Performance of non-biocidal wood modification techniques to enhance the durability of tropical plantation woods against biodeterioration

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Abstract. Fast-growing tropical plantation woods are increasingly important as renewable raw materials; however, their high proportion of juvenile wood results in low natural durability, poor dimensional stability, and high susceptibility to biodeterioration. This study reviews and evaluates major non-biocidal wood modification techniques developed to enhance the performance of plantation-grown species without relying on toxic preservatives. The methods assessed include smoked wood, acetylation, furfurylation, polymer impregnation (polystyrene and methyl methacrylate), bio-based polyesterification using sorbitol–citric acid, and wood–plastic composites. Their effectiveness is compared in terms of resistance to termites and fungi, dimensional stability, and mechanical performance. Results reported in the literature show that acetylation and furfurylation provide the highest and most consistent improvements in biological durability and moisture resistance, achieving performance levels comparable to naturally durable species. Polymer-based impregnation and bio-polyesterification significantly enhance stability and strength but require further optimization to reduce cost. Smoked wood offers a low-cost and environmentally benign alternative with moderate protection, while wood–plastic composites provide excellent durability through polymer encapsulation. Overall, non-biocidal modification technologies present a viable pathway for upgrading tropical plantation woods into high-performance and environmentally responsible materials, supporting sustainable utilization and extended service life.

1 Introduction

Indonesia is one of the largest tropical wood producers, with log output reaching 64.8 million m³ in 2024 [1]. About half of this production comes from fast-growing plantation forests managed under short rotation cycles. Although these systems ensure continuous supply, they yield timber rich in juvenile wood and sapwood with low density, poor dimensional stability, weak mechanical properties, and low natural durability, which restrict long-term applications

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[2]. Consequently, improving the intrinsic properties of plantation wood is necessary to maintain competitiveness and expand its industrial use.

Juvenile wood contains thinner-walled cells and higher microfibril angles, resulting in reduced stiffness and strength compared with mature wood. This anatomical immaturity causes lower MOE, MOR, and hardness, as well as high sensitivity to moisture-induced swelling and shrinkage. Higher nutrient content and lower extractives further increase susceptibility to fungi and termites, while its lighter color reduces market appeal. These constraints highlight the need for strategies that enhance the performance, durability, and appearance of plantation-grown timber.

Advances in wood processing have expanded wood products into sawn timber, laminated materials, reconstituted panels, and cellulose-based products. Engineered materials such as LVL, PSL, OSB, and WPC have improved structural reliability and resource efficiency. However, these developments increase dependence on raw materials with stable properties and environmental compliance, requiring plantation wood to be upgraded in durability, dimensional stability, and strength.

Historically, wood longevity was improved through traditional practices and later by chemical preservatives such as ACQ, CCA, and creosote. Despite their effectiveness, many preservatives pose environmental and health risks due to leaching, toxicity, and odor, leading to strict regulation or bans. This situation has driven the search for safer alternatives that protect wood without harming ecosystems.

Environmental pressure has promoted non-biocidal wood modification technologies that enhance performance through chemical reactions, polymer impregnation, or composite formation instead of toxic biocides [2]. Chemical modifications such as acetylation and furfurylation reduce hygroscopicity and improve durability by altering the wood cell wall [3]. Polymer impregnation using monomers such as styrene or methyl methacrylate improves stability and strength through in-situ polymerization [4]. Wood–plastic composites further enhance moisture resistance by encapsulating wood within thermoplastic matrices.

Given the growing contribution of plantation forests and the limitations of juvenile wood, understanding environmentally responsible modification techniques is essential. Therefore, this study aims to compare major non-biocidal wood modification methods, evaluate their effectiveness against termites and fungi, and assess their technological development and industrial potential. This synthesis is intended to support the advancement of sustainable and high-performance utilization of tropical plantation wood.

2 Result and discussion

2.1 Non-biocide preservation

2.1.1 Biodeterioration assessment

Evaluating the effectiveness of wood modification strategies requires reliable indicators of biodeterioration resistance and material stability. Laboratory assays using termite bio-tests, typically expressed through weight loss percentages, termite mortality, and calculated protection levels, provide essential quantitative evidence of how well a treatment improves resistance against insect attack [5]. Complementary assessments of dimensional stability, particularly measurements of swelling under controlled moisture changes, help determine whether a modification reduces hygroscopicity and enhances structural reliability. In addition to these parameters, visual observations and mechanical performance data, when available, offer further insight into the extent to which treatments preserve or improve the integrity and appearance of the wood. Together, these metrics form a comprehensive framework for assessing the durability enhancements achieved through non-biocidal modification technologies and for comparing the relative performance of different treatment approaches.

