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Integrating medicinal and aromatic plants with agroforestry systems: Ecological, biochemical, and socioeconomic synergies

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Abstract
The increasing global demand for medicinal and aromatic plants (MAPs) has placed significant pressure on natural ecosystems due to extensive wild harvesting. Medicinal and Aromatic Agroforestry (MAAF) offers a sustainable alternative by integrating MAPs with tree-based systems to enhance productivity while conserving ecological integrity. This study reviews the ecological, biochemical, and socioeconomic benefits of MAAF, including improved soil health, biodiversity conservation, carbon sequestration, and microclimate regulation. Various agroforestry models such as Agri-silviculture, multi-strata systems, forest farming, and Silvo-pastoral practices are evaluated for their adaptability and economic potential. The influence of shade on secondary metabolite production, a key determinant of MAP quality, is also highlighted. Additionally, challenges such as allelopathy, resource competition, and inefficient value chains are discussed along with management and post-harvest strategies. The role of international regulatory frameworks in promoting sustainable trade is emphasized. Overall, MAAF emerges as a viable approach for sustainable land use, ensuring ecological restoration and improved rural livelihoods.

Keywords: Medicinal and aromatic plants (MAPs), agroforestry systems, secondary metabolites, biodiversity conservation, carbon sequestration, soil health, shade effect, allelopathy, sustainable agriculture, rural livelihoods, value chain development, climate resilience

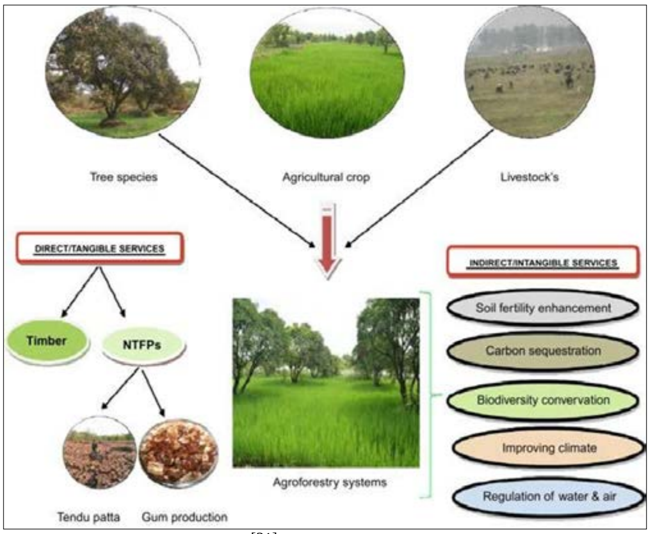
Introduction
The worldwide need for medicinal and aromatic plants (MAPs) has experienced a dramatic change, evolving from local traditional practices to a billion-dollar global market. As communities progressively adopt natural health products, Ayurveda, Traditional Chinese Medicine (TCM), and plant-based pharmaceuticals, the pressure on natural ecosystems has reached a pivotal limit. Traditionally, about 90% of the raw materials for these sectors have come from wild populations, frequently utilizing "slaughter harvesting" methods that emphasize short-term gain instead of the long-term survival of species (NAAS, 2016; Lead Journal, 2006) [21, 26]. This unchecked extraction has resulted in a 20% reduction of forest areas in Latin America and the Caribbean, with an additional 20% significantly degraded (Carlos Nobre, 2021) [5].

Medicinal and Aromatic Agroforestry (MAAF) provides a research-based option. Farmers can mimic the intricate structures of natural forests and sustain commercial productivity by consciously combining woody perennials with herbaceous medicinal crops. This land-use approach aims to maximize the yield of high-value secondary metabolites—the key components in herbal medicine—while also improving ecosystem services like carbon sequestration, soil stability, and conservation of biodiversity (Juno Reports, 2025; Rao *et al.*, 2004) [17, 33]. This article offers an in-depth examination of the structural, biochemical, and regulatory aspects of MAAF, integrating worldwide evidence to confirm its significance as a foundation for sustainable development

The Essential Need for Unified Cultivation
The motivation for MAAF is based in an economic and environmental crisis. The worldwide herbal market, estimated at around US $62 billion at the beginning of the century, is expected to grow to US $5 trillion by 2050 (NAAS, 2016; Prakasa Rao, 2012) [26, 30]. This expansion is fueled by the aging global population and a significant consumer trend toward organic and plant-based items. At present, roughly 12.5% of the 422,000 recognized plant species globally have medicinal properties, but merely a few hundred are cultivated systematically (Rao *et al.*, 2004; Yog *et al.*, 2024) [33, 42].

