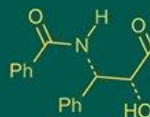


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(4): 738-743
www.biochemjournal.com
Received: 06-02-2026
Accepted: 10-03-2026

HB Roghan

Department of Agroforestry,
Forest College and Research
Institute, Mettupalayam,
Tamil Nadu, India

M Sivaprakash

Department of Agroforestry,
Forest College and Research
Institute, Mettupalayam,
Tamil Nadu, India

S Vennila

Department of Agronomy,
Agricultural College and
Research Institute,
Vazhavachanur, Tamil Nadu,
India

Sustainable production of high value phytomedicines via multifunctional agroforestry systems

HB Roghan, M Sivaprakash and S Vennila

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i4Si.8186>

Abstract

The need for sustainable production methods for high value phytomedicines has increased due to the rising demand for plant based treatments worldwide. By combining trees, crops, and medicinal plants, multifunctional agroforestry systems (MFAF) present a viable strategy for increasing productivity, ecological stability, and socioeconomic advantages. The importance of agroforestry in the sustainable production of medicinal plants is summarized in this paper, which highlights important systems such as riparian buffer plantings, alley cropping, forest farming, and multistrata home gardens. These systems influence the biosynthesis and accumulation of bioactive secondary metabolites by improving soil health and creating favourable microclimatic conditions. Agroforestry techniques lessen the strain on natural forests while making a substantial contribution to climate resiliency, carbon sequestration, and biodiversity protection. This review additionally examines how uniform production methods, tree crop relationships, and shade intensity affect phytomedicine productivity and quality. MFAF systems improve rural livelihoods through market opportunities for herbal products, income diversification, and inclusive engagement of women and underprivileged groups, in addition to their ecological benefits. However, obstacles such as a lack of understanding about the best species combinations, insufficient regulatory support, and difficulties scaling up technologies continue to be significant obstacles. Future studies should concentrate on building strong value chains, integrating traditional knowledge with contemporary scientific methods, and designing systems tailored to individual sites. Multifunctional agroforestry systems, which combine ecological sustainability with economic viability and social well-being, offer a resilient and sustainable route for the production of high value phytomedicines.

Keywords: Multifunctional agroforestry, phytomedicine, secondary metabolites and tree crop association

1. Introduction

Plant-based medications, often known as phytomedicines, are gaining popularity again due to the growing need for safe, economical, and efficient therapeutic agents. Due to their abundance of bioactive secondary metabolites, such as alkaloids, flavonoids, and phenolic compounds, which have antimicrobial, anti-inflammatory, and antioxidant qualities, medicinal plants have long been an essential part of traditional healthcare systems and are currently receiving recognition in contemporary pharmacology (Rates, 2001; Wink, 2015) [19, 25]. Despite their significance, overexploitation, habitat loss, and variations in the quality and consistency of raw plant materials pose a growing threat to the sustainable production of high-value phytomedicines (WHO, 2013) [27]. Multifunctional agroforestry systems (MFAF) have become a practical and environmentally sound solution to these problems. Agroforestry maximizes productivity while preserving environmental sustainability by combining trees, crops, and occasionally livestock into a single land-use system. These systems contribute to carbon sequestration and climate change mitigation, increase biodiversity, and improve soil fertility through effective nutrient cycling (Nair, 1993; Jose, 2009) [14, 6]. Incorporating aromatic and medicinal plants into agroforestry systems enhances rural livelihoods, diversifies agricultural income, and preserves important genetic resources (Pandey *et al.*, 2016) [17].