2.1.2 Smoked wood

Smoke treatment improves wood durability and surface quality by depositing volatile compounds from biomass combustion into the outer wood layers. These compounds, including phenols, aldehydes, organic acids, and resins, modify the chemical and physical behavior of wood and enhance resistance to biological degradation.

Phenolic compounds such as guaiacol and syringol exhibit antifungal and antioxidant activity, while aldehydes promote mild crosslinking and organic acids reduce surface pH, and resinous substances form hydrophobic barriers that limit moisture penetration. Microscopic evidence suggests that smoke compounds penetrate into outer layers rather than merely coating the surface, providing lasting protection. Together, these interactions create a protective layer that decreases susceptibility to decay and moisture-driven dimensional change [5].

Termite bioassays show that smoked wood suffers far less damage than untreated wood, with weight loss decreasing from 22.5% to 2.7% after 15 days of smoking [5]. Termite mortality reached 100% in smoked samples, indicating strong deterrent and toxic effects without synthetic insecticides [5].

Overall, smoke treatment is a low-cost, environmentally benign non-biocidal modification method that enhances resistance to fungi, termites, and moisture through combined chemical inhibition, hydrophobization, and structural stabilization [5].

2.1.3 Acetylated wood

Acetylation is a chemical wood modification process in which hydroxyl groups (-OH) in the cell wall polymers (mainly in cellulose and hemicellulose) are replaced with acetyl groups (-$COCH_3$). The chemically reaction could be expressed as followed:

Wood-OH + Acetic-Anhydride -> Wood-Acetate + Acetic Acid

$$(C_6H_{10}O_5)_n + (CH_3CO)_2O \quad CH_3COO\text{-}Wood + CH_3COOH$$

Acetylation modifies wood by substituting cell-wall hydroxyl groups with acetyl groups, which reduces hygroscopic sites and lowers equilibrium moisture content. This reduction in moisture uptake improves dimensional stability and resistance to biological degradation by limiting swelling–shrinkage cycles. Uniform penetration of acetyl groups produces a more homogeneous material that retains mechanical integrity under fluctuating conditions. These improvements extend service life and reduce maintenance requirements, making acetylated wood suitable for high-exposure environments.

Worldwide tests show that acetylation significantly decreases swelling and enhances resistance to termites and fungi [5, 7]. Swelling decreased from 28% in untreated wood to 15% at 10% WPG and 5% at 20% WPG. Protection levels against termites and decay increased with higher acetylation, reflecting reduced moisture availability and altered cell-wall chemistry. Although differences in termite protection were moderate, acetylated boards maintained more stable structure and predictable behavior. These results confirm that acetylation improves long-term performance under combined moisture and biological stress.

Outdoor exposure tests demonstrate that acetylated wood consistently outperforms untreated wood across different species. Untreated Indonesian pine and jabon showed nearly complete deterioration, whereas acetylated samples retained moderate to high protection levels with substantially lower mass loss. Although acetylation did not always equal the lowest weight loss achieved by biocidal treatments, it shifted performance from failure to substantial durability. These patterns indicate that reducing hygroscopicity through acetyl substitution effectively stabilizes the cell wall and slows decay.

Acetylation improves dimensional stability, decay resistance, and weathering performance by limiting water sorption and disrupting fungal activity [5]. Under outdoor conditions, acetylated wood better retains form and structural integrity than untreated wood. These combined effects result in longer service life and suitability for applications requiring durability and reliability. Commercial production of acetylated wood is exemplified by Accoya and Alpha Wood.

2.1.4 Furfurylated wood

Furfurylation modifies wood through physical filling of void spaces and chemical reactions with wood components, particularly lignin [6], as shown in Fig.1. During impregnation, furfuryl alcohol diffuses into the cell wall and polymerizes in situ to form polyfurfuryl alcohol, causing cell-wall bulking that restricts moisture pathways [7]. As a result, furfurylated wood shows reduced moisture uptake, improved dimensional stability, and enhanced resistance to biological degradation due to lower water availability. The process is environmentally favorable because furfuryl alcohol is derived from renewable biomass and avoids toxic preservatives. Visual observations indicate more uniform color and smoother surfaces, reflecting improved structural coherence and aesthetic quality. In general, furfurylation provides an effective non-biocidal modification method that strengthens the cell wall, stabilizes wood under humid conditions, and extends the service life of plantation-grown timber.

