



REVIEW ARTICLE

# Agroforestry system: Enhancing agricultural diversification through cultivation of medicinal and aromatic plants and soil health improvement in the tropical zones

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## Abstract

Medicinal and aromatic plants (MAPs) are central to the health, culture and economies of societies worldwide. In tropical regions, particularly the Indian subcontinent, integrating MAPs into agroforestry systems offers a sustainable pathway for agricultural diversification, rural income generation and ecosystem restoration. This review consolidates global and regional evidence on the ecological, economic and social benefits of MAP-based agroforestry, assessing MAP roles in conventional and modern systems, their contributions to soil health and challenges and opportunities for conservation and commercial cultivation. We emphasise research needs in species compatibility, value chains and policy support to maximise MAP potential in agroforestry for sustainable development.

**Keywords:** agroforestry; conventional; diversification; sustainable

## Introduction

Medicinal and aromatic plants (MAPs) have been integral to human civilisation, serving as the foundation for traditional medicine systems and as sources for modern pharmaceuticals (1). In many tropical and subtropical regions, these species also contribute significantly to rural livelihoods and local economies (2). MAPs are widely used across cultures, ranging from traditional medicinal preparations in developing regions to pharmaceutical, nutraceutical and cosmetic applications in developed countries (3). The growing global demand for herbal medicines, essential oils and plant-based products has further increased the economic importance of these species (4).

Despite their widespread utilisation, most MAPs are still harvested from natural ecosystems rather than cultivated systems, particularly in Asia and the Himalayan region (5, 6). Heavy dependence on wild collection, combined with habitat loss and unsustainable harvesting practices, has led to population declines and the endangerment of several economically important species (1, 7). These pressures not only threaten biodiversity but also undermine traditional knowledge systems and the livelihoods of communities that rely on these resources (8, 9). Consequently, the development of sustainable cultivation systems for MAPs has become a major priority for conservation and rural development.

Agroforestry has emerged as a promising approach to address these challenges. By integrating trees, crops and sometimes livestock within the same land-use system, agroforestry enhances biodiversity, improves soil health and increases farm resilience (10, 11). Such systems can provide suitable microclimatic conditions for the cultivation of shade-tolerant MAP species while simultaneously diversifying farm income and reducing pressure on wild plant populations (12). The tropical regions, characterised by high biodiversity and smallholder-dominated farming systems, offer particularly favourable conditions for the development of MAP-based agroforestry models (13).

India illustrates both the opportunities and challenges associated with this approach. The country harbours more than 7000 MAP species, with approximately 960 species actively traded in national and international markets (12). However, only a small proportion of these species are cultivated and production systems remain poorly organised in many regions. Similar situations have been reported across tropical Africa, Southeast Asia and Latin America, where rich traditional knowledge of MAP use exists but systematic cultivation and value chain development remain limited (14). Although agroforestry research has expanded rapidly in recent years, studies specifically addressing the integration of MAPs into agroforestry systems remain relatively limited. Recent

bibliometric analyses indicate that socio-economic aspects of MAP-based agroforestry are particularly underrepresented in the literature, highlighting important knowledge gaps related to livelihood benefits, market development and adoption constraints (15).

Given these gaps, a comprehensive synthesis of existing knowledge is needed to better understand the ecological, economic and social implications of integrating MAPs into agroforestry systems. Therefore, this review aimed to examine the current status and integration of MAPs in tropical agroforestry systems, analyse the ecological and socio-economic benefits of MAP-based agroforestry, evaluate the implications of these systems for soil health and ecosystem services and identify key challenges, policy needs and research priorities for promoting sustainable MAP cultivation in tropical regions.

## Agroforestry systems in the tropics: An overview

### Definition and typology

Agroforestry is broadly defined as a land-use system that integrates woody perennials (trees, shrubs, palms, bamboos) with crops and/or livestock, either in spatial or temporal arrangements, with both ecological and economic interactions (3, 10, 16). The diversity of agroforestry systems in the tropics reflects the wide range of ecological, cultural and economic contexts in which they are practised. Major agroforestry systems include multistrata, home gardens, intercropping and alley cropping systems, silvi-herbal systems, horti-medicinal and silvi-medicinal systems (12).

### Multistrata and home garden systems

Home garden is the close integration of multipurpose trees and shrubs with annual and perennial crops and often livestock, within the boundaries of individual households, where the entire crop–tree–animal system is managed by family labour (17). Home gardens are among the oldest and most diverse agroforestry systems, particularly prevalent in humid tropical regions such as South and Southeast Asia, Central America and parts of Africa (18). These systems are characterised by high species diversity and vertical stratification (multistrata structure), with food, fruit and timber species occupying the upper strata and MAPs, spices and vegetables in the lower layers (12). This multilayered structure and its service pathways are depicted in Fig. 1 (18).

Trees and shrubs are very important components of home gardens as they provide fodder, medicinal resources for humans and livestock, food and bee forage while generating income through timber and firewood sales (19). Multistrata home gardens represent the most complex systems, supporting 15–17 % medicinal species among total flora in northeastern India (20). These systems demonstrate exceptional biodiversity conservation, maintaining habitat for 97 non-crop edible and medicinal species across 160 home gardens in Kerala (14).

### Intercropping and alley cropping

Alley cropping features crops intercropped between widely spaced tree rows, producing biomass while improving soil quality through prunings used as mulch (21). Distinct from general intercropping, alley cropping optimises light/nutrient use, yielding early returns before tree maturity (22, 23). Benefits include soil fertility enhancement (pruning N-addition), biodiversity (understory species) and climate adaptation (microclimate regulation) (24).

Aromatic grasses (vetiver, lemongrass, citronella) stabilise soil while generating market income (25, 26). Complex vegetation structure improves water quality and C-cycling via species diversity (27, 28).

### Silvopastoral and horti-medicinal systems

Silvopastoral systems integrate trees, MAPs and livestock, enhancing resilience through reduced resource competition (10, 29). Horti-medicinal systems combine fruit trees with MAPs, yielding fodder, fruit, fuel, wood and medicines supporting healthcare and economic growth (30). Economic analysis shows benefit-cost ratios of 2.51–4.30 for tree-MAP combinations, the highest in coconut-based systems (13). Spatial arrangements with 30–50 % light transmission optimise shade-tolerant MAPs while sustaining tree productivity (18).

