

Recent Advances in the Inhibition of Wood-Degrading Fungi, Insects, and Enzymatic Attack Using Nanotech Solutions: A Review

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Wood is a widely used natural material in various industries due to its availability and versatility. In recent years, nanotechnology has been explored as a promising approach to improve wood durability and resistance against biological degradation. Studies on wood preservation using nanoparticles (NPs) have focused on enhancing wood's resilience to weathering and biological deterioration, as well as increasing its fire resistance. Nanosized metals can effectively preserve wood by penetrating deeply into it. Applications of nanotechnology may increase wood's resilience to fungus-induced deterioration. This review concentrates on the efficacy of NPs in enhancing the qualities of wood and wood-derived goods and shielding them from biological degradation, including fungal decay and enzymatic breakdown of wood.

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INTRODUCTION

Many people recognize that wood is a natural organic material that is safe for the ecosystem and has contributed to both ecological sustainability and overall well-being. Because carbon dioxide is retained in wooden items, boosting the usage of timber and products made from wood could help facilitate a more environmentally friendly future by lowering the release of carbon dioxide. Wood's remarkable qualities, including its impressive strength-to-weight ratio and appealing appearance, make it a great element for construction of buildings, bridges, furnishings, and wood siding for both interior and exterior applications. Its outstanding qualities make wood material an adaptable substance (Al-Rajhi and Abdelghany 2023; Papadopoulos 2023).

Researchers studying wood durability have long used the starkly straightforward names “white,” “brown,” and “soft” rot to characterize the fungal decay of wood, in addition to the less damaging mold and stain fungi. Although the meaning of these phrases has become nearly iconic, they are based only on how the damaged timber looks (Goodell *et al.* 2020).

Wood's main structural components are cellulose, hemicellulose, and lignin (Fig. 1). Cellulose gives wood many special material qualities and makes up 40% to 44% of its chemical composition. Cellulose is organized in distinct units called elementary fibrils at

the nanoscale (Mittal *et al.* 2018). Lignin, a heteropolymer made up of repeating phenyl propane units with a wide variety of linkages between three different monomer forms, makes up 18% to 35% of the wood cell wall. Because of the variety of bonding patterns, lignin is very resistant to breaking down, and only a few microbes aside from certain fungi that break down wood-have been able to do so.

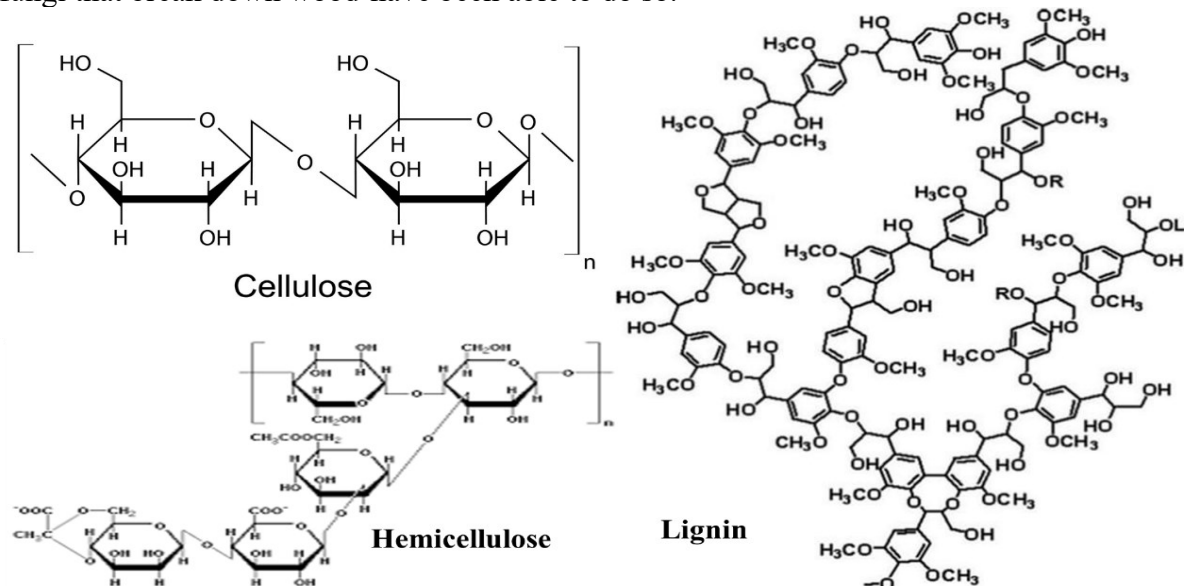


Fig. 1. Main structural components of wood (Zhang *et al.* 2012)

Moreover, wood's resistance to deterioration is largely due to its higher lignin content than other plant materials and the way it is closely bonded with the holocellulose components. Hemicellulose constitutes 15% to 32% of the wood composition. Additionally, hemicellulose is more prone to degradation, and extreme heat. In fact, thermal modification procedures employed in commercial wood protection, can break down the various forms of the hemicellulose polymer (Altgen *et al.* 2020).

