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Sustainable cultivation practices and market trends of Indian sandalwood: A comprehensive review

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Abstract

Indian sandalwood, renowned for its aromatic heartwood and essential oil, holds a revered status in traditional practices and modern industries. Its essential oil, celebrated for its exquisite fragrance, is a staple in perfumery, cosmetics and traditional medicine due to its antimicrobial, anti-inflammatory and anti-cancer properties**.** Culturally, sandalwood is deeply embedded in Indian traditions, where it is used in religious ceremonies and for crafting sacred artifacts symbolizing purity and serenity. From an economic perspective, the high demand for sandalwood, coupled with its slow growth rate, presents significant challenges in its cultivation and conservation. This review addresses the over-exploitation of natural sandalwood resources, emphasizing the need for sustainable cultivation practices to ensure its future availability. Such practices involve enhancing genetic strains, adapting to climate change and promoting biodiversity through agroforestry systems that provide multiple income streams for farmers. The review also highlights the critical challenges in cultivating sandalwood, such as its species-specific climatic requirements and susceptibility to pests and diseases. These challenges are compounded by the economic risks associated with the high value of sandalwood and its long maturity period, which can deter investment and conservation efforts. Technological advancements play a pivotal role in addressing these challenges, with innovations in biotechnology and precision agriculture enhancing yields and sustainability. The review advocates for a balanced approach that meets commercial demands while preserving ecological and cultural integrity. It calls for continued research, international cooperation and adaptive management strategies to secure a sustainable future for Indian Sandalwood cultivation and trade. Additionally, the review emphasizes the need for integrated approaches combining traditional knowledge with modern scientific and technological advances to optimize sandalwood cultivation.

Keywords

conservation efforts; essential oil; medicinal properties; sustainable cultivation; technological advancements

Introduction

Indian Sandalwood, scientifically known as *Santalum album* L., is a highly valued tree species native to the Indian subcontinent and now cultivated in other parts of the world like Australia. Known for its aromatic heartwood and essential oil, sandalwood has been celebrated for centuries in various cultural, medicinal and economic contexts (1). The essential oil derived from sandalwood is renowned for its fragrance and therapeutic properties, making it a staple ingredient in perfumes, cosmetics and

aromatherapy products. Recent studies have demonstrated that sandalwood essential oil possesses significant antimicrobial and anti-inflammatory properties, further enhancing its value in cosmetic and therapeutic applications (2, 3).

Culturally, sandalwood holds a revered place in Indian traditions and rituals. It is extensively used in religious ceremonies and for crafting idols, temple doors and other religious artifacts (4). Its presence is ubiquitous in Hindu rituals, where it is used in the form of paste or oil for anointing deities and participants during sacred ceremonies, as it is believed to purify the environment and calm the mind and spirit. Moreover, sandalwood's cooling properties make it a popular choice in spiritual practices to promote clarity and focus. Studies have indicated that sandalwood paste can effectively reduce stress levels and promote relaxation during meditation practices (5, 6).

Sandalwood cultivation requires specific silvicultural practices to optimise growth, yield and oil content. Sandalwood is a semi-parasitic tree that relies on host plant to obtains its nutrients from host plants. Therefore, intermediate culture and the choice of suitable practices are important for healthy growth (7). Typically, nitrogen-fixing plants such as legumes are planted alongside sandalwood to improve soil fertility. Additionally, silvicultural practices such as selective pruning, pest management and regulated irrigation contribute significantly improve wood quality and yield (8). In recent years, integrating sandalwood cultivation into agroforestry systems has gained importance. This approach not only diversifies farmer's income streams but also enhances biodiversity and support sustainable agricultural ecosystems (9).

The global market for Indian sandalwood and its derivatives is experiencing significant growth. While India and Australia are the two main producers, Australia's dominance in the market has surged due to large-scale plantations and advanced cultivation techniques. The rising demand for sandalwood essential oil in perfumery, cosmetic and aromatherapy is a major driver of this market (10). As a result, sandalwood has become a highly valued commodity, with its price reflecting its desirability. High demand from countries such as China, Japan and the United States of America, has further strengthened international trade networks. However, the scarcity of wild sandalwood and stringent international trade regulations have added layers of complexity to the market (11).

Medicinally, sandalwood oil holds a prominent place in traditional Ayurvedic medicine. Recent research has expanded its therapeutic applications, revealing anti-cancer properties, particularly against skin and breast cancers (12,13). A study found that sandalwood oil exhibits cytotoxic effects on breast cancer cells, suggesting its potential as a complementary treatment (14). Additionally, a clinical trial demonstrated that aromatherapy with sandalwood oil significantly reduces anxiety in patients undergoing medical procedures (15).

Economically, the demand for Indian Sandalwood has significant implications. It is among the most expensive woods in the world, driven by its extensive demand in the perfumery and pharmaceutical industries. This high demand has made sandalwood a lucrative crop, encouraging both large-scale and small-scale cultivation. However, its value also makes it a target for illegal harvesting and smuggling, contributing to sharp declines in wild populations. Controlled cultivation practices have therefore become essential to meet demand, while protecting natural resources. Recent conservation studies highlighted the importance of sustainable cultivation practices to ensure the long-term availability of sandalwood resources (16). Efforts are also underway to genetically enhance sandalwood trees for improved yield and disease resistance, offering promising solutions to meet growing demand (17).

Furthermore, the impact of climate change on sandalwood cultivation has emerged as a critical subject of recent investigation. Studies suggest that shifting climate patterns may influence the growth and oil composition of sandalwood trees, highlighting the necessity of adaptive strategies in cultivation practices (18). Additionally, integrating sandalwood cultivation with agroforestry systems has shown economic and ecological benefits, providing farmers with diversified income and promote biodiversity (19).

