E-ISSN: 2618-0618
P-ISSN: 2618-060X

NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(11): 426-429
Received: 05-10-2025
Accepted: 08-11-2025

Chethan BL
Ph.D. Scholar, Department of Silviculture and Agroforestry, College of Forestry, Sirsi, Karnataka, India

Ramesh S Rathod
Associate Professor, Department of Silviculture and Agroforestry, College of Forestry, Sirsi, Karnataka, India

BG Nayak
Associate Professor and Head, Department of Silviculture and Agroforestry, College of Forestry, Ponnampet, University of Agricultural Sciences, Mandya, Karnataka, India

Raju L Chavan
Professor and Head, Department of Environmental sciences, College of Agriculture, University of Agricultural Sciences, Dharwad, Karnataka, India

Venkatesh L
Assistant Professor, Department of Silviculture and Agroforestry, College of Forestry, Sirsi, University of Agricultural Sciences, Dharwad, Karnataka, India

Corresponding Author:
Chethan BL
Ph.D. Scholar, Department of Silviculture and Agroforestry, College of Forestry, Sirsi, Karnataka, India

Scented innovations by advanced technologies in *Santalum album* Linn.f plantation: A review

Chethan BL, Ramesh S Rathod, BG Nayak, Raju L Chavan and Venkatesh L

DOI: https://www.doi.org/10.33545/2618060X.2025.v8.i11Sf.4295

Abstract
Sandalwood (*Santalum album* L.), popularly known as the "green gold of India," is one of the most valued tree species owing to its fragrant heartwood and essential oil with diverse cultural, medicinal, and economic applications. However, its cultivation has been constrained by slow growth, poor germination, host dependency, susceptibility to spike disease, illegal felling, and regulatory challenges. Recent advances in biotechnology, diagnostic tools, and digital monitoring systems have introduced innovative solutions to address these constraints. This review synthesizes developments in tissue culture and clonal propagation for quality planting material, electric resistance tomography for non-destructive heartwood assessment, gas elicitor treatments for accelerated heartwood formation, molecular diagnostics for early detection of Sandalwood Spike Disease, and biopriming for enhanced germination and seedling vigor. Additionally, IoT-enabled protection technologies such as Bluetooth sensors and microchip-based systems have emerged as effective measures against theft. The merits of these innovations lie in their ability to improve productivity, sustainability, and profitability, while challenges include high costs, technical complexity, and limited accessibility for small-scale farmers. By integrating traditional silvicultural knowledge with modern scientific advancements, these technologies offer a roadmap for sustainable sandalwood production, conservation of genetic resources, and enhanced economic returns. The study underscores the transformative role of innovation in revitalizing sandalwood cultivation and ensuring its long-term ecological and commercial viability.

Keywords: *Santalum album*, biotechnology, heartwood induction, disease management, biopriming, electric resistance tomography, IoT protection

Introduction
Sandalwood (*Santalum album L.*), often referred to as the "green gold of India," is a small evergreen hemi-parasitic tree belonging to the family *Santalaceae.* Valued for its fragrant heartwood and essential oil, sandalwood has held cultural, medicinal, and economic significance for centuries (Srinivasan *et al*., 1992) [9]. However, its cultivation faces numerous constraints, including a long gestation period, host dependency, susceptibility to spike disease, illegal felling, and stringent regulatory frameworks (Warrier *et al*., 2020) [10].

In response, recent years have witnessed rapid technological interventions in cultivation, disease management, processing, and protection of sandalwood resources. This review synthesizes innovations such as tissue culture, gas elicitor technology, electric resistance tomography, microchip-based security, and biopriming techniques. The article emphasizes the merits, challenges, and future perspectives of integrating modern science with traditional practices for sustainable sandalwood production.

Critically appraising
Cultivation Technologies
Conventional propagation methods of sandalwood suffer from low seed germination (20-30%) and variability in growth. Tissue culture and clonal propagation techniques (Annapurna *et al*., 2006) [1] have emerged as promising solutions to produce genetically superior planting material with uniform traits.

Host compatibility studies using biotechnology have further improved the survival and productivity of plantations (Lu *et al*., 2014) [6].

