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The Potential Climate Resilient Agroforestry Systems for Tropics: A Review

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ABSTRACT
Climate change has emerged as a serious global issue, affecting food security, biodiversity, habitat loss, people's livelihoods, and poverty. The tropics are most affected by year-round high temperatures and limited per capita resources. Among the various tools for mitigating and adapting to climate change, agroforestry is a suitable option. Agroforestry is a sustainable land-use system with multiple outputs, in which woody plants are grown with herbaceous crops and/or animals on the same piece of land. Adoption of climate-resilient agroforestry practices can help provide climate-smart agriculture, ecosystem services, and other benefits in vulnerable ecosystems such as the tropics. In humid and sub-humid tropical regions, palm-based agroforestry systems, such as coconut-based, arecanut-based, and oil palm-based systems, are climate-resilient and provide good economic returns and ecosystem services. Similarly, fruit-based alley cropping systems such as mango, guava, apple, ber, aonla, and drumstick, as well as short-rotation wood-based alley cropping systems like *Eucalyptus*, *Melia*, *Acacia*, *Ailanthus*, and bamboo-based systems, are highly promising. In addition to these systems, multipurpose trees in farmlands and homegardens, integrated farming systems with woody plants, and rubber-based agroforestry systems are promising. In the semiarid and arid tropics, parkland or tiered systems, MPT-based alley cropping systems, silvipastoral systems, and windbreaks are potential agroforestry systems. In tropical highlands, coffee- and tea-based agroforestry systems, hedgerow intercropping systems, silvipastoral systems, and multipurpose trees and shrubs on farmland are suitable agroforestry systems.

Key words: Agroforestry, Climate resilient, Humid, Sub-humid, Semiarid, Arid and tropical highlands

INTRODUCTION

Climate change poses serious global challenges, particularly in tropical regions where persistently high temperatures intensify its impacts. These include threats to food security, health, water availability, and biodiversity, as well as rising displacement and habitat fragmentation. The tropics have already warmed by 0.7-0.8°C over the past century, with projections indicating a 1-2°C rise by 2050 and up to 4°C by 2100 (Corlett 2014). Increased frequency of extreme weather events such as droughts, floods, wildfires, and cyclones is expected across much of the tropics (Stocker et al. 2013). Agricultural systems in these regions are especially vulnerable due to their dependence on rainfed farming and limited adaptive capacity, making smallholder livelihoods increasingly precarious (Watts et al. 2022). Many tropical nations most affected by climate change rely heavily on agriculture (Hertel and Rosch 2010). Though smallholders produce nearly half of the world's food, many still face poverty and malnutrition (Ricciardi et al. 2018). Land-use practices like deforestation and unsustainable farming contribute about 21% of global greenhouse gas emissions (Anonymous 2016) and drive biodiversity loss (Scales and Marsden 2008). In response, agroforestry has gained recognition as a climate-smart land-use strategy. It integrates trees with crops and/or livestock, enhancing soil fertility, water retention, microclimate regulation, carbon sequestration, and income diversification (Sharma 2024, Roessler et al. 2025). Agroforestry supports nine of the UN's Sustainable Development Goals and mitigates climate change by reducing emissions and sequestering carbon. Land with over 10% tree cover qualifies as agroforestry, and about 43% of global agricultural land meets this criterion (Zomer et al. 2014).

Recent efforts have focused on developing context-specific, climate-resilient systems. For instance, in West Africa's Sudano-Sahelian zone, suitable woody perennials have been identified for silvopastoral systems (Roessler et al. 2025), while traditional homegardens and tea-based systems in the Eastern Himalayas continue to sustain biodiversity and livelihoods (Sharma 2024). However, resilience is not guaranteed. Climate stressors like drought and heatwaves are already affecting many systems (Watts et al. 2022). Effective implementation requires appropriate species selection, design, and adaptive management. Social and institutional factors, such as farmers' access to seedlings, extension services, and climate information, also play a critical role (Pret et al. 2025). Farmers' willingness to adopt agroforestry depends on their perception of climate risks and the availability of support systems (Pret et al. 2025). Therefore, scaling up climate-resilient agroforestry demands not only technical solutions but also inclusive policies, financial incentives, and strong community engagement.

This review examines key agroforestry systems suited for tropical climates, categorized as the Humid and sub-humid tropics, the Semiarid and arid tropics, and the Tropical highlands.

MATERIAL AND METHODS

Using particular keywords and online academic databases like Scopus, Web of Science (WOS), Science Direct, Google Scholar, and JSTOR, a systematic literature review utilizing preferred reporting items for systematic reviews and meta-analyses (PRISMA) (Liberati et al. 2009, Mengist et al. 2020) was carried out (Fig. 1). Four steps made up the review process: (i) keyword formulation and identification; (ii) keyword-based systematic literature search; (iii) gathering data and important results from the screened publications; and (iv) review synthesis. The primary keywords for the search terms were "Agroforestry in Humid and sub-humid tropics", "Agroforestry in semiarid and arid tropics" and "Agroforestry in Tropical highlands" and secondary strings were "major multipurpose tree species", "intercrops" and climate-smart resilience". Eligible articles were fully screened by evaluating the whole paper to capture all relevant information used in this review.

RESULTS AND DISCUSSION

Climate-resilient agroforestry systems for humid and sub-humid tropics

The humid tropics are characterized by consistently high mean monthly temperatures, with annual mean temperatures typically exceeding 22°C and exhibiting minimal seasonal and diurnal variation (Anonymous 2021). These regions generally experience rainfall that exceeds potential evapotranspiration for more than 270 days per year (Anonymous 2021). Annual precipitation in most humid tropical areas ranges from 1,500 to 2,500 mm, although it can exceed 6,000 mm in certain localities, such as parts of Southeast Asia and the Amazon Basin (Anonymous 1977). On an average, rainfall in the humid tropics is approximately three times the global mean (Richards 1996).

Adjacent to these zones are sub-humid tropical regions, which serve as transitional areas between the humid and semiarid zones. These areas share some climatic characteristics with the humid tropics but receive slightly less rainfall and exhibit greater seasonal variation. The ecological conditions in both humid and sub-humid tropics promote the rapid growth of diverse plant species, supporting a variety of agroforestry systems. These regions are often densely populated due to their high agricultural productivity and rich resources (Nair 1993). The potential climate-resilient agroforestry systems found in this ecological condition are discussed below.

Palm-based agroforestry systems

Palms are climate-resilient species, particularly resistant to cyclones (Bhol et al. 2022), drought, and flooding (Figs. 2-3).