Additionally, the growth and phytochemical content of medicinal plants are greatly influenced by the ecological interactions within MFAF systems. The biosynthesis of secondary metabolites is significantly influenced by variables like light intensity, soil moisture, and microbial diversity that are controlled by tree-crop interactions (Kumar and

Corresponding Author:**S Vennila**

Department of Agronomy,
Agricultural College and
Research Institute,
Vazhavachanur, Tamil Nadu,
India

Nair, 2011) [8]. Additionally, agroforestry systems strengthen traditional knowledge systems and improve local communities' access to medicinal resources, which supports primary healthcare (Kala *et al.*, 2006) [7]. Multifunctional agroforestry systems offer a robust and sustainable means of producing high-value phytomedicines because of these many benefits. The purpose of this review is to summarize what is currently known about the incorporation of phytomedicinal plants into MFAF systems and to suggest future lines of inquiry to improve their quality, production, and ecological sustainability.

2. Agroforestry systems for medicinal plant cultivation

Agroforestry systems combine productive land-use strategies with ecological principles to create a sustainable framework for growing medicinal plants. These methods preserve biodiversity and provide ecosystem services while increasing the output and quality of phytomedicinal chemical (Nair, 1993; Jose, 2009) [14, 6]. Various agroforestry models provide distinctive microenvironments that are especially well-suited to the production of valuable medicinal species.

2.1 Forest farming/Understory cultivation: Growing shade tolerant medicinal species

Understory cultivation, another name for forest farming, is the deliberate growing of medicinal plants that can withstand shadow under a controlled forest canopy. For species like *Withania somnifera*, *Curcuma longa*, and *Rauvolfia serpentina*, this system provides ideal light intensity, temperature, and humidity by simulating natural forest conditions. The moderated microclimate produced by the overstory trees promotes the build-up of secondary metabolites, which are frequently substances brought on by stress (Wink, 2015) [25]. Furthermore, plant health and phytochemical quality are enhanced by forest soils that are rich in organic matter and microbial diversity (Kumar and Nair, 2011) [8]. Additionally, by encouraging in situ conservation and sustainable harvesting, this method lessens the strain on wild populations (Pandey *et al.*, 2016) [17].

2.2 Alley cropping: Integrating medicinal herbs with tree rows

Growing medicinal plants in the alleys created between rows of trees or bushes is known as alley cropping. Woody perennials and understory crops can interact in a balanced way because to this system's effective use of space, light,

and nutrients. Alley systems frequently incorporate medicinal plants like *Andrographis paniculata*, *Ocimum sanctum*, and *Aloe vera*. In addition to providing partial shade that can affect the formation of bioactive chemicals, trees improve soil fertility through leaf litter and nitrogen fixation in the case of leguminous species (Jose, 2009) [6]. However, to reduce competition for water and nutrients, trimming and tree spacing must be properly managed (Nair, 1993) [14]. Alley cropping increases system productivity and provides farmers with a variety of revenue streams (Table 1).

2.3 Multistrata home gardens/Food forests: Intensive multistorey cultivation

Often called "food forests," multistrata home gardens are intensely varied agroforestry systems that resemble the vertical structure of real forests. These systems are made up of several layers, such as ground cover species, herbaceous plants, sub-canopy shrubs, and canopy trees. In these systems, fruit trees and vegetables are frequently grown with medicinal plants including *Centella asiatica*, *Phyllanthus amarus*, and *Tinospora cordifolia*. The layered structure improves biodiversity, encourages resource efficiency, and maintains microclimatic conditions all of which are essential for steady phytochemical production (Kumar and Nair, 2011) [8]. Additionally, home gardens are essential for maintaining traditional knowledge and guaranteeing household-level access to medical supplies (Kala *et al.*, 2006) [7].

2.4 Riparian buffers & boundary plantings for medicinal production

Cultivating medicinal plants near water bodies, field margins, and farm boundaries is known as riparian buffers and boundary plantings. These systems preserve the environment and produce resources. Such conditions are ideal for species including *Azadirachta indica*, *Vetiveria zizanioides*, and *Bacopa monnieri*. Riparian agroforestry systems provide raw materials for medicine while also preventing soil erosion, enhancing habitat connectivity, and improving water quality (Jose, 2009) [6]. Conversely, boundary plantings make use of otherwise unproductive area, enhancing overall farm sustainability and efficiency (Nair, 1993) [14]. In smallholder agricultural settings, where optimizing land usage is crucial, these techniques are especially beneficial (Table 1).

