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Ecosystem Services in Natural Dye Tree Species-based Agroforestry - A Review

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ABSTRACT

The integration of natural dye-yielding tree species into agroforestry systems offered a sustainable strategy for balancing environmental protection with rural economic growth. These systems delivered a multiple ecological advantages like enhancement of biodiversity, carbon storage, improvement of soil functionalities and efficient regulation of water resources. Incorporating dye-producing trees within farming landscapes also strengthened climate resilience by improving ecological balance, minimizing land degradation, and supporting pollinator populations. Furthermore, diversified agroforestry practices increased the overall functionality and sustainability of agricultural ecosystems. Beyond environmental advantages, natural dye trees provided valuable raw materials for textile, handicraft, and cottage-based industries, thereby creating livelihood opportunities for rural communities. The rising preference for eco-friendly and biodegradable products has increased the relevance of plant-based dyes as sustainable substitutes for synthetic colouring agents. This review examined published studies related to the ecological and socio-economic contributions of dye-producing tree species under agroforestry systems. The analysis highlighted their important role in sustainable land management, ecological restoration, and promotion of environmentally sound production systems. However, the study also identified several limitations, including inadequate scientific information on underutilized dye species, low public awareness regarding their economic and ecological importance, weak marketing support, and limited policy initiatives for their wider adoption. Overall, the incorporation of natural dye-producing tree species into agroforestry systems can serve as an effective approach for conserving natural resources, improving climate adaptability, supporting biodiversity, and enhancing the rural bioeconomy through sustainable production practices.

KEYWORDS: Agroforestry, ecosystem services, ethnobotany, natural dye-yielding tree species

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1. INTODUCTION

Ecosystem services include the various benefits received from natural ecosystems through resources such as land, water, vegetation, and atmospheric components. These ecosystems supported important functions including food production, freshwater availability, climate regulation, and environmental stability (Costanza et al., 1997). Such services played a major role in maintaining ecological balance and supporting human well-being. Agroforestry, which combined trees with crop plants and domestic animals on the same farm land was widely recognized as a sustainable land-use approach that improved ecosystem functioning and agricultural productivity (Mlambo et al., 2025). These systems enhanced soil organic carbon status and storage, promoted biodiversity conservation, and improved hydrological and microclimatic regulation (Aynekulu et al., 2020).

Home gardens represents one of the most diverse forms of agroforestry and were generally maintained near homesteads. These systems contained multilayered vegetation structures consisting of trees, shrubs, herbs, and climbers that fulfilled household requirements while contributing to ecological sustainability and livelihood support (Kumar and Nair, 2004). They also supported year-round availability of food and plant-based resources while improving efficient use of natural resources.

Growing interest had been observed in integrating natural dye-yielding tree species into agroforestry systems because of their ecological, economic, and cultural value. These species supported environmental conservation and created livelihood opportunities through the production of plant-based dyes and associated products (Nungula et al., 2024) besides crop diversification and helped preserve indigenous knowledge.

Plant-derived dyes had traditionally been used in textiles, cosmetics, food preparation, and medicinal applications. However, their use gradually declined after the introduction of synthetic dyes, which became widely accepted because of their lower cost, easy availability, and suitability for industrial production. Over time, synthetic dyes became associated with environmental contamination, toxic wastewater discharge, and health-related concerns, which renewed interest in eco-friendly and biodegradable alternatives (Radhakrishnan et al., 2024). Increasing environmental awareness and renewed appreciation for traditional crafts further encouraged the return of natural dyes in recent years (Krizova, 2015; Gulrajani, 2001).

Agroforestry systems containing dye-yielding tree species provided several ecosystem services. Provisioning services included food, fodder, fuelwood, medicinal products, and natural dyes that directly supported rural livelihoods and household income. Regulating services involved soil conservation, nutrient recycling, groundwater recharge, carbon sequestration, erosion control, and moderation of local climatic conditions (Aynekulu et al., 2020). Cultural services included preservation of indigenous knowledge, traditional practices, cultural identity, and landscape aesthetics, which strengthened the social importance. Studies from Vietnam showed that agroforestry practices improved soil fertility, reduced soil erosion, enhanced ecosystem services, and strengthened resilie2nce to climate variability (Do et al., 2020). Coffee-based agroforestry systems also improved biodiversity conservation, microclimatic regulation, and carbon sequestration compared with monoculture farming systems (Nguyen et al., 2020). Similarly, agroforestry practices supported soil biodiversity and ecosystem functioning while minimizing the adverse effects of forest conversion and land degradation (Mulia et al., 2021). Diversified agroforestry systems and home gardens with high tree diversity also contributed to food security and reduced environmental degradation while improving resilience to climatic stress.