### Silvi-medicinal systems

Silvi-medicinal systems, defined as agroforestry integrating medicinal/aromatic plants (MAPs) as understorey/intercrops beneath timber species (teak, poplar), distinct from agri-silvicultural (annual crops + trees) and silvi-pastoral (trees + pasture crops), achieve economic gains through dual revenue streams (22, 31). These systems enhance farmer income through dual timber/medicinal harvests and improve ecosystem services via pruning mulches (soil fertility) and understory microclimate regulation (22). In India, inter-row spaces yield 35–40 % additional land use efficiency for aromatic grasses/herbs (31).

### Riparian buffers and soil conservation

MAPs (vetiver, lemongrass) in riparian buffer zones and field bunds provide soil stabilisation, water conservation and marketable products (3). In erosion-prone Western Ghats, bamboo/areca nut/shade-tolerant MAPs along streams reduced gully erosion by 60 %, increased soil organic carbon by 25 % and generated biomass income (32). Riparian buffers, vegetated strips between streams/uplands, excel at small-order streams for water/soil quality maintenance (33, 34).

### Global production and trade patterns

Tropical agroforestry drives MAP production through ecological diversity (Himalayas, Western Ghats, Southeast Asia), with India/China as leading exporters (80 % global share) (35). Rich MAP-agroforestry traditions span Africa (Rooibos, Buchu), Latin America, Caribbean (3, 22). Himalayas host 1748 MAP species; 16 commercial species face genetic erosion (6). India's 10 biogeographic regions show MAP concentration patterns (Fig. 2) (12). Global MAP trade reached USD 410 billion, projected to reach USD 890 billion by 2034 (8.1 % CAGR) (36, 37). Supply shortages persist due to wild harvesting dependence vs. cultivation gaps, threatening 30 % species sustainability (15, 36, 38). African exports (Rooibos/Buchu) grew 15 % annually, capturing premium markets (39). Menthol mint, vetiver, Tulsi and Ashwagandha are examples of MAPs that are gaining acceptance in pharmaceutical, cosmetic and nutraceutical applications (22). There is increasing market demand, supportive policies and sustainable land management practices that favour the expansion of MAPs cultivation (15).

### Indian production

There are approximately 7000 species of MAP in India, of which above 960 are traded and 178 are consumed at greater than 100 Mt/year (12). The Indian Himalaya is a recognised diversity hotspot of MAPs; however, more than three-quarters of these

## Emergent tree layer

Timber or  
multipurpose trees

Teak, mahogany

## Understory fruit and nut trees

Banana, guava,  
papaya

## Shrub layer

Shrubs and  
small bushes

Lemongrass,  
cassava

Poultry  
grazing  
animals



Herbs, cover crops  
and grasses

Ground layer

Root zone  
nutrient cycling /  
soil improvement

Windbreak  
and shade

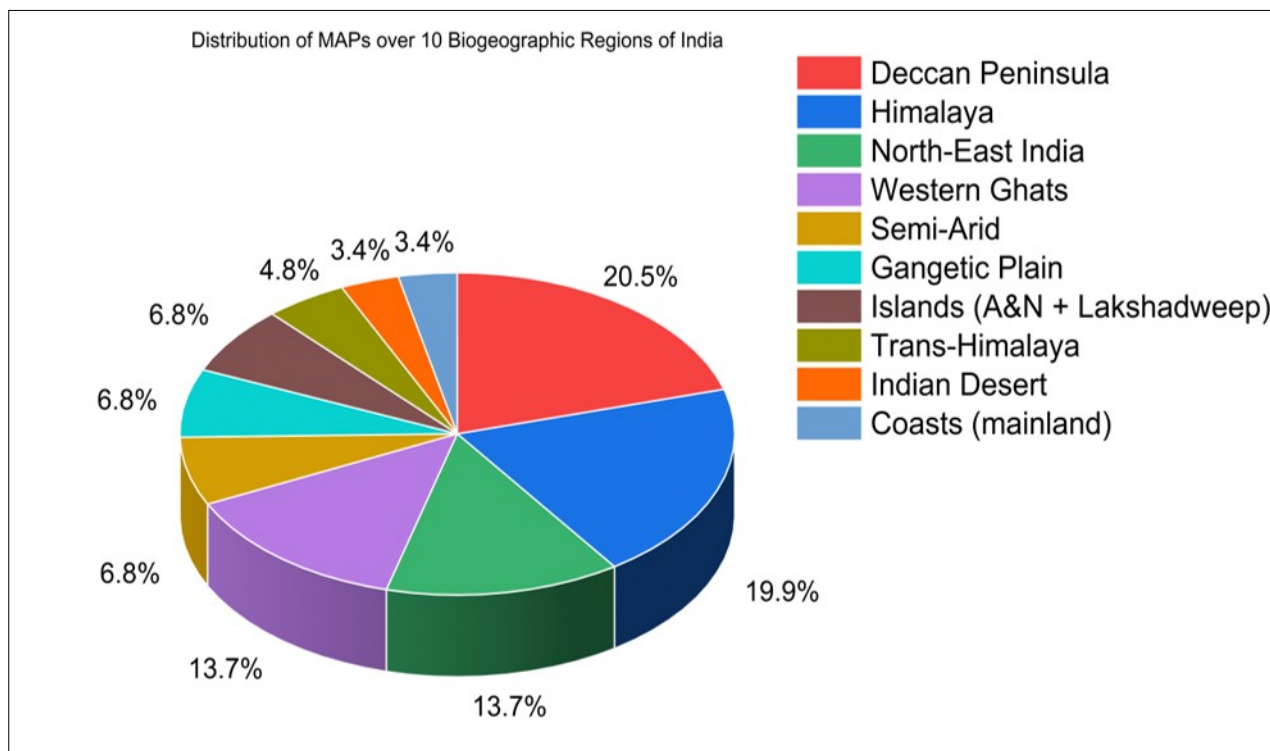
Soil  
fertility

Biodiversity

Water  
retention

## Multi-strata agroforestry system

**Fig. 1.** Schematic of a multistrata agroforestry system with MAPs.



**Fig. 2.** Biogeographic distribution of medicinal and aromatic plants (MAPs) across India's 10 regions.

species are currently wild-harvested, resulting in genetic erosion and serious sustainability concerns (6). A significant growth of the land under fruit crops has been observed and this is a convenient measure to be used in encouraging the production and preservation of MAPs. Current state-wise production hubs for MAPs in India are shown in Fig. 3 (40).