In countries such as India and China, the strain on natural resources is especially intense. For example, in India, almost five lakh households participate in cultivating menthol mint, but for numerous other high-yield species, wild harvesting continues to be standard (NAAS, 2016) [26]. Systematic cultivation via MAAF offers a means to secure botanical authenticity, a reliable industrial supply, and uniform quality—criteria that cannot be assured with wild-harvested resources (Rao *et al.*, 2004; Malik *et al.*, 2021) [22, 33]. Additionally, the Union Budget 2026-27 in India has recently highlighted high-value crops in mountainous and coastal areas, focusing on species such as agarwood, sandalwood, and premium nuts for the growth of agroforestry (PIB, 2026).

The effectiveness of an agroforestry system relies on the layout and timing of its elements. MAAF systems are typically classified into functional models designed for particular agro-climatic environments.



Source: Raj *et al.* (2022) [31]

Fig 1: Agroforestry system illustrating integration of trees, crops, and livestock with direct (timber, NTFPs) and indirect (soil fertility, carbon sequestration, biodiversity, climate, water regulation) benefits.

1. Agri-silvicultural Practices and Alley Farming

Agri-silviculture is the concurrent cultivation of agricultural plants and trees on the same land. Alley cropping is a notable technique where MAPs are cultivated in the spaces between rows of trees such as Populus deltoides (Poplar) or Eucalyptus (Raj *et al.*, 2021) [32]. This model works exceptionally well for short-cycle MAPs like Mentha (Mint) and *Ocimum basilicum* (Basil). Studies show that these crops can yield significant early profits before the main timber canopy closes (NAAS, 2016) [26]. In the Indian Himalayas, intercropping *Curcuma longa* (Turmeric) with *Populus deltoides* at a spacing of 6 m × 4 m has proven to be more lucrative than the tighter 4 m × 4 m setups, achieving net returns of 14,693 US$ ha^{-1} yr^{-1} (Dash *et al.*, 2024) [7].

2. Multi-layered Systems and Home Gardens

Multistrata systems mimic the structural intricacy of natural forests, employing several canopy layers to enhance light capture. Homegardens (Pekarangan in Indonesia) represent the most widespread form, encompassing approximately 8.0 million hectares in South and Southeast Asia (Burgess and Rosati, 2021; Astutik, 2025) [3, 4]. These systems generally include timber or fruit trees in the overstory, medicinal shrubs in the mid-story, and shade-friendly herbs such as Turmeric or Ginger in the understory (Astutik, 2025; Rao *et al*., 2004) [3, 33]. In Java, plants such as *Curcuma xanthorrhiza* (Javanese turmeric) are prioritized because of high local demand for traditional Jamu medicine (Astutik, 2025) [3]. In Ethiopia as well, homegardens are grouped into types like "taro-enset-coffee" or "maize-taro-sweet potato" according to their size and the predominant species (Ermias *et al*., 2023) [9].

3. Integration of Forest Farming and Silvo-pastoral Practices

Forest farming entails the careful cultivation of a forest understory for valuable MAPs such as *Panax ginseng* (Ginseng) or *Hydrastis canadensis* (Goldenseal) (University of Missouri, 2024) [39]. In contrast to wild harvesting, forest farming necessitates deliberate manipulation of the canopy. *P. ginseng* flourishes in around 70% shade for ideal growth, preferring mildly acidic soils (pH 5-6.5) beneath deciduous broadleaf trees like Walnut, Oak, and Poplar (CSIR-IHBT, 2026; Joe Ginseng, 2024) [7].

