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REVIEW ARTICLE

Evaluating the effectiveness of teak tissue culture in *ex situ* conservation, with a focus on its practical implementation and challenges in commercial forestry

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Abstract

Plant tissue culture is an important tool in forestry and biotechnology with its substantial improvements in plant propagation. The development of tissue culture is started with Haberlandt's totipotency theory and the mid-20th century discovery of plant growth regulators which transformed methods of plant multiplication. The utilization of tissue culture in the micropropagation of teak (*Tectona grandis* L.) is a valuable hardwood species used for building, furniture and lumber. Through the production of genetically identical seedlings with desired characteristics including disease resistance, rapid development and high wood density. Tissue culture overcomes the drawbacks of traditional teak propagation which includes low germination rates, pest susceptibility and slow growth. This method supports conservation and sustainable forestry practices by providing a few benefits such as disease-free plant production, quick multiplication and year-round availability. Highly expensive, somaclonal fluctuation, contamination dangers and acclimatization hurdles are still major drawbacks. The importance of tissue culture in genetic improvement which allows for the preservation of elite genotypes and the creation of faster-growing, pest-resistant teak varieties is also examined in the research. Tissue culture is still a vital technique for large-scale teak production, reforestation and biodiversity protection despite its difficulties. It provides a revolutionary approach to commercial forestry and environmental sustainability.

Keywords: acclimatization; genetic uniformity; reforestation; somaclonal variation; teak micropropagation

Introduction

Gottlieb Haberlandt's 1902 "Totipotency Theory" termed as the foundation for the early 20th century's introduction of plant tissue culture. He proposed that under the correct circumstances plant cells may develop into full-fledged plants. Due to technical obstacles such inadequate sterilization techniques and a shortage of appropriate nutrition media early development was difficult. However, major breakthroughs were made in the mid-20th century by the discovery of plant growth regulators like auxins and cytokinins which made plant tissue culture is a vital biotechnology tool. Since then Horticulture, Forestry, Plant breeding and Agriculture have all made extensive use of this method (1). Growing teak (*Tectona grandis* L.), a premium hardwood prized for its strength, durability and decay resistance, is one significant use of tissue culture. Teak is mainly utilized for construction, furniture and shipbuilding (2). Due to conservation initiatives as well as commercial demand its cultivation has spread throughout Southeast Asia and Africa (3). In India where commercial plantations and reforestation are expanding quickly tissue culture helps to maintain the genetic characteristics of teak to satisfy the growing demand for seedlings (4). Since natural forests are being overharvested due to the rising demand for teak worldwide proper management is crucial. Low germination rates, susceptibility to pests and diseases and poor roots in older cuttings are some of the issues that plague traditional propagation techniques such as growing teak from seeds or cuttings (5). A tissue culture method called micropropagation provides an answer by making it possible to produce many superior genetically identical seedlings (6). It also overcomes obstacles including woody plants, complicated anatomy and decreased growth activity (7). Tree species that are rare, endangered, or commercially significant can also be conserved using micropropagation (8). It contributes to the advancement of teak propagation techniques guaranteeing a consistent flow of superior planting material for long-term output (9). Acclimatization is a crucial stage in which plants cultivated in sterile laboratory settings are progressively acclimated to ambient circumstances such as fluctuating soil, humidity and temperature (10). Their development and survival in forests are guaranteed by this process. The finest genetic qualities of teak like high wood density, disease resistance and quicker growth rates can be preserved through micropropagation (11). Although species specific characteristics and slower growth make tissue culture for conifers more difficult (12), the technology offers a dependable substitute that lessens the strain on natural forests (13). By using techniques like cryopreservation, it also helps to conserve rare and endangered species (14).

