interdisciplinary cooperation and knowledge sharing must be encouraged and strengthened.

**Key words:** *Agroforestry; Carbon Sequestration; Co-benefits; Economic Valuation; Climate Change Mitigation; Sustainable Land Use.*

**Introduction**

Agroforestry is a technique of integrating trees with crops on the same plot, which has gained importance as an approach to environmental and socio-economic issues in India. Due to the different agro-climatic zones in India, there is high potential for adoption of agroforestry practices. At its core, one important attribute of agroforestry is that it helps sequester both carbon dioxide (CO2) from atmosphere into biomass and soils thus contributing to climate change mitigation efforts (Montagnini & Nair, 2004a; Nair et al., 2021). At present estimates are that approximately 25.32 million hectares of Indian land are covered by agroforestry which accounts for about 8.2% of the total geographical area (National Agroforestry Policy, 2014). Agroforestry incorporates various approaches such as alley cropping, silvopasture, windbreaks as well as forest farming specific ecological and socio-economic contexts (Nair et al., 2021). The National Mission for Sustainable Agriculture (NMSA) has set a target of extending the practice over an additional five million ha by 2030 because it offers multiple benefits like carbon sequestration, soil conservation, increase in biodiversity and provides extra income stream through farmers.

Agroforestry systems’ carbon sequestration potential has been highlighted by several studies through aboveground biomass and soil (Feliciano et al., 2018; Zomer et al., 2016). This, accompanied by the multiple functions that agroforestry systems offer, shows that it is a viable climate change mitigation strategy (Dagar & Tewari, 2016b; Jose & Bardhan, 2012; Rosenstock et al., 2019)da. There are diverse co-benefits of agroforestry systems over and above carbon sequestration which contributes to sustainable development and climate change adaptation such as biodiversity conservation, soil amelioration, water regulation and livelihood diversification (Coulibaly et al., 2017; Dagar & Tewari, 2016a; Jose, 2009; Jose & Bardhan, 2012). For successful realization of agroforestry systems’ full potential regarding climate change adaptation and mitigation measures all these co-benefits need to be properly understood and evaluated. For complete economic value of agroforestry systems to be captured as well as decision-making processes informed, it is important to quantify and appraise these co-benefits (Branca et al., 2013; Tschakert et al., 2007).

This review aims to provide a comprehensive overview of agroforestry systems and their role in climate change mitigation. It will explore the significance of carbon sequestration and associated co-benefits within the climate change framework, drawing on recent research and empirical evidence to underscore the importance of agroforestry as a sustainable land-use strategy in combating climate change.

**Conceptual framework**

The conceptual framework depicts an overall view of the article as shown in the Figure1. It delineates the intricate interaction between agroforestry systems, their potential for carbon sequestration, economic feasibility, and the many co-benefits they offer. The core premise claims that agroforestry systems essentially hold the capacity to trap atmospheric carbon, therefore contributing in climate change mitigation. However, the broad acceptance and scalability of these systems depend on their economic feasibility, which is influenced by the balance between incurred expenses and possible revenue sources. Additionally, agroforestry systems provide a wide array of co-benefits that support environmental sustainability, food security, and socioeconomic development, hence boosting their total value proposition and attractiveness.

**Figure 1 depicts the conceptual framework**

An overview of literature study is mentioned as a PRISMA flow chart as illustrated in Figure 2 as shown below.

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**Scholar**

**Excluded**

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**Figure 2: PRISMA diagram demonstrating systematic screening progress of the article**

**Carbon Sequestration Potential of Agroforestry Systems**

To mitigate climate change, carbon sequestration is a critical measure that involves trapping and holding onto atmospheric CO2. With Indian scholar’s insights and global sources’ perspectives, this review is meant to examine these differences. The efficiency of carbon sequestration in agroforestry systems varies significantly depending on factors such as different agroforestry techniques used, types of tree species involved, management practices adopted and environmental factors (Albrecht & Kandji, 2003).

**Carbon Pools in Agroforestry Systems**

Agroforestry systems can sequester carbon in a variety of ways, including aboveground biomass, belowground biomass, and soil organic carbon (SOC)(Montagnini & Nair, 2004a; Nair et al., 2009). Aboveground biomass consists of the trees’ main stem, branches and leaves including those from other perennials as well. It acts as an important carbon store for agroforestry systems (Nair et al., 2009). The latter is dependent on tree species, age, density and management practices that determine its potential capability to sequestrate. This reservoir’s capacity for sequestration is determined by variables such as type of tree species, density of trees per unit area, age of trees in the system and management operations (Albrecht & Kandji, 2003).