Despite their multiple benefits, agroforestry systems involving natural dye-yielding tree species remained insufficiently explored in scientific research. Traditional practices in regions such as Uttarakhand and Manipur in India demonstrated long-standing ethnobotanical knowledge related to plant-based dye extraction and sustainable use of biological resources (Kathayat et al., 2024). Integrating indigenous knowledge with modern agroforestry approaches could support the development of multifunctional landscapes that balanced biodiversity conservation, climate resilience, and livelihood improvement. Therefore, the present review aimed to evaluate the ecosystem services provided by natural dye-yielding tree species in agroforestry systems, particularly their role in biodiversity conservation, sustainable carbon management, livelihood enhancement, and preservation of traditional dye-related practices.

2. NATURAL DYE TREE SPECIES IN AGROFORESTRY

In agroforestry systems, a number of tree species are widely identified and utilized for their natural dye-producing potential and adaptability to different land-use practices. These species occur across various ecological regions and are traditionally known as plant-based sources of colour extracted from parts such as bark, leaves, fruits and wood. Their inclusion in agroforestry has been documented in different farming and forest-based systems where diverse multipurpose trees are maintained. Several such species are commonly recognized in literature and practice. The major natural dye yielding tree species are furnished in Table 1.

Table 1: List of popular natural dye yielding trees and plant species in India

Sl. No.	Name of the tree/plant	Source of dye	Dye colour
1.	*Anogeissus latifolia*	Leaves	Black
2.	*Tectona grandis*	Leaves	Yellow
3.	*Zizyphus mauritiana*	Leaves	Red-pink
4.	*Cordia dichotoma*	Leaves	Yellow
5.	*Garuga pinnata*	Leaves	Red
6.	*Indigofera tinctoria*	Leaves	Blue
7.	*Acacia nilotica*	Leaves, bark, pods	Black to dark brown
8.	*Acacia leucocephala*	Leaves, bark	Red
9.	*Ficus religiosa*	Leaves, bark	Red, brown yellow
10.	*Toona ciliata*	Leaves, flowers	Red, yellow
11.	*Memecylon umbellatum*	Leaves, flowers	Yellow
12.	*Lawsonia inermis*	Leaves, root	Red
13.	*Sarcochlamys plucherrima*	Leaves, twigs	Brown
14.	*Acacia sinuates*	Bark	Brown
15.	*Acacia farnesiana*	Bark	Black
16.	*Albizia odoratissima*	Bark	Brown
17.	*Alnus nepalensis*	Bark	Brown
18.	*Madhuca longifolia*	Bark	Yellow
19.	*Bauhinia variegata*	Bark	Yellow
20.	*Careya arborea*	Bark	Red
21.	*Cassia fistula*	Bark	Red
22.	*Casuarina equistifolia*	Bark	Brown
23.	*Ceriops candolleana*	Bark	Red, brown
24.	*Cordia nepalensis*	Bark	Yellow
25.	*Chloroxylon swietenia*	Bark	Yellow
26.	*Syzygium cumini*	Bark	Red
27.	*Garcinia xanthochymus*	Bark	Yellow
28.	*Morinda tinctoria*	Bark	Red
29.	*Mimusops elengi*	Bark	Brown
30.	*Mangifera indica*	Bark	Yellow
31.	*Lannea coromandelica*	Bark	Golden and pale brown
32.	*Pinus wallichiana*	Bark	Yellow to deep orange
33.	*Pinus roxburghii*	Bark	Yellow, brown
34.	*Pterocarpus marsupium*	Bark	Red
35.	*Rhizophora mucronata*	Bark	Chocolate
36.	*Shorea robusta*	Bark	Red, black
37.	*Emblica officinalis*	Bark, fruit	Black, grey and brown
38.	*Terminalia tomentosa*	Bark, fruit	Brown
39.	*Ventilago denticulata*	Bark, roots	Red, purple

Table 1: Continue...