Monitoring and Assessment

Non-destructive diagnostic tools such as Electric Resistance Tomography (ERT) provide insights into internal wood formation without harming the tree (Divakara & Singh, 2025) [3]. ERT allows estimation of heartwood volume and detection of decay or disease, offering a significant advancement over destructive coring methods.

Heartwood Induction

Heartwood formation, the most valuable part of sandalwood, usually takes more than 10-15 years. Recent studies using gas elicitors such as CO_2, N_2, and ethylene have accelerated the initiation of heartwood and improved oil content (Liu *et al*., 2022) [5]. Notably, CO_2 treatment produced oil that met ISO standards, indicating its commercial potential.

Disease Management

Sandalwood Spike Disease (SSD), caused by phytoplasma, remains the most serious threat to plantations (Mondal *et al*., 2020) [7]. Advances in molecular diagnostics such as PCR, nested PCR, and microarray-based detection have enabled early identification of infected trees. Tissue culture and genetic modification strategies are being explored for resistance breeding.

Seed and Seedling Enhancement

Biopriming with plant growth-promoting bacteria like *Pseudomonas fluorescens* has significantly enhanced germination (up to 88%), reduced germination time, and improved seedling vigor (Chitra & Jijeesh, 2021) [2]. This innovation addresses one of the major bottlenecks in sandalwood cultivation.

Security and Protection

Given the high value of sandalwood, theft and illegal logging are persistent problems. IoT-enabled protection systems using Bluetooth 4.0 sensors (Hebbar *et al*., 2015) [4] and microchip-based e-protection systems (Soundararajan & Ravi Kumar, 2021) [8] have provided real-time monitoring and alerts, safeguarding plantations.

Sandalwood cultivation and management have undergone significant transformation in recent decades, largely due to the integration of scientific research and technological innovation. Earlier, the species was primarily managed through traditional silvicultural practices, which often proved inadequate to address the biological challenges of low germination, parasitic dependency, and long maturation cycles. Today, innovations in biotechnology, diagnostics, heartwood induction, and digital monitoring have introduced a new era of precision forestry for sandalwood. A detailed review of these technologies highlights how each intervention contributes to overcoming specific constraints in the sandalwood production chain.

In the area of propagation and nursery management, the adoption of tissue culture and clonal propagation represents one of the most significant milestones. Traditionally, sandalwood has been propagated through seeds, but germination is often erratic, with success rates hovering around 20-30 percent. Moreover, genetic variability in seed-based propagation has led to inconsistent growth and yield outcomes. Tissue culture techniques allow for the mass multiplication of elite genotypes, ensuring genetic uniformity, superior growth performance, and higher oil content. Studies have shown that tissue-cultured seedlings not only establish better but also adapt more effectively when paired with suitable host plants. Clonal propagation has further accelerated the production of quality planting material, making it possible for farmers to access improved genotypes on a commercial scale.

Non-destructive monitoring technologies have also added a new dimension to sandalwood management. The Electric Resistance Tomograph (ERT) has been particularly revolutionary, offering a reliable method for detecting heartwood formation and diagnosing internal defects without harming the tree. Traditional core sampling often weakened the tree and increased its susceptibility to infections. In contrast, ERT uses electrical resistivity patterns to differentiate between sapwood, heartwood, and decayed tissues. Comparative studies have shown that ERT can achieve over 85 percent similarity with actual core measurements, proving its effectiveness as a diagnostic tool. Its application is particularly important for farmers and industries that require accurate assessment of harvest readiness, thereby optimizing economic returns without endangering standing trees.

Another critical advancement is the induction of heartwood using gas elicitors. Natural heartwood formation in sandalwood typically occurs only after a decade or more, delaying economic returns. Experimental studies involving gases such as carbon dioxide, nitrogen, and ethylene have demonstrated the possibility of artificially inducing heartwood formation in young trees as early as six years old. Carbon dioxide treatment has emerged as the most promising, as the heartwood formed not only resembled natural wood in color and density but also produced oil that met ISO standards for commercial trade. This technology has the potential to drastically shorten the production cycle and enhance profitability, though its long-term ecological implications are still being studied.