Coconut-based agroforestry systems

More than 90 countries grow *Cocos nucifera,* or coconut, with Asia and the Pacific accounting for the majority of global production (Pham 2016). As of 2024, Indonesia, the Philippines, and India together accounted for approximately 86% of global coconut production, with a harvested area of about 9.7 million hectares (Anonymous 2015). Coconut cultivation in agroforestry systems is economically

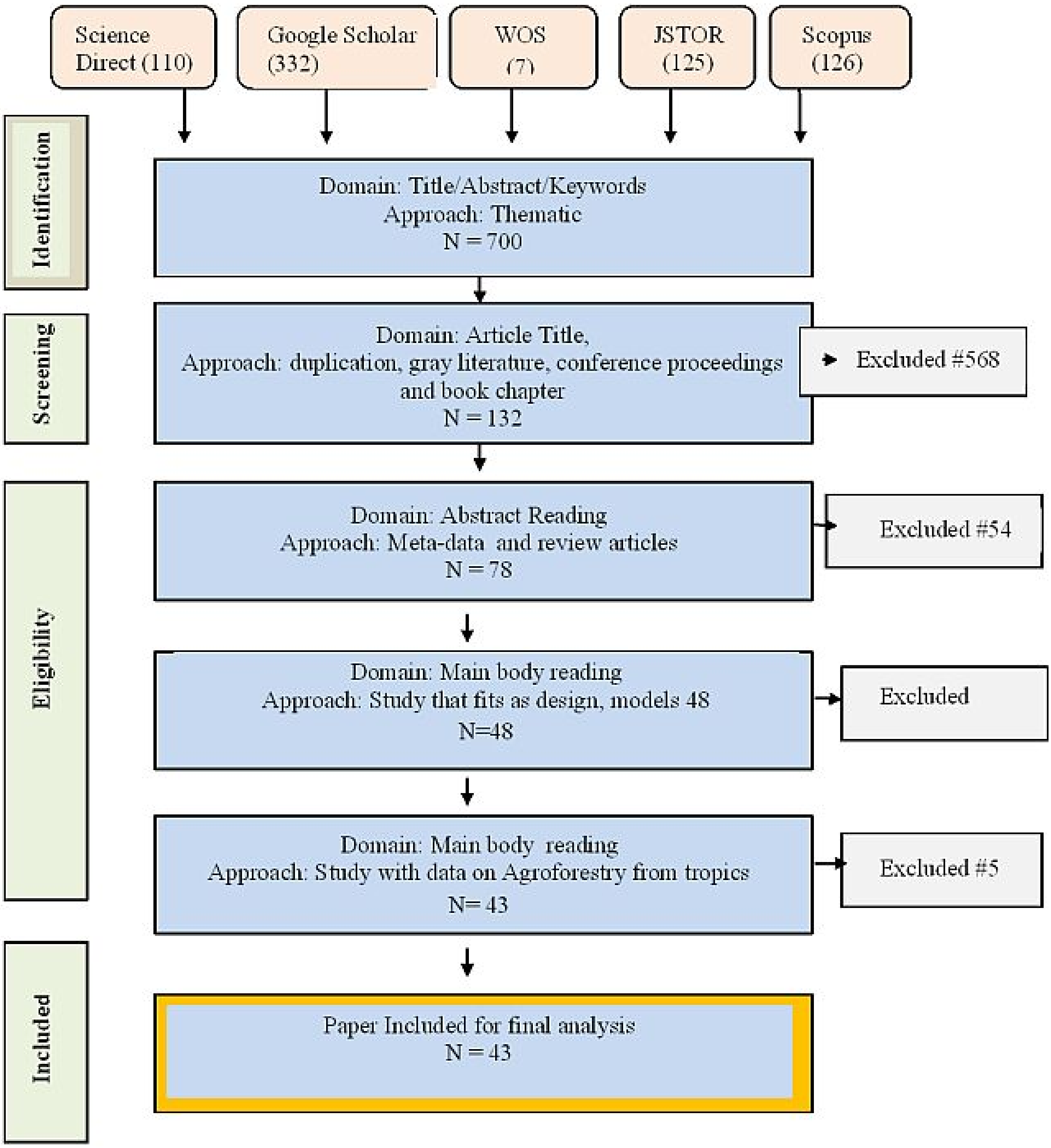


Figure 1. Flow diagram showing the database for review

viable and ecologically beneficial. Recent studies have shown that coconut-based multistoried systems using intercrops such as banana, turmeric, and cassava can significantly increase system productivity, profitability, and soil organic carbon (Namitha et al. 2025). Moreover, integrating crops in coconut plantations helps optimize land use and enhance biodiversity while maintaining sustainable yields.

Coconut cultivation in an agroforestry system is very economical and climate-resilient (Bhol et al. 2015, Sudha et al. 2021). Depending on the coconut variety, soil type, and intercrop spacing, spacing varies. The spacing for all tall varieties is 7-7.5 m in the triangular system; 7-9 m in the square system, and for dwarf varieties: 6 x 6 m in the square system.

Figure 2. Resiliency of coconut trees to extremely severe cyclone - Funi in coastal Odisha (India)

Figure 3. Paddy straw mushroom cultivation under coconut trees in coastal Odisha (India)

When coconut is grown in monoculture, closer spacing is used; when grown in mixed or intercrop, wider spacing is used (Table 1).

Intercrops: The crown structure of coconut palms allows sufficient light penetration for a variety of intercrops, particularly in the early years before canopy closure. In the initial 5–7 years, short-duration crops like pulses (e.g., cowpea, green gram), vegetables, banana, medicinal plants, mushrooms, and tuber crops such as cassava and elephant foot yam are effectively grown (Suja and Byju 2023, Ranjini et al. 2024). In some regions, paddy and sugarcane are also cultivated during this stage.

After canopy closure, generally around the 7th year, shade-tolerant crops such as turmeric, ginger, pineapple, black pepper, vanilla, cocoa, and nutmeg are suitable. Namitha et al. (2025) demonstrated that integrating turmeric and banana into a mature coconut plantation increased total productivity and improved economic returns per unit area. Free-ranging poultry is also commonly raised under coconut plantations as part of integrated farming practices in various regions.

Additionally, spacing directly influences the dynamics of ground vegetation and weed flora. Studies have shown that wider spacing (e.g., 7.5 × 7.5 m) supports a more diverse understorey crop environment and reduces weed pressure compared to closer plantings (Ranjini et al. 2024).

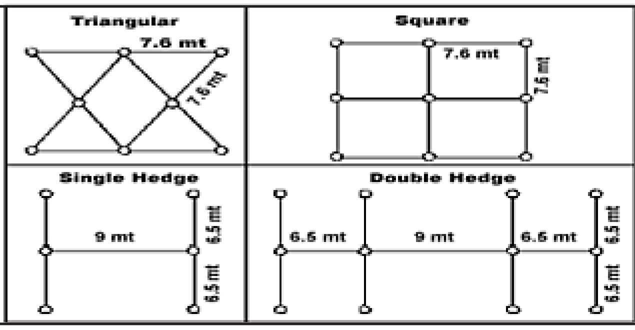
Oil palm-based agroforestry systems

Oil palm (*Elaeis guineensis*) is widely cultivated in many tropical countries like Malaysia, Indonesia, Papua New Guinea, India, Nigeria, the Ivory Coast, Ghana, Liberia, Sierra Leone, Cameroon, the Republic of Congo, Zaire, Costa Rica, Panama, Colombia, British Guyana, Peru, Ecuador, Venezuela, Brazil, etc. It is cultivated for vegetable oil, which is derived from both palm oil and kernel oil. About 16% of palm oil is used globally to make biodiesel. Over the past few years, the use of palm oil for biofuel has increased substantially. In Indonesia, about 45.9% of domestic palm oil consumption in 2023 was used for biodiesel, surpassing food use (44.4%) for the first time (Ahdiat 2024). The crop's high canopy, high spacing and crown architecture provide scope for integrating intercrops within an agroforestry system. Oil palm is generally planted using a triangular method with a spacing of approximately 9 m between trees, although spacing may vary across regions.