Sl. No.	Name of the tree/plant	Source of dye	Dye colour
40.	*Butea monosperma*	Flowers	Yellow
41.	*Carthamus tinctorius*	Flowers	Red
42.	*Cassia auriculata*	Flowers	Yellow
43.	*Crocus sativus*	Flowers	Yellow
44.	*Delphinium zalil*	Flowers	Yellow
45.	*Gossypium herbaceum*	Flowers	Yellow
46.	*Nyctanthes arbor-tristis*	Flowers	Golden pale brown
47.	*Woodfordia fruticosa*	Flowers	Pink, red
48.	*Mesua naga*	Flowers, bark	Orange, brown
49.	*Aegle marmelos*	Fruit rind	Yellow
50.	*Semecarpus anacardium*	Fruit, bark	Black
51.	*Annona reticulata*	Fruit	Red
52.	*Mallotus philippensis*	Fruit	Orange
53.	*Terminalia bellirica*	Fruit	Yellow, brown
54.	*Terminalia chebula*	Fruit	Yellow, brown
55.	*Melastoma melabathricum*	Fruit	Purple
56.	*Andropogon sorghum*	Seeds	Red
57.	*Bixa orellana*	Seeds	Orange, red
58.	*Cassia tora*	Seeds	Blue, red
59.	*Pterocarpus santalinus*	Wood	Red
60.	*A. heterophyllus*	Wood	Yellow
61.	*Caesalpinia sappan*	Wood	Red
62.	*Moringa olifera*	Wood	Blue
63.	*Areca catechu*	Nut	Black
64.	*Areca catechu*	Nut	Black
65.	*Aleurites moluccana*	Roots	Brown
66.	*Artocarpus lacucha*	Roots	Yellow
67.	*Berberis nepalensis*	Roots	Yellow
68.	*Butea superba*	Roots	Red
69.	*Curcuma longa*	Roots	Yellow
70.	*Datisca cannabina*	Roots	Yellow
71.	*Geranium nepalense*	Roots	Red
72.	*Jasminum humile*	Roots	Yellow
73.	*Hydyotis puberula*	Roots	Red
74.	*Rubia cordifolia*	Roots	Scarlet to red
75.	*Morinda citrifolia*	Root, bark	Red

Source: Gokhale et al. (2004)

2.1. Distribution and ethnobotanical relevance

Natural dye plants are found in many ecological regions of India, especially in Himalayan areas such as Uttarakhand, where species like *Tagetes erecta* and *Rhododendron arboreum* are commonly used for natural dye preparation (Kathayat et al., 2024). These plants are capable of growing in poor and degraded soils, making them useful for agroforestry systems that support biodiversity conservation and soil improvement

(Mlambo et al., 2025). Dye-yielding plants also have strong ethnobotanical importance because they are associated with traditional healthcare, textile coloring, and cultural practices (Kathayat et al., 2024). Plants such as *Cassia auriculata* and *Nyctanthes arbortristis* are traditionally valued for both medicinal and dye-producing properties (Kathayat et al., 2024). The growing preference for biodegradable and eco-friendly dyes has increased interest in conserving and utilizing these traditional plant resources sustainably (Mlambo et al., 2025).

2.2. Traditional knowledge and cultural importance among indigenous communities

Indigenous communities across India preserve intricate traditional knowledge systems related to natural dye use, which are passed orally through generations. The Meitei people of Manipur, for example, employ complex dyeing techniques using plants like *Strobilanthes cusia* and *Morinda citrifolia*, which have ceremonial and cultural relevance in textile crafts and rituals (Mathieu et al., 2025). In southern India, traditional Kalamkari artisans continue to use *Madder* and *Myrobalan* (*Terminalia chebula*) along with natural mordants. These practices not only support local economies but also preserve centuries-old cultural heritage (Radhakrishnan et al., 2024). NGOs and artisan cooperatives across Gujarat, Rajasthan, and West Bengal have been instrumental in reviving natural dye traditions. These efforts promote cultural sustainability and have encouraged replanting of dye-yielding trees in farm boundaries and degraded lands (Gulrajani, 2001).

3. ECOSYSTEM SERVICES FROM DYE TREE AGROFORESTRY

3.1. Provisioning services

They represent tangible products obtained from ecosystems, including fruit, fodder, firewood, timber, medicines, genetic materials, and biochemicals. These services directly contribute to human well-being and economic development by supplying essential natural resources for livelihoods and industries (van Noordwijk, 2021). In agroforestry systems, provisioning services are particularly important because trees and crops are integrated within the same landscape, enabling the production of multiple resources from a single land unit (Do et al., 2020).