Although wood is one of the most resilient cellulosic materials, a variety of biotic and abiotic factors can cause it to deteriorate. It is challenging to fully distinguish causative agents because these agents frequently work in tandem. Although many studies have focused on the wood degradation by fungi, there has been little concern on the role of nanoparticles in suppressing these fungi which destroy wood. Nanoparticles' distinctive physico-chemical characteristics are helping them make their way into the market. Nanoparticles (NPs) find extensive applications in the fields of cosmetics, coatings, agriculture, textiles, biomedical, personal hygiene products, and environmental cleanup (El-Batal *et al.* 2023; Amin *et al.* 2024 and 2025). Nanotechnology is being explored as a promising approach in the field of wood enhancement, particularly for improving dimensional stability and resistance to microbial degradation. The tiny NPs may quickly, efficiently, and profoundly enter the wood to change the chemistry of its surface and enhance its characteristics, producing a product with exceptional performance (Papadopoulos 2023). A major concern in several industries (plastics, chemistry, *etc.*) at the moment is the use of nanomaterials to produce innovative, cost-effective goods; the forest products sector has also recognized this issue. However, there hasn't been much research done on using NPs to enhance the main technical characteristics of wood. On the other hand, there are numerous encouraging findings on

the enhancement of mechanical, hydrophobic, combustion, and other characteristics in the cases of polymers, textiles, and paper (Zabihi *et al.* 2018). Nanotechnology has emerged as a powerful tool in material science, offering innovative solutions for controlling the development of microorganisms (Al-Rajhi *et al.* 2022; Alghonaim *et al.* 2024; Al-Rajhi *et al.* 2024a). This review will consider the vital role of NPs in improving the properties of wood and products made from wood, protecting them from weathering and other degrading factors, and preventing fungal enzymes from destroying wood.

MECHANISM OF WOOD DEGRADATION BY FUNGUS

There are three main types of fungal wood rot. Soft rot is a type of superficial decay in which little or no lignin degradation occurs along with the enzymatic breakdown of cellulose and hemicellulose in the wood's surface layers. Many Ascomycetes and their anamorphs have this trait. White rot is characterized by the quick and widespread enzymatic breakdown of all wood components, with the loss of lignin giving rise to the distinctive bleaching of the wood. Only a few higher Ascomycete taxa and Basidiomycetes have been found to exhibit white rot degradation thus far (Eichlerová and Baldrian 2020). The most resistant component of wood is lignin; hence, the function of white-rot fungus in lignocellulose turnover is crucial. In brown rot (Fig. 2), non-enzymatic oxidation is responsible for the extremely quick cellulose and hemicelluloses degradations with little to no lignin degradation (Abd El-Mongy and Abd El-Ghany 2009; Goodell 2020).