Intercrops: The gestation period to start fruiting in this system is generally 4-5 years in oil palm. During this stage, light availability is adequate for many crops. Different types of intercrops, such as vegetables, field crops, flowers, banana, tobacco, turmeric, ginger, pineapple, etc., can be grown. After the juvenile phase, when palms are more than 3 meters in height, the shade and root intensity in the ground increase and accordingly, crops are taken. Some suitable crops include yams, vanilla, cocoa, pepper, heliconia, turmeric, and pineapple (Table 2). Recent studies confirm the economic viability and productivity of such intercropping systems. For example, in Indonesia, intercropping oil palm with soybean increased plant height (9.4%), number of fronds (12.4%), and stem girth (9.2%) compared with mono-cropped palms, without reducing oil yield (Suherman et al. 2025). Similarly, experiments in juvenile oil palm plantations in the Central Telangana Zone, India, found that among maize, millets, cowpea, green gram, groundnut, and okra, the oil palm + groundnut combination provided the highest

Table 1. Some suitable spacing for coconut based agroforestry

Planting system	Some suitable spacing
Triangular	7.6 m
Square	7.6 x7.6 m, 8 x 8 m, 9 x 9 m
Single	6.5 – 7.0 m
Double hedge	6.5 m within rows and 9 m between pairs of rows



gross returns (Narayan Rao et al. 2024).

Arecanut-based agroforestry systems

Arecanut palm (*Areca catechu*) is a popular chewing nut among communities in South, East, and Southeast Asia. It is used as a divine fruit in Hindu religious ceremonies. It has medicinal properties, including as an aphrodisiac, breath freshener, and digestive aid. India is the largest producer and consumer of arecanut. It is a cash crop with climate resiliency and compatibility with intercrops. The optimum spacing for arecanut is 2.7 x 2.7 m. When it is mixed with cocoa, the spacing for arecanut is 2.7 x 2.7 m and cocoa is 2.7 x 5.4 m (one row of cocoa for every two rows of arecanut). Inside a coconut plantation, it is very often mixed in eastern India with a normal spacing of 2.7 x 2.7 m. In some areas, it is mixed with coffee.

Intercrops: Banana, ginger, turmeric, chilli, colocasia, upland paddy, elephant foot yam, pepper, and dioscorea are well adapted for intercropping in arecanut gardens. In low rainfall plains, *Dioscorea* and elephant foot yams are ideal intercrops with arecanut, but yield declines in ginger and turmeric are observed due to continuous cultivation. In established trees, beetle vine and nutmeg are grown. Some important agroforestry systems are listed in Table 3.

Alley cropping systems

Alley cropping is one form of an agrisilvicultural system. It involves planting tree crops in rows and cultivating herbaceous crops in the spaces between the rows (Bhol et al. 2020). In good sites, remunerative trees are cultivated systematically and commercially. The trees may include remunerative fruit, nut, or other speciality crop trees/shrubs, as well as valuable short-rotation tree species for timber, veneer, and wood fibre production (MacFarland 2017). Some potential woody plants are: *Mangifera indica, Psidium guajava, Ziziphus mauritiana, Emblica officinalis, Moringa olifera, Eucalyptus*

Table 2. Some findings of oil palm based agroforestry

Research work	**Salient finding**	**References**
Carbon Sequestration by Tropical Trees and Crops: A Case Study of Oil Palm	Finds that oil palm has favourable carbon sequestration potential; using oil palm in agroforestry / intercropping can increase carbon efficiency; comparable in some settings to tropical forests under appropriate management.	Murphy (2024), Singh et al. (2018), Ahirwal et al. (2022)
Carbon Stock Estimation on Oil Palm Plantations and Oil Palm-Based Agroforestry in Gunung Mas Regency	Compared carbon stocks of pure oil palm plantations vs oil palm based agroforestry; found that total carbon stock was higher in plantations but agroforestry lands had higher belowground carbon in some districts.	Rosaprana et al. (2023)
Impact of intercropping systems on the growth and yield of mature oil palms (*Elaeis guineensis* Jacq.) in Indonesia	Studied intercropping mature oil palm (Stage II) with food crops (rice, corn, soybean). The oil palm + soybean intercropping improved growth parameters (height, stem girth etc.) without significantly reducing yield compared to monoculture.	Suherman et al. (2025)
Multidimensional analysis sustainability of corn-soybean intercropping model in smallholder oil palm replanting	Assesses economic, environmental, social, institutional dimensions of corn soybean intercropping in smallholder oil palm replanting. Shows this intercropping model has promising sustainability outcomes across many dimensions.	Kusumawati et al. (2024)

Table 3. Important arecanut-based agroforestry systems

Research work	Findings	References
Model II: Arecanut + Black Pepper + Acid Lime + Turmeric	Highest total system productivity (31.5 to 131.1 q/ha), better yield than monoculture	Sit and Shil (2024)
Arecanut + Banana / Cocoa / Pepper	Improved resource utilization, soil fertility, profitability; good intercrop during first 5-6 years	Sujatha et al. (2016)
Arecanut + Nutmeg + Vegetables/ Spices	Enhanced farm resilience, diversified income, sustainable farming	Gayathiri et al. (2024)
Arecanut + Mahogany + Ginger	Improved soil pH and organic carbon; requires nutrient management	Dhimal and Sharma (2024)
Arecanut-based systems with organic farming & integrated nutrient management	Improved soil structure, fertility, and microbial activity leading to sustainable agriculture	Paramesh et al. (2025)

spp., *Melia* spp., *Acacia* spp., *Ailanthus* spp. and bamboo-based systems

The alley cropping system is found in large areas of the humid and sub-humid tropics. This system is highly remunerative, integrating high-yielding tree and herbaceous crop varieties. Trees are systematically planted in rows on farmland, and the inter-row or alley is used for growing suitable herbaceous crops. The alley width varies from 4 to 8 m, and the spacing of trees within a row varies from 2 to 8 m, depending on the tree's crown size, branching habit, and the harvest period (Table 4).

In different parts of tropical humid and sub-humid regions, various intercrops are used alongside tree species in alley cropping systems. In the first 1 to 3 years, light-demanding crops are planted, and as the tree crown grows, shade-loving crops are planted. Some crops that are generally grown in the initial years are arhar, cowpea, green gram, black gram, finger millet, sesame, okra, brinjal, mustard, watermelon, cucumber, pumpkin, etc. With the increase in shade crops like pineapple, turmeric, ginger, colocasia, arrowroot, tapioca, etc., which are also grown from the beginning, in some localities, pepper, betel vine and elephant foot yam are grown over trees.