In addition to its primary uses, sandalwood by-products are gaining recognition for their diverse applications. Research indicates that sawdust and other residues from sandalwood can be utilized to produce high value bioproducts, contributing to a circular economy (20). Moreover, advancements in extraction techniques have improved the efficiency and sustainability of sandalwood oil production, ensuring higher purity and yield (21).

The integration of sandalwood in modern pharmacological formulations is also being explored. Studies shown promising results in developing new therapeutic agents for various diseases, reinforcing its importance in comtemporary medical research (22). These developments underscore the continued relevance and untapped potential of Indian Sandalwood in modern industry and research.

The purpose of this review is to provide a comprehensive analysis of these diverse aspects. It explores the current state of sandalwood cultivation, emphasizing sustainable practices to preserve this precious resource for future generations. Additionally, the review examines global market trends, analyzing price dynamics, emerging markets and the impact of international trade policies on the supply and demand of sandalwood.

Botanical Description and Geographic Distribution

Indian Sandalwood (*Santalum album*) belongs to the Santalaceae family and is one of the most valuable aromatic woods in the world. This small tropical tree can grow 10 to 15 meters tall, featuring brown bark with a distinct hearty scent. As a semi-parasitic species, it derives nutrients from the host plants. The tree's ovate, shiny leaves help to reduce water loss, while its small purple-brown flowers are fragrant. The fleshy drupes turn black when ripe. Although sandalwood trees begin producing oil between 10 and 15 years, the optimal oil quality is achieved in trees aged 40 to 60 years (23, 24).

Santalum album is native to the deciduous and semi-evergreen forests of southern India, especially Karnataka, Tamil Nadu and Kerala, thriving in red-rusty clay soils and low-rainfall areas. Due to overexploitation, the species is now listed as endangered by the IUCN. Its cultivation has since expanded to regions with similar climates including Australia (Fig. 1), Indonesia and the Pacific islands, supporting the global sandalwood production (25, 26).

Understanding the natural habitat and ecological characteristic of Indian sandalwood is essential for sustaining its cultivation and conservation practices, which underpin its economic importance (27)

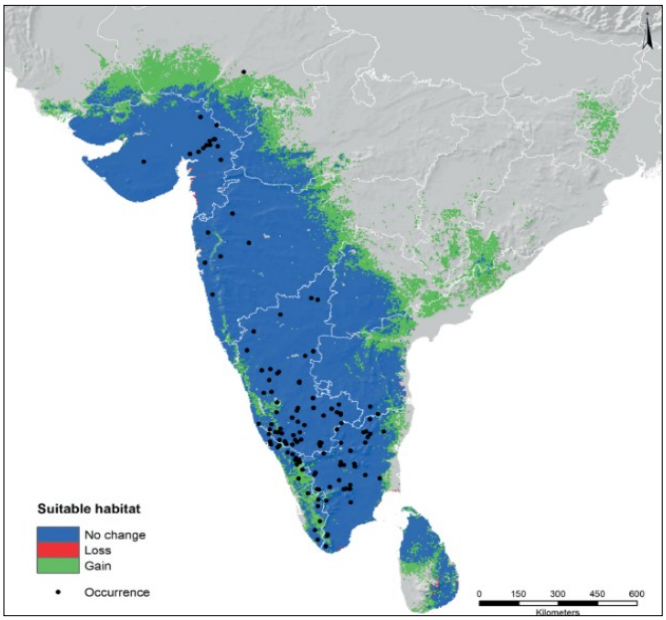

Fig. 1. Modelled distribution and threat to sandalwood in India (11).

Sustainable Cultivation Practices

The cultivation of Indian Sandalwood (*Santalum album*) requires specific practices tailored to its unique botanical characteristics and slow growth cycle.

Site Selection and Soil Requirements

Successful cultivation of Indian Sandalwood begins with careful site selection, ensuring conditions closely resemble its native habitat. The ideal environment includes a a climate characterized by dry periods interspersed with moderate rainfall and altitudes ranging between 600 to 900 meters above sea level. While the tree is adaptable to variety of altitudes, it requires that other environmental conditions are met (28,29). Soil quality is critical factor for optimal growth. The tree prefers sandy loam soils with good drainage and a neutral to slightly acidic pH (6.0-7.5) (30). The soil must be deep enough to support the extensive root system and its hemiparasitic nature, while relies on suitable host plants for nutrient acquisition (31, 32). Pre-planting soil treatments can further improve growth conditions by enhancing soil structure and fertility. Adding organic matter increase the soil's nutrient content and water-holding capacity, creating a more supportive environment for the trees (33).

Propagation Methods

Propagation of Indian Sandalwood can be achieved through seeds or vegetative methods. Seed propagation is the most common method due to its simplicity and effectiveness (34). However, seeds must be handled carefully as they are prone to losing viability quickly when dried. Stratification, pre-treatment to overcome dormancy, involves soaking the seeds in water for 48 hours to improve germination rates (35). Once germinated, the seedlings are typically grown under nursery conditions before being transplanted to the field (36). Vegetative propagation, involving techniques like grafting or tissue culture, is utilized to preserve desirable genetic traits and enhance disease resistance (37). Tissue culture, in particular, facilitates the rapid multiplication of superior strains, making it ideal for large-scale plantations that require consistency in wood and oil quality (38).

Plantation Management

Effective management of a sandalwood plantation covers several aspects, including irrigation, pest and disease management. Irrigation must be carefully managed as sandalwood is intolerant of waterlogging, but requires consistent moisture, especially in the dry season. Drip irrigation systems are often recommended as they provide controlled water delivery directly to the root zone (39). Pest and disease management is equally important, as sandalwood is susceptibility to issues like root rot, sandalwood spike disease and attacks from insects such as borers (40). Regular monitoring and integrated pest management strategies, such as biological control agents and selective pesticide application, are essential to maintain plant health (41).