Advantages

Rapid multiplication

Tissue culture greatly speeds up plantation efforts by making it possible to produce teak clones on a wide scale quickly from a small amount of starting plant material (9). The rate of multiplication has increased due to new technologies making it possible to efficiently grow thousands of teak clones (4). Optimizing elements like gelling agents and light sources which significantly increase the development rates of *in vitro* plantlets results in faster production cycles (6). Techniques utilizing stem cuttings, leaves and roots provide versatility in tissue culture applications contingent on the plant species and available resources (15). This method reduces the dependency on natural forests and promotes reforestation efforts by offering a constant supply of high-quality planting material (16). Faster plantlet production is possible by the development of advanced procedures that have highly increased the effectiveness of shoot regeneration from a variety of explant sources (17). Compared to conventional propagation techniques tissue culture allows for the quick creation of genetically identical teak plants significantly boosting reforestation and plantation operations (18). Mass production of teak plants is made possible using plant growth regulators (PGRs) in tissue culture which is essential for accelerating shoot proliferation (2). Numerous clones can be produced quickly using modified techniques that maximize shoot proliferation rates (19). Cytokinins are known to encourage shoot development, increasing the number of shoots per explant and speeding up the multiplication process (20).

Genetic uniformity and stability

Each cloned plant has the required traits such as growth rate, wood quality and resistance to insects and diseases and is genetically identical to the original plant micropropagation (18). This technique assures stability in growth patterns, timber quality and other important characteristics by maintaining the genetic integrity of the original plant (21). The technique guarantees that every plant that is propagated retains the genetic traits of its parent resulting in uniform growth patterns, flower traits and therapeutic properties (22). By assuring that every clone has the same traits as growth patterns and wood quality, the application of optimal cytokinin levels during micropropagation further enhances genetic consistency (20). This clonal propagation technique is essential for maintaining the genetic integrity of the parent plants and producing consistently high-quality timber which is needed for both commercial forestry and conservation programs.

Disease-free plants

A crucial step in the tissue culture process is the rooting and acclimatization of teak plantlets to soil conditions is improved protocols in micropropagation have significantly improved the success rates of these steps compared to earlier methods ensuring robust establishment and growth of teak plants in natural environments (4). As meristematic tissues are actively dividing and lack the vascular connections that typically carry viruses and pathogens tissue culture uses them to produce disease-free plants ensuring healthier plant stock for plantations (9).

Year-round production

Unlike traditional approaches that depend on the yearly availability of seed tissue culture allows for year-round plant development that is not influenced by seasonal fluctuations (12). By overcoming the obstacles related to seed collecting and germination this method offers forestry operations a steady and dependable supply of planting material (18). Tissue culture assures constant propagation for teak cultivation which is a clear benefit over conventional seed-based methods where variations in germination rates and seed availability might be problematic (21) in Fig. 1.

Improved efficiency

Large-scale commercial applications the tissue culture approach is essential since it greatly increases the pace at which teak plantlets multiply allowing for the development of more plants in a shorter amount of time (4). For forestry nurseries it is a highly scalable method of mass propagation because a single explant can yield thousands of plantlets (9). By making the method more appropriate for commercial nurseries and forestry operations its scalability and efficiency help to meet the increasing demand for teak (23). By employing strong sterilizing chemicals such as mercuric chloride to reduce microbial contamination and increase micropropagation efficiency the method also increases the effectiveness of *in vitro* explant establishment (24). This development improves the tissue culture process overall efficacy and shortens the time needed to generate healthy plantlets (25). Micro propagated plants that are gradually acclimated to their natural environment acquire useful root systems and adaptable characteristics that are necessary for field survival (10). In addition, explant released phenolic compounds are adsorbent by activated charcoal in the medium which prevents tissue growth inhibition and enhances shoot development (24). This approach has larger scientific and practical applications for the investigation of cellular differentiation, organogenesis and totipotency in monocots (26). For both commercial and conservation uses this all-encompassing strategy guarantees the effective and dependable production of teak plantlets in Fig. 2.

Reduced soma clonal variation

Micropropagation techniques minimize the soma clonal variation or genetic modifications during the culture phase ensuring that emergent plantlets remain genetically stable and similar to the parent genotype (4). This improved procedure protects clones' genetic integrity which is essential for preserving the desired characteristics of elite teak genotypes like resistance to disease, excellent wood quality and steady growth patterns (19). Micro propagation technique is an essential tool for commercial forestry applications and large-scale propagation because it prioritizes genetic fidelity which guarantees that clonal propagation consistently yields

Fig. 1. *In vitro* culture of teak.