Silvo-pastoral systems integrate trees, forage, and animals. In the North Western Himalaya, more than 201 medicinal species have been recognized in these areas, emphasizing their significance in human and animal healthcare (Lata *et al.*, 2025) [20]. Typical families present in these systems include Fabaceae, Lamiaceae, and Rosaceae, with numerous herbs acting as ethnoveterinary treatments for grazing animals (Lata *et al.*, 2025) [20].

Ecological Interactions: Soil Vitality and Climate Adaptability

The incorporation of MAPs with woody perennials transforms the soil's biological and chemical environment in ways that monocultures cannot replicate.

1. Nutrient Transport and Microbial Function

Established trees promote "nutrient pumping," drawing minerals from deeper soil layers and leaving them on the surface via fallen leaves (Rao *et al.*, 2004) [33]. Intercropping MAPs such as Basil with fruit trees improves soil microbial communities and boosts nitrogen cycling (MDPI, 2025). Studies show that areas with medicinal plants demonstrate a 23.5% rise in organic carbon levels (1.21% compared to 0.98% in controls) and notably greater soil moisture (25.4% against 21.3%) (Tiwari *et al.*, 2020) [36].

2. Alteration of Microclimate

Trees act as "biological canopies," regulating extreme temperatures and lowering the vapor pressure deficit for ground-level MAPs (Raj *et al.*, 2021) [32]. This is crucial for species vulnerable to temperature stress. Moreover, hydraulic lift—the mechanism by which trees with deep roots extract water from damp subsoil and transfer it to drier upper soil layers at night—can serve as a vital water supply for shallow-rooted medicinal plants during periods of drought (MDPI, 2025) [3].

3. Capturing Carbon and Adapting to Climate Change

Agroforestry acts as an excellent carbon sink. Implementing these practices on merely 5% of appropriate agricultural land in the U.S. Midwest could capture 43 million tons of CO2 equivalent each year (University of Illinois, 2024) [38]. In a Poplar-Turmeric system, the overall carbon density in the ecosystem was observed to be greatest at broader tree spacings (6 m × 4 m), achieving 119.04 Mg ha^{-1} (Dash *et al.*, 2024) [7]. Additionally, the existence of secondary metabolites in MAP species aids the system in enduring unfavourable climatic conditions, as these compounds frequently act as defense mechanisms against physiological stress (Mishra, 2016; Laftouhi *et al*., 2023) [19, 26].

Biochemical Dynamics: The Effects of Shade

A key emphasis in MAAF research is the impact of canopy shade on secondary metabolite (SM) production. Secondary metabolites like polyphenols, alkaloids, and terpenoids are the main active components in MAPs, and their levels are significantly influenced by the amount and type of light (Yang *et al*., 2018; Zubay *et al.*, 2024) [41, 43].

1. **Intensity of Light and Soil Moisture Content**

Light intensity acts as a catalyst for metabolic processes. For numerous species, direct sunlight enhances antioxidant levels and phenolic compounds as protection against UV radiation (MDPI, 2020) [36]. For example, *Marrubium vulgare* cultivated in full sun exhibits the greatest antioxidant levels, whereas deep shade (50%) markedly diminishes these amounts (MDPI, 2020) [37]. In contrast, certain species, such as Lemon Balm (*Melissa officinalis)*, exhibit enhanced antioxidant levels and greater total extractive compounds when cultivated in moderate (50%) shade (MDPI, 2021).

2. **Performance Indicators of Essential MAP Species in Shaded Environments**

Table 1: The table below outlines the physiological and biochemical reactions of key medicinal and aromatic species in shaded agroforestry settings.

MAP Species	Shade Tolerance	Secondary Metabolite Response	System Compatibility
Basil (*Ocimum basilicum*)	High	Stable EO profile under 30% shade	Stable EO profile under 30% shade
Mint (*Mentha* spp.)	Moderate	Higher menthol in full sun	Poplar, Coconut
Ginseng (*Panax* spp.)	Very High	Requires 70-90% shade for roots	Managed Forest
Lemon Balm (*Melissa officinalis*)	Moderate	Increased antioxidants in shade	Fruit Orchards
Turmeric (*Curcuma longa*)	High	13% increase in curcumin under trees	Poplar, Mango, Teak

(**Sources:** Dash *et al*., 2024; MDPI, 2021; Zubay *et al*., 2024) [7, 43]

Studies indicate that moderate shading (30-50% light decrease) does not inherently diminish the quality of essential oils (EOs). In plants such as *Ocimum basilicum* (Basil) and *Satureja hortensis* (Savory), the volatile profile stays consistent or may even enhance regarding consumer preference, even with a minor decrease in overall biomass (Zubay *et al.,* 2024) [43]. Nonetheless, some plants such as *Dracocephalum moldavica* exhibit marked changes in EO composition when in shade, necessitating careful light management (Zubay *et al.,* 2024) [43].