Table 1: Significant agroforestry systems for the environmentally beneficial and sustainable production of medicinal plants (Nair, 1993 and Jose, 2009) [14, 6]

Agroforestry system	Description	Key medicinal plants	Ecological/Production benefits
Forest farming/Understory cultivation	Managed forest canopy cultivation of shade-tolerant medicinal plants to replicate natural forest conditions.	<i>Withania somnifera</i> , <i>Curcuma longa</i> , <i>Rauvolfia serpentina</i>	Promotes the accumulation of secondary metabolites, improves soil health through organic matter and microbial activity, supports in situ conservation, lessens pressure on wild populations, and provides the ideal microenvironment (light, temperature, and humidity).
Alley cropping	Growing medicinal herbs between rows (alleys) of trees or shrubs allows for the efficient use of resources.	<i>Ocimum sanctum</i> , <i>Aloe vera</i> , <i>Andrographis paniculata</i>	Promotes phytochemical production, maximizes light and nutrient utilization, increases soil fertility through litter fall and nitrogen fixation, offers a variety of revenue streams, and necessitates appropriate spacing and pruning to lessen competition.
Multistrata home gardens/Food forests	Multi-layered system that resembles the stratification of a natural forest and includes trees, bushes, herbs, and ground cover.	<i>Centella asiatica</i> , <i>Phyllanthus amarus</i> , <i>Tinospora cordifolia</i>	Increases biodiversity and resource efficiency, maintains traditional knowledge, stabilizes the microclimate, promotes constant phytochemical production, and guarantees household-level access to medicine.
Riparian buffers & boundary plantings	Cultivation of medicinal plants near farms, fields, and bodies of water.	<i>Bacopa monnieri</i> , <i>Vetiveria zizanioides</i> , <i>Azadirachta indica</i>	Prevents soil erosion, boosts habitat connectivity, improves water quality, makes effective use of marginal areas, and supports smallholder systems' sustainable medicinal production.

3. Sustainability and ecological benefits

The capacity of multifunctional agroforestry systems (MFAF) to provide significant ecological advantages while promoting the sustainable production of valuable phytomedicines is becoming more widely acknowledged. These systems improve ecosystem resilience and functionality by combining trees, crops, and occasionally livestock, making them a competitive substitute for traditional monocropping systems (Nair, 1993; Jose, 2009) [14, 6].

3.1 Biodiversity conservation and reduction of pressure on natural forests

Because they support a variety of plant and animal species and offer habitat heterogeneity, agroforestry systems are essential to biodiversity conservation. By incorporating therapeutic plants into these systems, precious genetic resources are conserved on farms, which lessens reliance on wild harvesting from natural forests (Pandey *et al.*, 2016; Schroth *et al.*, 2004) [17, 22]. This is especially crucial for valuable medicinal species that are frequently overused in the wild. Agroforestry systems improve landscape connectivity and ecological stability by establishing a semi-natural habitat that acts as buffer zones and biodiversity corridors (Garritty, 2004) [4]. Additionally, by supporting traditional knowledge and ethnomedical practices, these systems aid in the conservation of both culture and biology (Kala *et al.*, 2006) [7].

3.2 Soil health enhancement: Nutrient cycling and nitrogen fixation

The capacity of agroforestry systems to promote soil health through increased nutrient cycling and biological activity is one of their main ecological benefits. Through leaf litter, root turnover, and pruning residues, trees add organic matter to the soil, which breaks down and releases vital nutrients (Young, 1997) [29]. Shallow-rooted medicinal crops can more easily absorb nutrients from deeper soil layers when deep-rooted tree species are present (Nair, 1993) [14]. Furthermore, the addition of leguminous tree species like *Gliricidia sepium* and *Leucaena leucocephala* increases nitrogen availability through biological nitrogen fixation (Jose, 2009; Palm *et al.*, 2001) [6, 16]. The growth and phytochemical quality of medicinal plants are further promoted by improved soil structure, increased microbial diversity, and improved water retention (Kumar and Nair, 2011) [8].