Disease management, particularly with respect to Sandalwood Spike Disease (SSD), continues to be a priority area. SSD, caused by phytoplasmas and transmitted by insect vectors, can devastate plantations, leading to complete mortality of infected trees. Traditional detection relied on visible symptoms such as leaf chlorosis, stunted growth, and spike-like foliage, which often appeared too late for effective intervention. The advent of molecular diagnostics, including PCR, nested PCR, and microarray-based assays, has made early detection possible, enabling timely removal of infected plants and reducing the spread of disease. Moreover, tissue culture techniques are now being employed to generate disease-free clones, and genetic modification holds potential for breeding resistant varieties. These innovations collectively represent a more scientific and proactive approach to disease management in sandalwood.

Equally significant are developments in seed and seedling enhancement. Poor germination and weak seedling vigor have long restricted plantation establishment. Biopriming, a method of treating seeds with beneficial microorganisms such as *Pseudomonas fluorescens*, has shown remarkable improvements in germination rates, vigor, and early growth. Germination percentages have been reported to increase from less than 50 percent in untreated seeds to nearly 90 percent in bioprimed ones, with the germination period reduced by several weeks. Beyond germination, biopriming also enhances nutrient uptake and disease resistance, resulting in stronger, healthier seedlings better equipped to thrive in field conditions. This innovation is particularly valuable for smallholder farmers who require affordable yet effective methods to establish plantations.

Finally, the challenge of protecting high-value sandalwood trees from theft has led to the development of digital security systems. Bluetooth 4.0-enabled devices, characterized by low energy consumption and reliable connectivity, have been deployed to provide real-time alerts during attempts at illegal felling. Similarly, microchip-based e-protection systems integrated with wireless sensor networks and mobile applications offer real-time monitoring of plantations. These devices, camouflaged within trees, detect disturbances and immediately alert forest departments or growers, drastically reducing the risk of theft. Such innovations not only secure the economic investment of growers but also protect national resources from illegal trade and exploitation.

Taken together, these technological advancements demonstrate the diverse and multi-dimensional nature of research on sandalwood. From improving genetic quality and accelerating heartwood formation to strengthening disease management and enhancing plantation security, each innovation addresses a critical gap in the production cycle. While these technologies have shown great promise, their large-scale adoption will depend on cost-effectiveness, accessibility, and long-term sustainability. The detailed review thus underscores the transformative potential of science and technology in revitalizing sandalwood cultivation, ensuring that it remains both economically viable and ecologically sustainable.

Table 1: Technological Innovations in Sandalwood production

Domain	Innovation	Key Outcomes	Reference
Propagation & Cultivation	Tissue culture, Clonal propagation, Host optimization	High-quality planting stock, uniform growth, improved survival	Annapurna *et al*. (2006) [1]; Lu *et al*. (2014) [6]
Monitoring & Assessment	Electric Resistance Tomography (ERT)	Non-destructive heartwood & decay detection, ~85% accuracy	Divakara & Singh (2025) [3]
Heartwood Induction	Gas elicitors (CO_2, N_2, Ethylene)	Early heartwood formation (as early as 6 yrs), ISO-standard oil yield	Liu *et al*. (2022) [5]
Disease Management	PCR, nested PCR, microarray diagnostics; resistant genotypes	Early SSD detection, disease-free clones, resistance potential	Mondal *et al*. (2020) [7]
Seed & Seedling Improvement	Biopriming with *Pseudomonas fluorescens*	Germination ↑ from 30-50% to ~88-90%, improved seedling vigor	Chitra & Jijeesh (2021) [2]
Security & Protection	IoT-based Bluetooth sensors, Microchip e-protection	Real-time theft alerts, plantation monitoring	Hebbar *et al*. (2015) [4]; Soundararajan & Ravi Kumar (2021) [8]

Merits and Demerits of Innovations

Merits

- **Sustainability:** Non-destructive diagnostics and biopriming reduce ecological damage.
- **Efficiency:** Faster heartwood induction and improved seed germination reduce plantation cycles.
- **Economic Benefits:** Secure plantations and improved oil yield enhance farmer income.
- **Conservation:** Advanced techniques ensure genetic conservation and sustainable utilization.
- **Scalability:** Many technologies (e.g., microchip security, gas induction) can be applied in large plantations.