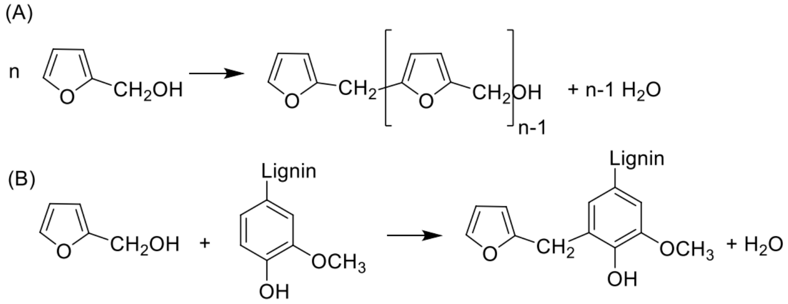

Fig. 1. Reaction in polymerization of furfuryl alcohol; a Polymerization between FA molecules, and b co-polymerization between FA and lignin.

Termite bioassays show that furfurylation greatly improves wood durability, reducing significantly weight loss of sample after treatment. Termite mortality increased from 2.3% in untreated wood to 100% in furfurylated specimens, indicating strong deterrent and toxic or repellent effects. Protection level also increased, demonstrating near-complete mitigation of biodeterioration risk. These results indicate that polyfurfuryl alcohol bulking restricts moisture availability and disrupts termite feeding behavior, thereby enhancing structural integrity and service life.

Field exposure tests confirm the superior performance of furfurylated wood compared with untreated and chemically preserved samples. Cell-wall bulking improves dimensional stability and biological resistance by limiting moisture penetration and reducing access for fungi and termites. After one year outdoors, control samples showed severe decay, whereas furfurylated wood retained shape and surface quality. Increased surface hardness further reflects the densifying effect of the polyfurfuryl alcohol network, which enhances abrasion resistance for exterior use.

The combined durability and stability have enabled commercial application of furfurylated wood in products such as those produced by Kebony ASA in Norway [2]. Furfurylated wood achieves EN 350 Class 1 durability, comparable to naturally durable species such as teak. These findings demonstrate that furfurylation provides a sustainable, non-biocidal alternative to conventional preservatives using renewable furfuryl alcohol.

2.1.5 Polymer-impregnated woods

2.1.5.1 Polystyrene-impregnated wood

Polystyrene impregnation modifies wood through in-situ polymerization of styrene that fills lumens and porous regions, reducing void spaces that normally absorb water. This internal filling limits moisture ingress, improves dimensional stability, and reduces swelling–shrinkage cycles. The polymer network also increases density and mechanical strength while creating a denser substrate that is less accessible to termites and microorganisms. Consequently, polystyrene modification provides an effective non-biocidal approach for upgrading low-density wood species.

Termite resistance tests show that polystyrene impregnation significantly reduces biodeterioration compared with untreated wood [8]. Weight loss decreased significantly after modification as well as protection level rose due to treatment, reflecting reduced porosity and restricted moisture movement that disrupt feeding behavior. This densification also improves mechanical stability, allowing modified wood to retain integrity under biological stress.

Field and laboratory evaluations confirm that polystyrene-impregnated wood exhibits improved dimensional stability [9], mechanical strength, and biological resistance [8]. In graveyard tests, untreated samples showed severe decay, whereas polystyrene-treated specimens remained structurally sound. Although CCA-treated wood performed best, polystyrene modification provided substantial protection without heavy-metal biocides. Treated wood also showed reduced surface erosion and improved resistance to thermal and chemical degradation, supporting its suitability for long-term outdoor use.

2.1.5.2 Methyl methacrylate impregnation

MMA modification improves wood stability through in-situ polymerization of methyl methacrylate that forms poly-methyl methacrylate (PMMA) within lumens and porous cell-wall regions. The polymer network restricts water mobility and enhances dimensional stability under fluctuating moisture conditions [4]. PMMA also reinforces the internal structure, increasing mechanical strength and reducing the risk of cracking under load. Lower moisture availability further improves resistance to biodeterioration, while treated wood shows more uniform surface appearance and improved weathering resistance [4].