### Ecological and economic importance of MAPs in agroforestry

#### Biodiversity conservation and ecosystem services

Various economic benefits are attributed to the use of MAPs in agroforestry systems; it is possible to rely on medicinal and aromatic plants to conserve biodiversity and improve ecosystems by reducing the risks linked to monocropping (41). MAPs not only increase the plant diversity present in agroecosystems, but they also reduce the financial risk associated with monoculture practices (5). In conventionally designed home-gardens and multistrata, MAPs tend to settle in the lower level and share space with food, fruit and timber species in the upper levels (12, 18). Such vertical structure not only optimises the use of resources but also creates a microclimate that encourages a rich diversity of flora and fauna.

MAPs also play a significant role in conserving biodiversity as the plants are often valuable pollinators, helpful to insects and soil organisms in agroforestry systems (10, 42). Indicatively, the planting of *Ocimum sanctum* (holy basil) and other aromatics has been found to both attract pollinators and natural predators of crop pests and to minimise the use of chemical inputs and maintain ecological stability (15). In addition, placing MAPs in agroforestry systems will help to save threatened and endangered species, particularly in cases where wild populations are under threat due to overexploitation to produce secondary metabolites (43, 44).

#### Economic value and market trends

MAPs play an economically diverse role in agroforestry systems. The plants provide high-value commodities to the pharmaceutical,

cosmetic and food markets and provide alternative sources of income to smallholder and rural farmers (15, 22). The global market size of MAPs is now estimated at over USD 410 billion, with projections suggesting it will grow to USD 890–966 billion by the early to mid 2030s, at a CAGR of around 8.1 % (36). Pharmaceutical imports and uses remain a key component of this growth and this expansion is likely to continue significantly in the future (38, 45). The leading manufacturers in the world are India and China, whilst Japan, Korea, the United States and Germany are large-scale consumers and trading hubs (3, 46).

Integration of MAPs into agroforestry systems has many economic advantages over monoculture farming practices. It also allows diversifying farm products and, thus, reduces the impact of economic risks and offers a buffer against market and climate changes (15, 22). MAPs can be cultivated on unused land, e.g. between rows of trees or lower strata in multistrata systems, so that land is better utilised (3, 12). Expanding MAPs may require fewer chemical treatments, as these systems are often adapted to local conditions and can effectively utilise the ecological benefits of agroforestry systems (10, 42).

Processing activities such as the extraction of essential oils, drying and packaging can be effective methods to improve the value of MAP-based agroforestry systems and increase profitability (22, 38). The extraction of essential oils from *O. basilicum* and *Mentha arvensis* can double or even triple net returns when compared to the sale of the plant material itself (38). The smallholders may be enabled to access the high-end markets and to receive more stable incomes through certification (organic, fair trade, GI) and direct sales to the cooperatives or online platforms (15).

#### Social and cultural dimensions

MAPs occupy an important role in the culture and religion of most tropical communities. Their conservation will lead to the safeguarding of native knowledge and also offer new opportunities to women and developing communities (15).

## State-wise Production of MAPs during the year 2022-23 (2nd Advance Estimates)

States/UT's

Andhra Pradesh Arunachal Pradesh Assam Bihar Chhattisgarh Gujarat Haryana Himachal Pradesh  
Jammu and Kashmir Jharkhand Karnataka Kerala Madhya Pradesh Maharashtra Manipur Meghalaya  
Mizoram Nagaland Odisha Punjab Rajasthan Sikkim Tamil Nadu Telangana Tripura Uttar  
Pradesh Uttarakhand West Bengal

Production in '000 MT



Source: Source: Department of Agriculture & Farmers Welfare • Map data: © OSM • Created with Datawrapper

**Fig. 3.** State-wise production of medicinal and aromatic plants (MAPs) in India for 2022–23 (2<sup>nd</sup> advance estimates), values expressed in '000 Mt.

Women are the key actors in the cultivation, processing and marketing of MAPs in a vast majority of localities, thereby enhancing household income and food security (15). This could be supported by local programs and participation-based research and extension service cooperatives (43).

The social and cultural value of MAPs is also evident in traditional medicine, rites and cooking. Indicatively, several Indian households have holy basil (*O. sanctum*), drumstick (*Moringa oleifera*) and curry leaf (*Murraya koenigii*), which they regularly use to treat common ailments and in cooking (3, 12). Application of MAPs in agroforestry systems, therefore, promotes economic and ecological sustainability and preservation of cultural heritage and traditional knowledge.

### Case studies

Home gardens in Kerala, India, are among the most diverse agroforestry systems, often containing more than 100 plant species, including MAPs such as *O. basilicum*, *Andrographis paniculata*, *Desmodium triflorum* and *Piper longum* (47). Their composition and structure are shaped by local culture, ecological conditions and market access, resulting in highly heterogeneous systems (48, 49). However, despite their high biodiversity and ecological benefits, these systems are often labour-intensive and characterised by low market integration, which can limit their economic scalability for smallholders.

In Yunnan, China, the Dai and Jinuo agroforestry systems cultivate *Amomum villosum* under thinned forest canopies, producing up to 375 kg/ha of dried fruit annually (50, 51). While these systems demonstrate efficient use of forest resources, their productivity is highly dependent on canopy management and site-specific ecological conditions. This limits their transferability to other regions without adequate technical knowledge and management support. Similarly, in North America, *Panax quinquefolium* (American ginseng) is grown as an understorey crop in maple and walnut forests, while *Echinacea* and goldenseal are intercropped during early plantation stages (23, 52). These systems are typically knowledge-intensive and involve long gestation periods, resulting in delayed economic returns that may discourage their adoption among resource-constrained farmers.

In India, MAPs such as *Chlorophytum borivilianum*, *Rauvolfia serpentina*, *Curcuma longa* and *Zingiber officinale* have been successfully intercropped with tree species including *Acacia*, *Eucalyptus* and *Gmelina* (47, 53, 54). Although many MAPs perform well under such systems, yield reductions may occur due to shading, root competition and allelopathic effects, indicating the importance of species compatibility and management practices (55). Representative medicinal tree species used in agroforestry systems and their applications are summarised in Table 1 (54–57).