Harvesting Techniques and Age of Maturity

Indian Sandalwood trees are typically ready for initial harvesting after 10-15 years, when they start producing significant amounts of oil. However, for optimal heartwood and oil quality, trees are ideally harvested between 30 to 60 years (42). The harvesting process involves the complete removal of the tree, including its roots, since the valuable heartwood extends into the root system (43). Harvesting techniques must minimize damage to the wood to preserve its quality. After harvesting, the wood is processed through steam distillation, , a method that efficiently captures the essence of sandalwood oil while maintaining its purity and essence (44).

The successful cultivation of Indian sandalwood requires detailed attention to every stage of agricultural practices, from site selection and soil preparation to the tree care and harvesting. Given its high economic value and slow growth, each step must be meticulously planned and executed to ensure the sustainability of cultivation and profitability of the crop.

Market Trends

Indian Sandalwood (*Santalum album*), also known as white sandalwood, holds significant global economic position due to its high demand. Historically, it has been highly valued in India for religious rituals and medicinal applications, with its importance extending thousands of years. In ancient times, sandalwood was revered for its use in crafting religious artifacts and its therapeutic properties in Ayurvedic medicine. Over the centuries, its demand has steadily increased, driven by expansion of global trade. Today, Indian sandalwood has achieved prominence in industries such as perfumery, cosmetics, pharmaceuticals, spices and dyes (45, 46).

In modern markets, the appeal of Indian Sandalwood has evolved significantly, with demand primarily driven by the fragrance industry. Known for its deep, woodsy scent that blends well with other aromas, sandalwood oil has become a corner-stone of high-end perfumes. Its growing popularity in Western markets has cemented it as an essential ingredient in luxury fragrance formulations. Beyond its olfactory appeal, sandalwood's medicinal properties, including anti-inflammatory and antimicrobial effects, have boosted its use in pharmaceuticals and cosmetics, where it is marketed for its supposed health benefits and luxurious allure (47).

Recent market reports indicate that the global sandalwood oil market was estimated at around USD 120 million in 2023 with projection indicating compound annual growth rate (CAGR) of 8.5% through 2030. This growth is primarily furled by rising demand for natural and sustainable products in the perfume and cosmetics industries (48). India and Australia are the two primary producers of

sandalwood, with Australia supplying over 70% of global demand due to its well-established plantations. The major importers of sandalwood oil include the United States, China and Japan, where it remains a crucial ingredient in perfumes, aromatherapy and medicinal products (49).

The supply of Indian sandalwood has been limited due to over-harvesting and strict regulations on wild sandalwood extraction. This scarcity has driven prices up, with premium-grade sandalwood oil costing as much as $1,500 per kilogram. In response to this high demand and limited supply, countries like Australia have emerged as major players in the market, cultivating sandalwood on plantations. This cultivated supply has helped stabilize prices by ensuring a consistent flow of the product. However, the market continues to face challenges due to high cost of cultivation and the tree's long maturity period of 10-15 years, which limit rapid expansion. Looking forward, the sandalwood market is expected to continue growing as consumer demand for natural, sustainably sourced products increases. This growth underscores the importance of sustainable agricultural practices to support supply while ensuring that this valuable natural resource remains available for future generations (50,51)

Major Markets (Domestic and International)

Domestically, India remains a significant consumer of sandalwood, not just for traditional and religious purposes but also in domestic industries such as handicrafts and small-scale aromatic products (52). Internationally, the United States, Europe and Japan are major markets for Indian Sandalwood oil, primarily driven by the perfume industry (53). Additionally, China has also emerged as a significant player, with increasing use in aromatherapy and traditional Chinese medicine (54).

The trade of Indian sandalwood has been significantly influenced by both domestic and international regulations. In India, sandalwood is classified as a "reserved tree," meaning its cutting and transport are regulated by the government to curb illegal cutting and smuggling, which was rampant due to the high value of the wood . Internationally, CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora) regulates its trade to prevent over-exploitation (55).

Such regulations have had mixed impacts. While they have contributed to conservation efforts and stabilizing legal supplies, they have also inadvertently fueled a black market where illegal wood can fetch extraordinarily high prices (56). Additionally, regulations have led to significant paperwork and bureaucratic delays in the legal trade, sometimes affecting the freshness and quality of the wood and oil (57).

The market for Indian Sandalwood is complex and influenced by a myriad of factors from cultural heritage and industrial demand to conservation efforts and global economics. Moving forward, the sustainability of sandalwood production will hinge on advanced cultivation techniques, stricter enforcement of harvesting regulations and a balanced approach that meets commercial demands without compromising the ecological and cultural integrity of this valuable species. Innovations in cultivation and regulatory frameworks will be essential to balance economic benefits with ecological conservation (58). As global awareness of environmental issues grows, consumers and businesses are increasingly prioritizing sustainably sourced products, which could shift market preferences and influence pricing structures significantly (59). Furthermore, advancements in biotechnology, such as genetic modification and improved propagation techniques, hold the potential to increase yields and reduce the maturity time of sandalwood trees, thereby addressing some of the supply constraints (60). Additionally, the development of synthetic alternatives to sandalwood oil may relieve some pressure on natural stocks, but it's also likely to create a market segmentation between 'natural' and 'synthetic' products, each catering to different consumer bases (43). These evolving dynamics underscore the need for ongoing research, international cooperation and adaptive management strategies to ensure that the Indian Sandalwood industry thrives in a economically viable and environmentally responsible manner.

The global sandalwood market was valued at approximately USD1.5 billion in 2020 and is projected to reach around USD 4.6 billion by 2027, growing at a CAGR of about 16.9% from 2020 to 2027 (61).

Sustainable Practices and Challenges

The cultivation and conservation of Indian Sandalwood (*Santalum album*) present unique set of challenges and opportunities. Sustainable cultivation of Indian Sandalwood involves several practices designed to ensure the long-term viability of sandalwood resources while minimizing environmental impact. One fundamental technique is the use of host plants, such as leguminous species that provide the necessary nutrients to the parasitic sandalwood trees without depleting the soil., These plants maintain soil fertility by fixing nitrogen (62).