3.3 Carbon sequestration in agrosilvopastoral systems

Agroforestry systems are efficient carbon sinks that help mitigate climate change, especially agrosilvopastoral models. By storing carbon in their biomass and the soil, trees lower the amount of carbon dioxide in the atmosphere (Montagnini and Nair, 2004) [13]. Compared to monoculture systems, the integration of perennial vegetation with crops and livestock improves long-term carbon storage and increases system biomass overall (Albrecht and Kandji, 2003) [1]. Continuous litter intake and less soil disturbance also increase soil organic carbon, which is essential for preserving soil fertility and ecological sustainability. These carbon sequestration advantages improve the environmental sustainability of phytomedicine production systems and are in line with global climate goals.

3.4 Climate change resilience: Microclimate regulation

Agroforestry systems increase resilience to climate unpredictability by regulating microclimatic elements such as temperature, humidity, wind speed, and light intensity. For medicinal plants that can tolerate shadow, the reduction of evapotranspiration and heat stress caused by tree canopies is particularly beneficial (Jose, 2009; Lin, 2007) [6, 12]. While trees' windbreak benefits reduce crop damage and soil moisture loss, improved soil structure promotes water uptake and retention (Nair, 1993) [14]. These controlled conditions influence secondary metabolite biosynthesis, which in turn influences the quality of phytomedicinal compounds, in addition to encouraging plant development (Wink, 2015) [25]. As climate change intensifies, these systems provide as a buffer against extreme weather events, ensuring consistent productivity and the stability of livelihoods (Verchot *et al.*, 2007) [24].

4. Production and quality of high value phytomedicines

In multifunctional agroforestry systems (MFAF), the quality and consistency of bioactive compounds have an impact on the production of high-value phytomedicines in addition to biomass yield. The accumulation of secondary metabolites, which affects the therapeutic efficacy of medicinal plants, is extremely susceptible to management strategies and environmental factors (Wink, 2015; Yang *et al.*, 2018) [25, 28]. Because of their intricate ecological relationships, agroforestry systems offer special chances to maximize phytochemical quality and output.

4.1 Impacts of shade intensity on secondary metabolite accumulation

Plant physiological activities and the formation of secondary metabolites are significantly influenced by shade. Different canopy densities in agroforestry systems produce gradients of light intensity that affect the synthesis of substances like terpenoids, flavonoids, and alkaloids (Li *et al.*, 2020) [11]. Moderate shade often enhances the accumulation of certain bioactive compounds by inducing mild stress conditions and altering photosynthetic pathways (Ghasemzadeh *et al.*, 2010) [5]. As an illustration, it has been found that medicinal herbs grown in shadow, such *Centella asiatica* and *Withania somnifera*, contain higher amounts of pharmacologically active components than those grown in full sun (Wink, 2015) [25]. However, too much shadowing might limit metabolite production and lower total biomass, highlighting the need for careful canopy management (Kumar and Nair, 2011) [8].

4.2 Tree crop interactions and their effects on medicinal yield

The growth and productivity of medicinal plants in agroforestry systems are significantly influenced by tree-crop interactions. Depending on variables including species composition, spacing, and resource availability, these interactions may be either competitive or facilitative (Jose, 2009) [6]. By recycling nutrients and depositing litter, trees improve soil fertility, which boosts the growth and yield of understory medicinal crops (Nair, 1993) [14]. Furthermore, deep-rooted trees have less competition with shallow-rooted medicinal plants because they can acquire nutrients from lower soil strata (Ong *et al.*, 2015) [15]. Higher yields and higher-quality plant material are frequently the outcome of positive interactions, such as enhanced microclimate and

soil moisture retention. However, improper management of competition for light, water, and nutrients can have a detrimental effect on production, highlighting the significance of system design and species selection (Schroth *et al.*, 2004) ^[22].