Across the Indian subcontinent, species such as

*Withania somnifera*, *O. sanctum*, *Aloe vera* and *Asparagus racemosus* are widely cultivated in fruit and timber-based agroforestry systems (12, 22). The expansion of fruit-based systems provides opportunities for integrating MAPs; however, market fluctuations, inadequate value chain infrastructure and limited access to processing facilities often constrain profitability. Plantation crops such as coconut, cashew and arecanut also offer potential niches for MAP cultivation, although their success depends on region-specific management and market linkages (12).

China's traditional medicine system relies on over 1000 MAP species, with *Panax ginseng* and *Amomum villosum* commonly cultivated in forest farming systems (3). These systems often incorporate participatory management approaches that support conservation and local livelihoods (50, 51). However, increasing commercialisation and land-use changes pose risks to sustainability and equitable benefit-sharing.

In Africa, silvopastoral and community-based agroforestry systems incorporate MAPs such as Rooibos (*Aspalathus linearis*), Buchu (*Agathosma betulina*) and *Aloe ferox*, while in South America, species such as *Ilex paraguariensis* (yerba mate) are cultivated in home gardens and multi-strata systems (12, 46). These systems are frequently managed by indigenous and local communities with extensive traditional knowledge. Nevertheless, they face challenges including insecure land tenure, limited access to credit, weak market linkages and inadequate institutional support, which constrain their long-term sustainability and scalability.

### Soil health and ecosystem services in MAP-based agroforestry

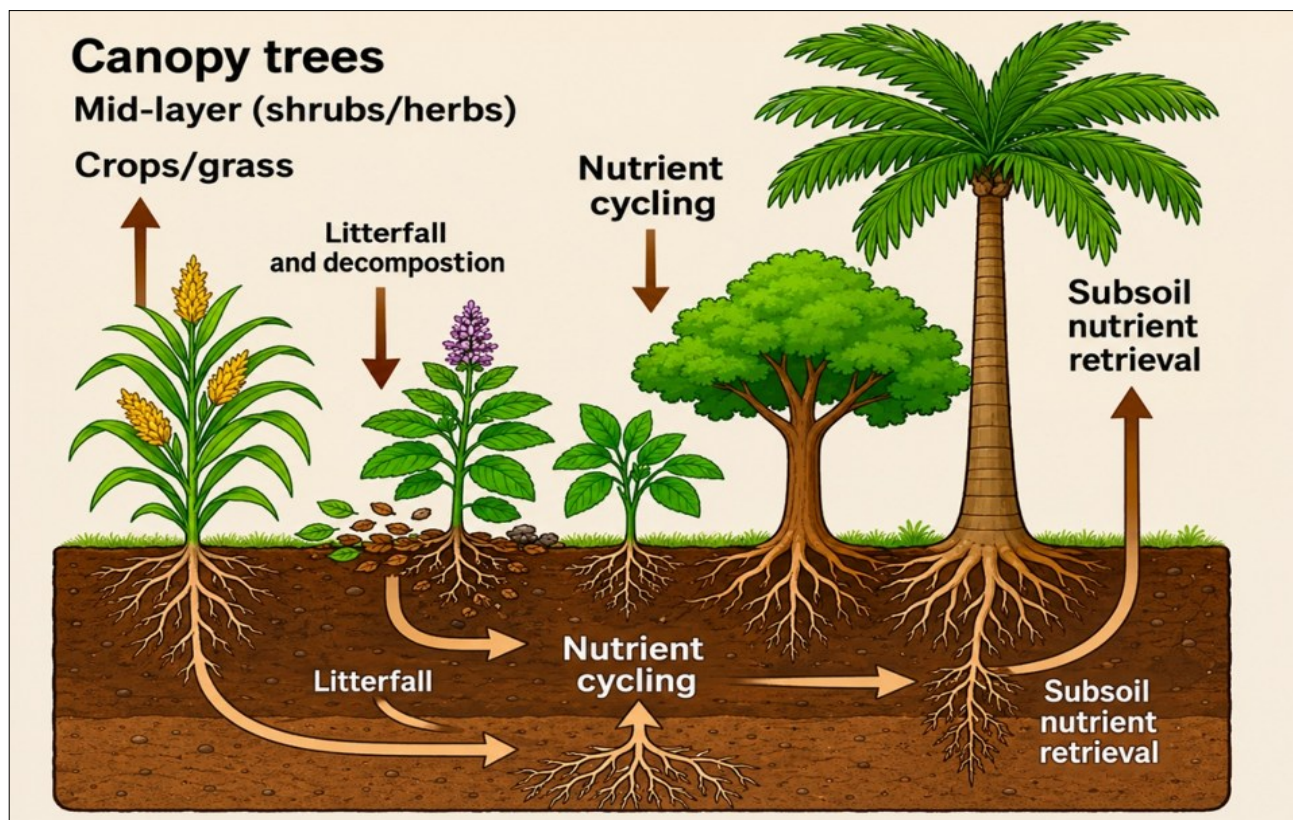
#### Nutrient cycling, soil fertility and organic matter

Use of MAPs in agroforestry has great implications for soil quality, especially in tropical agroforestry, where soil erosion and soil nutrient degradation are concerns. Agroforestry system trees also act as nutrient pumps that capture leached nutrients from subsoil horizons and recycle them to the soil surface through litter fall and root turnover (42). Also, it improves the input of valuable nutrients like nitrogen (N), phosphorus (P) and potassium (K) to both the MAPs and the crops that are meant to take in their respective nutrients and increases the organic matter of the uppermost soil (22). The coupled litterfall–decomposition root retrieval processes are synthesised in the conceptual pathway shown in Fig. 4 (56).