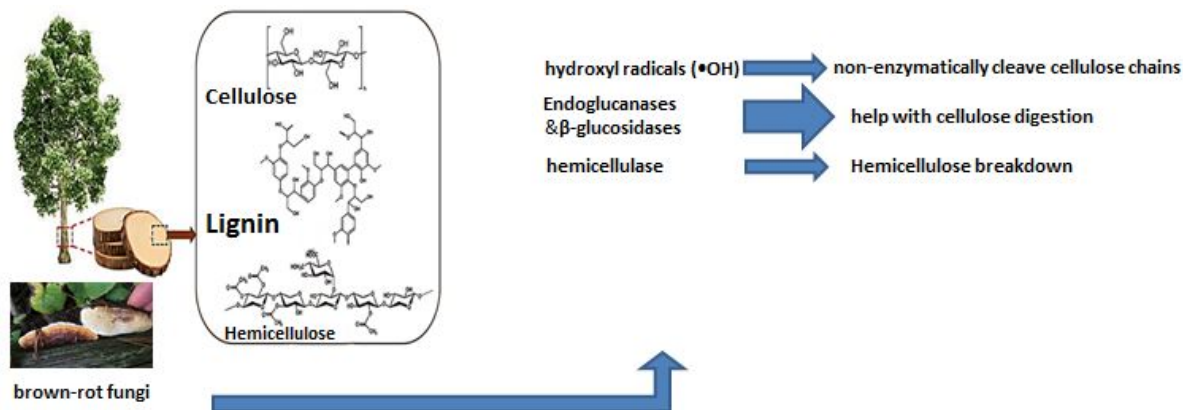


Fig. 2. Effect of brown rot fungus and enzymes on wood

Soft rot and white rot are known to be caused by certain marine fungi. Fungi that cause wood degradation usually start as mycelial fragments or fungal spores. When appropriate conditions are met, spores sprout into fungal hyphae, which are tiny, hair-like structures that are elongated, end-to-end growing fungal cells. In many instances, hyphal particles that fall onto wood can also start development, which spreads the colonization of the wood. Certain species of fungi can create a mat made up of several layers called a mycelial mat, as their hyphae develop along the surface of materials. To stretch from one fiber to the next and propagate throughout the wood in this way, the tips of the fungal hyphae first seek comparatively easy routes through the microstructure of the wood. They do this by taking advantage of interconnecting cell wall pits, which are channels that

connect wood cells. All fungi that live in wood look for stored products in the parenchyma during this early growth phase. This allows the fungus to quickly obtain nutrients for energy and to accumulate fungal biomass inside or on top of the wood structure (Goodell *et al.* 2020). The most aggressive biological agents that damage wood in service are xylophagous fungi, which cause brown and white rot, and subterranean termites which are highly destructive to wood and are among the most serious insect pests. These fungi cause structural changes that affect the wood's natural resistance by attacking the polymeric fraction of the cell wall, which includes cellulose, hemicelluloses, and lignin, with enzymes. Termites contribute to the structural weakening of wood by mechanically chewing and enzymatically digesting lignocellulosic components, a process made possible by symbiotic microorganisms living in their digestive tract (Scharf 2020).

According to Gabriel and Švec (2017), most wood-rot fungus are members of the Basidiomycetes, and they can be classified as either brown or white rot. Fungi that cause brown rot can break down cellulose and hemicelluloses; however, they can only alter lignin and cannot substantially break it down. Because of the oxidation of lignin, the wood shrinks and the brown rot residues break down into cubic shapes with brown staining (Al-Rajhi *et al.* 2024b). Fungi that cause wood rot are the primary cause of wood degradation. They have several enzymes that are employed to undermine living trees' physiological processes and structural integrity. White-rot fungus primarily releases cell oxidases for delignification during the wood breakdown process (Fig. 3). Because of its strong ligninolytic qualities, quick growth, and simplicity of handling in culture, *Phanerochaete chrysosporium* has emerged as the standard laboratory fungus for researching the physiology and chemistry of lignin breakdown (Giri and Sharma 2020).

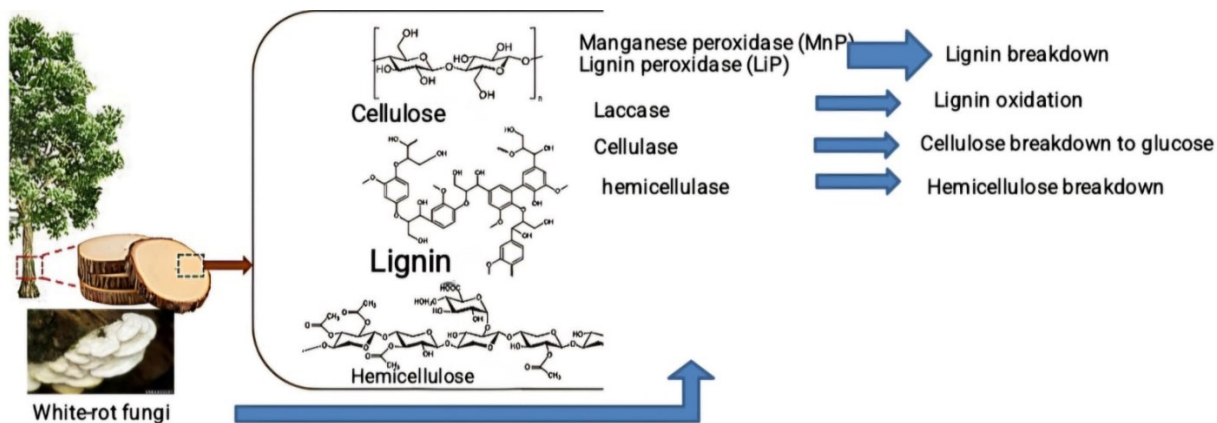


Fig. 3. Effect of white rot fungus and enzymes on wood

Ligninases, or ligninolytic enzymes, are a class of enzymes that can degrade wood lignin (Fig. 3), characterizing the fungi responsible for white wood rot. This type of fungi primarily decompose lignin, responsible for the brown coloration of wood, resulting in the residual white cellulose, which is the origin of its nomenclature. These fungi derive their energy and carbon from lignocellulosic materials. Lignin stands out among these due to its intricate structure, which consists of many aromatic rings. Fungi produce a number of extracellular oxidative enzymes, primarily lignin peroxidase, manganese peroxidase, and laccase, to break down the lignin (Dao *et al.* 2021). The characteristics of