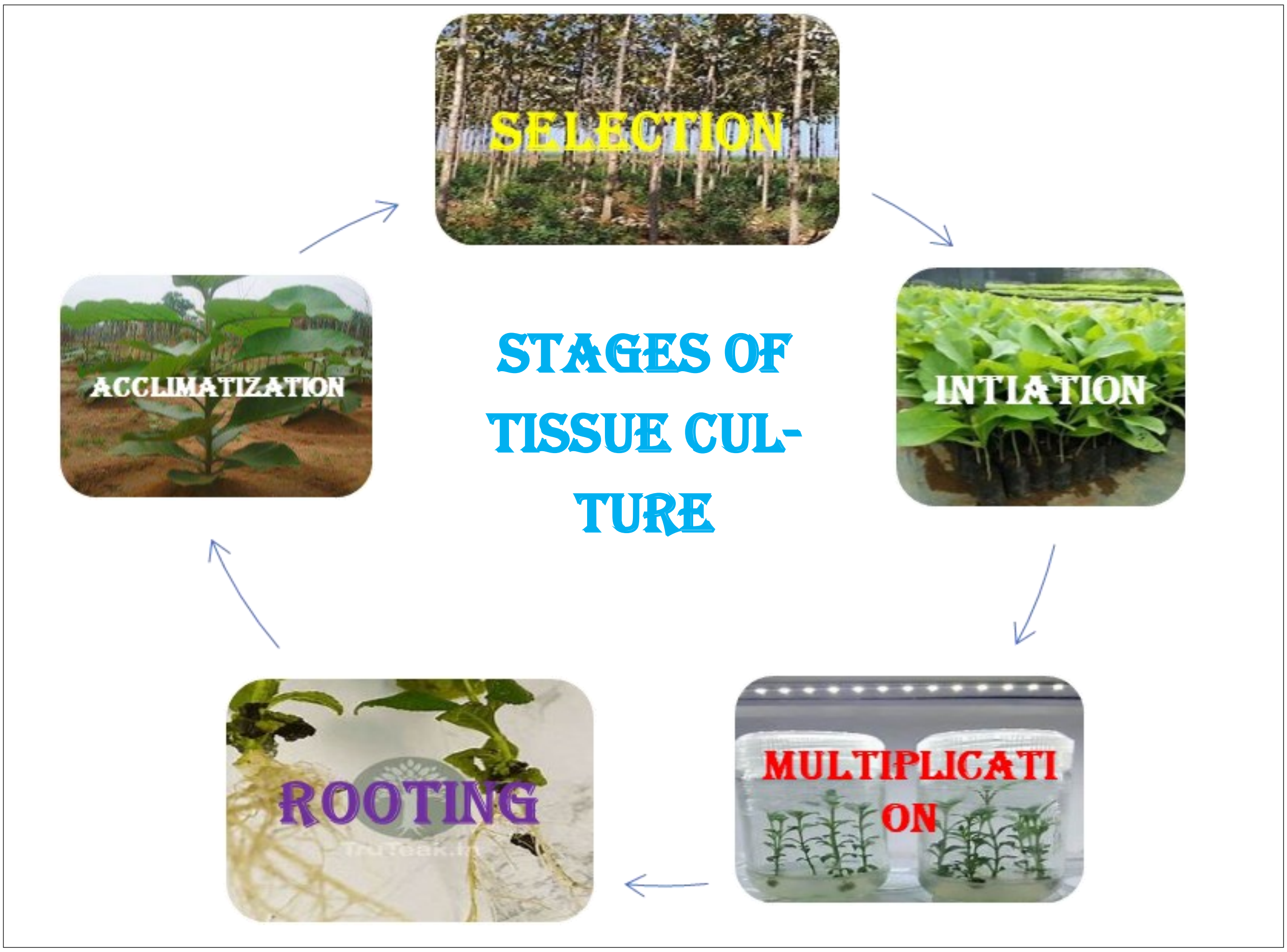

Fig. 2. Stages of tissue culture.

plantlets that preserve the desirable traits of the parent tree (23).