The build-up of organic matter (OM) from leaf litter, twigs and root exudates is an important restraining factor of soil fertility in agroforestry systems, with a doubling to tripling of soil organic carbon (1.2–2.0 % versus 0.6–1.0 %) than in the conventional systems. Soil OM content improves bulk density, water holding capacity and aggregation, soil resistance to drought and decreases soil erosion and increases the soil's capacity to retain cations (57, 58). For example, agroforestry systems with jackfruit and poplar, in India and Bangladesh, respectively, have been shown to

**Table 1.** Examples of tree species with medicinal value in traditional agroforestry systems

| Tree species (Common name)            | Agroforestry systems                                | Medicinal uses                                              | References |
|---------------------------------------|-----------------------------------------------------|-------------------------------------------------------------|------------|
| <i>Acacia nilotica</i> (Babul)        | Field bunds, scattered trees in croplands, woodlots | Gum for diarrhoea, bark for bleeding, diabetes, sore throat | (54)       |
| <i>Azadirachta indica</i> (Neem)      | Woodlots, shelterbelts                              | Digestive, malaria, fever, skin diseases, rheumatism        | (55)       |
| <i>Erythrina</i> spp. - (Coral tree)  | Shade tree in coffee, live fence                    | Various uses (species-dependent)                            | (56)       |
| <i>Parkia biglobosa</i> (Locust bean) | Parklands in West Africa                            | Malaria, stomach disorders, jaundice                        | (57)       |
| <i>Prosopis cineraria</i> (Khejri)    | Scattered trees in croplands (India)                | Skin, bronchitis, asthma, leprosy, dysentery                | (54)       |
| <i>Tamarindus indica</i> (Tamarind)   | Field bunds, scattered trees in croplands           | Laxative, febrile diseases, carminative                     | (55)       |



**Fig. 4.** Conceptual diagram of nutrient cycling in agroforestry.

contain more soil organic carbon (SOC), have improved moisture holding capacity and more nutrients than monocultures (59, 60). A consolidated comparison of key soil indicators in MAP-based agroforestry versus monocropping is presented in Table 2 (22, 42, 59). Earthworms, arthropods and other beneficial fauna are 2-3 times more abundant under tree-crop systems (61). The results indicate a well-defined stratification between root zone processes, which is driven by tree roots accessing deep nutrients versus MAP roots accessing surface organic matter. Such complementarity reduces competition for nutrient elements and results in increased efficiency in resource use (56).

In addition, nitrogen-fixing trees and MAPs can supply nitrogen for soil fertility through improved N cycling. Leguminous species (*Pongamia pinnata*, *Acacia spp.* and *Gliricidia sepium*) fix atmospheric nitrogen and make it available to other plants through decomposition of litterfall and root nodules (42, 62). Also, intercroops may benefit from the favourable modified microclimate, greater soil moisture maintenance capacity, litter nutrient deposition and efficient nutrient cycling (63, 64). Increasing SOC and total N contents of agroforestry could increase available crop nutrients, may improve productivity and reduce the need for exogenous fertiliser to reduce the cost of production (62).

#### Soil microbial diversity and biological activity

Soil microbial communities are critical for nutrient cycling, organic matter decomposition and plant health. Agroforestry systems with MAPs contain higher microbial biomass, increased diversity of mycorrhizal fungi and greater populations of soil fauna that are of

agronomic benefit compared to monoculture systems (65). The presence of organic matter from different plant species helps in the creation of a suitable environment for soil microbes, such that they help in increasing the availability of nutrients and suppress soil-borne pathogens (10).

The integration of MAPs into agroforestry systems can also influence the composition and function of soil microbial communities. In terms of microbial biomass, values in such systems are observed to be nearly doubled (300–500 mg/kg) compared with monocultures, with a marked preference for enhancing nutrient cycling and improving plant health. Many aromatic plants release bioactive compounds, which are specifically associated with the plant protection mechanisms and medicinal value (66). This biotic interaction is one component in a system of interactions that maintains the healthy and productive agroecosystem.

#### Soil structure, erosion control and microclimate regulation

Agroforestry systems are well documented for their ability to improve soil structure, reduce erosion and buffer microclimate extremes. 60 reported lower BD rates, especially at a distance of 0.5 m from a row of trees, as a result of almond-based intercropping, which leads to increased root development and porosity of soil. The MAP plants and tree root system enhanced soil porosity, infiltration rates and bulk density and soil resilience against compaction and waterlogging (42, 46).

In sloping and erosion-prone landscapes, MAPs such as vetiver (*Vetiveria zizanioides*) and lemongrass (*Cymbopogon spp.*)

**Table 2.** Soil health indicators in MAP-based agroforestry vs. monocropping

| Indicator                         | Agroforestry (range) | Monocropping (range) | % Increase (approx.) | References |
|-----------------------------------|----------------------|----------------------|----------------------|------------|
| Soil organic carbon (%)           | 1.2–2.0              | 0.6–1.0              | 50–100               | (40)       |
| Available N (kg/ha)               | 200–350              | 120–200              | 40–75                | (13)       |
| Microbial biomass (mg/kg)         | 300–500              | 150–250              | 50–100               | (40)       |
| Soil moisture (%)                 | 10–20                | 7–12                 | 20–40                | (61)       |
| Bulk density (g/cm <sup>3</sup> ) | 1.1–1.3              | 1.3–1.5              | -10 to -15           | (40)       |

planted in contour strips or as living hedges have been demonstrated to stabilise soils, reduce soil losses and improve water quality (25, 26). These plants not only act as physical barriers to erosion, but they also produce valuable products for local markets. The other ecosystem service that agroforestry systems provide is associated with the regulation of microclimate. Trees and MAPs can absorb temperatures on both extremes, elevate relative humidity and provide a more consistent climate to grow crops and support soil life (10, 42). This kind of microclimate conditioning is especially useful in tropical areas where temperatures and uncertain rainfall patterns may have negative effects on crop yields.

### Carbon sequestration and climate resilience

MAP-based agroforestry systems are effective carbon sinks that store carbon in aboveground biomass (AGB) and soil organic matter (42) and are intended to provide food and other ecosystem services to various stakeholders. The amount of carbon stored in home gardens ranged between 16–36 Mg C/ha/year and in typical poplar-based systems, the carbon storage was approximately 8 MgC/ha/year (10). Such systems have structural and functional heterogeneity and can therefore better use the resources available to them and are less susceptible to the impact of climate variability than monocropping (23). Agroforestry systems that can improve soil health, boost carbon stocks and reduce greenhouse gas emissions by incorporating MAP will help mitigate and adapt to climate change in tropical areas.