wood-decay fungus are ligninolytic and hydrolytic enzymes, which are involved in non-specific oxidation and hydrolysis processes. Hydrolytic enzymes are important parts of commercial enzymatic cocktails that turn pretreated lignocellulosic materials into plant biomass (Al-Rajhi *et al.* 2023). The hydrolysis of cellulose and hemicelluloses through specific combinations of enzymes is fundamental to modern biorefineries. Lignin-degrading enzymes encompass manganese peroxidases (MnPs), phenol oxidases (laccases), lignin peroxidases (LiPs), and versatile peroxidases (VPs). Endoglucanases, exoglucanases, and β -glucosidases are enzymes associated with cellulolytic reactions, as reported by Andlar *et al.* (2018). Fungal enzymes may be utilized in various biofuel production processes, including the elimination of fermentation inhibitors, cellulose saccharification, and the pretreatment of lignocellulosic biomass, as noted by Saldarriaga-Hernández *et al.* (2020).

Enhancing Wood's Insect Resistance Using Nanoparticles

The development of nanotechnology has contributed to improving the characteristics of wood and wood-derived products (Tarmian *et al.* 2012). Research on the use of wood nanotechnology has focused on several areas: 1) modifications to mechanical and physical traits; 2) wood's dimensional stability; 3) wood's appearance (color) and resistance to outdoor conditions; and 4) resistance to microorganism attack. According to Taghiyari *et al.* (2013), silver nanoparticles have improved thermally-treated physical characteristics and fire resistance of wood protection.

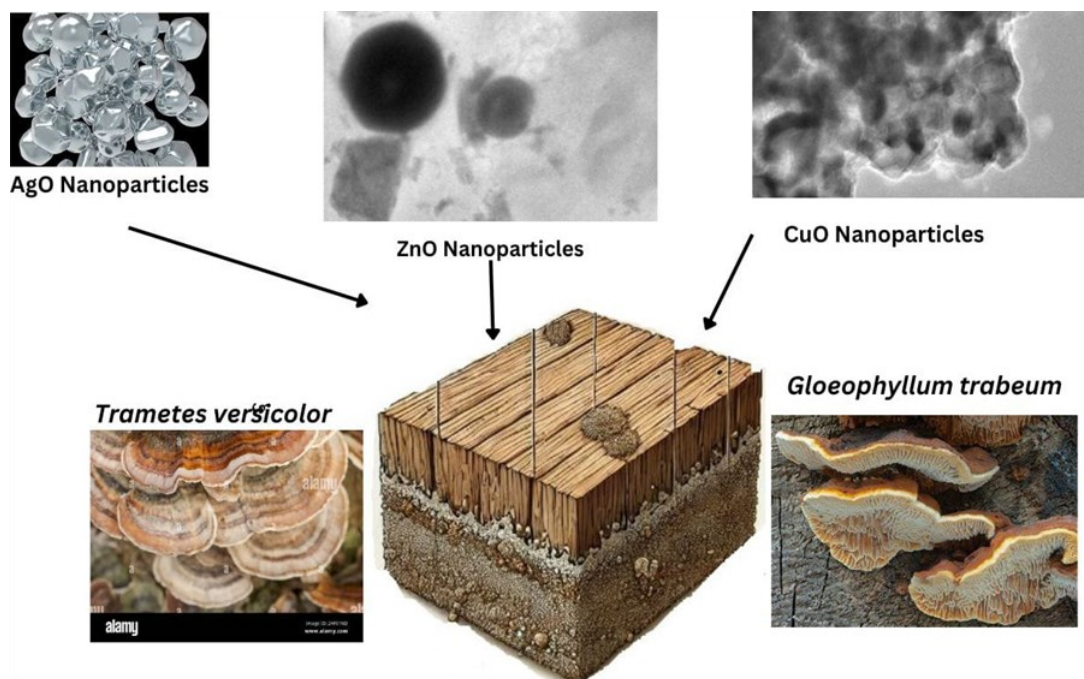


Fig. 4. Effect of nanoparticles on wood-degrading fungi

Usage of various metal NPs offers an excellent defense against termites and another wood-decaying fungi. Several formulations of silver, copper, zinc, boron, silver, titanium, and other commonly studied NPs are effective in previous studies (Fig. 4). In addition to laboratory experiments, outdoor tests have demonstrated NPs' effectiveness in protecting wood. They outperformed the traditional wood preservatives employed as

controls in certain instances (McIntyre and Freeman 2011). Wood may become more biologically resistant to mold and decomposing fungus. Additionally, it was discovered that nano-copper, nano-zinc, and nano-silver offer efficient defense against the development of *Aspergillus brasiliensis* and *Penicillium funiculosum* (Huang *et al.* 2015).