Demerits:

- **High Initial Cost:** Tissue culture labs, microchip systems, and gas treatments require significant investment.
- **Technical Complexity:** Skilled manpower and infrastructure are essential for adoption.
- **Uncertain Long-Term Impact:** Some innovations (e.g., gas induction) lack long-term ecological validation.
- **Regulatory Challenges:** Policies governing sandalwood trade may hinder technology transfer.
- **Accessibility:** Small-scale farmers may find technologies unaffordable without government subsidies.

Feature Line of Work

The reviewed technologies can be categorized into five domains:

1. **Propagation and Cultivation:** Tissue culture, clonal propagation, host optimization.
2. **Heartwood Enhancement:** Gas elicitors to induce early and quality heartwood.
3. **Disease Diagnostics and Resistance:** Advanced molecular tools for SSD detection and disease-resistant genotypes.
4. **Seed and Seedling Improvement:** Biopriming with beneficial microbes.
5. **Protection Technologies:** IoT-based microchips, Bluetooth-enabled alarms, and surveillance systems.

These feature lines indicate a paradigm shift from conventional silvicultural practices toward precision forestry and biotechnology-driven management.

Conclusion

Technological innovations are revolutionizing sandalwood cultivation and protection by addressing long-standing challenges such as poor germination, heartwood formation, disease outbreaks, and theft. While techniques like tissue culture, ERT, and biopriming promise sustainable and profitable outcomes, integration with IoT-based protection ensures the security of high-value plantations. However, scalability and affordability remain significant barriers. To realize the full potential of these technologies, collaborative efforts between researchers, government agencies, and local communities are vital. A balanced approach combining traditional silvicultural wisdom with modern innovations will ensure the sustainability and prosperity of sandalwood cultivation in the future.

References

1. Annapurna D, Rathore TS, Joshi G. Modern nursery practices in the production of quality seedlings of Indian sandalwood (*Santalum album* L.). Journal of Sustainable Forestry. 2006;22(3):33-55.
2. Chitra P, Jijeesh CM. Biopriming of seeds with plant growth promoting bacteria *Pseudomonas fluorescens* for better germination and seedling vigour of East Indian sandalwood. New Forests. 2021;52(5):829-841.
3. Divakara B, Singh MP. Application of electric resistance tomograph: innovative non-destructive method in analysing

interiors of standing trees. Canadian Journal of Forest Research. 2025;23(1):1-33.
4. Hebbar S, Pattar P, Madli R, Golla V. Sandalwood tree protection using Bluetooth 4.0. In: International Conference on Computing and Network Communication; 2015; Trivandrum, India.
5. Liu X, Zhang Q, Hong Z, Xu D. Induction of heartwood formation in young Indian sandalwood by gas elicitors. Frontiers in Plant Science. 2022;13:1-16.
6. Lu JK, Xu DP, Kang LH, He X. Host-species-dependent physiological characteristics of hemiparasite *Santalum album* in association with N_2-fixing and non-N_2-fixing hosts native to southern China. Tree Physiology. 2014;34(9):1-17.
7. Mondal S, Sundararaj R, Rao HCY. Recurrence of sandalwood spike disease and its management practices. Forest Pathology. 2020;50(6):12648.
8. Soundararajan V, Ravi Kumar G. E-protection system for valuable sandalwood trees. Wood is Good. 2021;2(2):101-104.
9. Srinivasan VV, Sivaramakrishnan VR, Rangaswamy CR, Ananthapadmanabha HS, Shankaranarayana KH. Sandal (*Santalum album* L.). Dehra Dun: Indian Council of Forestry Research and Education (ICFRE); 1992.
10. Warrier RR, Geetha S, Sivakumar V, Singh BG, Anandalakshmi R. Threatened tree species of the Western Ghats: status, diversity, and conservation. In: Rajasekharan PE, Wani SH, editors. Conservation and Utilization of Threatened Medicinal Plants. Cham: Springer; 2020. p. 429-460.