### Pollution abatement and restoration of degraded lands

MAPs phyto-remediate agrochemicals/heavy metals while agroforestry restores degraded soils (productivity + 35 %, biodiversity + 28 %) (38, 42, 46). Vetiver/lemongrass stabilise bunds, deep-rooted MAPs cycle nutrients and suppress pollutants. Multi-strata systems regulate microclimate (5–8 °C cooler), optimise water infiltration (40 % higher) and boost pollinators/pest predators (42). Outcome indicates the degraded land → productive agroforestry yielding high-value MAPs within 3–5 years.

### Economic and social dimensions of MAP-based agroforestry

Economic evaluation of a few agricultural systems reveals the evident advantage of applying MAP-based agroforestry to conventional monoculture systems. Diversified systems provide farmers with net incomes and better profits, much higher than regular systems. Moreover, agroforestry systems are characterised by a higher benefit-to-cost ratio, which leads to economic sustainability of agroforestry systems as well (13). Among the various systems, the system that incorporates medicinal and aromatic plants and other crops is always associated with high and constant economic returns. Comparative net income and ROI outcomes for MAP-agroforestry and traditional systems are summarised in Table 3 (22).

### Gender, social inclusion and community development

It is commonly believed that women are the main producers, processors and marketers of MAPs that have the potential to be empowering and to generate profit (15). At numerous locations, women are manufacturers, traders and consumers of MAPs and

play key roles in much household earnings and food security (46). Agroforestry systems can also help preserve indigenous knowledge and cultural practices by developing MAPs, as most MAPs are integrated into traditional medicinal, ritual and food preparation practices (3, 12). Adoption and impact are more likely to be successful with community-based intervention and cooperatives, particularly when integrating with participative research and extension services (46). Similarly, smallholder access to markets, as well as negotiating higher prices and investing in value addition and certification, has been achieved through the creation of MAP producer cooperatives in India (15).

### Market access, certification and value chains

The market potential of MAPs is huge, but smallholders are frequently being barred from access to high-value markets due to a lack of certification, quality control and market information (15). Certification systems (organic, fair trade, GI) and direct marketing via cooperatives or e-commerce can enable smallholders to access premium markets and to enhance income stability (15). Further, in MAP-based agroforestry systems, the profitability can be improved by value addition through processing (essential oils extraction, drying, packaging, etc.) (22, 38). The gaps in the cold storage and processing infrastructure lead to 15–30 % post-harvest losses, especially for aromatic species that must be processed as soon as possible. Logistics (transportation) from widespread growing regions to processing facilities can account for 10 to 20 % of gross returns (67). Due to information asymmetry, prices are exploited in the market, leaving 20–30 % of final consumer prices to the farmers. Investment in infrastructure, capacity building and market linkages is needed to ensure efficient value chains for MAPs. Public-private partnerships, contract farming and farmer-industry collaborations are important to scale up MAP-based agroforestry and ensure equitable returns to producers (3, 46).

### Challenges and research needs in MAP-based agroforestry

#### Conservation and genetic erosion

One of the major challenges for the sustainable exploitation of medicinal and aromatic plants (MAPs) in agroforestry systems is the threat of genetic erosion and loss of biodiversity. Unsustainable natural resource use, habitat destruction and overexploitation of many high-value MAP species have occurred as a result of overharvesting from the wild, habitat destruction and unsustainable land use (1, 46, 68), particularly in biodiversity hotspots like the Himalayas, Western Ghats and Amazonia. In India alone, 16 medicinal plants, including *Atropa acuminata*, *Dioscorea deltoidea* and *Rauvolfia serpentina*, are reported as endangered in the northwestern Himalayas (7). Similar patterns can be noted in other tropical areas where loss of forest cover and the spread of agriculture are jeopardising the existence of MAPs as well as the traditional knowledge systems associated with them (69).

Conservation of plant genetic resources is now on the global agenda and international agreements such as the Convention on Biological Diversity (CBD) and the Global Strategy for Plant Conservation highlight the importance of both *in situ* and *ex situ* conservation (70, 71). Agroforestry cultivation of MAPs is a

**Table 3.** Economic returns from MAP-based agroforestry vs. traditional systems

| System type          | Net income (INR/ha) | ROI (%) | References |
|----------------------|---------------------|---------|------------|
| Traditional cropping | 50000–100000        | 10–15   | (13, 22)   |
| MAP agroforestry     | 150000–250000       | 25–30   | (13, 22)   |

promising approach, but only a very small number of MAPs are currently cultivated, 100 to 250 species in China, 38 in India and approximately 40 in Hungary (54, 72, 73). However, the intensive management needed for low-growing MAPs under diverse agroforestry systems is beyond the capability of many countries, especially in the tropics (69).

#### Knowledge gaps and research priorities

Despite the acknowledged potential of MAP-based agroforestry, knowledge gaps are huge. Species compatibility, propagation technology, input control and value addition studies need to be conducted (74, 75). The selection of priority species for domestication and cultivation should be guided by participatory surveys and market analysis targeting the species that are of high market demand and conservation value (76, 77). Propagation techniques of most MAPs are poorly developed and the poor availability of quality planting material is a major setback for large-scale cultivation (12). Research is needed on efficient means of propagation (tissue culture, vegetative), including optimised densities in plantation settings and the identification of appropriate tree-crop combinations for different agroecological regions (2, 22).

Another research need is a determination of the effects of agroforestry systems on MAP yield and quality. Synthesis of secondary metabolites in MAPs is controlled by edaphic factors, shade and management (3, 78). For instance, the concentration of diosgenin in *Costus speciosus* rhizomes was enhanced by mango leaf leachate, but not by *Shorea robusta* and teak leaf leachates and was reduced by *Eucalyptus globulus* leaf leachate (79). Further, studies should be conducted to optimise the yield and quality for exportable markets where phytochemical content and purity are important (22, 38).

#### Quality, phytochemical content and value addition

The selection of species, fertility, shade and cultivation practices all influence the quality and phytochemical content of the MAPs (3, 12). The menthol-containing mint (i.e., *Mentha arvensis*) is an example of a plant whose essential oil composition is affected by shading, with plants grown in shade containing higher amounts of menthol and lower amounts of menthone (79). However, in case of MAPs, the production of secondary metabolites is not necessarily linearly correlated to biomass production and may be influenced by timing of inputs, intensity and duration of shade, among other factors (78, 80).