Integrated pest management (IPM) are also essential, utilizing biological pest control methods to reduce reliance on chemical pesticides. This approach not only protects the plantation from pests but also preserves the surrounding biodiversity and prevents the build-up of chemical residues in the environment (63).

Additionally, rotational harvesting and selective logging ensure that not all trees are harvested at once, allowing younger trees more time to mature fully and guaranteeing a continuous supply of sandalwood (36). Water conservation measures, such as drip irrigation, are also critical in regions prone to drought, ensuring that sandalwood cultivation does not strain local water resources (64).

Challenges in Cultivation

The cultivation of Indian Sandalwood faces several significant challenges:

Climatic Challenges: Sandalwood trees require specific climatic conditions to thrive, including well-defined dry and wet seasons. Climate change poses a significant threat by altering rainfall patterns and increasing temperatures, which can lead to stress on plants, reduced growth rates and increased susceptibility to diseases (65).

Biological Challenges: Being a hemiparasitic plant, sandalwood relies on suitable host plants throughout its lifecycle. The selection, management and timing of host plant introduction are critical to the health and productivity of sandalwood plantations. Additionally, the trees are susceptible to a range of pests and diseases, including spike disease, which can devastate plantations if not managed promptly (43).

Economic Challenges: The high value of sandalwood increases the risk of over-exploitation and illegal trading. The long maturity period of the trees (10-15 years at a minimum for initial harvesting) requires substantial upfront investment and poses financial risks, particularly for smallholders. Also, price volatility in the global market can adversely affect growers, who may face years of low prices after making significant investment in plantation development (27).

Conservation Status and Efforts

Indian Sandalwood is classified as vulnerable by the IUCN Red List due to its declining natural populations, primarily driven by habitat loss and over-harvesting. Conservation efforts are thus focused on both protecting existing forests and encouraging the sustainable cultivation of sandalwood (21).

In-situ conservation efforts include protecting natural habitats and implementing strict regulations on the harvesting of wild sandalwood. Ex-situ conservation strategies include establishing sandalwood plantations that utilize sustainable practices, thereby reducing pressure on wild populations (29). Government and non-governmental organizations are working to strengthen the enforcement of laws against illegal logging and trading. Additionally, there is a significant push towards community involvement in sandalwood cultivation, which not only provides economic benefits to local communities but also promotes a stewardship model of conservation. In this model those who live with the resource become its most passionate protectors (66).

Sustainable practices in the cultivation of Indian Sandalwood are crucial for its survival and for the ecological health of its native and adopted regions. Addressing cultivation challenges through advanced research, community engagement and strict enforcement of conservation laws will be key to ensuring valuable species thrives in the future. These efforts not only protect the species but also secure the livelihoods of those dependent on sandalwood for economic and cultural reasons (67).

Advances in technology and research in agriculture and forestry can greatly enhance the sustainability of sandalwood cultivation. Modern techniques such as precision agriculture, which utilizes GPS and IoT sensors, can optimize water usage and monitor plant health on a granular level, thereby increasing yield while minimizing waste (23). Research into genetically improved varieties of sandalwood that are more resilient to diseases, pests and variable climatic conditions can also contribute significantly to the sustainable cultivation practices. Collaborative international research and sharing of best practices are crucial for developing such innovations (34). These technological advancements, combined with traditional knowledge and sustainable management practices, have the potential to revolutionize sandalwood cultivation, making it both environmentally sustainable and economically viable for generations to come (68).

Technological Advances

The cultivation and trade of Indian Sandalwood (*Santalum album*) have significantly benefited from technological advancements in recent years. Innovations in cultivation and harvesting techniques, biotechnological interventions and the application of information technology have all played pivotal roles in enhancing the efficiency, sustainability and profitability of sandalwood production. Technological innovations have revolutionized the cultivation and harvesting of Indian Sandalwood. Precision agriculture technologies, including the use of GPS and drones, allow for precise mapping and monitoring of sandalwood plantations. These technologies aid in efficient land management, optimizing irrigation schedules and applying fertilizers and pesticides more judiciously. Drones, in particular, can be used for aerial seeding and spraying, significantly reducing labor costs and improving coverage accuracy (19, 59, 69).

Harvesting technologies have also seen significant improvements. Automated harvesting machines have been developed to carefully extract sandalwood trees with minimal damage to the wood, thereby preserving its quality for further processing. These machines are adaptable to the size and shape of the tree, ensuring efficient and sustainable harvesting practices (19, 48 & 53). Biotechnology has provided powerful tools for improving the propagation and health of Indian Sandalwood trees. Tissue culture techniques, in particular, have been transformative, enabling the mass production of disease-free and genetically uniform plantlets. This method not only ensures the rapid propagation of sandalwood but also helps preserve genetic diversity while selecting for traits such as improved growth rates and higher oil content (57).

Genetic engineering and molecular marker-assisted selection are being explored to develop disease-resistant sandalwood strains. These techniques can identify and enhance specific genetic traits that make plants less susceptible to common diseases like root rot or the sandalwood spike disease, significantly reducing crop losses and chemical use in plantations (53, 54).

Information technology has dramatically transformed market analysis capabilities for Indian Sandalwood. Big data analytics and artificial intelligence are now used to analyze market trends, consumer preferences and price fluctuations, providing stakeholders with actionable insights. These technologies help in forecasting demand and supply dynamics, enabling producers and traders to make informed decisions about production scales, marketing strategies and resource allocation (11, 56).

Blockchain technology is also making its way into the sandalwood market, providing a transparent and secure method for tracking the provenance and trade of sandalwood products. This not only helps in combatting illegal trading but also enhances consumer trust by guaranteeing product authenticity (48, 70).