Improved rooting and acclimatization

By improving success rates in roots and acclimatization two crucial phases when plantlets frequently encounter difficulties in tissue culture the technique provides a notable benefit. When plantlets are transferred to soil the enhanced method guarantees greater survival rates, reducing losses and increasing overall effectiveness (19). Research indicates that the use of hormones such as IAA and IBA is essential for rooting success. Hormonal therapies have the potential to improve propagation outcomes. For example, cuttings treated with IBA (0.8 %) had a 76 % rooted success rate when compared to untreated controls (27). A crucial stage in the tissue culture process moving plantlets to field settings has become much more successful to this protocol advancement in rooting and plantlet acclimatization (7). Vegetative propagation, especially in controlled conditions (such as greenhouses or mist chambers) facilitates the acclimatization process. Plants grown via stem cuttings, leaves and roots can grow in perfect condition, reducing stress during the early phases of development (15).

By maximizing root induction rates and quality improved *in vitro* rooting techniques tackle major hurdles in teak tissue culture (16). Plantlet mortality is further decreased by better aftercare practices and optimal climatic conditions during acclimatization which gives robust development in natural environments and increases process efficiency overall (6). It has been demonstrated that using composite treatments that include thiamine and auxins like IBA improves the success of rooting in teak cuttings. For teak plants to successfully establish in the field these treatments not only raise the proportion of rooting but also encourage stronger healthier root systems (28). This development offers a dependable method to enable large scale teak growth by addressing one of the major obstacles in vegetative propagation (29) in Table 1.

Disadvantages

Initial costs and investment

The establishment of the specialized facilities and equipment needed for the method can highly increase the production costs even if tissue culture has many benefits for teak propagation (9). When compared to more conventional methods like seed sowing micropropagation is still somewhat costly since it requires sterile settings, regulated growth conditions and skilled workers, despite continuous advancements (2). Another level of intricacy that may not be possible in all nursery setups is the precise regulation of auxin concentrations and branch placement which are essential for efficient propagation (28). The procedure is less feasible for small scale or low-budget operations due to the high setup and maintenance expenses of tissue culture facilities including specialized laboratories and growth chambers (19). These expenditures, which are especially for small forestry projects or areas with limited resources involve not only the initial equipment investment but also the continuing expenses of maintaining sterile surroundings and hiring skilled people (23). Further increasing labor costs and operational complexity are methods like the isolation and propagation of epicormic buds which call for careful handling and specialized knowledge. The method's cost needs are exacerbated by its dependence on plant growth regulators (PGRs) growth chambers and continual monitoring which restricts its applicability in smaller nurseries or developing regions (6). In contrast to conventional seedling nurseries or vegetative propagation techniques tissue culture still requires large upfront investments despite developments that increase economic viability (25). These financial limitations highlight the necessity for additional optimization to make the procedure more affordable and accessible (2).

Soma clonal variation

Soma clonal variation, genetic or epigenetic changes that take place during the process remains a possible disadvantage even if tissue culture is intended to accomplish clonal replication (9). The dependability of clonal propagation may be impacted by these variances which may lead to unfavorable changes in important qualities such as growth rate, wood quality or disease resistance (18). For large-scale forestry operations where uniformity is crucial prolonged *in vitro* culture might make this problem worse by producing genetic and phenotypic variants that differ from the parent genotype (21). Genetic instability can result from the dedifferentiation process which makes callus culture especially vulnerable to causing soma clonal variation. However, in terms of maintaining genetic integrity shoot culture techniques are typically more dependable (30). Even shoot culture, however, is susceptible to genetic or epigenetic alterations which can be brought on by a number of things including stresses from the artificial environment of tissue culture changes in hormone levels or extended culture length (31). Gene and protein expression may change under the artificial conditions of *in vitro* settings which could result in phenotypic irregularities in regenerated plants (32). Even though these variants may not occur frequently it is difficult to reliably generate plantlets that preserve every desirable characteristic of the parent genotype due to their

Table 1. Improved rooting and acclimatization.