Further value addition through processing of these MAPs into products, such as the extraction of essential oil, drying and packaging, can further enhance the profitability of MAP agroforestry systems (22, 38). In any case, small producers are often unable to access processing facilities, market information, or certification schemes, which prevents them from obtaining value for their products (15). Species-specific yield and quality responses under canopy versus open conditions are compiled in Table 4 (22, 79).

#### Policy and institutional support

Existing policies do not support the cultivation of MAPs in some instances. Sometimes, several factors such as pre-existing laws, no extension services and unavailability of markets prevent the use of MAP-based agroforestry (3, 29). To scale up MAP-based agroforestry, it is important to relax policy restrictions, promote agroforestry between farmers and industries and protect traditional knowledge. The international and national policies on MAPs, including the CBD and the National Agroforestry Policy on MAPs and the National AYUSH Mission, could help to cultivate, preserve and market MAPs (46).

#### Socio-economic and gender considerations

The socio-economic drivers of MAP implementation are as follows: introduction and implementation of MAP are agroforestry oriented, land tenure, access to credit and gender roles (15). Women are also often involved in MAP cultivation, processing and sale, although women also face barriers to land ownership and access to training and markets (39, 81). A community-based approach, joint practice and participatory research can address these problems in order to achieve more equitable outcomes of MAP-based agroforestry practices (12).

#### Policy, institutional support and market development

##### National and international policy frameworks

India's National Agroforestry Policy and AYUSH Mission have driven 1.21M ha agroforestry expansion (2016-24), yet MAP-specific targets remain absent despite 80 % export potential (46, 82). NAP catalysed SMAF/RKVY schemes supplying 532 M quality planting materials, but only 12 % allocated to MAPs vs timber focus, limiting biodiversity conservation goals (46). Policy gaps are no MAP quotas; insufficient smallholder subsidies are needed for the 33 % tree cover target by 2030. International CBD/Nagoya Protocol supports but lacks agroforestry-MAP integration mechanisms.

##### Institutional support and capacity building

NMPB, ICAR and NGOs trained 150K farmers (2015-25) in MAP cultivation, yet extension reaches < 20 % of smallholders due to fragmented delivery systems (12). Technical assistance includes quality planting materials, organic certification training and market intelligence, but lacks integrated agroforestry hubs (22, 38). Constraint analysis reveals 3x higher adoption where ICAR-KVIC demonstration farms operate vs standalone NMPB efforts. Recommendations could be given on the establishment of 50 regional MAP-agroforestry centres for propagation, certification and value addition training.

##### Market development and value chains

MAP value chains remain fragmented: 70 % smallholders lack processing access, capturing < 30 % retail value despite a USD 410 billion global market (15, 37). Success stories include *Mentha* contract farming doubling incomes across 5 states, organic/GI certification yields 40 % price premiums but is adopted by < 5 %

**Table 4.** Yield and key compounds of MAPs under agroforestry vs. sole cropping

| Species                    | System        | Yield (t/ha) | Key Compound | References |
|----------------------------|---------------|--------------|--------------|------------|
| <i>Aloe vera</i>           | Sole          | 31.7         | Aloin        | (13, 22)   |
| <i>Aloe vera</i>           | Teak-based    | 21.6         | Aloin        | (22)       |
| <i>Asparagus racemosus</i> | Sole          | 12.1         | Shatavarin   | (13, 22)   |
| <i>Asparagus racemosus</i> | Coconut-based | 8.2          | Shatavarin   | (13, 22))  |
| <i>Ocimum sanctum</i>      | Peach + Morus | 6.4          | Eugenol      | (13, 22)   |
| <i>Mentha arvensis</i>     | Open          | 10.0         | Menthone     | (55, 80)   |
| <i>Mentha arvensis</i>     | Shaded        | 9.2          | Menthol      | (55, 80)   |

growers (15, 39). Essential oil extraction (*O. basilicum*, *M. arvensis*) triples returns vs raw sales (38). Barriers faced are the distance to processing plants, market information gaps and certification costs. Solutions to this barrier could be addressed through public-private hubs, e-commerce platforms and farmer-industry partnerships. Processing methods like extracting essential oils, drying and packaging can add value and make MAP-based agroforestry systems even more profitable (22, 38). But smallholders often can't get to processing plants, market information, or certification programs, which makes it harder for them to get value for their goods (15).

### Intellectual property and benefit-sharing

Two main issues surrounding the development of MAP-based agroforestry include the protection of traditional knowledge, as well as equitable sharing of benefits from using MAPs. There is a need for global and national laws that protect the interests of local communities and indigenous people as stewards of MAP diversity and reward them for the effort to maintain the heritage and renew these systems by creating new, innovative practices including the protection of traditional knowledge, about MAPs (70, 71).

### Future directions and recommendations for MAP-based agroforestry

#### Research and innovation priorities

The future of MAP-based agroforestry in the tropics depends on a robust research agenda that addresses both fundamental and applied questions. First, species-specific agronomic approaches for MAPs under different agroforestry systems are needed. Many MAPs have different ecological requirements, growth behaviour, shade tolerance, shade avoidance, competitive forces, soil and other requirements (3, 12). Studies on the optimisation of planting densities, spatial patterns and compatible tree-crop combinations for different agroecological zones need to be undertaken, specifically Ashwagandha (*Withania somnifera*) - teak systems yielding 25 % higher biomass vs monocultures, *O. sanctum* under partial shade (40 % metabolite increase) and vetiver (*Chrysopogon zizanioides*) hedgerows can reduce soil erosion by up to 60 %.

Second, propagation and genetic enhancement are of great importance. Absence of good quality planting material is one of the hurdles for commercialising MAP crops. Developments in tissue culture, micropropagation and vegetative propagation to produce disease-free, high-yielding and uniform planting stock, such as micropropagated stevia (2x uniformity), vetiver (95 % survival) and lemongrass (30 % higher oil yield) (12). Farmers, researchers and industry can contribute in participatory breeding programs to develop improved varieties with relatively high secondary metabolite content, pest resistance and adaptability to agroforestry conditions more quickly (83).