Additionally, digital platforms for trading sandalwood have expanded market reach, allowing producers to connect directly with buyers worldwide. These platforms often incorporate tools for secure payments, contract management and logistics planning, streamlining the entire trade process (39, 49).

The integration of advanced technologies in the cultivation, propagation and trade of Indian Sandalwood is crucial for addressing current challenges and capitalizing on new opportunities. These technologies not only enhance the economic viability of sandalwood production but also contribute to sustainable practices essential for the long-term preservation of this valuable species. By continuing to invest in and adopt these technological advancements, the sandalwood industry can ensure a prosperous and sustainable future (48).

Table 1. Research insights and trends in Indian sandalwood and market dynamics

Title	Main Focus	Reference
Analysis of Policies in Sustaining Sandalwood Resources in India	Discusses policies affecting sandalwood cultivation and highlights the need for policy liberalization.	8
Looking ahead - global sandalwood production and markets in 2040 and implications for Pacific Island producers	Provides a prognosis for global sandalwood production and demand, predicting strong markets up to 2040.	34
Tropical Forestry Services: A Case Study of Embracing Entrepreneurial Leadership in Charting East-West Markets for Ancient Indian Sandalwood	Highlights the entrepreneurial strategies of Tropical Forestry Services in the sandalwood market.	37
Progress and future research trends on *Santalum album*: A bibliometric and science mapping approach	Analyzes research trends on Indian sandalwood and suggests future research areas.	39
Economics of *Santalum album* L. Cultivation Under Semiarid Tropics of Karnataka, India	Evaluates the economic viability of sandalwood cultivation under different intercropping systems.	17
The Population Decline of Indian Sandalwood and People's Role in Conservation-An Analysis	Discusses the decline in sandalwood population and the role of policy changes in its conservation.	19
Biopriming of seeds with plant growth-promoting bacteria Pseudomonas fluorescens for better germination and seedling vigor of the East Indian sandalwood	Investigates the effect of biopriming on sandalwood seed germination.	24
Sandalwood Plantations - Points to Ponder	Examines the ecological and silvicultural aspects of sandalwood plantations.	26
Identification of market adulterants in East Indian sandalwood using DNA barcoding	Uses DNA barcoding to identify adulterants in the sandalwood market.	42
Trends in the marketing of some important medicinal plants in Uttarakhand, India	Analyzes marketing trends of medicinal plants including sandalwood.	46
Population Dynamics of the Striped Mealy Bug *Ferrisia virgata* (Cockerell) (Hemiptera, Pseudococcidae) and the Scope of its Biological Suppression in the Present Scenario of Cultivation of Indian Sandalwood	Investigates the population dynamics and biological control of a major pest affecting sandalwood.	45
Santalum album L. (Indian sandalwood) oil content variation of Welimada region, Sri Lanka	Examines the variation in oil content of sandalwood trees in Sri Lanka.	41
A threat to sandalwood cultivation in the naturalised Marayoors sandalwood reserve (Kerala, India) through single and mixed phytoplasma infections	Reports on the threats to sandalwood cultivation from phytoplasma infections.	47
Participatory value chain study for yasi sandalwood (*Santalum yasi*) in Fiji	Presents a value chain analysis for yasi sandalwood in Fiji.	48

Table 2. Effect of different agricultural practices on sandal cultivation and impacts

Agricultural Practice	Impact on Sandalwood Tree	Possible Solutions	Reference
Over-Harvesting	Depletes natural populations, leading to scarcity and increased prices.	Implement regulated harvesting practices and sustainable management plans	50
Land Degradation	Compromised soil health affecting growth and yield.	Implement soil conservation techniques, such as cover cropping and reduced tillage	50
Inadequate Cultivation Practices	Poor growth and lower oil yield due to nutrient deficiencies and soil erosion.	Promote proper soil management and fertilization strategies	51
Monoculture Plantations	Increased vulnerability to pests and diseases; loss of biodiversity.	Encourage agroforestry systems that integrate sandalwood with other crops	52
Climate Change	Altered growth patterns and susceptibility to stress (e.g., drought).	Adapt planting strategies to select more resilient varieties and improve irrigation systems	53
Pest and Disease Management	Potential decline in health and productivity of sandalwood trees.	Use integrated pest management (IPM) strategies to minimize chemical use and enhance natural predator populations	54

Conclusion

The exploration of market trends, cultivation practices and technological advancements associated with Indian Sandalwood (*Santalum album*) underscores its significant cultural, medicinal and economic value. As the industry progress it faces the dual challenge of meeting growing global demand while ensuring the sustainability of both the tree species and the ecosystems in which it thrives. This comprehensive review highlights the importance of integrating traditional knowledge with modern scientific and technological innovations to cultivate and utilize sandalwood more efficiently and sustainably. Moreover, the evolving global market landscape demands continual adaptation and vigilance to protect this valuable species from over-exploitation and ensure its availability for future generations. Ultimately, the future of the Indian Sandalwood industry will depend on its ability to innovate, adapt and conscientiously manage this unique natural resource, reflecting a broader commitment to balancing economic development with environmental stewardship. Furthermore, the ongoing development of new markets and the discovery of novel uses for Indian Sandalwood offer exciting prospects for expanding its economic impact while contributing to global well-being. Potential applications in pharmaceuticals, aromatherapy and luxury goods exemplify how this ancient resource can meet modern needs. However, these opportunities also bring responsibilities, particularly in terms of ethical sourcing and maintaining biodiversity. To sustainably harness the full potential of Indian Sandalwood, a collaborative approach involving researchers, cultivators, industry stakeholders and policymakers is essential. Such a multifaceted strategy will ensure that the benefits of sandalwood cultivation are distributed equitably and that this venerable tree continues to thrive in its native habitats and beyond, safeguarding its legacy and ecological benefits for future generations.