4.3 Standardized cultivation practices for quality consistency

Adopting consistent cultivation and post harvest procedures is necessary to guarantee the quality and uniformity of phytomedicines. Significant variations in the concentration of active chemicals can result from variations in agronomic techniques, genetic material, and environmental circumstances (WHO, 2013) ^[27]. Maintaining consistency in the cultivation of medicinal plants requires the application of (GACP) Good Agricultural and Collection Practices (WHO, 2003) ^[26]. These methods include regulated harvesting methods, fertilizer management, appropriate spacing, and the use of approved planting material. To maintain ideal growing conditions in agroforestry systems, extra factors like canopy management, pruning schedules, and soil conservation techniques are essential (Kumar and Nair, 2011) ^[8].

Additionally, improvements in analytical methods like gas chromatography mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) have made it easier to standardize phytochemical profiles, guaranteeing the efficacy and safety of herbal medicines (Sahoo and Manchikanti, 2013) ^[21]. The reliability of phytomedicine production systems can be further improved by combining traditional knowledge with contemporary scientific methods (Kala *et al.*, 2006) ^[7].

5. Socioeconomic aspects and livelihoods

In addition to promoting ecological sustainability, multifunctional agroforestry systems (MFAF) are essential for improving rural lives and socioeconomic resilience. Agroforestry enhances market prospects, generates numerous revenue streams, and promotes equitable involvement across social and gender groups by incorporating medicinal plants into diverse farming systems (Nair, 1993; Garrity, 2004; Jose, 2009) ^[14, 4, 6].

5.1 Income diversification for smallholder farmers

By providing a variety of items, such as timber, fruits, fodder, and valuable medicinal plants, agroforestry systems allow smallholder farmers to diversify their sources of income. This diversity lessens reliance on a single crop and lowers the financial risks brought on by changes in the market and the climate (Pandey *et al.*, 2016; Place *et al.*, 2004) ^[17, 18]. Small-scale farmers can benefit from the high market value and comparatively cheap input needs of medicinal plants like *Withania somnifera*, *Aloe vera*, and *Ocimum sanctum*. Furthermore, agroforestry systems yield both immediate and long-term benefits, with trees acting as long-term assets and therapeutic plants producing instant revenue (Leakey, 2012) ^[10]. This comprehensive strategy improves financial stability and helps reduce poverty in rural areas (FAO, 2013) ^[3].

5.2 Market development for agroforestry based herbal products

There are substantial prospects for market expansion in agroforestry-based systems due to the rising demand for

natural products and herbal remedies worldwide. Effective value chains, including cultivation, processing, quality assurance, and marketing, are necessary for the commercialization of phytomedicines (Sahoo and Manchikanti, 2013) ^[21]. Through certification programs like organic and fair-trade labelling, agroforestry systems can facilitate decentralized production, allowing farmers to engage in local and regional markets as well as access global markets (Raynolds *et al.*, 2007) ^[20]. However, obstacles like a lack of standardization, insufficient market data, and poor infrastructure frequently prevent smallholder farmers from accessing markets (Pandey *et al.*, 2016) ^[17]. Enhancing market competitiveness requires bolstering institutional support, encouraging farmer cooperatives, and upgrading post-harvest processing and storage facilities (FAO, 2013; Leakey, 2012) ^[3, 10].

5.3 Gender and social roles in harvesting and processing

In agroforestry systems, the production, harvesting, and processing of medicinal plants are heavily influenced by gender and social dynamics. Women actively participate in the gathering, processing, and marketing of herbal products in many rural communities, making significant contributions to household income and healthcare (Kala *et al.*, 2006; Shackleton *et al.*, 2011) ^[7, 23]. The sustainable use of these resources depends on their traditional knowledge of the management and application of medicinal plants. However, women frequently encounter obstacles that prevent them from fully participating in the value chain, such as restricted access to loans, land, and market opportunities (FAO, 2011) ^[2].