S.No	Aspect	Details
1	Improved Success in Rooting and Acclimatization	Enhanced tissue culture techniques lead to better rooting and acclimatization, increasing plantlet survival rates
2	Role of Hormones	Hormones like IAA and IBA are essential for rooting success. Example: IBA (0.8 %) yielded 76 % rooted cuttings compared to untreated controls
3	Tissue Culture Process	Advancements in rooting and acclimatization protocols improve plantlet transfer to field settings
4	Vegetative Propagation	Controlled conditions, such as greenhouses or mist chambers, reduce stress during early development stages
5	*In Vitro* Rooting Techniques	Maximized root induction rates and quality tackle challenges in teak tissue culture
6	Aftercare Practices	Optimal climatic conditions during acclimatization decrease plantlet mortality and enhance development
7	Composite Treatments	Thiamine and auxins (e.g., IBA) improve rooting success and foster stronger, healthier root systems
8	Implications for Large-Scale Growth	These advancements support reliable large-scale teak propagation by addressing vegetative propagation challenges

random nature (33). To combat this protocols, place a strong emphasis on reducing the length of culture and improving conditions to lessen the possibility of soma clonal variation protecting the genetic integrity of elite genotypes. To preserve uniformity and the high standards needed for commercial forestry operations these steps are essential (23).

Contamination risk

In tissue culture microbial contamination by bacteria, fungus or other pathogens is a main problem that causes serious dangers to the propagation process success (9). Contamination is still a major worry despite improvements in sterilization techniques since it can harm entire batches of cultures and cause large plantlet losses (4). Maintaining strict sterile conditions always is essential because any deviation could compromise the culture's integrity and reduce productivity (18). The vulnerability of tissue culture to microbial incursion demands careful attention to sterility at every stage even with advancements in methods. In addition to endangering plantlets, survival contamination raises expenses because it takes more work and money to restore, or restart impacted cultures (19). Effective sterilization techniques that lessen this risk must include the use of potent antimicrobial agents, air filtering systems and aseptic handling. However, even tiny mistakes can have far-reaching repercussions underlining the ongoing need for strict attention to detail and stringent adherence to sterilizing measures in tissue culture processes (21).

Limited applicability to field conditions

Even with enhanced acclimatization procedures micro propagated teak plantlets may encounter difficulties when adjusting to field settings. Careful handling is necessary during this crucial stage since environmental stressors can have a substantial impact on survival rates if they are introduced too soon (4). Although improvements have improved the success of acclimatization the wide applicability of tissue culture techniques is limited since various plant species frequently require distinct protocols (34). Variability in plantlet performance may result from environmental factors such soil composition and climate that affect the quantities of bioactive compounds in plantlets (13). For tissue-cultured plantlets, the shift from controlled laboratory settings to field settings frequently presents challenges. If this phase is not carefully handled, transplant shock or environmental stress may cause significant losses (18). Large-scale applications are made more difficult by the fact that many woody species, particularly gymnosperms, show some resistance to tissue culture and genetic transformation (35). When plantlets are exposed to outside environments, careful management is still necessary to minimize losses, even though current techniques have increased acclimatization success (19).

Application

Commercial teak production

Tissue culture in teak is primarily used for commercial timber production on a big scale taking advantage of the ability to quickly generate genetically identical high-quality trees (9). This technology helps to teak a very valuable hardwood by facilitating rapid multiplication for forestry use and guaranteeing a regular supply of trees with similar features such wood density and grain pattern which are crucial for the timber sector (36). This technique is especially crucial for the commercial wood sector where there is a growing need for teak's strength, beauty and insect resistance (37). Establishing teak plantations more effectively with the use of advanced tissue culture methods can help mitigate climate change by sequestering carbon in biomass and soils in addition to providing timber (36). Improved micropropagation methods guarantee that the supply of premium teak which is highly valued worldwide can meet market demands (19). This is especially crucial for the commercial forestry sector because it helps to assure a steady supply of wood for furniture and other wood-based industries by quickly multiplying elite genotypes with desired qualities like strength, pest resistance and superior wood quality (25). By increasing the quantity of genetically homogeneous plantlets available for plantations the research presented in this paper answers the high demand for teak timber by offering an optimized technique for large-scale teak plantlet propagation (21). This technology improves the tissue culture methods dependability and affordability while assuring effective generation of teak plantlets fit for commercial forestry (6). Further satisfying the rising demand for premium teak wood is the use of plant growth regulators (PGRs) in the propagation process which dramatically speeds up rates of multiplication (2). The global teak timber business is growing sustainably thanks to these optimizations which make the method extremely useful for large scale teak plantations (20) in Table 2.