Authors' contributions

Conceptualization, M.M, M.G, K.K, P.R & JS; Formal analysis, M.M, M.G, P.R, M.T & JS; Supervision and validation, M.G, M.M & JS; Language, M.M & M.G

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References

1. Akbar S, Akbar S. *Santalum album* L. (Santalaceae). Handbook of 200 medicinal plants: A comprehensive review of their traditional medical uses and scientific justifications. 2020:1601-08. https://doi.org/10.1007/978-3-030-16807-0_165
2. Kumar A, Ac J. Potential species of aromatic plants for cultivation in semi-arid tropical (Sat) regions of Deccan region. Journal Medicinal Plants Studies. 2017;5:269-72.
3. Moy RL, Levenson C. Sandalwood album oil as a botanical therapeutic in dermatology. The J Clini Aesthetic Dermatol. 2017;10 (10):34-39.
4. Kumar AA, Joshi G, Ram HM. Sandalwood: history, uses, present status and the future. Current Science. 2012;103(12):1408-16.
5. El Or T. The soul of the biblical sandal: on anthropology and style. American Anthropologist. 2012;114(3):433-45. https://doi.org/10.1111/j.1548-1433.2012.01444.x
6. Verma M, Fatima S, Mishra P, Ansari IA. Wild edible medicinal and aromatic plants in ancient traditions. In: Ethnobotany and Ethnopharmacology of Medicinal and Aromatic Plants. CRC Press; 2023. p. 89-114. https://doi.org/10.1201/b22842-6
7. Harbaugh DT, Baldwin BG. Phylogeny and biogeography of the sandalwoods (Santalum, Santalaceae): repeated dispersals throughout the Pacific. American Journal of Botany. 2010;94 (6):1028-40. https://doi.org/10.3732/ajb.94.6.1028
8. Das SC. Silviculture, growth and yield of sandalwood. Sandal Silvicult Conser Appli. 2021:111-38. https://doi.org/10.1007/978-981-16-0780-6_7
9. Boruah T, Parashar P, Ujir C, Dey SK, Nayik GA, Ansari MJ, Nejad ASM. Sandalwood essential oil. Essential Oils. 2024.pp. 121-45. https://doi.org/10.1016/B978-0-323-91740-7.00003-7
10. Analysts GI, Agents II. A global strategic business report. San Jose, CA; 2010.
11. Yazdani K. Mysore. In: India, Modernity and the Great Divergence; 2017. pp. 115-360. https://doi.org/10.1163/9789004330795_004
12. Naik GG, Sahu AN, Kaushik V, Kaushik A, Sarkar BK. Phytopharmaceuticals and herbal drugs: prospects and safety issues in the delivery of natural products. Phytopharmaceuticals and Herbal Drugs. 2023 Jan 1:15-48. https://doi.org/10.1016/B978-0-323-99125-4.00006-8
13. Van RRM. The use of essential oils for pain relief and anxiety during childbirth: a systematic review [dissertation]. North-West University (South-Africa); 2021.
14. Sharifi-Rad J, Quispe C, Turgumbayeva A, Mertdinç Z, Tütüncü S, Aydar EF. *Santalum* genus: phytochemical constituents, biological activities and health promoting effects. Z Naturforsch C J Biosci. 2023;78(1-2):9-25. https://doi.org/10.1515/znc-2022-0076
15. Bapat VA. Sandalwood biotechnology: Challenges, opportunities and outlook. Sandal Silvicult Conser Appli. 2021:243-65. https://doi.org/10.1007/978-981-16-0780-6_13
16. Roy UK, Kouser M, Shohan SM, Zaman F, Chakraborty S, Jahan S. A review study on traditional herbal medicines of Bangladesh against different skin disorders. Malay. 2024;22(1):139-87. https://doi.org/10.21315/mjps2024.22.1.8
17. Rao M, Ravikumar G, Triveni P, Rajan V, Nautiyal S. Analysis of policies in sustaining sandalwood resources in India. Sustainable Forestry and Forest Products. 2016:327-46. https://doi.org/10.1007/978-3-319-31014-5_19
18. Carreto C, Carreto R. Design as an enhancer of the circular economy in fashion. Hum Factors Apparel Text Eng. 2022;32:106-32. https://doi.org/10.54941/ahfe1001544
19. Desam NR, Al-Rajab AJ. The importance of natural products in cosmetics. Bioactive Natural Products for Pharmaceutical Applications. 2021:643-85. https://doi.org/10.1007/978-3-030-54027-2_19
20. Kumar N, editor. In: Biosynthesis of Natural Products in Plants: Bioengineering in Post-genomics Era. Springer Nature; 2024. https://doi.org/10.1007/978-981-97-2166-5
21. Rao PS, Bapat VA. Micropropagation of sandalwood (*Santalum album* L.) and mulberry (*Morus indica* L.). Micropropagation of Woody Plants. 1993:317-45. https://doi.org/10.1007/978-94-015-8116-5_19
22. Shekhawat MS, Mehta SR, Manokari M, Priyadharshini S, Badhepuri MK, Jogam P. Morpho-anatomical and physiological changes of Indian sandalwood (*Santalum album* L.) plantlets in *ex vitro* conditions to support successful acclimatization for plant mass production. Plant Cell Tissue Organ Cult. 2021;47:423-35. https://doi.org/10.4038/jnsfsr.v43i3.7949
23. Jayawardena M, Jayasuriya KMGG, Walck J. Confirmation of morphophysiological dormancy in sandalwood (*Santalum album*, Santalaceae) seeds. J Natl Sci Found Sri. 2015; 43(3):209-15. DOI: 10.4038/jnsfsr.v43i3.7949
24. Kala CP. Traditional health care systems and herbal medicines. Eur J Environ Public Health. 2017;1(1):03. https://doi.org/10.20897/ejeph.201703
25. Valluri J. *Santalum album* L. (Sandalwood): *In vitro* culture and the bioreactor production of secondary metabolites. Biotechnology in Agriculture and Forestry. 1994:401-11. https://doi.org/10.1007/978-3-662-30369-6_24
26. Divakara BN, Viswanath S, Nikhitha CU, Kumar S. Economics of *Santalum album* L. cultivation under semiarid tropics of Karnataka, India. For Res. 2018;7:1-7. DOI: 10.4172/2168-9776.1000223
27. Jain S, Arya R, Kumar H. Distribution of sandal (*Santalum album* L.), current growth rates, predicted yield of heartwood and oil content and future potential in semi-arid and arid regions of Rajasthan, India. For Trees Livelihoods. 2007;17:261-66. https://doi.org/10.1080/14728028.2007.9752601
28. Arunkumar A, Joshi G, Rao MS, Rathore T, Ramakantha V. The population decline of Indian sandalwood and people's role in conservation-An analysis. In: Sustainable Utilization and Conservation of Natural Resources in the Era of Climate Change. Springer, Cham; 2016. p. 377-87. https://doi.org/10.1007/978-3-319-31014-5_22
29. Mandal S, Choudhury B, Satpati L. Soil site suitability analysis using geo-statistical and visualization techniques for selected winter crops in Sagar Island, India. Appl Geogr. 2020;122:102249. https://doi.org/10.1016/j.apgeog.2020.102249
30. Mamatha G, Jayanthi S, Bagyaraj D, Suresh CK. Microbial and enzymatic analysis from sandal root zone soil growing in red sandy loam. Indian J Microbiol. 2001;41:219-21.
31. Annapurna D, Rathore T, Joshi G. Modern nursery practices in the production of quality seedlings of Indian sandalwood (*Santalum album* L.)-Stage of host requirement and screening of primary host species. J Sustain For. 2006;22:33-55. https://doi.org/10.1300/J091v22n03_03