In addition to this, belowground biomass contributes to carbon sequestration in agroforestry systems through roots and associated organic matter which includes leaf litter deposition root exudation etcetera. Extensive root systems produced by these types of vegetation are essential in enhancing soil carbon storage through which carbon gets transferred from above ground biomasses into the soil hence helping the entire process of managing agroforestry systems (Montagnini & Nair, 2004a). They may also lead to higher SOC levels due to increased input through processes like adding leaf litter or pruning residues while they build more solid soil structures at the same time mitigating erosion thus favoring environment conducive for SOC buildup. Soil structure is improved by having trees and perennials integrated into these systems so that instead of being eroded away lessened amounts are stored as Carbon concerned.

**Factors Influencing Carbon Sequestration in Agroforestry Systems**

**Tree Species and Density**

The choice of trees species and their densities in agroforestry determine the capacity for carbon capture. Plant materials with high biomass production rates, deep root systems and long life spans generally have substantial carbon capture potential (Chavan et al., 2023; Nair et al., 2010a). Notably Chavan (2023) provides empirical evidence showing that certain tree species including poplar and eucalyptus found in the Indo-Gangetic plains of India possess substantial capacities for accumulating carbon.

**Management Practices**

Among agroforestry practices such as pruning, thinning and coppicing that are effective in managing carbon sequestration within these systems (Mandal et al., 2022; Montagnini & Nair, 2004b; Murthy et al., 2013).These management activities enhance system resilience, promote synergies between adaptation and mitigation strategies, and contribute to soil health improvement, thereby augmenting carbon sequestration. However, further investigation and research are required to accurately quantify the extent of this potential and its actualization.

**Environmental Conditions**

Carbon sequestration capacity of agroforestry systems is significantly influenced by environmental variables such as climate conditions, soil characteristics, and topographical features (Montagnini & Nair, 2004b; Nair et al., 2009). For example, in warmer climates trees grow faster and store more carbon while nutrient-rich soils result in high biomass production(Minj, 2008). They are known to be more efficient at capturing and holding atmospheric carbon dioxide than conventional land tillage practices do (Wang & Feng, 1995). In tropical areas especially, these methods can add above-ground and soil carbon sinks lead to lessened soil deterioration and reduced greenhouse gas emissions(Mutuo et al., 2005).

**Types of Agroforestry Systems and Their Carbon Sequestration Potential**

Agroforestry encompasses a diverse array of land-use strategies integrating trees, crops, and livestock, offering numerous benefits, notably including carbon sequestration. The subsequent sections delineate various agroforestry modalities along with their respective capacities for carbon storage.



**Source: Authors work**

**Figure 3 depicts the types of agroforestry**

**Agri silvicultural Systems**

Agro-silvicultural systems that incorporate both trees and crops within the same agricultural setting come with numerous advantages like improved soil fertility, better water quality, as well as increased biodiversity (basawa et al., 2017). These are economically and ecologically viable options which also contribute to climate change mitigation by enhancing other resources and services(Toppo & Toppo, 2019). They are important for broadening agricultural outputs diversified income sources and enhanced delivery mechanisms for environmental goods. (Cardinael et al., 2020). However, further research is needed to optimize the integration of vegetable crops with fruit trees within these systems (Maqrot et al., 2023).

**Alley Cropping**

Alley cropping, a type of agroforestry has diverse advantages such as carbon storage, conserving soil and increased nutrient cycling(Marin, 2016; Quinkenstein et al., 2009). In this method, food crops are grown in alleyways formed by hedgerows of trees or shrubs that are regularly pruned to reduce shade and competition for nutrients (Ya & Qi, 2001)Carbon sequestration rates have been observed to range from 1.5 to 3.5 t C ha-1 yr-1 in different studies depending on tree species diversity, pruning frequency, soil fertility and climate(Albrecht & Kandji, 2003; Nair et al., 2009). These results demonstrate the potential of alley cropping as a sustainable land management practice that enhances both food production and biomass while providing ecological benefits.

