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Editorial

Advances in Sustainable Processing of Wood and Lignocellulosic Materials: From Molecular Engineering to Industrial Implementation

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1. Introduction

Wood and lignocellulosic biomass are among the most versatile renewable resources. As industry faces pressure to reach carbon neutrality, replace fossil-derived synthetics, and adopt circular economic models, these materials have become central to materials science and bioeconomy strategy [1,2]. Wood is organized hierarchically, from nanoscale cellulose microfibrils embedded in an amorphous hemicellulose–lignin matrix up to macroscopic growth rings, combining strength, lightness, and chemical richness [2,3]. Exploiting these properties demands multi-scale understanding, from genetic regulation in the vascular cambium to industrial thermal processing, timber preservation, green fractionation, and eco-efficient thermochemical conversion [3,4].

This Special Issue, "Advances in Sustainable Processing of Wood and Lignocellulosic Materials: From Molecular Engineering to Industrial Implementation," gathers research linking molecular insights to industrial applications. The papers examine how tubulin isoforms determine microfibril angle [5]; how SNPs govern wood density and shrinkage [6]; how deep eutectic solvents (DES) and life-cycle assessments optimize biopolymer extraction [7,8]; how steam treatment homogenizes wood color and alters acidity [9]; how technical lignins improve durability [10]; how transparent wood manages light [11]; how lignin thin films enable organic electronics [12]; how transpiration-inspired wood–plastic composites regulate building temperatures [13]; how sustainability indicators optimize preservation [14]; and how portable metal kilns improve charcoal production in community forests [15]. Together, they show that intervening at one structural scale can improve performance, economic value, and environmental compliance at another.

2. Summary of Papers Included in the Special Issue

The cellulose microfibril angle strongly influences wood stiffness, tensile strength, and longitudinal shrinkage. Taylor et al. [5] characterized the alpha- and beta-tubulin gene families in Eucalyptus grandis and showed their direct role in determining this angle. Cortical microtubules guide cellulose synthase complexes along the plasma membrane, and the authors identified five alpha- and six beta-tubulin genes, with specific isoforms expressed more strongly in secondary xylem than in leaves. Using Induced Somatic Sector Analysis (ISSA) to alter gene expression in vivo, they tested overexpression and microRNA knockdown constructs. Plant Class I alpha-tubulins and Class I/Class I-like beta-tubulins specifically regulated the angle: knockdown increased it by 2.3° to 4.2°, while dual overexpression of EgrTUA1 and EgrTUB1 decreased it by 1.9°. Cell wall thickness, fiber length, cell

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Received: 24 November 2026
Accepted: 27 November 2026
Published: 29 November 2026

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area, and lumen area were unchanged, showing that cytoskeleton genes can tune fiber microarchitecture independently of cell geometry and offering molecular targets for breeding trees with tailored mechanical properties.

Falade et al. [6] examined the genetic basis of dimensional stability and basic density in *Eucalyptus pellita* and its hybrids. Excessive tangential shrinkage and drying defects limit the structural use of fast-growing hardwoods, and stability is a polygenic trait shaped by anatomy, microfibril orientation, and hemicellulose–lignin interactions. Across two plantation sites in the Tiwi Islands, Australia, they evaluated parent trees, F1 hybrids, and backcross (BC) hybrids with *E. urophylla* and *E. brassiana*. *E. pellita* × *E. urophylla* F1 hybrids were the most stable, with the lowest tangential shrinkage (0.06%–0.16%), whereas *E. pellita* × *E. brassiana* backcrosses had the highest basic density (651 kg/m^3), suiting heavy structural uses. Marker-trait analysis of 3000 SNPs showed that all significant markers clustered on Chromosome 1, in an intergenic regulatory region near Eucgr.A00211, which encodes a CGI-141 family lipase. The authors propose that it modulates lipid-mediated interactions at the hemicellulose–lignin interface, altering matrix hydrophobicity, water retention, and stress relief during drying. These markers enable marker-assisted selection for dimensional stability without sacrificing growth rate or density.

Chemical fractionation is another pillar of sustainable processing. Quek et al. [7] studied ultrasound-assisted deep eutectic solvent (DES) pretreatment of oil palm empty fruit bunches [16,17]. Among choline chloride-based DES with lactic acid, glycerol, or urea, choline chloride-lactic acid was the most effective, reducing lignin content to 18.8%. Sonication accelerated mass transfer into cell walls, and the solvent kept its capacity over several recycling cycles [12,13], yielding clean cellulose fiber and high-purity technical lignin [16,18].