32. Gathara M, Makenzi P, Kimondo J, Muturi G. Prediction of *Osyris lanceolata* (Hochst. Steud.) site suitability using indicator plant species and edaphic factors in humid highland and dry lowland forests in Kenya. J Hortic For. 2014;6:99-106. DOI: 10.5897/JHF2014.0365

33. Chitra P, Jijeesh C. Biopriming of seeds with plant growth promoting bacteria *Pseudomonas* fluorescens for better germination and seedling vigour of the East Indian sandalwood. New For. 2021;1-13. https://doi.org/10.1007/s11056-020-09823-0

34. Liu X, Xu D, Xie Z, Zhang N. Effects of different culture media on the growth of Indian sandalwood (*Santalum album* L.) seedlings in Zhanjiang, Guangdong, southern China. For Stud China. 2009;11:132-38. DOI: 10.1007/s11632-009-0023-4

35. Anon D, Chittapur B. Sandalwood plantations – points to ponder. Curr Sci. 2021. https://doi.org/10.18520/cs/v120/i7/1184-1193

36. Sanjaya, Bagyalakshmi M, Rathore TS, Rai V. Micropropagation of an endangered Indian sandalwood (*Santalum album* L.). J For Res. 2006;11(3):203-09. https://doi.org/10.1007/s10310-006-0207-x

37. Pandey G, Modi A, Shah S, Patil G, Narayanan S. Expression pattern of *in vitro* organogenesis-associated genes as transcriptional marker in Indian Sandalwood (*Santalum album* L.) micropropogation. Plant Tissue Cult Biotechnol. 2022;32(2):103-13. https://doi.org/10.31220/agriRxiv.2021.00094

38. Thinley P, Jambay J, Gurung DB, Rabgay T, Penjor P, Kumar M. Ecology of sandalwood (*Santalum album* L.) at Lingmethang, eastern Bhutan. Bhutan J Nat Resour Dev. 2020;7(2);12-22. https://doi.org/10.17102/cnr.2020.48

39. Gomes D, Adnyana A. The effect of legume and non-legume to the sandalwood (*Santalum album*, Linn.) growth in Timor Leste. Int J Sci Basic Appl Res. 2017;32:207-37.

40. Jalonen R, Gaisberger H, Warrier RR, Yuskianti V, Krishnan S. Modeled distribution of and threats to sandalwood in a changing environment. In: Indian Sandalwood: A Compendium; 2022. p. 493-513. https://doi.org/10.1007/978-981-16-6565-3_32

41. Arunkumar AN, Joshi G, Rao MS, Rathore TS, Ramakantha V. The population decline of Indian sandalwood and people's role in conservation-an analysis. In: Climate Change Challenge (3C) and Social-Economic-Ecological Interface-Building: Exploring Potential Adaptation Strategies for Bio-resource Conservation and Livelihood Development; 2016. p. 377-87. https://doi.org/10.1007/978-3-319-31014-5_22

42. Rajan NM, Jayalakshmi S. Predictive species habitat distribution modelling of Indian Sandalwood tree using GIS. Pol J Environ Stud. 2017;26(4):1627-42.