Allelopathic Interactions and Competitive Disruption

The integration of agroforestry does not always result in mutual benefits. Allelopathy—the chemical suppression of one plant by another—and competition for resources can restrict MAAF productivity.

1. **The Mechanism of Juglone and the Inhibition of Cineole**

Juglans nigra (Black Walnut) generates juglone, a respiratory inhibitor that remains in the soil due to leaching and root exudation, resulting in yellowing, wilting, and death of susceptible companion plants (Shibu and Eric, 2008; Extension Illinois, 2018) [10, 34]. Likewise, Eucalyptus varieties emit 1,8-cineole and various volatile organic compounds (VOCs) that notably restrict the development of understory plants such as Wheat when situated within 16 feet (5 meters) of the tree boundary (Andualem *et al.,* 2024; Shibu and Eric, 2008) [2, 34]. In Ethiopia, leaf extracts from *Eucalyptus camaldulensis* have been demonstrated to decrease chlorophyll fluorescence in wheat varieties by as much as 53.97%, significantly affecting yield (Andualem *et al*., 2024) [2].

2. **Managing Resource Competition**

Farmers employ polyethylene root barriers, trenching, or the addition of activated carbon to the soil to absorb allelochemicals and reduce these impacts (Shibu and Eric, 2008) [34]. Notably, certain interactions are stimulatory; low levels (5-10 g/L) of *Ficus carica* (Fig) stem extract have been shown to enhance the biomass and photosynthetic characteristics of the medicinal plant *Siraitia grosvenorii* (monk fruit), while elevated concentrations turn inhibitory (Jiang *et al*., 2025) [15]. In Western Kenya, Artemisia annua demonstrated a 30% higher competitiveness compared to maize grain, requiring specific spatial configurations (0.75m x 0.75m) to promote complementarity (Ouma *et al*., 2024) [29].

Agricultural Management and Maximizing Output

Shifting from wild-harvesting to MAAF necessitates exact agrotechnology, which encompasses spacing, nutrient management, and selection of nursery stock.

1. **Arrangement and Spacing**

Crop yield is greatly influenced by planting arrangement. For Ashwagandha (*Withania somnifera),* a spacing of 30 cm × 20 cm in a wide bed furrow arrangement has been recognized as ideal, producing 790 kg/ha of dry roots, which is 33% greater than conventional flatbed techniques (JMaps, 2025). Elevated nitrogen levels (120 kg/ha) have been associated with optimal plant height and biomass production in Ashwagandha-peach systems (Thakur and Dutt, 2014) [35]. In systems based on Mango, Ginger demonstrates considerably greater fresh weights beneath the tree canopy (57.84 q/ha) than in open fields (5.25 q/ha), highlighting the beneficial impact of shade for specific rhizomatous crops (Gupta *et al.,* 2022) [13].

2. **Processing After Harvest and Enhancing Value**

The primary substance of MAPs is extremely perishable, with global losses of 20-40% arising from infrastructure shortcomings (Kumar *et al*., 2025) [18]. Studies on drying medicinal plants indicate that temperatures ranging from 30°C to 50°C are typically advised to safeguard delicate active compounds (FiBL, 2021). For instance, drying Sage (*Salvia officinalis*) at 50°C yields the best results; elevated temperatures lead to noticeable discoloration and a reduction in volatile compounds (Horticulture Institute, 2024) [1].

Steam distillation continues to be the standard for essential oils, usually functioning between 60°C and 100°C at 15-20 PSI (Horticulture Institute, 2024) [1]. More sophisticated techniques like supercritical CO^2 extraction function at reduced temperatures (35-60°C) and elevated pressures, safeguarding heat-sensitive bioactive substances without solvent residue (Agriculture Institute, 2024) [1].