Table 4. Examples of suitable tree spacing for alley cropping system

Name of tree species	Suitable spacing for alley cropping (m)
Mangifera indica	8x8, 8x7, 8x6
Psidium guajava	8x6
Ziziphus mauritiana	8x6
Moringa oleifera	8x8, 8x7, 8x6, 8x5, 7x5, 8x4, 7x4, 6x4, 5x4, 4x4
Melia dubia	8x3, 8x2
Acacia auriculiformis	8x3, 8x2, 7x3, 7x2, 6x3, 6x2, 5x3, 5x2
Ailanthus triphysa	8x3, 8x2
Eucalyptus spp.	8x2, 7x2, 6x2
Bambusa balcooa	8x8, 8x7, 8x6
Bambusa nutans	8x8, 8x7, 8x6
Bambusa vulgaris	8x8, 8x7, 8x6

Multipurpose trees and shrubs on farmlands

In the farm lands of tropical humid and sub-humid areas, many multipurpose and shrubs are grown, either planted systematically or randomly (Bhol et al. 2020). Some plants also regenerate naturally, and farmers allow them to provide different benefits, such as goods and ecosystem services. From an economic point of view, fruit trees and shrubs are preferred on bunds and boundaries of the farm. Fruit trees such as *Cocos nucifera, Moringa oleifera*, and *Borassus flabellifer* are common in coastal lowlands and medium lands. *Madhuca indica* (mahua tree, butter tree), a tree of Indian origin, is found largely in central, eastern, and southern India. Three basic needs are met by this multipurpose tree: fuel, food, and fodder. Country wine and a number of food products with additional value are made from flowers.

Albizia falcataria, also known as *Paraserianthes falcataria* (*Moluccan albizia)*, is one of the fastest-growing trees in the world, grown on farmlands in the Philippines and neighbouring countries. This Southeast Asian tree is widely planted in the tropics as a shade tree and prefers moist, acid-to-neutral soils. Its wood is low-density and low-calorific, but it is used for pulpwood, boxes, and particleboard. In the Philippines, when plantations are harvested every 10–15 years, certain varieties have been chosen for usage as matchsticks and other items. Some well-known agroforestry tree species grown on farms for fodder, food, or fuelwood are *Acacia nilotica* (babul tree) in India and Africa; *Azadirachta indica* (neem tree) throughout Asia and Africa; *Parkia biglobosa* (*nereì* or the locust bean tree) in Africa; and *Tamarindus indica* (tamarind tree) in India and Africa. *Adansonia digitata*, commonly known as the baobab tree, is native to Africa and is found in farmland across Africa. Baobab is a multipurpose tree that provides protection, food, clothing, and medicine, as well as raw materials for many useful items. Every part of the baobab tree is reported to be useful. Different species and clones of eucalyptus, *Acacia auriculiformis, Casuarina* spp., and *Leucaena leucocephala* are increasingly cultivated by farmers across different parts of the tropics. On their farmlands, farmers in South India incorporate a variety of multipurpose tree and shrub species in close proximity to crops and/or cattle. *Borassus flabellifer, Tamarindus indica, Ceiba pentandra, Acacia leucophloea,* and *A. nilotica* are the most prevalent.A variety of other woody plants are also grown in this system. Some popular plants are: *Tectona grandis* (teak), *Swietenia mahagoni* (mahogany), *Gmelina arborea* (white teak), *Mangifera indic*a (mango), *Carrica papaya* (papaya), *Punica granatum* (pomegranate), *Citrus* spp., *Terminalia arjuna* (arjun), *Terminalia tomentosa* (sain), *Phoenix sylvestris* (wild date palm), etc.

Regarding intercrops, there are plenty of options because this system requires non-woody crops. Suitable crops for the land are usually selected, and trees and shrubs compatible with the crops are integrated accordingly. The competition between woody and non-woody crops is less when spacing between the plants is more. A variety of crops, including rice, maize, finger millet, sesame, arhar, green gram, black gram, cowpea, sugarcane, tobacco, cotton, cabbage, cauliflower, tomato, beans, mustard, medicinal plants, melons, and cucurbits, are grown.

Homegardens

The humid tropics are assumed to be the home of home gardens. The origins of home gardens can be traced back to the beginning of settled agriculture, which came before the shifting cropping era. From these prehistoric and probably scattered origins, many humid areas of South and Southeast Asia, such as Java (Indonesia), the Philippines, Thailand, Sri Lanka, India, and Bangladesh, have gradually adopted home gardens. Some prominent gardens include the Javanese home gardens in Indonesia and the Kerala home gardens of India. Home gardens vary in their local vocabulary. For instance, the Javanese home gardens are known as 'Talun-Kebun' and 'pekarangans', while Kerala home gardens are known as 'purayidakrishi'. At the same time, those found in Mount Kilimanjaro in East Africa are often described as 'Chagga homegardens' with coffee and banana integrated with multipurpose trees, 'Enset coffee' homegardens in Ethiopia. Home gardens, which are mostly prevalent in tropical regions, are integrated tree-crop-animal production systems that are typically found on small plots of land surrounding homesteads. Despite being widely regarded as the pinnacle of sustainability, these agroforestry systems

- which farmers have cultivated over many generations of ingenuity and experimentation - have long been disregarded by the scientific community. However, because to their apparent ability to reduce environmental issues like biodiversity loss and rising atmospheric CO_2 levels while offering their owners substantial financial benefits and food and nutritional security, these ancient systems are currently attracting more attention. Varieties of trees, shrubs, crops, animals, fish, and birds are integrated in such land use. However, in most gardens, plant arrangements are not systematic, and genotypes are local.

Home gardens are widespread throughout the world, including in Southeast Asia (including Indonesia, Thailand, Vietnam, and the Philippines), South Asia (including India, Sri Lanka, Nepal, and Bangladesh), the Pacific and Caribbean islands, Central and South America, and tropical Africa (Anonymous 1996, Nair 1993, Kumar and Nair 2004, Sahoo et al. 2005, Sahoo 2007). The tropical rainforests of South India, which include the plains of Kerala State, Tamil Nadu State, Karnataka State, and the Andaman and Nicobar Islands, are where they are most commonly found in India. Northeastern India, particularly Assam State, is the subject of a sizable number of reports (Linthoingambi and Das 2010, Tynsong and Tiwari 2010). The humid, high-rainfall areas between 40°N and 30°S of the equator have the biggest expanses of home gardens. However, the areas with the highest densities of household gardens include Mesoamerica, East and West Africa, the Pacific Islands, and South and Southeast Asia. According to Nair and Kumar (2006), home gardening is a common land use in tropical nations including Bangladesh, Sri Lanka, Nepal, and the Philippines. According to their cautious estimates, there are 5.13 million hectares of land under pekarangans in Indonesia, 0.54 million hectares under homesteads in Bangladesh, 1.05 million hectares in Sri Lanka, and 1.44 million hectares in Kerala, India. Homesteading is common in Sudan, Ethiopia, Nigeria, Kenya, Tanzania, and other prominent African locations. At the same time, Peruvian Amazon homegardens, as well as Brazilian, Mexican, Guatemalan, Honduran, Nicaraguan, and Costa Rican homegardens, are potential homegarden regions in Latin America.