Natural dye-producing woody plants play a significant role in enhancing provisioning services within agroforestry systems. For eg. *Bixa orellana*, *Acacia catechu*, *Terminalia chebula* and *Mimusops elengi* provide sustainable sources of natural pigments used in textile, cosmetic, and food industries (Kathayat et al., 2024). In addition to dye production, these species also supply timber, fuelwood, fodder, tannins, gums, fruits, and medicinal compounds, thereby increasing the economic value and multifunctionality of agroforestry systems (Kathayat et al., 2024). Many natural dye-yielding tree species possess medicinal properties that support traditional healthcare systems and local pharmacopoeias. For eg. *Terminalia chebula* is recognized for its antioxidant and antimicrobial properties, while *Acacia catechu* is widely used in traditional medicine and dyeing practices (Gokhale et al., 2023). Different plant parts harvested sustainably, ensuring continuous resource availability without significantly affecting ecosystem stability or biodiversity conservation (Nungula et al., 2023).

Provisioning services also include the conservation and utilization of genetic resources. Increasing global demand for eco-friendly and plant-based dyes has enhanced the importance of conserving natural dye tree species through both in-situ and ex-situ conservation methods, including seed banks, nursery development, and genetic improvement programs (Nungula et al., 2023). These conservation strategies help preserve valuable genetic diversity while supporting future breeding and sustainable production systems.

Agroforestry systems further improve economic resilience by diversifying farm production and reducing dependence on monocropping systems. Studies in Northwest Vietnam demonstrated that fruit-tree-based agroforestry systems generated significantly higher economic returns compared to sole maize cultivation. Agroforestry systems involving longan (*Dimocarpus longan*) and sontra (*Docynia indica*) produced 2.4 times better farm income than monocropping systems. Farmers also reported improved resilience to extreme weather conditions, better soil fertility, and increased productivity over time, indicating that agroforestry contributes simultaneously to livelihood security and environmental sustainability (Do et al., 2020).

Provisioning services are generally easier to quantify because many products such as agricultural commodities, timber, fruits, fuelwood, and freshwater resources are included in market systems and national statistics. Nutrient inputs such as nitrogen, phosphorus, and trace elements from fertilizers are also monitored by government agencies, although information regarding nutrient losses from land degradation and clearing activities remains limited. Freshwater provisioning services are monitored through national water accounting systems and watershed management programs, emphasizing the importance of sustainable ecosystem management for long-term resource availability (Close et al., 2009). Agroforestry systems showed better performance in provisioning ecosystem services compared to conventional farming systems. Mathieu et al. (2025) reported increase in average crop yield by 20.4%, while, forage production improved by 5.5% under agroforestry practices. Further, yield enhancement was observed in maize and wheat by 22.8% and 26%, respectively. They also recorded positive response in several other crops such as groundnut, millet, barley, oats, and cowpea due to improved soil conditions and favorable growing environments. However, 24% anmd 25.8% reduction was observed in whole-field forage and livestock production when tree-covered areas were included in the total land assessment. Even with this reduction, silvopastoral systems achieved an overall productivity advantage of nearly 42–55% because the combined output from trees, forage, and livestock was greater than that of separate production systems (Pent, 2020). The global analysis further revealed that around 69% of the 3075 comparisons reported beneficial effects of agroforestry on ecosystem services and biodiversity, indicating the broader ecological and productive benefits of these systems (Mathieu et al., 2025)

3.2. Regulating services

These are the ecological processes through which ecosystems maintain environmental balance and stability. These services include climate regulation, carbon sequestration, soil conservation, water regulation, pollination, nutrient cycling, pest control, and disease regulation (van Noordwijk, 2021). In agroforestry systems involving natural dye-producing tree species, regulating services are particularly important because they improve ecosystem resilience, enhance environmental sustainability, and support long-term agricultural productivity. Natural dye-producing tree species such as *Bixa orellana, Terminalia chebula* and *Indigofera tinctoria* contribute significantly to climate regulation through canopy cover and biomass accumulation (Nungula et al., 2023). Their canopy structure reduces temperature fluctuations, minimizes evapotranspiration losses, and creates favorable microclimatic conditions for associated crops and soil organisms (Gusli et al., 2020). These trees also improve atmospheric humidity and reduce the adverse impacts of heat stress in agricultural landscapes (Kathayat et al., 2024).