Social justice and livelihood outcomes can be improved by inclusive agroforestry techniques that acknowledge and promote the responsibilities of women and underprivileged groups. To empower these groups and guarantee fair benefit-sharing, gender-sensitive policies, extension services, and capacity-building initiatives are crucial (Place *et al.*, 2004; Shackleton *et al.*, 2011) ^[18, 23]. Additionally, community based resource management strategies can improve social cohesiveness and encourage sustainable methods of producing medicinal plants.

6. Challenges and future directions

Multifunctional agroforestry systems (MFAF) have great potential for the sustainable production of high-value phytomedicines, but a number of obstacles prevent their broad adoption and optimization. Targeted research, encouraging regulations, and the expansion of suitable technology are necessary to address these limitations (Nair, 1993; Jose, 2009; Kumar and Nair, 2011) ^[14, 6, 8].

6.1 Knowledge gaps in optimal medicinal tree crop associations

The lack of thorough knowledge about the best tree-crop pairings is one of the main obstacles to the manufacture of phytomedicines based on agroforestry. Trees and medicinal plants have intricate relationships that are highly species-specific and site-dependent. These interactions include competition for light, water, and nutrients as well as beneficial effects like microclimate regulation (Ong *et al.*, 2015; Schroth *et al.*, 2004) ^[15, 22]. Designing effective systems is hampered by a lack of experimental data on appropriate species combinations, spacing, and management techniques (Jose, 2009) ^[6]. Furthermore, not enough

research has been done on how agroforestry settings affect secondary metabolite pathways, especially when there are different environmental pressures (Wink, 2015; Yang *et al.*, 2018) ^[25, 28]. To close these information gaps and improve system performance, long-term, site-specific research combining agronomy, ecology, and phytochemistry is crucial.

6.2 Policy support and technical training needs

Institutional support and policy frameworks play a major role in the effective implementation of agroforestry systems for the growth of medicinal plants. Farmers are discouraged from using agroforestry practices in many areas due to uncertain land tenure structures, stringent forest restrictions, and a lack of incentives (Garrity, 2004; FAO, 2013) ^[4, 3]. Further impeding sector expansion is the lack of clear regulations for the production, processing, and sale of medicinal plants (Sahoo and Manchikanti, 2013) ^[21]. Another major obstacle is farmers' lack of technical understanding. Skills in species selection, canopy management, soil fertility maintenance, and post-harvest handling are necessary for effective agroforestry management (Nair, 1993) ^[14]. However, training programs and extension services pertaining to the production of medicinal plants are frequently insufficient or unavailable (Place *et al.*, 2004) ^[18]. Strengthening capacity-building initiatives, promoting farmer field schools, and integrating traditional knowledge with scientific approaches can enhance adoption and improve system efficiency (Kala *et al.*, 2006; Leakey, 2012) ^[10].

6.3 Scaling up sustainable production technologies

Disseminating sustainable and standardized methods across various agroecological zones is necessary to scale up the production of phytomedicines based on agroforestry. Despite the existence of a number of effective models at the experimental and pilot stages, financial, technological, and infrastructure limitations prevent their widespread implementation (Kumar and Nair, 2011; Pandey *et al.*, 2016) ^[8, 17]. Problems include poor market connections, insufficient processing facilities, and restricted access to high-quality planting material.

Agroforestry system monitoring and resource efficiency can be enhanced by integrating contemporary technology like computerized decision-support systems, remote sensing, and precision agriculture (FAO, 2013) ^[3]. Additionally, implementing quality certification programs and Good Agricultural and Collection Practices (GACP) is essential to maintaining uniformity and competitiveness in international herbal markets (WHO, 2003) ^[26]. Scaling up production requires value chain expansion, public-private partnerships, and investments in rural infrastructure (Leakey, 2012) ^[10].