43. Thomson L. Looking ahead – global sandalwood production and markets in 2040 and implications for Pacific Island producers. Aust For. 2020;83(4):245-54. https://doi.org/10.1080/00049158.2020.1841441

44. Iyengar A. The East Indian sandalwood oil. Indian For. 1968;94(2):57-68. DOI: 10.36808/if/1968/v94i1/25973

45. Rashkow ED. Perfumed the axe that laid it low: The endangerment of sandalwood in southern India. Indian Econ Soc Hist Rev. 2014;51(1):41-70. https://doi.org/10.1177/0019464613515553

46. Peden C, D'Sa D, Raje P, Weerakoon C. Tropical forestry services: A case study of embracing entrepreneurial leadership in charting East -West markets for ancient Indian Sandalwood. In: Sustainable Development and Social Responsibility. 2017;2:53-70. https://doi.org/10.1057/978-1-137-57940-9_3

47. Ramanan SS, George A, Chavan S, Kumar S, Jayasubha S. Progress and future research trends on *Santalum album*: A bibliometric and science mapping approach. Ind Crops Prod. 2020;158:112972. https://doi.org/10.1016/j.indcrop.2020.112972

48. Market Research Future. Global sandalwood oil market analysis and forecast; 2023. Retrieved from: https://www.marketresearchfuture.com/reports/sandalwood-oil-market-1234

49. Eternity insights. Sandalwood: An ancient resource with modern applications; 2020. Retrieved from: https://www.eternityinsights.com/sandalwood

50. World wildlife fund. Biodiversity and ethical sourcing in sandalwood markets; 2021. Retrieved from: https://www.worldwildlife.org/sandalwood-sourcing

51. Global Sandalwood Alliance. Sandalwood sustainability: Best practices for cultivation; 2021. Retrieved from: https://www.globalsandalwoodalliance.org

52. Tonts M, Selwood J. Niche markets, regional diversification and the reinvention of western Australia's sandalwood industry. Tijdschr Econ Soc Geogr. 2003;94(5):564-75. https://doi.org/10.1046/j.1467-9663.2003.00283.x

53. Samarasekera S, Subasinghe S, Hettiarachchi D. *Santalum album* L. (Indian sandalwood) oil content variation of Welimada region, Sri Lanka. In Proceedings: 17th International Forestry and Environment Symposium; 2012.

54. Dev SA, Muralidharan EM, Sujanapal P, Balasundaran M. Identification of market adulterants in East Indian sandalwood using DNA barcoding. Ann For Sci. 2013;71(4):517-22. https://doi.org/10.1007/s13595-013-0354-0

55. Kushalapa KA. Trade liberalisation in sandalwood. Indian For. 1999;125(8):891-94.

56. Misra B, Dey S. Culture of East Indian sandalwood tree somatic embryos in air-lift bioreactors for production of santalols, phenolics and arabinogalactan proteins. AoB Plants. 2013;5:plt025. https://doi.org/10.1093/aobpla/plt025

57. Shanbhag R. Population dynamics of the striped mealy bug *Ferrisia virgata* (Cockerell) (Hemiptera, Pseudococcidae) and the scope of its biological suppression in the present scenario of cultivation of Indian sandalwood. Agri Res Tech Open Access J. 2017;11(1):555808. https://doi.org/10.19080/ARTOAJ.2017.11.555808

58. Kuniyal CP, Kuniyal PC, Butola J, Sundriyal RC. Trends in the marketing of some important medicinal plants in Uttarakhand, India. Int J Biodivers Sci Ecosyst Serv Manag. 2013;9:324-29. https://doi.org/10.1080/21513732.2013.819531

59. Ramachandran S, Kirdat K, Mondal S, Reddy MK, Thorat V, Raja R. A threat to sandalwood cultivation in the naturalised Marayoors sandalwood reserve (Kerala, India) through single and mixed phytoplasma infections. Phytopathogenic Mollicutes. 2020;10(2):89-95. https://doi.org/10.5958/2249-4677.2020.00011.0

60. Thomson L. Looking ahead - global sandalwood production and markets in 2040 and implications for Pacific Island producers. Aust For. 2020;83:245-54. https://doi.org/10.1080/00049158.2020.1841441

61. Volza. Sandalwood market analysis and trends; 2023. Retrieved from: https://www.volza.com

62. Sundararaj R, Mondal S, Kanthareddy M. Pruning effects on the health of Indian sandalwood (*Santalum album* Linn) in agroforestry conditions of South India. Am J Plant Biol. 2019;4(1). https://doi.org/10.11648/j.ajpb.20190401.11

63. Doble J. Sandalwood - growing industry for northern Australia. The Official Journal of Irrigation Australia. 2013;29:16-17. https://doi.org/abs/10.3316/INFORMIT.306831693723655

64. Srikantaprasad D, Gowda A, Pushpa T, Umesha K. Natural regeneration of flora in cultivated sandalwood. Int J Agric Sci. 2021;17(2):544-47. https://doi.org/10.15740/HAS/IJAS/17.2/544-547

65. Chattopadhyay A. A study of aromatic woods in seventeenth-c India: circulation of aloewood and sandalwood through facilitating port cities and trade. Crossroads. 2022;20(1-2):76-117.

66. Bisht SS, Ravindra M, Gayathri D. Variability in yield and composition of oil from Indian sandalwood (*Santalum album* L.) trees grown in homogeneous conditions. Trop Plant Res. 2019:6(1):31-36. https://doi.org/10.22271/tpr.2019.v6.i1.006

67. Debta H, Kunhamu T, Petrík P, Fleischer P, Jisha K. Effect of hydropriming and osmopriming on the germination and seedling vigor of the East Indian sandalwood (*Santalum album* L.). Forests. 2023;14(6):1076. https://doi.org/10.3390/f14061076

68. Liu X, Xu D, Yang Z, Zhang N, Pan L. Investigation of exogenous benzyladenine on growth, biochemical bomposition, photosynthesis and antioxidant activity of Indian sandalwood (*Santalum album* L.) seedlings. J Plant Growth Regul. 2018;37 (4):1148-58.

69. Yadav RK, Mukhopadhyay S, Tah J. A short review on white sandalwood (*Santalum album* L.). Int J Sci Res Rev. 2019;8(4):73-136. https://doi.org/10.37794/ijsrr.2019.8408

70. Shanbhag R, Sundararaj R, Lingappa B. Population dynamics of the striped mealy bug *Ferrisia virgata* (Cockerell) (Hemiptera, Pseudococcidae) and the scope of its biological suppression in the present scenario of sultivation of Indian sandalwood. Acta Sci Agric. 2017;11(2):45-50. https://doi.org/10.19080/ARTOAJ.2017.11.555808