**Silvopastoral Systems**

In India, there are systems for silvopastoral that have been shown to sequester a significant amount of carbon by integrating trees and grasses that result in the increase of organic carbon reserve in the soils compared to single tree or pasture configurations(Mangalassery, 2014). These arrangements also promote biodiversity, facilitate nutrient recycling, and optimize resource utilization efficiency(Mosquera-Losada et al., 2013). Silvopastoral systems have revealed great improvements in carbon sequestration as well as nitrogen cycling particularly in sodic soils through proper selection of tree and grass species(Kaur et al., 2004).

**Protein Banks**

Protein banks are one type of silvopastoral system where high protein tree species like Leucaena leucocephala are planted in dense hedges or blocks that are regularly pruned for cattle feed. The practice promotes carbon sequestration by the trees themselves and also by soils with figures ranging between 2.0 and 4.0 t C ha-1 yr-1 based on varying factors such as tree density, grazing intensity and soil properties (Haile et al., 2008; Nair et al., 2010a).

**Tree-Based Fodder Systems**

To achieve this end, these systems involve planting and maintaining trees or bushes for purposeful fodder production thus becoming a source of animal feed which satisfies both ecological and economic needs. The extent to which these systems can sequester varies depending on tree species involved, management practices employed as well as the environmental conditions prevailing in the area (Murgueitio et al., 2011)

**Agro-silvopastoral Systems**

Agro-silvopastoral is where trees are integrated with crops and livestock within one landscape unit. These systems have potential to sequester carbon across tree biomass, soil besides nutrient and organic matter cycling.The effectiveness of carbon sequestration in agro-silvopastoral systems depends on factors such as tree species composition, density, crop rotation patterns, and animal management practices (Mosquera-Losada et al., 2013).

**Other Agroforestry Systems**

Furthermore, various agroforestry systems, including home gardens, windbreaks, riparian buffers, enhanced fallows, and the Taungya system, also contribute to carbon sequestration. These systems exhibit diversity in their design, management strategies, and carbon sequestration potential, influenced by factors such as tree species diversity, soil properties, hydrological dynamics, and climatic conditions (Dagar & Tewari, 2016b; Saha et al., 2009).

**Table 1 illustrates carbon sequestration potential of several agroforestry systems**

|  |  |  |  |
| --- | --- | --- | --- |
| **Agroforestry System** | **Estimated Carbon Sequestration Rate (tons/ha/year)** | **Influencing Factors** | **References** |
| Alley Cropping | 1.5 - 3.5 | Tree species, pruning management, soil fertility, climate | (Albrecht & Kandji, 2003; Nair et al., 2009) |
| Silvopasture | 2.0 - 6.0 | Tree density, grazing intensity, soil type, rainfall | (Haile et al., 2008; Nair et al., 2010b) |
| Home Gardens | 5.0 - 10.0 | Tree species diversity, management intensity, soil quality, altitude | (Nair et al., 2009; Saha et al., 2009) |
| Windbreaks | 0.5 - 2.0 | Tree species, spacing, climate, soil conditions | (Dagar & Tewari, 2016a; Nair et al., 2009) |
| Riparian Buffers | 1.0 - 4.0 | Tree species, buffer width, hydrological regime, soil texture | (Dagar & Tewari, 2016a; Nair et al., 2009) |
| Improved Fallows | 2.0 - 5.0 | Tree species, fallow duration, soil fertility, rainfall | (Albrecht & Kandji, 2003; Nair et al., 2010b)  |
| Taungya System | 1.0 - 3.0 | Tree species, crop rotation, soil management, climate | (Dagar & Tewari, 2016b; Nair et al., 2009) |
| Multispecies Trees | 3.0 - 8.0 | Tree species composition, density, soil conditions, climate | (Swamy & Puri, 2005) |

For instance, indigenous home gardens have been registered to fix between 5.0 and 10.0 tons of carbon per hectare on an annual basis through the integration of a combination of trees, crops, and meticulous management practices within these systems (Saha et al., 2009). An alternative example would be multi-species trees, having their sequestration rate ranging from 3.0 to 8.0 tons per hectare per year, which depend on the combinations of different tree species, correct density as well as favorable soil and climatic conditions acting in a synergistic manner. Similarly, silvopasture systems are known to range from improved fallows to riparian buffers with moderate sequestration rates between 1.0-6.0 tC/ha/year. Tree density; intensity of grazing; fallow duration; hydrological dynamics among others are factors that influence their sequestration potential.