In northeast India, about 60253 km^2 (ca. 77%) of the region's arable land has very good to good suitability for agroforestry adaptation. In contrast, nearly 27% of the area has high suitability for agroforestry (Nath et al. 2021). A wide variety of agroforestry systems, mostly traditional ones, are in practice (Reang et al. 2021), which provide sustainable production, in-situ biodiversity conservation, and climate change mitigation while maintaining cultural values. The home gardens are increasingly recognized as naturally climate-resilient systems that provide ecological, economic, and social resilience. High biodiversity characteristics of the systems (Sahoo and Rocky 2015, Thangjam et al. 2021) act as built-in buffer towards total crop failure against drought, pest or erratic rainfall (Jeeceelee and Sahoo 2021); multi-tier canopy modifies the local climate, a critical feature of the homegardens under the climate vulnerability and heat stress (Thangjam et al. 2023, Thong et al. 2023). Many studies have shown that home gardens act as carbon sinks, helping mitigate climate change. Leaf litter and organic waste continuously enrich soil organic matter. At the same time, a very significant amount of carbon is stored in biomass and soil (Singh and Sahoo 2018, 2019, Singh et al. 2018). Further, the system reduces evaporation, improves soil structure, and makes them more resilient to drought and irregular rainfall patterns. Home gardens also have lower dependence on external inputs of fertilizers, making these systems again adaptive to climate-induced supply disruptions (Thangjam et al. 2023, Thong et al. 2023). Studies have shown that home gardens provide year-round production of fruits, vegetables, fuelwood, fodder, medicinal plants (Rocky and Sahoo 2002, Sahoo 2009, Sahoo et al. 2012, Singha et al. 2021), thus ensuring food security and income stability under climate stress events (Sahoo and Rocky 2019, Jeeceelee and Sahoo 2021). Most home gardens in the tropics are managed using indigenous knowledge systems to continuously adjust species composition in response to changing conditions, thereby enhancing long-term adaptability to climate change. In addition to all these, home gardens support various ecosystem services, including pollination, nutrient cycling, and habitat for beneficial organisms (Devi et al. 2023), thus strengthening overall ecosystem resilience.

Integrated farming system with woody plants

An integrated farming system with woody plants is an improved form of home gardening in which woody perennials are systematically integrated with non-woody components. In the current climate change context, this form of agroforestry is a highly effective tool for sustainable farm productivity and climate-smart farming. This is a very suitable agroforestry model for the humid tropics because of high rainfall, high temperatures, high rates of litter decomposition, and greater availability of solar energy. However, this form of agroforestry is also suitable for other agroecological zones. This system includes various tropical trees and shrubs. For example, coconut, arecanut, guava, mango, drumstick, ber, casuarina, subabul, eucalyptus, mahogany, Malabar neem, teak, bamboo, acid lime, pomegranate, custard apple, etc. Similarly, various suitable tropical crops are grown in this system, including pineapple, turmeric, arhar, green gram, black gram, and cowpea. Remunerative pasture crops like hybrid napier, guinea grass, stylo grass, etc., are included in suitable locations of the farm.

There are numerous enterprises integrated into this system. For example, mushroom cultivation, apiculture, aquaculture, poultry, dairy, sericulture, etc. High-yielding varieties of trees, shrubs, herbaceous crops, animals, birds, fish, and bees can be used in this system. Various components can be raised in line with the standard package of practices to maximise returns while maintaining a continuous flow of ecosystem services.

Table 5. General spacing of rubber

Panting material	Spacing	Number of trees/ha
Budded plants		
Hilly areas	6.7 x 3.4 m	445
Plains	4.9 x 4.9 m	420
Seedlings		
Hilly areas	6.1 x 3.0 m	539
Plains	4.6 x 4.6 m	479

Rubber-based agroforestry systems

Hevea brasiliensis, or rubber, is grown in tropical areas of West Africa, South America, and Southeast Asia that have the perfect climate for rubber trees. Approximately 90% of the world's rubber supply is cultivated in Asia, even though natural rubber is native to the Amazon basin. Nations such as Thailand, Indonesia, Malaysia, Vietnam, Nigeria, and Brazil dominate the global rubber market. For growing rubber, a tropical climate with 2000–4500 mm of annual rainfall is ideal. The optimal temperature range for growing was between 25 and 34°C, with a relative humidity of 80%. Regions prone to heavy winds are avoided. Rubber-based farming systems enable rubber growers to earn extra income from their land by integrating other crops and animals. Although most crops can be grown with rubber, their suitability depends on the rubber's growth stage. High-yielding rubber varieties suited to the region should be selected. During the long, immature stage of rubber tree growth, when little latex is generated, intercropping with short-term crops generates a substantial additional income.The general spacing of rubber used is mentioned in Table 5. However, little variation is found in different parts of the world. In Sri Lanka, the spacing adopted is 8.1 x 2.4 m.

Intercrops: In most rubber intercropping systems, annual and short-term crops such as upland rice, banana, pineapple, watermelon, maize, lemon grass, pea, mung bean, etc., are grown with the normal

Table 6. Crops suitable for different growth stages of rubber

Only during the immature phase of rubber	Intercropping throughout the lifecycle of rubber		Only during the mature phase of rubber
	With no change in planting density of rubber	With reduced planting density of rubber	
Banana	Coffee	Tea	Cardamom
Pineapple	Cocoa	Cinnamon	Vanila
Passion fruit		Pepper	Rattan
Sugarcane (only for dry areas)			Anthurium
Annual/ seasonal crops			

rubber planting density in the early years due to their need for full sunlight. As rubber trees grow larger, shade-loving plants are grown. Crops suitable for different growth stages of rubber are given in Table 6.

Climate-resilient agroforestry systems for semiarid and arid tropics

The semiarid environment is characterized by high atmospheric water demand; a high mean annual temperature (>18°C); and a low, variable annual rainfall ranging from 400 to 1900 mm (Swindale 1982). It covers an area of about 20 million km^2. It covers most of West, East and the southern part of central Africa; most of India, northeastern Myanmar, northeastern Thailand and northern Australia; most of Mexico; and large parts of eastern and central South America. Arid areas are close to semiarid areas, where the dryness is even greater. The annual rainfall ranges from 100 to 500 mm, with a coefficient of variation of 40-70 %. The region is characterized by low, erratic rainfall, extreme temperatures (1-48°C), high wind velocity, and sandy soils. In some years, they may even receive no rain at all. An arid zone is highly prone to land degradation, including soil erosion, wind erosion, desertification, frequent drought, and soil salinity. All deserts and areas under desertification experience an arid climate. Various forms of agroforestry are found in the semiarid and arid tropics (MacDicken and Vergrara 1990), and the major forms are discussed here.