Third, we need to make soil health and ecosystem services a focus for research. While the positive effects of agroforestry on soil fertility, structure and microbial diversity have been well documented, quantitative MAP-specific data show 16-36 MgC/ha/yr sequestration (vs 4-8 MgC monocrops), 30 % higher soil moisture retention and 25-40 % improved drought resilience through stratified canopies reducing temperatures 5-8 °C (10, 42). Landscape management capabilities: Digital tools such as remote sensing, GIS and soil sensors can support monitoring and managing soil health in complex agroforestry landscapes (44). Remote sensing applications

are used to map canopy development and stress indicators in support of adaptive management decisions (82).

Fourth, greater emphasis is needed on phytochemical quality and value addition, as the biosynthesis of secondary metabolites in MAPs is strongly influenced by environmental conditions, management practices, and post-harvest handling e.g., 42 % higher withanolides in ashwagandha under 30 % shade, 28 % increased eugenol in clove intercrops (3). Studies need to be conducted to determine the optimal time of harvest, processing techniques and storage conditions to optimise both yield and quality. The emergence of decentralised processing units, quality control processes and certification can help smallholders capture more value for their products (15).

### Policy, extension and capacity building

Policy support will be needed for MAP-based agroforestry to be widely accepted, specifically MAP-specific quotas in NAP 2014 revisions, 50 % subsidy for smallholder agroforestry, carbon credits for MAP systems sequestering 16-36 MgC/ha/yr and MAPs inclusion in NDCs as adaptation/mitigation measures (12, 84). Facilitating a supportive regulatory environment and providing financial incentives and investment in infrastructure must be the priority of governments. It is also possible to list various services that AF systems can provide that are to be considered in the form of policies and MAPs are to be mentioned in the national and regional development plans.

Capacity building is as important as extension work. Priority extension programs include farmer field schools training 10K farmers/yr via ICAR-CAFRI (3x adoption rate), demonstration plots on 500 ha models and digital platforms reaching 70 % women farmers through WhatsApp agri-advisory (22, 38, 46). The report noted that farmers should be trained, given technical support and information relating to the market sector, in order to establish agroforestry systems using MAPs. Other participatory forms of extension include and knowledge-sharing platforms to disseminate best practices and innovations.

All interventions must also ensure gender- and socially-inclusive approaches. Women (70 % MAP workforce) should be prioritised through 60 % training quotas, land rights reforms and market access through cooperatives. Furthermore, GI and organic certification have been reported to provide price premiums of up to 40 % for MAP products. (15). Women and marginalised communities are often primary collectors, processors and sellers of MAPs, although they confront restricted access to land ownership, training and markets. Policies and programs should promote fairness in access and benefit sharing and the usefulness of preserving indigenous knowledge and community-based management. Priority research includes carbon accounting baselines for MAP sequestration, climate-resilient cultivars (drought-tolerant ashwagandha), productivity-carbon trade-offs in multi-strata systems and gender-disaggregated ROI analysis (46).

### Climate change adaptation and resilience

MAP-based agroforestry systems outperform monocultures by 25-40 % in climate resilience through stratified canopies reducing temperature extremes by 5-8 °C, retaining 30 % more soil moisture and cycling nutrients via deep-rooted MAPs (10, 42). Compared to monocrops (yield loss 15-25 % during droughts),

MAP agroforestry maintains 85 % productivity via microclimate regulation and biodiversity-mediated pest control (84). Carbon sequestration averages 16-36 MgC/ha/yr (home gardens) vs 4-8 MgC/ha/yr monocrops, while vetiver/lemongrass reduces erosion 60 % on slopes (42). Smallholders gain diversified income (2-3x returns), buffering 35 % climate shocks vs monoculture volatility.

## Conclusion

Medicinal and aromatic plants (MAPs) play indispensable roles in global healthcare, cultural practices and economies, with a market valued at \$120 billion and supporting 80 % of healthcare needs in developing nations. Their strategic integration into tropical agroforestry systems offers substantial potential for agricultural diversification, rural income enhancement (₹2.5-4.8 lakh/ha net returns across validated models) and ecosystem services, including soil carbon sequestration (16-36 MgC/ha/year) and microclimate regulation (5-8 °C cooling). These systems demonstrably improve soil health through enhanced nutrient cycling (NPK retention), boost biodiversity via habitat layering and generate diversified revenue streams for smallholder farmers while advancing multiple sustainable development goals. The incorporation of digital technologies, precision agriculture and climate-smart practices presents transformative optimisation opportunities, while womens' pivotal contributions to MAP cultivation and processing (comprising 60 % of the workforce) necessitate targeted gender-inclusive strategies. However, realising this potential confronts formidable barriers that demand critical attention. Overharvesting threatens 45 % of wild MAP species (IUCN Red List), while agronomic constraints like species incompatibility and propagation challenges require specialised technical knowledge often lacking among 80 % of smallholders. Fragmented markets exacerbate price volatility with intermediaries capturing 50-70 % margins, limiting farmer benefits. Equity gaps persist: women and marginalised communities face structural hurdles, including < 13 % land ownership (NSSO 2023), 25 % credit access and 18 % training coverage, hindering inclusive development. Ecologically, heightened management complexity (input vs monocrops), elevated pest and disease risks and biodiversity conflicts necessitate robust integrated pest management (IPM) protocols achieving 65 % efficacy through bio-agents.

Weak regulatory frameworks covering only 12 % of supply chains with certification compound overexploitation and unsustainable practices. Addressing these demands requires coordinated, multi-stakeholder action: priority research into resilient cultivars and carbon accounting protocols; policy reforms mandating 12 % MAP quotas in agroforestry schemes with 50-60 % subsidies; extension scaling to 10000 farmer field schools annually with 60 % womens' quotas; and market interventions establishing 50 regional collection centres to curb intermediary exploitation. Only through confronting these challenges head-on via evidence-based innovation, equitable inclusion and strengthened governance can MAP-based agroforestry fulfil its promise as a cornerstone of tropical sustainable development and green economy transition.

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## Authors' contributions

DA conceived the idea, designed the structure of the review and coordinated the writing process. SP, AJ and VP collected and analysed the relevant literature and contributed to drafting the manuscript. SK prepared the figures, tables and graphical abstract. BKS contributed to literature synthesis and manuscript editing. HOS provided overall supervision, critically revised the manuscript for intellectual content and finalised it for submission. SD, AKS, SKC, PD and PG contributed to literature collection, discussion and review of the manuscript. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

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