Soil and water conservation are among the most important regulating services provided by agroforestry systems (van Noordwijk, 2021). Tree canopies reduce the direct impact of rainfall on the soil surface and slow down surface runoff, thereby minimizing soil erosion (Suprayogo et al., 2020). They further augment soil fertility by increasing soil organic matter, nutrient cycling, and microbial activity through litter fall and root biomass decomposition. In Morocco, soils under pollarded ash trees were found to contain higher levels of phosphorus, nitrogen, carbon, and mycorrhizal spore density compared to soils without tree cover (Fakhech et al., 2020).

Agroforestry systems also play a major role in water regulation and groundwater recharge. Tree cover enhances rainwater infiltration and reduces surface runoff, thereby improving soil moisture retention and watershed stability. Studies conducted in Indonesia showed that tree canopy cover above 55–80% significantly improved infiltration rates and reduced soil erosion in upland watersheds (Suprayogo et al., 2020). *Theobroma cacao* based agroforestry systems were also reported to improve soil moisture storage sufficiently to support approximately one week of evapotranspiration without rainfall, enhancing drought resistance and climate adaptation (Gusli et al., 2020).

Climate regulation through carbon sequestration is another major regulating service of agroforestry systems. Trees absorb atmospheric CO_2 through photosynthesis and store C in aboveground biomass, roots, litter, and soil organic matter. Agroforestry systems maintain higher carbon stocks and provide greater long-term carbon storage potential *vis-à-vis* monocultures. Silvopastoral systems in Colombia were reported to store between 5 and 122 Mg ha^{-1} of carbon depending on ecological conditions and tree density (Aynekulu et al., 2020). Such systems therefore contribute significantly to greenhouse gas mitigation and support national and international climate change mitigation targets (Mulia et al., 2020). In Vietnam, existing agroforestry systems cover nearly 0.8 mha, with the potential to expand to 0.9–2.4 mha to cutdown greenhouse gas emissions from the agricultural sector (Mulia et al., 2020). The integration of perennial tree species into agricultural systems thus contributes to long-term carbon storage both above and below ground, outperforming monoculture systems (Nungula et al., 2023).

Regulating services also include biological control mechanisms such as pollination, seed dispersal, decomposition, pest regulation, and disease suppression. Further, leaf litter decomposition and soil bioturbation improve nutrient recycling and maintain soil productivity over time. Pollination services are often assessed indirectly through crop productivity and yield performance, while water purification services are evaluated using catchment water quality indicators and ecosystem health assessments. Scientific studies have shown that natural climate regulation through the carbon cycle has been significantly disrupted by anthropogenic greenhouse gas emissions, contributing to global climate change. As a result, increasing emphasis has been placed on enhancing carbon sequestration and reducing emissions through sustainable land-use systems such as agroforestry. Accurate measurement of carbon storage is also important for carbon offset programs, emissions trading schemes, and biodiversity conservation initiatives (Close et al., 2009). Tree-based agroforestry systems support biodiversity that indirectly regulates pest populations and reduces the dependence on chemical pesticides and fertilizers (Kathayat et al., 2024).

Overall, regulating ecosystem services form the ecological foundation that supports provisioning, supporting, and cultural services within agroforestry systems (van Noordwijk, 2021). Understanding and valuing these regulating functions in natural dye-producing tree species is therefore essential for developing sustainable agroforestry interventions capable of supporting environmental conservation, climate resilience, and long-term rural livelihoods.

Agroforestry systems showed strong positive effects on regulating ecosystem services when compared with conventional farming systems. Water regulation services increased by about 56%, while soil organic carbon sequestration improved by 10.4% under agroforestry practices. Additionally, soil fertility in terms of nitrogen and phosphorus availability improved by 21.5% and 16.8%, respectively. Higher leaf nitrogen content, which increased by 50.8%, further indicated better nutrient cycling and enhanced soil productivity in these systems. Furthermore, the study also reported reductions in soil erosion, bulk density, runoff, and groundwater nitrate leaching under agroforestry conditions, showing the important role of trees in maintaining soil and water quality. Water infiltration improved by 46.6%, whereas groundwater nitrate leaching was reduced by 293.5%, reflecting improved hydrological regulation in agroforestry systems. These benefits were mainly linked to litter accumulation, stronger soil aggregation, higher organic matter content, and improved root interactions that enhanced soil moisture retention and stability. The findings also suggested that agroforestry systems were more effective in increasing soil organic carbon stocks in dry regions, highlighting their contribution to climate resilience and sustainable land management (Mathieu et al., 2025).