Parkland or tiered systems

Parkland or Tiered systems are vast intercropping beneath sporadic tree stands, is the most common type of agroforestry, especially in the semiarid regions of sub-Saharan Africa. Mature tree densities vary throughout the Sudano-Sahelian region of West Africa, where cereals are cultivated. With cultivation intensities and input levels not found in the area today, some of these older parklands might be the remains of complex pre-colonial agricultural systems (Hervouet 1991). Prosopis cineraria with millet combinations in eastern Rajasthan, India, and Faidherbia albida/Acacia albida with grain systems predominating throughout the Sahelian zone and in some portions of East Africa are the systems that have drawn the greatest attention (Mann and Saxena 1980).

Many studies have demonstrated the remarkable positive impact of *Faidherbia albida* on crops grown beneath its canopy, with yield increases reported up to 100% compared to crops grown away from the trees. Known as the "albida effect," this species uniquely sheds its nutrient-rich foliage during the cropping season, providing essential soil nutrients just when crops need those most. Its green foliage during the dry season offers protective shade for soil and livestock, while its leafless state during the rainy season avoids competition with crops. The tree also enriches the soil through nitrogen fixation, contributing about 21 kg of nitrogen per hectare annually. Crops such as peanuts and millet show significant yield improvements under *F. albida* with millet yields increasing up to 5-fold. The pods, available during fodder-scarce months, serve as nutritious feed for livestock. Additionally, *F. albida* parklands provide shade, protect soil humus, and supply branches for fodder, making them vital for sustaining pastoral livelihoods and enhancing dryland agricultural productivity.

Acacia tortilis is a potential tree that tends to shed its leaves at the onset of the rainy season and remain leafless until the beginning of the dry season, when new leaves appear and flowering commences. Therefore, it has a lot of potential to be grown with rainy-season crops like rice because during rice cultivation (the rainy season), it remains leafless, with no competition for light. It is necessary to implement canopy management where shade intensity is high. When mung beans were cultivated beneath 12-year-old *A. tortilis* trees spaced 4 x 4 m apart and trimmed, Mann and Saxena (1980) found a six-fold increase in mung bean output. The significance of vigorous lopping of competitive trees in tiered systems was shown by Singh et al. (1989). Sorghum grain yields under pollarded Leucaena leucocephala spaced at 2 x 6 m were only half that of solo sorghum plots, but they were 10 times higher than those under lightly lopped treatments. As a result, lopping could increase the variety of species that are appropriate for parkland systems, and the prunings could be utilized for firewood, mulch, feed, organic fertilizer, and other uses.

Terminalia brownie in the parkland system in Ethiopia has established improved soil organic carbon and nutrient availability, and has positive farmer perceptions (Handiso et al. 2025). Similarly, Abdella and Akuma (2025) have reported a positive impact of Parkland Trees *(Faidherbia albida* and *Cordia africana)* on sorghum yield in Ethiopia. In this system, sorghum yield and biomass increased near tree canopies, and benefits decreased with distance from trees.

Some common trees and shrubs in parklands in the Sahelian and Sudanian zones of Western Africa include: A*cacia nilotica* (babul), *Acacia senegal* (gum arabic tree), *Acacia tortilis* (umbrella thorn acacia), *Adansonia digitata* (baobab), *Afzelia africana* (mahogany bean), *Anogeissus leiocarpus* (african birch), *Balanites aegyptiaca* (desert date), *Bombax costatum* (red flowered silk cotton), *Borassus aethiopum* (fan palm), *Ceiba pentandra* (American silk cotton), *Faidherbia albida* (winter thorn), *Hyphaene thebaica* (dum palm), *Khaya senegalensis* (African mahogany), *Lannea acida* (Plum mango), *Parkia biglobosa* (locust bean), *Prosopis Africana* (African mesquite), *Scelocarya birrea* (jelly plum), *Tamarindus indica* (tamarind) and *Vilellaria paradoxa* (shea tree).

MPTs-based alley cropping systems

Alley cropping is not generally a significant agroforestry system in arid and semiarid tropics. But in areas with more than 9000 mm of annual rainfall or with irrigation facilities, people practice alley cropping. Tree species such as *Acacia albida, Acacia tortilis, Acacia nilotica, Acacia catechu, Prosopis cineraria, Leucaena leucocephala, Dalbergia sissoo, Morus alba, Melia dubia, Melia azedarach, Ailanthus excelsa, Azadirachta indica*, etc., are integrated with food crops. In some suitable localities, fruit trees such as *Ziziphus mauritiana, Tamarindus indica, Emblica officinalis, Phoenix dactylifera, Punica granatum*, etc., are grown. Sorghum, pearl millet, chickpea, lentil, arhar, sunflower, safflower, groundnut, maize, etc., are intercropped with trees. In some semiarid areas of Maharashtra and Odisha (India), Betel pepper (*Piper betel*) is grown in association with dense stands of *Sesbania grandiflora, Erythrina indica, and Leucaena leucocephala* under irrigated conditions.

Silvipastoral systems

Silvipastoral systems are widely found agroforestry systems in the semiarid tropics. The silvipastoral systems that exist are: (i) Protein bank, (ii) Trees and shrubs on pasture land, (iii) Forest grazing, and (iv) Live fence of fodder tree and hedges. There are many animal husbandry systems, but two extremes may be recognized (the silvipastoral system with a crop component and without a crop component). In the first, animals are mostly stall-fed with additional pasturing and are a permanent part of the farming system (as in much of India). The other extreme is the nomadic and transhumant systems, in which animals are herded to far-off pastures during the rainy season to protect crops or relocated from one location to another in response to shifting pasture conditions throughout the year. Through the generation of manure, cattle contribute significantly to maintaining field fertility in both situations. Most grazing lands in the semiarid tropics of Africa and India are public lands and are freely accessible (Jodha 1985, Jahnke 1982). In India, livestock are free to graze on harvested fields and common pasturelands. Fodder trees such as *Acacia tortilis, Acacia nilotica,* and *Hardwickia binata*, along with fodder grasses such as *Cenchrus ciliaris, Sehima norsum, Lasirus sindicus, Chrysopogon fulvus*, and *Stylosanthes* spp., are potential plants for silvipastoral systems in the semiarid tropics. These species should be integrated into pasture lands. The trees should be heavily lopped for fodder in the off-season or when they become competitive with grasses.

Livestock rearing is a major component of livelihoods in arid zones, where silvipasture is a dominant land-use system. In the absence of favourable conditions for agriculture, animal husbandry is the alternative source of livelihood for the majority of the rural population in the arid zone. Besides its direct economic relevance, the trees and grass in the silvipasture system bind the soil and reduce erosion through their deep root systems. Leguminous trees can fix atmospheric nitrogen and convert it into soil nitrate, making the soil more fertile. Trees also prevent dune migration and nutrient leaching from the soil.

Silvipastoral systems in arid regions of India include naturally occurring grasses growing in community pastureland in association with indigenous shrubs and trees. The major grasses are *Cenchrus ciliaris, C. setigerus, C. biflorus, Lasiurus sindicus, Dichanthium annnlatum, Panicum turgidum, Sporobolus* sp., etc. The associated tree species are *Prosopis cineraria, Tecomella undulata, Hardwikia binnata, Acacia senegal, A. tortilis, A. luecoploea, Zizyphus mauritiana, Z. nummularia, Salvadora oleoides, S. persica, Capparis decidua,* etc. Silvipasture is a cost-effective technique adopted in arid regions to meet fodder demands and improve people's livelihoods. The co-cultivation of trees and grasses has been a traditional practice in the desert areas. Silvipasture, in the true sense, has been recognized as a need of the day in arid regions.