Laboratory termite tests indicate that MMA impregnation significantly enhances the biological resistance of wood. The treatment effectively reduces material degradation and limits termite penetration, reflecting improved durability. In addition, the modified wood becomes less attractive as a food source, leading to decreased feeding activity. Termite survival is also slightly reduced, suggesting that changes in wood density and chemical composition create a less favorable environment for infestation. From these observations, the formation of PMMA within the wood structure improves durability by filling voids, restricting moisture access, and increasing mechanical resistance [4].

Mechanical tests show that MMA impregnation consistently increases MOR and MOE in wood. Hardness also increases due to surface densification caused by polymer deposition [4]. These improvements result from PMMA filling voids and distributing stresses more uniformly within the wood. The combined increase in stiffness and hardness enables low-density woods to meet higher structural performance requirements.

In general, MMA impregnation improves dimensional stability, mechanical strength, and durability by reducing hygroscopicity and reinforcing the cell-wall structure. The polymer network also enhances resistance to thermal and chemical degradation by acting as a protective barrier. These outcomes demonstrate that MMA modification is an effective non-biocidal strategy for upgrading low-durability woods for demanding applications [4].

2.1.5.3 Sorbitol–citric acid polyesterified wood

Sorbitol–citric acid (SorCA) modification alters wood structure through esterification and polyesterification reactions that form a crosslinked bio-polyester network within the cell wall [3]. This polymer reduces access to hydrophilic sites, thereby limiting moisture uptake and improving dimensional stability. The integrated network also increases stiffness and surface hardness while producing more uniform and darker coloration that indicates strong interaction with the wood matrix. Because the system uses bio-based reactants, it avoids the environmental risks of synthetic resins and shows reduced leachability under wet conditions. Overall, SorCA treatment creates a composite-like material with enhanced stability, mechanical reliability, and resistance to environmental stress [3].

Decay and soft-rot tests show that SorCA treatment markedly improves biological durability depending on concentration and curing temperature [3]. Untreated wood exhibited high mass loss and low durability, whereas 10% SorCA already reduced fungal degradation to a slightly or moderately durable class. Higher concentrations produced stronger effects, with 20% SorCA cured at 160 °C yielding durable performance and 30–55% SorCA achieving very durable classifications with mass loss around 2–5%. Low x-values indicate that the crosslinked polyester matrix restricts enzymatic access and reduces available carbohydrates. Soft-rot resistance followed the same trend, while heat-only treatment provided minimal improvement.

Microscopic observations show that SorCA treatment reduces porosity by partially or fully filling lumens with a polyester matrix [3]. This compact structure improves dimensional stability by limiting moisture-induced swelling and shrinkage. Treatments cured at 160 °C outperform those cured at 140 °C in mass change, decay resistance, and chemical modification. The richer and more uniform color further indicates strong chemical integration and improved surface stability. Together, reduced porosity, restricted moisture movement, and increased crosslink density explain the high durability of SorCA-modified wood, confirming it as a promising bio-based alternative for upgrading low-performance species for humid or soil-contact applications [3].

2.1.5.4 Wood plastic composite (WPC)

The Wood–plastic composites (WPCs) combine lignocellulosic fillers with thermoplastic matrices to improve stiffness, moisture resistance, and processability [10]. Dimensional stability and durability arise from mechanical interlocking, chemical bonding via coupling agents, and encapsulation of wood particles by molten polymer. As a result, WPCs show lower water absorption and slower biological degradation than solid wood, enabling use in outdoor products such as decking and cladding. Manufacturing routes such as extrusion, injection molding, and compression molding influence composite uniformity and performance. Recent advances including 3D printing and hybrid WPC systems further expand design flexibility and microstructural control.

Performance evaluations indicate that wood–plastic composites (WPCs) exhibit substantially higher resistance to termite attack compared to untreated wood. The WPC materials effectively inhibit termite survival and feeding activity, resulting in minimal material consumption and very limited structural degradation. Both laboratory and field observations confirm that WPC boards, particularly those incorporating polymer matrices, maintain strong structural integrity under termite exposure. In contrast, untreated wood is highly susceptible to termite damage, showing severe deterioration and significant loss of material over time.

These durability advantages stem from polymer encapsulation that restricts moisture uptake and biological colonization [9]. Encapsulation improves dimensional stability, weathering resistance, and service life in exterior environments. WPCs also offer design flexibility through molding and extrusion into architectural components. From a sustainability perspective, WPCs enable the use of wood residues and recycled plastics to produce durable materials with chemical resistance and recyclability, positioning them as attractive alternatives to preservative-treated wood.