Novel extraction methods also need environmental validation. Müller-Carneiro et al. [8] performed a prospective, scenario-based life-cycle assessment (LCA) of cellulose nanocrystal (CNC) production from agro-industrial byproducts projected to 2040 [14,15], modeling acetosolv pulping and acid hydrolysis under process upscaling and a decarbonizing energy mix. Solvent recovery, notably of acetic acid and organosolv liquors, was the critical bottleneck [15,16]: closed-loop recovery cut global warming potential by over 40%, showing that early prospective LCA is essential to guide eco-efficient design before scale-up [19,20].

Physical and hydrothermal treatments can immediately upgrade solid wood quality. Older beech (*Fagus sylvatica* L.) logs often develop false heartwood, a dark brown-red core caused by polyphenol oxidation after branch injury or air infiltration, and the color contrast with sapwood lowers the value of furniture and panels. Dudiak [9] evaluated high-pressure saturated steam to homogenize beech color and modify acidity, using Mode I (105 °C, 0.12 MPa) and Mode II (125 °C, 0.23 MPa) for 6 to 24 h. Colorimetry and surface pH measurements showed that sapwood lightness (L*) fell from 80.5 to 60.0 under Mode I and to 47.5 under Mode II after 24 h, owing to hemicellulose hydrolysis and new chromophores in lignin. Color unification between sapwood and false heartwood was reached after 18 h at 105 °C or 12 h at 125 °C. Released organic acids, mainly acetic acid from glucuronoxylan, lowered pH from 5.2 to 3.6 in sapwood and from 5.0 to 3.9 in false heartwood. Second-degree polynomial models relating total color difference (ΔE*) to surface pH fit well ($R^2 = 0.9557$ for sapwood; 0.9540 for false heartwood), allowing operators to predict color non-destructively from pH during thermal modification.

Non-toxic bio-based treatments can also protect solid timber. Herrera Diaz et al. [10] vacuum-impregnated pine (*Pinus nigra*) and beech with technical lignins (kraft lignin, acetylated kraft lignin, and lignin nanoparticles) [21]. The lignins coated cell lumens, increased hydrophobicity, reduced water vapor sorption, and limited UV-induced degradation and color fading during accelerated weathering. This valorizes a pulping byproduct while avoiding synthetic preservatives [18,21].

Lignocellulosic biopolymers also enable functional materials. Zhu et al. [11] made highly anisotropic transparent wood by rapidly removing lignin along the low-tortuosity channels of balsa and infiltrating refractive-index-matched polymers such as poly(methyl methacrylate). The composite reached up to 90% visible light transmittance and ~90% optical haze from microfibrillar scattering. As a light-management layer on thin-film solar cells, it raised energy conversion efficiency by 18%, showing potential for smart building envelopes and solar harvesting.

Lignin thin films are also advancing organic electronics and sensors. Tronci and Marrocchi [12] reviewed technical lignins in organic field-effect transistors (OFETs), electrolyte-gated transistors (EGTs), and flexible sensors [22–24]. Thanks to its aromatic structure, dielectric properties, and reactivity, purified kraft lignin works as a gate dielectric and organic electrolyte [22]. Spin-coated films form electric double layers with capacitances up to 4.1 $\mu F/cm^2$, enabling 0.1 V operation and synapse-like behavior [23]. Carbonized lignin nanostructures also serve as conductive inks for biodegradable circuits on transparent wood, with stable resistance over 1000 folding cycles [12,24].

Biomimetic design expands the functionality of bio-based composites in architecture. Zhou et al. [13] developed leaf transpiration-inspired wood–plastic composites (WPCs) for energy conservation, incorporating form-stable phase-change materials (polyethylene glycol in bio-carbon scaffolds) into a wood fiber matrix. Inspired by stomatal cooling, the porous structure speeds heat conduction and latent heat absorption, reducing indoor temperature fluctuations by up to 12 °C and increasing mechanical strength by 50%.