In East African deserts, different species of *Acacia* dominate silvopastoral systems. Alongside these trees are a number of annual grasses, including *Aristida adscensionis, A. mutabilis, Chloris pycnothrix, Tetrapogon cenchriformis,* and others, as well as perennial grasses including *Panicum turgidum, Chrysopogon plumulosus, Cenchrus ciliaris,* and *Andropogon* spp. *Acacia albida* (*Faidherbia albida*)- based silvipastoral systems are promising and climate-resilient. Silvipasture is a cost-effective technique adopted in arid regions to meet fodder demands and improve people's livelihoods. In desert regions, co-cultivating grasses and trees has long been a custom. Silvipasture, in a true sense, has been realised as a need of the day in arid regions. Most silvipastoral systems in semiarid and arid zones of Africa and other developing regions of the world involve extensive open grazing by free-roaming animals under scattered natural stands of trees and shrubs, as in the parklands of sub-Saharan Africa.

Wind-breaks

In semiarid temperate parts of North America, Europe, and Asia, tree rows have long been utilized as windbreaks to prevent wind erosion and damage to crops and soil. In the drier regions of the semiarid tropics, especially sub-Saharan Africa, their efficacy in boosting crop output has been proven. Ujah and Adeoye (1984) found that a *Eucalyptus camaldulensis* windbreak in northern Nigeria increased millet yield by an average of 14%. Sur (1986) reported an average 21% increase in protected cowpea yield during a six-year period in India's desert zone. In Egypt, where more than 100,000 hectares of crops are shielded by windbreaks, El-Kankany (1986) recorded yield improvements of 36% for cotton, 38% for wheat, 47% for maize, and 10% for rice. In two different experiments, double-rowed *Azadirachta indica* (neem) windbreaks placed 100 meters apart in the Majjia Valley of central Niger increased crop output by 20% (Vandenbeldt 1990). Choose the appropriate species, prune the tree roots, and control the canopy during the crop season to lessen competition between the trees in a windbreak and the crops.

Climate-resilient agroforestry systems for tropical highlands

The tropical highlands are characterized by the mountains and upland ecosystems above 900 m elevation. Generally, rainfall is high here, covering about 23% of the tropics. About half of the Andean highlands of Central and South America, parts of Venezuela and Brazil, the mountain regions of the Caribbean, many parts of East and Central Africa, the Cameroons, the Deccan Plateau of India, and some parts of the mainland of Southeast Asia comprise the 20% of tropical lands that are elevated between 900 and 1800 meters. With elevations exceeding 1800 meters, the Andes, the Ethiopian and Kenyan Highlands, northern Burma, and portions of Papua New Guinea comprise the remaining 3% of the tropical highland regions. These areas are always subject to soil and water erosion. Agroforestry systems are very beneficial for the economy and ecology of this ecosystem. The important agroforestry systems of this ecosystem are explained here.

Coffee and tea-based agroforestry systems

In tropical highlands with annual rainfall exceeding 1200 mm, plantation crops such as tea and coffee are grown under shade trees. Black pepper is grown on shade trees. Coffee is grown in more than 70 countries. In India, 60% of the coffee area is under *C. arabica*, and 40% is under *C. conephora*. In such areas, *Grevillea robusta* is the main shade tree with black pepper growing over it. Traditionally, tea and coffee are grown on waste and marginal lands either in monoculture or in association with indigenous forest tree species. The species of shade tree depends on site conditions. *Albizia chinensis*, which fixes atmospheric nitrogen in the roots of tea plants and offers shade for the growth and upkeep of new tenders, is used to manage tea estates in Kangra Valley, Himachal Pradesh, India. Additionally, *Albizia* tree leaf litter contributes nutrients to the soil. In a similar vein, *Alnus nepalensis* oversees the tree gardens in Assam and West Bengal. For tea in North Eastern India, the recommended species are: *Albizzia odoratissima, A. chinensis, A. lebbek, Derris robusta, Acacia lenticularis, Adenanthera pavonina* and *Dalbergia sericea.* The common shade trees of tropical highlands are: *Grevillea robusta, Albizia chinensis, Erythrina poeppigiana, Cordia alliodora, Gliricidia maculata/sepium, Leucaena leucocephala* and *Ficus natalensis.* Some recent findings on coffee- and tea-based agroforestry systems are presented in Table 7.

Hedgerow intercropping system

In a tropical highland hedgerow intercropping system, it is highly beneficial for soil health. Hedgerow intercropping consists of growing one/two rows of perennial trees or shrubs (preferably leguminous) at a close spacing in the form of hedges. These hedges are spaced 4–8 m apart, and crops are grown between the hedgerows. The hedgerows help in soil and water conservation. Once established, hedges are pruned regularly and added to the soil surface as mulch, which helps check soil erosion, reduce evaporation, enhance weed suppression, and add nutrients to the soil. Crop growth and production are enhanced by the hedgerow intercropping system's improved nutrient cycling and soil quality and health. Gradually, terraces form over time. *Leucaena leucocephala*, *Gliricidia sepium*, and *Cassia siamea* are suitable species for hedgerows in humid to semi-humid climates due to their capacity to rapidly form dense hedges and produce high biomass. Nonetheless, some native plants have also shown a great deal of promise for serving as hedgerows. Table 8 highlights the scope of hedgerow intercropping in reducing runoff and soil loss across varying slope gradients.

Hedgerows are effective for soil health in tropical highlands. On sloping land, after five to six years, hedgerow systems are converted into a biological-terrace measure (Tang 2000). The government should provide support to farmers to encourage this system. Some recent findings on the effect of hedgerow intercropping systems are given in Table 9.

Silvipastoral systems

In the highland tropics, silvipastoral systems are more common in dry areas than in the moist areas. The prevalent systems are: (i) Protein bank, (ii) Trees and shrubs on pasture and (iii) Forest grazing. Commercial animal husbandry is practised under the protein bank system. The subsistence systems are mostly open grazing systems. Various fodder trees and shrubs are grown on forest lands and village commons, and grasses also grow naturally with woody plants. People also collect grasses and green fodder from woody plants and feed the animals. Agricultural crop residues are very much used as animal feed. Cattle, goats, and sheep are taken to forests and village commons for grazing. Fodder cultivation on private land is negligible, except in the cases of commercial animal production.

Multipurpose trees and shrubs on farm lands

Multipurpose trees and shrubs are both deliberately planted along bunds and field boundaries or grow naturally on farmlands in many tropical regions. In the Eastern Ghats highlands of India, the toddy palm (*Caryota urens*) is widely cultivated, especially among rural and tribal communities that dominate the region. The sap extracted from its inflorescence is used to produce sugar and various alcoholic beverages. One of its primary products in rural areas is a sugar substitute known as kitul honey or jaggery, derived from the juice of its flowers. The fermented sap, inoculated with wild yeast, is used to make toddy, which can be further distilled into stronger alcoholic spirits, similar to coconut toddy. Additionally, the starch extracted from the plant's stem is used to prepare sago, particularly during periods of food scarcity. The young unfolding leaves and leaf buds are also consumed as vegetables, while the seeds can serve as a masticatory alternative to betel nut (*Areca catechu*) (Kumar et al. 2016).