3 Comparative evaluation of all non-biocidal methods

A comparative analysis of five major non-biocidal wood modification techniques was conducted to evaluate their performance, mechanisms, and industrial potential. The assessment covers dimensional stability, biological durability, mechanical improvement, and environmental compatibility. Table 1 summarizes the functional outcomes and mechanisms of smoked wood, acetylation, furfurylation, polystyrene impregnation, and MMA impregnation. Table 2 presents their development pathways and industrial readiness levels, indicating scalability and long-term relevance. Together, these tables provide a structured framework to support research and industrial decision-making.

Table 1. Comparative evaluation of non-biocide wood modification technologies

Criteria	**Smoked Wood**	**Acetylated Wood**	**Furfurylated Wood**	**Polystyrene-Impregnated Wood**	**MMA-Impregnated Wood**	**Wood Plastic Composite (WPC)**
Primary Mechanism	Deposition of phenols, organic acids, aldehydes, and tar compounds onto/into cell wall	Esterification of hydroxyl groups by acetyl substituents	In-situ polymerization of furfuryl alcohol into poly (furfuryl alcohol) (PFA)	In-situ polymerization of styrene within wood porous structure	In-situ polymerization of methyl methacrylate forming PMMA	Encapsulation of wood particles within thermoplastic matrix
Dimensional Stability	Moderate improvement (surface-level modification)	Strong enhancement due to reduced hygroscopicity	Substantial increase (cell-wall bulking)	Significant improvement (pore filling by polystyrene)	Strong improvement (PMMA stiffening and pore occupation)	High stability due to polymer matrix and low water uptake

Table 1. Comparative evaluation of non-biocide wood modification technologies (continue)

Criteria	**Smoked Wood**	**Acetylated Wood**	**Furfurylated Wood**	**Polystyrene-Impregnated Wood**	**MMA-Impregnated Wood**	**Wood Plastic Composite (WPC)**
Biological Durability	Moderate to high (dependent on smoke intensity and exposure time)	High decay and insect resistance, Class 1–2 durability	Very high resistance (fungi, termites, marine borers)	High termite resistance and notable decay resistance	High resistance to termites and moderate fungal resistance	Very high termite resistance and moderate decay resistance (matrix limits biological access)
Mechanical Performance	Minimal to moderate improvement	Small to moderate increase (slightly increased hardness & MOE)	Significant improvement (increased density and hardness)	Marked increase in strength and hardness	Significant improvement in MOR, MOE, and hardness	Improved stiffness but lower tensile strength than solid polymers; depends on fiber loading
Moisture Resistance	Improved due to hydrophobic smoke components	Excellent (limited hydroxyl accessibility)	Excellent (hydrophobic polymer network)	High reduction in water uptake	High reduction due to PMMA filling	Exceptional moisture resistance (plastic encapsulation)
Thermal Performance	Minor improvement	Slight increase	Improved thermal stability	Moderate thermal resistance	Improved thermal resistance	High thermal resistance based on polymer matrix type (especially PVC/PP)
Environmental Profile	Natural, low-chemical, low emission; limited scalability	Low toxicity, biodegradable by-products; industrial process demands high energy	Bio-based precursor, low environmental toxicity; moderate VOC during polymerization	Petroleum-based polymer; limited recyclability	Petroleum-based polymer; moderate environmental footprint	High recyclability; enables use of wood waste and recycled plastics; depends on polymer type

Table 1. Comparative evaluation of non-biocide wood modification technologies (continue)

Criteria	**Smoked Wood**	**Acetylated Wood**	**Furfurylated Wood**	**Polystyrene-Impregnated Wood**	**MMA-Impregnated Wood**	**Wood Plastic Composite (WPC)**
Industrial Maturity	Low-medium (traditional technique with limited standardization)	Very high (commercialized e.g., Accoya®)	High (Kebony®, industrial adoption increasing)	Medium (promising but niche applications)	Medium (applied for specialty products)	Very high (global commercial use in decking, cladding, automotive)
Processing Complexity	Low (simple smoking setup)	High (strict chemical control, reactor-based process)	High (requires controlled polymerization)	Medium (requires vacuum/pressure and curing)	Medium (polymerization step under heat initiator)	Low to medium (extrusion, injection molding widely available)
Cost Level	Low	High	High	Medium	Medium	Low–Medium (cost-effective for large-scale production)

Table 2. Analysis possibility future development priorities and industrial readiness of major non-biocidal wood modification methods