In contrast, alley cropping is rated at <1 ton C/ha for annual carbon sequestration while other examples such as windbreaks and Taungya system comes second lowest rating among all land uses with total amount annexed estimated at not less than 2 tonnes C/ha/year (Garrity et al., 2010).While contributing to carbon sequestration, their effectiveness is contingent upon variables such as tree species selection, pruning practices, spatial arrangement, crop rotation patterns, and soil management techniques.

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**SOFTWARE: R-4.4**

**Figure 4 displays the carbon sequestration rate**

**Regional and Practice-Specific Variations in Carbon Sequestration Potential**

The carbon sequestration capacity of agroforestry systems is influenced by various factors, resulting in significant variability across different geographical regions and practices. Understanding these variations is crucial for identifying effective agroforestry systems and expanding their use for climate change mitigation (Rosenstock et al., 2019).

**Regional Variations in Carbon Sequestration**

Disparities in the potential of carbon sequestration on a regional basis are mainly because of climatic conditions, soil characteristics and socioeconomic aspects (Feliciano et al., 2018). Carbon sequestration capacity differs widely between regions due to variation in temperature, soil attributes and land use management practices. For example, tropical regions usually have a high carbon sequestration capacity due to their rich vegetation cover and favourable climatic conditions. Tropical forests contribute significantly to global carbon sequestration capacity than temperate zones as highlighted by (Pan et al., 2011)and(Swamy & Puri, 2005), which emphasizes the need for preservation of these ecosystems.

In India, there is considerable heterogeneity in carbon sequestration potential as indicated by regional studies. As an illustration, Western Ghats which is a biodiversity hotspot has significant potential for carbon storage through large forested area and high biomass density (Ravindranath et al., 1997). Similarly, researches conducted in Himalayan region reveals that there is significant amount of carbon being stored within the sub-alpine and alpine forests that are important for the regional carbon balance (Singh et al., 2010)..

Studies in Kerala, India, indicate that home gardens, a form of agroforestry, harbor substantial carbon stocks due to the presence of long-lived, multi-purpose tree species (Saha et al., 2009). Conversely, agroforestry systems in arid and semi-arid regions may exhibit reduced carbon sequestration capacity due to water limitations and harsh environmental conditions (Nair et al., 2009). However, the inclusion of drought-tolerant tree species and appropriate management practices can enhance the carbon sequestration potential of agroforestry systems in these regions (Swamy & Puri, 2005).

**Practice-Specific Variations in Carbon Sequestration**

Soil carbon sequestration potential is greatly affected by farming methods. Soil organic carbon (SOC) storage in agricultural soils has been shown to be enhanced by conservation tillage practices such as reduced tillage, cover crops, and the use of organic amendments (Lal, 2004). Agronomic improvements can increase soil organic carbon stocks considerably; zerotillage and organic farming impacts positively on these stores in Punjab and Haryana (India) (Siddiqui et al., 2012).

The choice of agroforestry technology also determines its capacity for storing carbon. Silvopastoral systems which integrate trees with grasslands or livestock are known to have a greater capacity for sequestering carbon especially in the soil component(Haile et al., 2008). Conversely, alley cropping systems where trees are grown in rows together with field crops may have lesser capacities for carbon sequestration as a result of regular pruning or coppicing of the trees(Albrecht & Kandji, 2003).

Another important factor that affects the carbon sequestration capacity is the selection of tree species and their management practices. Longer lived tree species with deep root systems and high biomass production per unit area tend to store more C than short lived low density species. (Saha et al., 2009) gives an account that long-lived high-density trees that develop extensive root systems and produce large amounts of biomass are expected to take up more CO2 during photosynthesis than short-lived low-density species. Proper management techniques, such as pruning, thinning, and fertilization, can also enhance the carbon sequestration potential of agroforestry systems(Dagar & Tewari, 2016a).

**Impact of Land Use Change**

Changes in land use, mainly deforestation and urbanization, have significant effects on carbon sequestration capacity. Deforestation in tropical areas such as parts of India results in massive emissions of carbon dioxide as well as a decline in storage capacities. On the other hand, restoration projects and afforestation can replenish carbon stocks. (Kaul et al., 2010)observed that afforestation programmes undertaken in Central India led to significant improvements towards carbon sequestration hence making reforestation a prospective mitigation strategy.