Tamarindus indica (tamarind) is another common tree species found abundantly in the farmlands of the Eastern Ghats, providing significant economic returns from its fruit. . Other frequently grown fruit trees include jackfruit (*Artocarpus heterophyllus*),

Table 7. Some findings of coffee and tea based agroforestry systems

Study title	**Key findings**	**Reference**
Carbon storage in coffee agroforestry systems: Role of native and introduced shade trees in the Central Peruvian Amazon	Native shade species stored more carbon above- and below-ground than introduced species.	Veramendi et al. (2025)
Coffee-based agroforestry and food security through dietary diversification in West Wollega, Ethiopia	Coffee agroforestry improved food availability and dietary diversity through diversified crops.	Beshea et al. (2024)
Impact of traditional coffee farming practices on composition and regeneration of indigenous woody species	Maintained woody species composition; regeneration of some species declined with intensive management.	Fekadu et al. (2025)
Shaded agroforestry systems: A review on enhancing coffee growth, yield and sustainability	Shade trees enhance coffee yield stability, bean quality, and long-term sustainability via microclimate regulation.	Rudragouda et al. (2025)
Coffee and shade trees show complementary use of soil water in a traditional agroforestry ecosystem	Shade trees used shallow soil water; coffee accessed deeper layers - reducing drought stress.	Muñoz-Villers et al. (2020)
Intercropping green manure species with tea plants enhances soil fertility and microbial diversity	Alfalfa intercropping improved tea yield, soil nutrients, enzyme activity, and microbial diversity.	Wang et al. (2025)
Tea plantation intercropping legume improves soil ecosystem multifunctionality and tea quality	Legume intercropping improved soil ecosystem functions and tea quality by regulating rare bacterial taxa.	Wang et al. (2023)
Improving tea quality and fruit yield through intercropping with climbing plants	Intercropping with *Siraitia grosvenorii* and *Passiflora edulis* enhanced tea biochemical quality and fruit yield.	Liao et al. (2025)
Optimizing landscape patterns for tea plantation agroecosystems: A case study of an important agricultural heritage system in Enshi, China	Spatial modelling identified conservation cores and connectivity zones balancing tea production and ecosystem services.	Wu et al. (2025).
The resilience effort of Indonesian tea smallholder plantation by intercropping and agroforestry tea farming system	Intercropping fruits, vegetables, and timber improved biodiversity, income diversification, and soil health.	Sita and Aji (2024)

Table 8. Runoff and soil loss reduction in different agroforestry systems

Agroforestry systems	Cropping system	Runoff reduction (%)	Soil loss reduction (%)	Remarks	References
Leauceana hedgerows	Sole maize	71–80	86–97	–	Lal (1989)
Leucaena hedgerows	Castor and pigeonpea	83	72	During 5 years	Rao et al. (1991)
Calliandra calothyrsus hedgerows	Sole maize	30	26	During 3 years	McDonald et al. (1999)
Gliricidia sepium hedgerow and grass filter strip	Finger millet (*Eleusine coracana*)	33	35	During 5 years	Lenka et al. (2012)
Vetiveria zizanioides and *Amorpha fruticosa grass* strip	–	63–71	82–86	During 8 years	Lin et al. (2009)
Gliricidia + miniature trench	Paddy	23.3–32.5	49.5–52.7	During 5 years	Adhikary et al. (2017)
Inga edulis hedgerows	Rice cowpea	82.7	92.6	Average of 5 years	Alegre and Rao (1996)
Hemerocallis citrina, alfalfa hedgerows	Maize	81–83.3	94–94.7	Average of 4 years	Tao et al. (2012)
Contour pair rows of *Leucaena* spp.	Maize	39.7	48	Doon Valley, India	Narain et al. (1997)

Table 9. Key findings of some hedgerow intercropping systems

Aspects of hedgerow intercropping system	Key findings	References
Crop–hedgerow systems (mulberry + crops) tested under different slope positions and layouts.	Improved soil organic carbon and total N; reduced runoff and erosion; mustard yields increased 8–10% in optimal layouts; shading reduced yields in some plots.	Lei et al. (2021)
Long-term hedgerow (day-lily) system on sloped land.	Significantly reduced erosion and improved soil structure and moisture. Crop yields increased over multiple years.	Zheng et al. (2020)
Synthesized effects of agroforestry (including hedgerows) on soil physical, chemical, and biological indicators.	Agroforestry increased soil C and N overall, but magnitude depends on climate zone and soil type; smaller gains in dry zones.	Ngaba et al. (2024)

mango (*Mangifera indica*), jamun (*Syzygium cumini*), cashew (*Anacardium occidentale*), drumstick (*Moringa oleifera*), guava (*Psidium guajava*), citrus species, Indian gooseberry (*Phyllanthus emblica*), and Indian jujube (*Ziziphus mauritiana*).

In Odisha, India, high-yielding eucalyptus clones are widely cultivated and promoted by the paper industry due to their commercial value. Other prominent tree species grown by farmers include *Acacia auriculiformis*, *Melia dubia*, *Leucaena leucocephala*, *Bambusa vulgaris*, and *Grevillea robusta*. Additionally, introduced tropical pine species such as *Pinus kesiya*, *Pinus caribaea*, and *Pinus patula* have shown promising growth performance in this region.

Tree-based cropping systems are common in the highland tropics, where various crops are intercropped with trees. In the Eastern Ghats, staple and cash crops such as finger millet, rice, ginger, and turmeric dominate. Other crops grown in association include pigeon pea (*Cajanus cajan*), maize (*Zea mays*), horse gram (*Macrotyloma uniflorum*), sesame (*Sesamum indicum*), green gram (*Vigna radiata*), black gram (*Vigna mungo*), mustard (*Brassica juncea*), linseed (*Linum usitatissimum*), cowpea (*Vigna unguiculata*), tobacco (*Nicotiana tabacum*), cotton (*Gossypium* spp.), cabbage, cauliflower, tomato, potato, various beans, and medicinal plants. .

CONCLUSIONS

Agroforestry provides a flexible portfolio of options to increase climate resilience across many agroecological contexts in the tropics. The system's design, especially its choice of species and spatial arrangement, determines agroforestry outcomes. The heat stress reduction, forage diversification, soil cover in silvopasture, wind/sun buffering, nitrogen fixation and erosion control in alley cropping, high diversity and redundancy and continuous harvest in homegardens/multistoried agroforestry systems, wind spread reduction and reduced evapotranspiration in windbreak or hedgerow farming, and deep rooting for ground water access and shade characteristics in Parkland are some of the key resilience mechanisms. This evidence increasingly supports the role of agroforestry in adaptation and co-benefits for mitigation and livelihoods; however, scaling these systems requires targeted policy support, finance, tenure security, and long-term, evidence-based findings.

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