Extending the service life of wood products is essential for carbon storage, yet traditional preservatives face environmental scrutiny, so transparent decision-support tools are needed. Fritz et al. [14] created the Wood Protection Sustainability Index (WPSI), a multicriteria tool based on the Analytic Hierarchy Process (AHP). Applied to Chile's preservation sector, where non-durable *Pinus radiata* dominates construction, it evaluates five pathways, Copper Azole (CA), Micronized Copper Azole (μCA), Alkaline Copper Quaternary (ACQ), traditional heavy-metal formulations, and Chemical Modification, across four attributes: Protection Treatment performance, Wood Durability, In-Service Risk, and Sustainability. In Scenario 1, reflecting traditional priorities (50% weight on treatment cost and availability, 20% on sustainability), CA scored highest (74%), followed by ACQ (70%), Chemical Modification (68%), and traditional treatments (67%). Under ESG-oriented priorities (Scenario 2: 60% on sustainability, 20% on treatment performance), CA remained first at 60%, followed by ACQ (59%), μCA (56%), and Chemical Modification (56%), while heavy-metal formulations fell to last (52%). Although μCA costs more in high-retention ground contact (Risk Classes 4 and 5), its cost in building construction (Risk Classes 1–3) is nearly identical to traditional treatments ($33 vs. $34 per cubic meter). With a SWOT analysis, the authors show that replacing toxic heavy metals with copper-azole or acetylated timber supports UN Sustainable Development Goals (SDGs 3, 6, 12, and 13), giving regulators and specifiers an objective tool to mandate safer preservatives.

Thermochemical conversion of wood residues into solid biofuels offers a clean alternative to fossil fuels, but traditional earthen-pit charcoal production is inefficient and polluting. Navarro-Martínez et al. [15] evaluated carbonization efficiency and charcoal quality of white oak (*Quercus scytophylla* Liebm.) in a portable octagonal metal kiln (CEVAG design) in the community forests of the Cordón Grande ejido, Guerrero, Mexico. Their 2 × 3 factorial design tested sapwood vs. heartwood and lower, middle, and upper kiln positions. The kiln holds 3000 to 3200 kg of wood per batch, uses manual dampers for air control, shortens pyrolysis to 28–36 h, and reduces toxic emissions. Yields were 20.0% (green basis) and 26.7% (dry basis), matching commercial benchmarks, and the charcoal met DIN 51749 and EN 1860-2, with low moisture (1.49%–3.56%) and ash (2.18%–2.52%) and high fixed

carbon (73.73%–74.05%). The upper kiln section gave the highest fixed carbon and lowest ash, the lower section the highest gross calorific values (6751 to 7508 cal/g), and sapwood charcoal had higher density (up to 0.57 g/cm^3) than heartwood (0.50–0.52 g/cm^3). The authors conclude that portable kilns turn low-value oak thinnings into high-grade bioenergy, supporting conservation, fire risk reduction, and local livelihoods.

Industrial biorefining further links research to commercial practice [25–27]. The UPM Biochemicals Leuna biorefinery [25] converts 220,000 metric tons of hardwood per year into renewable glycols and functional lignin fillers, validating commercial scale. Techno-economic and life-cycle analyses [26,28,29] show that closed-loop solvent integration and high-value co-product valorization are essential for profitability and carbon negativity.

3. Concluding Remarks

This Special Issue shows that sustainable wood processing requires an integrated, interdisciplinary approach. Tubulin isoform regulation shows that microfibril orientation can be tuned through gene expression [5], and genomic association studies show that regulatory genes such as Eucgr.A00211 can guide breeding toward high-density, low-shrinkage timber [6]. Green extraction with deep eutectic solvents [7,12,13] and prospective life-cycle assessment [8,14,15] optimize biopolymer recovery with minimal impact. In primary processing, steam modification offers mathematical control of acidity and color, turning visual defects into uniform products [9], while lignin impregnation provides non-toxic durability [10]. Functional materials, from transparent wood solar covers [11] and lignin transistor dielectrics [12,22] to phase-change biocomposites [13], extend lignocellulose into optoelectronics and energy-efficient buildings. Indicators such as the WPSI [14] help industries replace toxic preservatives with ESG-aligned alternatives, and portable metal kilns [15] validate sustainable energy conversion for community forestry.

Future progress will depend on strengthening the links between these domains [25,26,29]: integrating genomic selection with non-destructive phenotyping, refining eco-friendly modification chemistries, and adopting life-cycle sustainability metrics across supply chains [8,14,28]. As Guest Editors, we thank the authors, peer reviewers, and editorial staff of *Forests* who made this Special Issue possible, and we hope these studies inspire further innovation and industrial adoption, keeping wood a cornerstone of global sustainable development.

Author Contributions: Conceptualization, P.L.-A. and J.G.R.-Q.; writing—original draft preparation, P.L.-A.; writing—review and editing, J.G.R.-Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The Guest Editors thank all authors who submitted their valuable research to this Special Issue and the peer reviewers for their rigorous evaluation and constructive comments.

Conflicts of Interest: The authors declare no conflicts of interest.

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