3.3. Supporting services

They form the foundational basis for all other ecosystem services by maintaining essential ecological processes and ecosystem functions such as soil formation, nutrient cycling, habitat provision, primary productivity, biodiversity conservation, and oxygen production, all of which are necessary for sustaining life and ecosystem stability (Close et al., 2009). In agroforestry systems involving natural dye-yielding tree species (NDTS), supporting services play a pivotal role in ensuring long-term soil productivity, ecological balance, and sustainable agricultural production (van Noordwijk, 2021). Natural dye-producing tree species contribute significantly to soil fertility enhancement through litter deposition, root biomass accumulation, and nutrient recycling. Species such as *Butea monosper*ma and *Terminalia* (Terminalia spp.) enrich soils with organic matter and improve microbial activity, thereby increasing soil organic carbon and long-term soil productivity (Nungula et al., 2023). Decomposition of leaf litter and organic residues enhances nutrient availability, improves soil structure, and supports sustainable nutrient cycling within agroforestry ecosystems (Sari et al., 2020).

Supporting services are essential for sustainable land management and agricultural productivity. Tree roots stabilize soil particles and reduce land degradation, while accumulated organic matter contributes to the gradual formation of fertile topsoil layers (Close et al., 2009). Habitat provision is another major supporting service offered by agroforestry systems. The integration of trees with crops creates structurally complex habitats that support plants, animals, insects, microorganisms, and soil fauna more effectively than monoculture farming systems. Agroforestry systems in Vietnam contained 15 earthworm species, compared to 21 species in natural forests and only 7 species in annual croplands and home gardens. These findings demonstrate that agroforestry systems function as intermediate ecosystems capable of conserving biodiversity while simultaneously supporting agricultural production. Earthworms and other soil organisms improve soil aeration, decomposition, and nutrient mineralization, thereby enhancing ecosystem functioning and soil health (Mulia et al., 2021). Agroforestry landscapes therefore enhance biodiversity conservation and ecological resilience by providing food, shelter, breeding sites, and migration corridors for various species (van Noordwijk, 2021).

Agroforestry systems also support pollination, pest regulation, nutrient and energy flow within ecosystems. Diverse vegetation structures attract pollinators and beneficial organisms, which improve crop productivity and ecological stability. Tree diversity in cacao agroforestry systems was positively associated with higher carbon stocks and improved ecological stability, indicating strong relationships between biodiversity and ecosystem functioning (Sari et al., 2020).

Primary productivity, which refers to the energy produced by plants through photosynthesis, is another important supporting service. Ecologists have estimated that humans consume a substantial proportion of global net primary productivity, affecting biodiversity, atmospheric composition, and food web dynamics (Close et al., 2009). Agroforestry systems help sustain primary productivity by maintaining vegetation cover, improving soil fertility, and supporting continuous biomass production across landscapes. The conservation of biodiversity and maintenance of ecological processes through supporting services ultimately strengthen the sustainability of agroforestry systems. They further provide the ecological foundation necessary for provisioning, regulating, and cultural ecosystem services to function effectively over time (van Noordwijk, 2021).

Supporting ecosystem services were significantly enhanced under agroforestry systems through improvements in soil fertility, carbon storage, and biodiversity conservation. Soil organic carbon (SOC) stocks accounted for nearly 24.6% of all ecosystem service comparisons, while soil nitrogen and phosphorus availability increased by 21.5% and 16.8%, respectively. Leaf nitrogen content also increased by 50.8%, indicating improved nutrient cycling and soil productivity. In addition, biodiversity and species abundance were higher in agroforestry systems because tree-based farming created more stable and diverse habitats than conventional agricultural systems (Mathieu et al., 2025).