**Co-Benefits of Agroforestry Systems**

While some agroforestry systems may excel in carbon sequestration, others may provide additional co-benefits such as improved soil fertility, biodiversity conservation or enhanced livelihoods. Consequently, for sustainable promotion of agroforestry practices there is need for comprehensive approach that looks at both carbon sequestration and other co-benefits (Coulibaly et al., 2017).

**Ecosystem Services**

Agroforestry systems supply a number of ecosystem services that contribute to environmental sustainability.

**Figure 5 depicts the agroforestry services**

**Soil Conservation**

The practices of agroforestry help improving soil health by reducing erosion, enhancing soil structure and increasing organic matter content. Windbreaks whose main role is to mitigate wind erosion while root systems prevent soil from being washed away are formed by trees and shrubs.(Nair, 2011) emphasizes the better physical attributes for soil quality and erosion control through agroforestry compared to those found under conventional agriculture.

**Biodiversity**

To foster biodiversity, agroforestry systems create varied habitats for plants and animals. The use of different plant species and the development of multi-layered vegetation structures enable a broad range of species to be supported in one system. In the Western Ghats in India, Agroforestry landscapes are shown by (Bhagwat et al., 2008) to have significant biodiversity like natural forests which is important for ecosystem stability and resilience. In southern India, (Nair et al., 2009) research reveals that agroforestry practices contribute to carbon sequestration as well as other co-benefits such as preservation of biodiversity and improved livelihoods.

**Water Regulation**

The Trees in agroforestry ecosystems control water through promotion of groundwater recharge, reduction of surface runoff, and improvement in its quality. According to (Verchot et al., 2007), mitigation of floods and drought risks is achieved by water infiltration into the soil through agroforestry systems.

**Food Security and Livelihood Enhancement**

Diverse sources of income are created in these agroforestry systems leading to large food security improvements and better livelihoods because crop yields are increased dramatically. Such systems produce different goods including food crops, fuelwood and feed; they also provide critical ecosystem services like pollination necessary for food production.They also provide small-scale farmers with an additional source of earnings by selling tree products and surplus foodstuffs.

**Diversified Income Sources**

The integration of fruit, nut, and timber-yielding trees and shrubs can substantially increase farm income and mitigate economic risks associated with market fluctuations. By incorporating these alternative products into their farming systems, farmers can generate additional income and enhance their economic resilience.

**Improved Crop Yields**

Trees in agroforestry systems can ameliorate microclimatic conditions, thereby enhancing crop growth and yields.

**Climate Change Adaptation and Resilience**

Agroforestry systems enhance resilience to climate change by improving ecosystem stability and providing climate-regulating services.

**Resilience to Climatic Extremes**

Extreme weather events like droughts and floods can be mitigated through agroforestry practices. The study by(Quandt et al., 2017) also showed that it has direct and indirect impacts on livelihood resilience against this kind of climate variation, thereby adding to its robustness as a concept. Studies by (Nguyen et al., 2013) and (Simelton et al., 2015)further support these findings, highlighting the role of agroforestry in mitigating vulnerability to climatic variability.

**Carbon Sequestration**

Agroforestry systems effectively sequester carbon, thus aiding in climate change mitigation. Nair et al. (2009) estimated significant global carbon sequestration in agroforestry systems, underscoring their role in reducing atmospheric CO2 levels.

**Economic Valuation of Co-Benefits**

Quantifying the economic value of co-benefits provided by agroforestry systems is crucial for policy and decision-making.

**Valuation Methods**

Economic valuation approaches such as cost-benefit analysis, contingent valuation, and ecosystem service pricing are employed to assess the monetary value of agroforestry benefits. Incorporating ecosystem service values into economic models can profoundly influence land-use planning and policy decisions, as noted by(Costanza et al., 1997).

**Indian Context**

Research carried out in India consistently shows the great economic value of agroforestry systems, particularly when assessed using economic valuation methods.(Yadav et al., 2018) case study in partial equilibrium analysis demonstrates profitable returns to farmers in Indian central Himalayas with higher benefit cost ratio at greater heights. Similarly, Sangeetha & Shanmugam, 2015 have evidenced significant net returns from tree yield under commercial agroforestry systems operating in north Tamil Nadu. Dhyan et al., 2016 ideas emphasize the economic advantages of agroforestry systems found within varied Agroclimatic zones across India whereby basic needs are met and income is enhanced among rural folks. The work highlights on the potential for Agri- forestry to meet subsistence requirements for farming families living across various Agro-climatic zones in India while emphasizing economic benefits associated with such land use systems.