Regulatory Structures: CITES, Nagoya, and the TCM Strategy of China

The international exchange of MAPs is regulated by a system of agreements aimed at reconciling economic interests with preservation.

1. CITES and Sustainable Commerce

The Convention on International Trade in Endangered Species (CITES) oversees the cross-border transfer of endangered MAPs. For species such as Jatamansi (*Nardostachys jatamansi)*, which contributes to 25% of the yearly earnings for 15,000 individuals in the Himalayas, CITES regulations are strict (Traffic, 2020) [37]. MAAF systems enhance CITES compliance by supplying a documented, "artificial" source of these plants, labeling them as cultivated and thereby streamlining legal export (Traffic, 2024) [1]

2. Nagoya Protocol (Access and Benefit-Sharing)

The Nagoya Protocol focuses on the "fair and equitable distribution of advantages" stemming from genetic resources. It necessitates Prior Informed Consent (PIC) and Mutually Agreed Terms (MAT) between users (e.g., global pharmaceutical companies) and providers (e.g., local indigenous populations) (Darwin Initiative, 2021) [8]. This stops the historical "bio-piracy," where businesses took advantage of native knowledge without adequate compensation (Nagoya Protocol, 2014) [28].

3. Modernization of Traditional Chinese Medicine in China

China has incorporated MAP cultivation into its national development framework via the 13th Five-Year Plan, with the goal of delivering essential TCM healthcare to every resident by 2020[37] and achieving complete coverage by 2030 (State Administration of TCM, 2016). This encompasses the "One Belt, One Road" initiative for worldwide TCM promotion and stringent Regulations on Safeguarding Wild Medicinal Resources, categorizing wild plants into three priority tiers according to rarity (State Council Information Service, 2016) [26].

Socioeconomic Conditions and Market Entry

Agroforestry based on MAP presents strong rural poverty reduction potential but encounters notable value chain challenges.

1. Profitability and Income Diversification

MAAF permits various income sources: immediate earnings from herbs, intermediate profits from fruits, and long-lasting capital from timber (Rao *et al*., 2004) [33]. In Brazil, the organic pulp from Açaí and Macaúba palm has the potential to produce yearly gross revenues ranging from US $27,000 to $39,000 per hectare, representing a 24-fold rise compared to degraded cattle pasture (Carlos Nobre, 2021) [5]. In India, Turmeric yields a gross income of ₹133,500 per hectare, with Ashwagandha closely trailing at ₹130,200 (Tiwari *et al*., 2020) [36].

2. The Intermediary Challenge

A significant obstacle for smallholders is disorganized trade led by middlemen and monopolistic wholesalers (NAAS, 2016). Interventions like "contract farming" with buyback agreements and the formation of Self-Help Groups (SHGs) and tribal cooperatives have enabled communities to create value at the local level (Prakasa Rao, 2012; Gupta and Sinha, 2020) [30, 36]. In Nepal, FairWild certification has enabled Jatamansi harvesters to achieve prices 5% higher than market rates while maintaining ecological traceability (FairWild, 2024).

Final Thoughts and Upcoming Opportunities

The incorporation of MAPs into agroforestry systems signifies a refined union of environmental sustainability and economic progress. To unlock the complete potential of MAAF, several strategic gaps need to be tackled:

- **Integration of R&D:** Phytochemical studies should be more effectively connected with field extension services to guarantee that agrotechnologies reach the farm level (NAAS, 2016) [26].
- **Technological Integration:** Employing computer vision and AI for automatic species recognition and quality evaluation has the potential to transform traceability and quality control (MDPI, 2024; Jiang *et al*., 2025) [15].
- **Circular Economy:** Transforming waste, like repurposing spent biomass from the essential oil sector for composting or bioenergy, can improve the system's overall sustainability (FiBL, 2021; Agriculture Institute, 2024) [1, 5].

Through enhancing biological synergies and adapting to international regulatory frameworks, MAAF systems can rejuvenate the ecological health of damaged landscapes while ensuring consistent, high-quality livelihoods for rural communities globally.

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