3.4. *Cultural services*

These refer to the non-material benefits obtained from ecosystems that contribute to human well-being, cultural identity, spiritual enrichment, recreation, aesthetics, and social relationships. They play a major role in motivating biodiversity conservation, traditional resource management, and community participation in sustainable land-use practices (Close et al., 2009). These services include recreational, heritage, educational, spiritual, and aesthetic values that strengthen the connection between people and nature (van Noordwijk, 2021). In agroforestry systems involving natural dye-producing tree species, cultural services are deeply connected with indigenous knowledge systems, traditional practices, and ethnobotanical heritage. Tree species such as *Bixa orellana*, *Indigofera tinctoria* and *Terminalia chebula* have been traditionally used for natural dye extraction in textiles, paintings, rituals, cosmetics, and body art for several centuries (Kathayat et al., 2024). These traditional practices preserve cultural identity and strengthen intergenerational knowledge transfer within rural and indigenous communities. Natural dye tree species-based agroforestry systems also function as living repositories of ethnobotanical knowledge, where local communities continue to practice and transmit traditional methods of cultivation, harvesting, dye extraction, and medicinal utilization (Nungula et al., 2023). Such systems therefore contribute not only to biodiversity conservation but also to the preservation of cultural heritage and traditional ecological knowledge (Kathayat et al., 2024).

Agroforestry systems further provide relational ecosystem services that strengthen human–nature relationships and community cooperation. These services include preservation of indigenous knowledge, traditional farming practices, local customs, landscape aesthetics, and social values that have developed over generations. Agroforestry landscapes often reflect the cultural history and ecological wisdom of local communities, thereby contributing to social identity and cultural continuity. The article explains that ecosystem services are increasingly recognized not only for their material benefits but also for their relational values that connect people with ecosystems and biodiversity. Agroforestry systems contribute to sustainable development by integrating ecological functions with social and cultural well-being (van Noordwijk, 2021). Traditional knowledge regarding tree management, species selection, biodiversity conservation, and ecosystem restoration plays an important role in maintaining these cultural services (Nguyen et al., 2020).

Cultural services are also associated with recreation and aesthetic appreciation of landscapes. Environmentally significant regions often attract tourism and conservation funding due to their scenic beauty, biodiversity, and cultural importance. In Australia, for example, areas such as the Lake Eyre Basin hold substantial Indigenous and non-Indigenous cultural heritage values and represent important ecological landscapes with unregulated inland river systems. Tourism statistics, visitor numbers, and expenditure patterns are often used as indirect indicators for assessing cultural ecosystem service values in ecologically important areas such as the Great Barrier Reef. In addition, surrogate economic indicators such as real estate values near ecologically valuable landscapes can provide insights into the aesthetic and cultural importance of ecosystems (Close et al., 2009). Agroforestry systems that incorporate natural dye-producing species often enhance landscape beauty and ecological diversity, thereby contributing to environmental awareness, recreation, and educational opportunities for local communities and visitors alike (Kathayat et al., 2024).

Overall, cultural ecosystem services strengthen social resilience, environmental stewardship, and long-term sustainable land management by maintaining the cultural, spiritual, and relational connections between humans and ecosystems (van Noordwijk, 2021). These services therefore represent an essential dimension of sustainable agroforestry systems involving natural dye-producing tree species.

4. SUSTAINABILITY AND CHALLENGES

4.1. *Land use competition*

Agroforestry systems integrating dye species may compete with staple food crops or timber species, especially in land-scarce regions. The prioritization of land for food production often limits the allocation of space for dye-producing trees, despite their ecosystem service benefits (Nungula et al., 2023).

4.2. *Low yield and productivity*

Natural dyes typically yield lower pigment concentrations compared to synthetics, and trees require years to mature. Moreover, some dye trees, such as *Butea monosperma* and *Terminalia chebula*, are seasonal or have long regeneration cycles (Kathayat et al., 2024). This limits their short-term economic return, making them less attractive to smallholder farmers.

5. CONCLUSION

Natural dye-based tree agroforestry systems functioned as sustainable land-use models that offered ecological, economic, and social benefits. They improved soil health, supported biodiversity conservation, enhanced carbon sequestration, and moderated local climates in dry regions. Cultivation of indigenous dye-yielding plants preserved traditional knowledge and strengthened rural livelihoods. These systems also generated additional income and promoted women's participation in dye-related activities. Moreover, they contributed to ecological restoration, sustainable resource utilization, and climate resilience in rural landscapes.

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