Research and genetic improvement

These developments in tissue culture techniques provide a strong basis for future research into teak biotechnology including genetic modification and the development of new enhanced cultivars (4). These techniques promote the improvement of features like growth rate, disease resistance and wood qualities by enabling breeding innovations. By facilitating the research of tree genetics and trait heritability and serving as a model system for examining totipotency, somatic embryogenesis and cellular differentiation. Tissue culture is a crucial tool in forest genomics (38). Tissue culture offers a controlled environment for examining how plants react to abiotic stressors such salt, drought, temperature fluctuations and nutrient shortages which advance our knowledge of plant adaptability (39). Applications in genetic modification, somatic hybridization and other biotechnological techniques that have important forestry consequences are examples of its adaptability (40). Tissue culture practical application is evidenced by its effective use in large-scale plantations throughout Southeast Asia and Latin America where it aids in the management of genetic resources and the production of lumber (41).

Companies such as pharmaceuticals and nutraceuticals rely on callus and cell cultures cultivated in optimized conditions to produce important phytochemicals (42). Tissue culture techniques are also essential for preserving endangered species and propagating forest trees which support conservation and afforestation initiatives (18). A possible path forward for hybridization research is the fusion of protoplasts to produce hybrids across species or genera (43). Tissue culture capacity to generate secondary metabolites has been used to create other bioactive substances and develop new drugs (1). In teak biotechnology, tissue culture offers hitherto unheard-of research

Table 2. Development in teak tissue culture

S.No	Key Aspect	Development/Findings	Source(s)
1	Haberlandt's Totipotency Theory	Tissue culture was founded on the totipotency idea, which was first suggested in 1902	(1)
2	Discovery of Auxins and Cytokinins	The 1930s and 1940s saw the discovery of auxins and cytokinins	(1)
3	Nutritional Medium	In 1934, White's nutritional medium was created	(1)
4	Optimized Shoot Multiplication	Enhanced genetic fidelity, germplasm preservation and *in vitro* establishment	(2)
5	Developments in Micropropagation	Enhanced acclimatization, reduced somaclonal variation, improved multiplication efficiency	(4)
6	Technical Challenges	Despite improvements, problems including cost, contamination and somaclonal variance still exist	(6)
7	Improvements in Light Sources and Aftercare	Improved plantlet development, survival rates and scalability for extensive operations	(6)
8	Advantages of Tissue Culture	Year-round production, disease-free plants and rapid clonal replication	(9)
9	Challenges in Tissue Culture	Expensive, labour-intensive, prone to contamination and acclimatisation problems	(18)
10	Callus and Shoot Culture	Costly, labour-intensive, contaminated and prone to issues with acclimatisation	(20)
11	Application in Forestry and Conservation	Tissue culture supports conservation, biodiversity preservation, genetic improvement and reforestation	(23)
12	Elite Genotype Preservation	Better shoot multiplication and the preservation of superior genotypes are guaranteed by softwood shoots from epicormic buds	(25)
13	Omics Technologies	Proteomics and genomes integration speeds up the production of resistant species and breeding	(34)
14	Genetic Engineering	Increased wood quality, growth and resistance to pests	(35)
15	Rooting in Mature Teak Cuttings	In mature teak, rooting hormones such as Indole-3-Butyric Acid (IBA) enhance rooting	(36)
16	Innovations in media and bioreactors	Large-scale propagation is made possible by bioreactors, which have growth regulators and medium compositions that are optimised	(39)
17	Clonal propagation benefits	Enhanced wood qualities, biotic stress resilience and regular growth patterns	(47)
18	Seed propagation techniques	The shortcomings of the traditional approach are addressed and germination is enhanced by soaking and scarification	(48)