**Cost-Benefit Analysis and Economic Feasibility of Agroforestry Systems**

Agroforestry has considerable environmental and economic benefits. However, the effective implementation of agroforestry systems depends significantly on their economic feasibility, which can be examined through cost-benefit analysis (CBA).

**Cost Components**

**Establishment Costs**

Initial costs in agroforestry consist of those related to site preparation, planting materials, labor and initial infrastructure (B. M. Swaminathan et al, 1982). These expenses can be substantial depending on the scale and type of agroforestry system(Rao et al., 1997). Effective creation of agroforestry systems in India needs initial investment in tree seedlings, fencing and manpower for planting (C.Dey & Mishra,2014). However, such systems are not easily implemented due to variables like high labour charges and low seed prices (Puri & Nair, 2004). Nevertheless, India's experience with research into agroforestry highlights the promise of these systems especially when their scientific basis is acknowledged and their advantages to society are compelling (Puri & Nair, 2004).

**Maintenance Costs**

The maintenance budget involves recurrent expenditures incurred in running the agro forestry system such as pruning, pest management, fertilization, irrigation among others. It also includes training fees and extension services that ensure farmers adhere to optimum practices. Maintenance costs can be high; nonetheless they are necessary for maintaining production capacities as well as health status of the AF system (Rao et al., 1997).

**Opportunity Costs**

Opportunity costs refer to the potential earnings which are forgone when one chooses agro forestry over other land uses such as grazing or monocropping. The expenses can be very different depending on the kind of agroforestry system that is used as well as alternative uses for land. According to (Swamy & Puri, 2005), in Indian contexts, opportunity costs might be a crucial factor affecting farmer’s decisions to embrace agroforestry practices.

**Potential Revenue Streams**

**Carbon Credits**

Carbon credits are among the major sources of revenue from agroforestry. In carbon markets, carbon can be sequestrated by agroforestry systems and therefore, monetized.(Lal, 2004) explores the potential of agroforestry in carbon sequestration and how trading in carbon credits can yield economic benefits as well.In India, initiatives registered under Clean Development Mechanism (CDM) have proven that farmers can benefit from useful incomes through selling carbon credits (Kaul et al., 2010).

**Timber and Non-Timber Products**

The income derived from nontimber products like fruits, nuts, medicinal plants forms the largest proportion of the economic benefits of agro foresty. (Nair et al., 2009) note that a diversity of products from agroforesty systems enable multiple revenue streams of stable nature thereby giving farmers a lot of economic stability.(Dhanya et al., 2016) established the economic worthiness of traditional agroforesty systems where those with high value trees within irrigated systems were found to be most profitable. (Romabai et al.,2023) identified important commercially valuable tree-based NTFPs in Indo-Burma region indicating possibilities for value addition towards improved market prices.The researcher’s study points out that dry deciduous forests have higher net present values arising out NTFPs such as honey which is three times more profitable than other alternative land use.

**Successful Examples and Best Practices from Different Regions**

**Subabul Agroforestry System in Haryana**

The Subabul Agroforestry System in Haryana is a strong force in the socio-economic realm, contributing around 30% of the family’s income and sequestering approximately 2.5-3.0 tonnes of carbon per hectare annually. It also enhances soil fertility and is profitable in other parts of India (Rizvi et al., 2016). Such systems present in semi-arid regions of North-West India have positive effects on crop and fodder yields, soil organic carbon content and soil pH (Kaushik et al., 2017), with implications for agriculture and ecosystem services within Haryana.

**Agri-Horti-Silviculture Systems in North-Eastern Hill Regions**

In these northeastern hill areas, traditional Agri-Horti-Silviculture systems have been successful in terms of carbon sequestration as well as generating various economic benefits. For instance, they have flourished into food, fodder, fruit-bearing trees, timber trees that play vital roles in local economy for states like Nagaland, Mizoram and Meghalaya(Yadav et al., 2019). Rainfed Vertisols – horti-silvi-agricultural systems are adaptable to these conditions (TN, 2002).