Modification Method	**Key Future Development Priorities**	**Industrial Readiness Level (IRL*)**	**Industrial Readiness Assessment**
Smoked Wood	Standardization of smoke formulation and processing parameters	IRL 3–4	Early-stage industrial adoption; mostly artisanal or small-scale; lacks standardized protocols for large-scale manufacturing.
	Optimization of penetration depth and long-term performance		
	Development of controlled smoke reactors to reduce variability		
	Assessment of VOC emission and environmental compliance		
Acetylated Wood	Reduction of acetic anhydride usage and process energy	IRL 9	Fully commercialized globally (e.g., Accoya®); high scalability and stable supply chain; strong regulatory compliance and global certification.
	Integration of bio-based acetylating agents		
	Cost reduction for wider market penetration		
	Development for tropical wood species		

Table 2. Analysis possibility future development priorities and industrial readiness of major non-biocidal wood modification methods (continue)

Modification Method	Key Future Development Priorities	Industrial Readiness Level (IRL*)	Industrial Readiness Assessment
Furfurylated Wood	Wider availability of bio-based FA with reduced cost	IRL 8–9	Commercially established (e.g., Kebony®); high industrial maturity; expanding applications in high-performance outdoor and marine environments.
	Process optimization to minimize color darkening		
	Improvement in polymerization kinetics and curing efficiency		
	Expansion to engineered wood products (CLT, LVL)		
Polystyrene-Impregnated Wood	Development of greener styrene alternatives	IRL 4–6	Moderate readiness; demonstrated in pilot and semi-industrial scale; adoption limited due to environmental considerations and polymer sourcing.
	Improvement of polymer penetration and uniformity		
	Enhancing recyclability and reducing petroleum dependency		
	Scaling vacuum–pressure processes for industry		
MMA-Impregnated Wood (PMMA)	Substitution of MMA with bio-based methacrylate monomers	IRL 4–6	Pilot-scale maturity; suitable for specialty applications; broader commercialization limited by cost and environmental footprint.
	Optimization of initiator and curing systems		
	Enhancement of interface bonding and long-term weatherability		
	Minimization of polymerization shrinkage		
Wood Plastic Composite (WPC)	Improvement of interfacial adhesion with advanced coupling agents	IRL 9	Highly commercialized globally; widely used in decking, cladding, automotive parts; mature processing (extrusion, injection molding); strong supply chain & recyclability systems.
	Development of fully recyclable or bio-based polymer matrices		
	Enhancement of mechanical strength for structural-grade WPC		
	Integration with additive manufacturing (3D printing & hybrid composites)		
	Long-term weathering and UV stabilization		

4 Conclusions

This review synthesizes current developments in non-biocidal wood modification technologies applied to tropical plantation species, emphasizing their effectiveness in improving resistance to termites, fungi, and other biodeterioration agents. Comparative analysis of major techniques including smoking, acetylation, furfurylation, polymer impregnation (polystyrene, and polymethyl methacrylate), and bio-based poly-esterification shows that each method contributes meaningful enhancements in durability, dimensional stability, and mechanical performance, particularly for juvenile woods commonly found in fast-growing plantations. Among these approaches, acetylation and furfurylation exhibit the highest level of technological maturity and industrial validation, consistently delivering superior long-term performance. Polymer-based treatments such as polystyrene and MMA impregnation, as well as sorbitol–citric acid polyesterification, demonstrate considerable promise; however, further optimization is required to increase reaction efficiency, reduce production costs, and enable wider adoption.

Growing environmental concerns over the past two decades have accelerated the search for modification technologies that improve wood properties without relying on toxic preservatives. Treatments such as acetylation, furfurylation, polymer impregnation, smoking, polyesterification, and wood–plastic composites have shown clear improvements in physical, chemical, and biological performance, positioning them as viable alternatives to conventional preservative systems. While several of these methods are already established at an industrial scale, others remain at earlier stages of development and require additional refinement to enhance process stability and large-scale feasibility. Future work should focus on advancing bio-based reaction pathways, conducting comprehensive life-cycle assessments, and validating long-term field performance under tropical conditions. Integration of these modification technologies into engineered wood products including CLT, LVL, and WPC represents a key opportunity to strengthen the competitiveness and sustainability of plantation-based wood industries. Collectively, non-biocidal wood modification technologies offer a credible pathway to increase the value, service life, and environmental performance of tropical plantation woods, supporting the transition toward safer, high-performance materials for future structural and ecological demands.

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