opportunities, particularly in cryopreservation and genetic modification aimed at producing variations with desired traits including improved wood quality, pest resistance and quicker growth (9). By combining cutting edge biotechnological tools the techniques discussed also improve breeding programs by creating clonal material with high genetic fidelity to investigate important qualities including growth rate, wood density and insect resistance (19). Plant growth regulators (PGRs) are used optimally to support tissue culture and genetic improvement research, allowing scientists to test novel PGR combinations, investigate genetic traits and create improved teak varieties through selective breeding and genetic engineering (2). Contributing broadly to the study of plant physiology and developmental biology, the knowledge gathered from researching shoot and callus culture techniques illuminates important elements affecting shoot proliferation, root development and the effects of gelling agents and light on tissue growth (6). By maintaining and propagating parental line these advancements can also be utilized to improve tissue culture practices for other tree species, hybrid production and advance propagation methods for a range of forestry species (26).

Conservation of elite genotypes

Teak is a highly prized timber species with increasing market demand because of its remarkable mechanical and physical qualities (44). Tissue culture has great promise as a method for reintroducing and conserving rare and endangered tree species (13). This approach has the potential to preserve elite genotypes of teak which are distinguished by characteristics such as rapid growth, high wood quality or resistance to disease (9). Enhanced micropropagation methods are especially beneficial for conserving valuable or uncommon teak genotypes allowing for the preservation of biodiversity (4). A key factor in preserving genetic variety is the capacity to grow elite and endangered teak genotypes via tissue culture. This is important because overharvesting and habitat degradation are major problems for teak populations (18). The effective application of sophisticated micropropagation techniques in conservation and reforestation projects enables the large-scale production of teak plantlets for ecological restoration. These initiatives maintain vital genetic resources in addition to restoring degraded forests (19).

Using tissue culture techniques to quickly multiply many teak plantlets has been extremely beneficial for reforestation projects. The ecological and economic importance of teak makes it a priority species for these kinds of programs and tissue culture's effectiveness speeds up these initiatives (23). This method is made more useful by using epicormic buds from mature trees, which allow for the propagation of older trees with genetic value for forest restoration. This method aids in preserving features essential for ecological recovery and genetic diversity (25). Teak tissue culture is an effective method for reforestation because of its high success rate and efficiency especially in areas where teak plays an important ecological role or acts as a keystone species (6).

Furthermore, there are similarities between tissue culture methods which are frequently employed in crop development and forestry. Similar to improvements in cereals made possible by genetic transformation, they allow the creation of trees with improved features such pest resistance, stress tolerance and increased yield (45).

When it comes to protecting exceptional teak genotypes with desirable traits like high wood density, pest resistance and rapid development conservation techniques are especially helpful (49). These techniques guarantee the preservation of genetic variety, especially in vulnerable teak populations (2). Superior traits of selected mature trees can be duplicated through tissue culture, ensuring the availability of high-quality

Fig. 3. Quality planting material of teak.

genetic material for forestry applications (21) in Fig. 3.

Clonal propagation of elite genotypes

Large-scale creation of elite teak clones with superior traits like faster growth, improved wood quality and increased resilience to diseases and pests is made possible by advanced tissue culture procedures (4). This skill is essential for raising the teak plantations economic worth. These techniques are especially helpful for the propagation of high-performing teak genotypes because they give consistency across plantations which boosts productivity and maximizes financial returns (19).

The goal of clonal propagation techniques is to replicate elite teak genotypes while maintaining desirable characteristics including exceptional wood quality, quick growth and resistance to pests and diseases (23). These strategies are crucial for maintaining uniformity in extensive forestry operations and maximizing financial gains. The ability to clone mature valuable trees guarantees the preservation and widespread distribution of beneficial features which enhances the general quality and profitability of teak plantations (25).