**Wadi Model in Gujarat**

Tribal Settlements in Gujarat have been transformed by the Wadi model, which was developed by BAIF Development Research Foundation. This method plants fruit trees with cereal crops to promote carbon sequestration through agroforestry and food security as well as income stability. Children cultivate their English language skills and knowledge of Spanish culture through total immersion, live-in programs (Tripathy, 2018). The Wadi model has been successful in southern Gujarat, western Maharashtra, southern Rajasthan and parts of Karnataka and it involves creating market opportunities for tribal farmers’ produce while generating livelihoods. It fosters community engagement and collective action that strengthens social cohesiveness and resilience. The technique captures about 4.5-5.0 tons of CO2 per acre every year while giving monetary returns from the sale of fruits like mangoes and cashews in addition to traditional crops. Capacity building activities make farmers improve in terms of their skills hence increasing their abilities.

**Challenges and Barriers to Adoption**

Despite excellent examples, various constraints and barriers limit the broad adoption of agroforestry systems for carbon sequestration and economic benefits:

**1.Limited Information and Technical Expertise:** Inadequate knowledge and technical skills among farmers and extension workers regarding the carbon sequestration potential and economic benefits of agroforestry systems restrict adoption(Nair et al., 2009).

**2.Lack of Policy Support and Financial Incentives:** Insufficient government support, lack of financial incentives, and limited access to carbon markets prevent farmers from implementing agroforestry practices for carbon sequestration (Pandey, 2007).

**3.Land Tenure Issues**: Insecure land tenure is a key hurdle, as farmers are reluctant to invest in long-term agroforestry activities without certain land rights(Bhattacharya et al., 2010). This issue is frequent in places with fragmented landholdings and ambiguous land titles.

4.Information and understanding: Limited understanding about the benefits and procedures of agroforestry, coupled with limited extension services, causes a gap in information transfer from research to practice.

**Lessons Learned and Potential Scalability for Carbon Sequestration in Agroforestry and Their Economic Benefits in India**

**1.Enhancing information Transmission**: Effective extension services are vital for information dissemination. Training programs, farmer field schools, and ICT tools can bridge the knowledge gap (Mittal & Mehar, 2016).

**2.Integrating Agroforestry with Existing Agricultural Systems:** Promoting the integration of agroforestry systems with existing agricultural practices will assist manage competing land and resource demands while boosting carbon sequestration and economic benefits (Nair et al., 2009).

**3.Developing Policy Support and Financial Incentives:** Implementing policies that support agroforestry for carbon sequestration, giving financial incentives, and allowing access to carbon markets can inspire farmers to embrace these practices (Pandey, 2007).

**4.Resolving Cultural Considerations:** Understanding and resolving cultural variables can facilitate adoption. Involving local populations in planning and decision-making ensures that agroforestry practices are customized to local conditions and embraced by farmers.

**5.Improving Access to Financial Resources: Economic** incentives and financial support are crucial for scalability. Government subsidies, low-interest loans, and carbon credits can make agroforestry financially viable for smallholder farmers.

**6.Securing Land Tenure:** Promoting community-based land tenure systems can give collective security and stimulate investment in agroforestry. Clear and secure land rights are vital for long-term planning and investment.

**Conclusion**

This research highlights the significant potential of agroforestry systems in terms of carbon sequestration and economic benefits, as well as other sustainable development co-benefits. Alley cropping, silvopasture, home gardens and other types of agroforestry practices have different rates of carbon sequestration due to various tree species, management practices and environmental conditions. Economic appraisals show that through carbon credits, timber and nontimber products agroforestry can bring money. This is illustrated by examples from India such as Subabul system, Agri-Horti-Silviculture or Wadi model.

Nevertheless, some constraints which include lack of technical skills, policy gaps and land tenure issues hinder their wider application. Future research should consider this by focusing on quantifying regional-specific carbon capture in monetary terms; pricing co-benefits more comprehensively; replicating successful models via supportive policies and financing; integrating climate resilient agriculture with current agricultural practices using agroforestry. Interdisciplinary cooperation are crucial to bridge knowledge gaps and assist the transition to agroforestry-based sustainable land use.

In tropical regions, various forms of agroforestry provide a wide range of benefits with respect to carbon stock influenced by such factors as tree type, density or management approaches and weather circumstances. Tropical forests offer the highest carbon sequestration rates, with home gardens achieving between 5.0 to 10.0 tons per hectare yearly. Understanding tree selection determinants is vital to combining local food and fuel needs with global climate regulation aims.

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**Compliance with ethical standards**

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