In addition, participatory approaches involving farmers, researchers, and policymakers can facilitate the co-creation of locally adapted solutions and enhance the sustainability of agroforestry interventions (Garrity, 2004) ^[4]. To fully realize the promise of multifunctional agroforestry systems for high-value phytomedicine production, it will be necessary to address these issues through coordinated research, policy support, and technical innovation.

7. Conclusion

Multifunctional agroforestry systems (MFAF) represent a transformative and sustainable approach for the production

of high-value phytomedicines, effectively addressing the ecological, economic, and social challenges associated with conventional monocropping and overexploitation of wild medicinal resources. By integrating trees, crops, and medicinal plants within a single, diversified land-use framework, these systems create synergistic interactions that enhance both productivity and environmental sustainability. The evidence presented in this review clearly demonstrates that MFAF systems not only improve biomass yield but also significantly influence the quality and consistency of bioactive secondary metabolites, which are critical for the therapeutic efficacy of phytomedicines. One of the most significant strengths of MFAF lies in its ability to mimic natural ecosystems, thereby creating favourable microclimatic conditions such as moderated light, temperature, and humidity. These conditions play a crucial role in regulating plant physiological processes and stimulating the biosynthesis of secondary metabolites. Additionally, improved soil health through enhanced nutrient cycling, organic matter accumulation, and microbial activity further contributes to the growth and phytochemical richness of medicinal plants. The incorporation of leguminous trees and deep-rooted species enhances nutrient availability and resource-use efficiency, making these systems ecologically robust and resilient.

Beyond ecological benefits, MFAF systems play a vital role in biodiversity conservation and reducing pressure on natural forests. By cultivating medicinal plants within managed landscapes, the dependence on wild harvesting is minimized, thereby preserving endangered species and maintaining genetic diversity. Moreover, the carbon sequestration potential and climate-regulating functions of agroforestry systems position them as important tools in mitigating climate change while ensuring stable and sustainable production systems under changing environmental conditions. From a socioeconomic perspective, MFAF systems offer substantial opportunities for improving rural livelihoods. The diversification of farm outputs including medicinal plants, timber, fruits, and other non-timber forest products reduces economic risks and enhances income stability for smallholder farmers. The growing global demand for herbal products further strengthens market potential, while inclusive participation of women and marginalized communities contributes to equitable development. However, realizing these benefits at scale requires stronger value chains, improved market access, and institutional support. Despite their immense potential, several challenges remain. Limited knowledge regarding optimal species combinations, inadequate policy frameworks, lack of technical expertise, and constraints in scaling up technologies hinder widespread adoption. Addressing these issues requires interdisciplinary research focusing on tree crop interactions, phytochemical responses, and site-specific system design. Furthermore, the implementation of standardized cultivation practices such as Good Agricultural and Collection Practices (GACP), along with advancements in analytical techniques, is essential to ensure quality consistency and global competitiveness.

8. Acknowledgments

The authors express their sincere gratitude to the researchers and scholars whose original work has contributed to the information presented in this paper. Their valuable findings

and insights have formed the foundation for this compilation.

9. Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

- Albrecht A, Kandji ST. Carbon sequestration in tropical agroforestry systems. *Agric Ecosyst Environ*. 2003;99:15-27.
- Food and Agriculture Organization of the United Nations (FAO). The state of food and agriculture 2010-2011: Women in agriculture-closing the gender gap for development. Rome (Italy): FAO; 2011.
- Food and Agriculture Organization of the United Nations (FAO). Advancing agroforestry on the policy agenda: A guide for decision-makers. Rome (Italy): FAO; 2013.
- Garrity DP. Agroforestry and the achievement of the Millennium Development Goals. *Agrofor Syst*. 2004;61-62:5-17.
- Ghasemzadeh A, Jaafar HZE, Rahmat A. Elevated carbon dioxide increases contents of flavonoids and phenolic compounds in Malaysian young ginger (*Zingiber officinale* Roscoe). *Molecules*. 2010;15(11):7907-7922.
- Jose S. Agroforestry for ecosystem services and environmental benefits: An overview. *Agrofor Syst*. 2009;76:1-10.
- Kala CP, Dhyani PP, Sajwan BS. Developing the medicinal plants sector in northern India: Challenges and opportunities. *J Ethnobiol Ethnomed*. 2006;2:32-32.
- Kumar BM, Nair PKR. Carbon sequestration potential of agroforestry systems: Opportunities and challenges. Dordrecht (Netherlands): Springer; 2011.
- Lal R. Soil carbon sequestration impacts on global climate change and food security. *Science*. 2004;304:1623-1627.
- Leakey RRB. Living with the trees of life: Towards the transformation of tropical agriculture. Wallingford (UK): CABI; 2012.
- Li Q, Kubota C, Kroggel M. Effects of supplemental light quality and intensity on growth and phytochemicals in plants. *Horticulturae*. 2020;6(3):1-18.
- Lin BB. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. *Agric For Meteorol*. 2007;144:85-94.
- Montagnini F, Nair PKR. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agrofor Syst*. 2004;61-62:281-295.
- Nair PKR. State-of-the-art of agroforestry research and education. *Agrofor Syst*. 1993;23(2):95-119.
- Ong CK, Black CR, Wilson J. Tree-crop interactions: Manipulation of water use and root function. In: Tree-crop interactions: Agroforestry in a changing climate. 2nd ed. Wallingford (UK): CAB International; 2015.
- Palm CA, Myers RJK, Nandwa SM. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Replenishing soil fertility in Africa. 2001;51:193-217.
- Pandey AK, Tripathi YC, Kumar A. Non-timber forest products (NTFPs) for sustained livelihood: Challenges and strategies. *Res J For*. 2016;10(1):1-7.
- Place F, Franzel S, DeWolf J, Rommelse R, Kwesiga F, Niang A, *et al*. Agroforestry for soil fertility replenishment: Evidence on adoption processes in Kenya and Zambia. *Agrofor Syst*. 2004;61-62:185-205.
- Rates SMK. Plants as source of drugs. *Toxicol*. 2001;39(5):603-613.
- Raynolds LT, Murray D, Wilkinson J. Fair trade: The challenges of transforming globalization. London (UK): Routledge; 2007.
- Sahoo N, Manchikanti P. Herbal drug regulation and commercialization: An Indian industry perspective. *J Altern Complement Med*. 2013;19(12):957-963.
- Schroth G, da Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL, Izac AMN. Agroforestry and biodiversity conservation in tropical landscapes. Washington, DC (USA): Island Press; 2004.
- Shackleton CM, Paumgarten F, Kassa H, Husselman M, Zida M. Opportunities for enhancing poor women's socio-economic empowerment in the value chains of three African non-timber forest products. *Int For Rev*. 2011;13(2):136-151.
- Verchot LV, van Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, *et al*. Climate change: Linking adaptation and mitigation through agroforestry. *Mitig Adapt Strateg Glob Change*. 2007;12:901-918.
- Wink M. Modes of action of herbal medicines and plant secondary metabolites. *Medicines*. 2015;2(3):251-286.
- World Health Organization (WHO). WHO guidelines on good agricultural and collection practices (GACP) for medicinal plants. Geneva (Switzerland): WHO; 2003.
- World Health Organization (WHO). WHO traditional medicine strategy 2014-2023. Geneva (Switzerland): WHO; 2013.
- Yang L, Wen KS, Ruan X, Zhao YX, Wei F, Wang Q. Response of plant secondary metabolites to environmental factors. *Molecules*. 2018;23(4):762-762.
- Young A. Agroforestry for soil management. 2nd ed. Wallingford (UK): CAB International; 1997.