In vitro conservation methods are particularly helpful in protecting teak genotypes with desirable traits including high wood density, quick development and pest resistance. These techniques are important for preserving genetic diversity, especially for populations that are threatened by habitat loss or overharvesting (2). Propagating particular mature trees ensures the development of superior genetic material supporting conservation efforts and forestry applications (21). It is successfully clonal propagating superior teak genotypes to improved tissue culture techniques which ensure the preservation and reproduction of desired traits including outstanding wood quality, rapid growth and resistance to environmental stressors or pests. These changes have significant conclusions for commercial forestry where quality and consistency are essential and biodiversity conservation (6).

Conclusion

Auxins and cytokinins were discovered in the 1930s and 1940s, Haberlandt's totipotency theory (1902), White's nutritional medium (1934) and other significant developments in plant tissue culture are highlighted in the work. By using rooting hormones such as indole-3-butyric acid (IBA) which is a breakthrough for teak propagation it highlights better rooting in mature teak cuttings. Clonal propagation techniques have shown several advantages such as consistent growth patterns, wood characteristics and biotic stress resistance.

The study discusses ways to improve seed propagation including soaking and scarification which raises germination rates and overcomes some of the main drawbacks of conventional methods. With advantages including quick clonal replication and the creation of disease-free plants tissue culture is advanced technique in forest biotechnology especially for teak. Not with standing these benefits problems like being highly expensive and the need for specialized skills still exist. These techniques produce genetically engineered trees with improved characteristics such as increased growth, better resistance to pests and higher-quality wood.

Improved plantlet acclimatization decreased soma clonal variance and enhanced multiplication efficiency are some of the developments in teak micropropagation. Although there are many uses for these advancements in commercial forestry, research and conservation obstacles including high expenses, contamination hazards and the requirement for specialized labor are still major. Innovations in media compositions and growth regulator combinations have further boosted regeneration efficiency across numerous species. Tissue culture is now more scalable and financially feasible to the development of bioreactors which have transformed large scale propagation and metabolite production.

The preservation of exceptional genotypes, quick clonal replication and year-round output are some advantages of tissue culture for teak. However, problems like exorbitant expenses, the possibility of contamination and difficulties with acclimatization still present concerns. Notable advancements in teak micropropagation highlight increased shoot multiplication, greater acclimatization and higher rooting effectiveness which makes the method advantageous for research, conservation and commercial forestry. Even though the technique is still labor intensive and resource-intensive these developments show how adaptable it is for reforestation and large-scale timber production. Recent advancements in teak tissue culture techniques concentrate on maximizing acclimatization, rooting effectiveness and shoot multiplication offering scalable options for conservation and forestry applications. Not with standing the technical and financial obstacles these techniques promote biodiversity preservation, genetic improvement programs and large-scale teak production. Breeding programs can be expedited and techniques for resistant species can be developed by combining tissue culture with omics technologies such as proteomics and genomes.

A new method for effectively clonal propagating mature teak trees uses softwood shoots from epicormic buds. While maintaining elite genotypes essential for conservation and commercial forestry this technique improves *in vitro* establishment and shoot multiplication. By focusing on plant growth regulators and *in vitro* conservation major issues including high costs and acclimatization barriers have been addressed and optimized shoot multiplication, long-term germplasm preservation and genetic fidelity have been achieved.

Year-round production of genetically homogeneous teak plantlets is made possible by improved procedures such as shoot and callus culture. The method is used in commercial forestry, conservation and genetic research but it is still vulnerable to contamination and soma clonal variation. The effectiveness and scalability of teak micropropagation have been further improved by developments in light sources, gelling agents and aftercare techniques making it a practical instrument for large-scale forestry operations. These enhancements emphasize the potential of tissue culture in teak propagation and conservation by increasing plantlet survival rates and speeding up growth.

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Authors' contributions

RR helped in choosing the review topic and its outline. AB, PSD, KBS and BS, participated in giving ideas related to the topic and drafted the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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