Impact of Metal and Inorganic Nanoparticles on Wood-Degrading Fungi, and Ligninolytic Enzyme Activity

NPs are capable of offering sustainable and eco-friendly solutions for the conservation of wood. A research investigation by Pietka *et al.* (2022) discovered that silver and copper NPs exhibit antifungal abilities *versus* the white rot fungus *Fomes fomentarius*, hence protecting *Fagus sylvatica* wood. The silver NPs (AgNPs) suppressed fungal colony formation at the maximum concentration of 50 ppm, while exhibiting no impact on growth at concentrations of 5 ppm and 25 ppm. Silver NPs enhanced the rot tolerance of beech wood, but just at its highest concentration levels. These results from *in vitro* tests are consistent with those obtained on beech wood specimens, showing that the concentrations of the two NPs used were too low to protect the beech wood from decomposition by Xylophagous fungus. It has been demonstrated that high concentrations of silver, copper, and zinc oxide NPs can effectively shield paulownia, European beech, and Scots pine wood from *T. versicolor* (Pařil *et al.* 2017). Furthermore, titanium dioxide NPs stop *Hypocrea lixii* and *Musor circinelloides* from colonizing eight distinct wood species (De Filpo *et al.* 2013). In a study on a composite of chitosan and AgNPs in preventing Xylophagous fungal degradation of *Populus* × *Euramericana* wood was evaluated. When the binary solution at AgNPs 4 ppm and chitosan (20 g/L) was compared to the untreated control, the weight loss for white-rot fungi decreased from 42.0% to 30.2%, and for brown-rot fungus, it decreased from 41.9% to 27.2% (Spavento *et al.* 2023). Also, Giménez-Bañón *et al.* (2023) showed that calcium phosphate NPs doped with methyl jasmonate increase cell wall material (CWM) and produced a diminution in the amount of cellulose in contrast to an increase in hemicellulose. The metallic silver in this process goes through release of ions as a result of oxidation in the presence of water, so the exoenzymatic activity of both brown and white rot fungi is greatly impacted by these silver ions in solution. Their particular impact is noticeable in the activity of cellulase enzymes generated by decay fungi, as explained previously (Abdel Ghany *et al.* 2018). Because this chemical reaction transition is fundamentally slow, particle size plays a crucial role in preventing fungal development. Because of the prolonged, gradual release of silver ions, smaller particle sizes offer better protection against these spoiling agents by increasing specific surface area and improving oxidation effectiveness. Furthermore, AgNPs, especially those with smaller diameters, can cause fungal cells to produce free radicals, which can result in oxidative stress and, eventually, cell death. By interfering with proton pumps and the electron transport chain, these AgNPs infiltrate cells and cause damage to proteins, lipids, and nucleic acids as well as an increase in ROS generation (Pietka *et al.* 2022).

When applied to the tropical species (*Acacia mangium*, *Cedrela odorata*, and *Vochysia guatemalensis*) of Costa Rica, the AgNPs increased the wood's resilience. In every instance, the woods treated with NPs were categorized as Class A, or highly resistant, to white (*Trametes versicolor*) decay fungi, in contrast to untreated wood, which saw weight losses exceeding 20%. Along with greater resistance to fungal assault, the AgNPs also reduced the wood's ability to absorb water from the three species studied (Moya *et al.* 2014). In mini-agar slant and wood block tests, pure nano-copper exhibits

wood-protective qualities against *Gloeophyllum trabeum* and *T. versicolor* (Weitz *et al.* 2011). Nanosilver was successfully encapsulated in a polystyrene-soybean co-polymer by Can *et al.* (2018). The capsules were used to impregnate Scots pine, which was then tested against *T. versicolor*, a fungus that causes white rot. According to the study's findings, polystyrene, nanosilver, and soybean oil all contributed significantly to the synergistic impact of enhancing Scots pine's resistance to decay.

For the protection of wood, copper is a necessary biocide. Copper by itself, however, is insufficient to shield wood against fungi that kill copper-tolerant wood. A new type of copper that is based on wood preservatives is copper NPs. When copper NPs are used in place of regular copper, wood is more durable against fungi that cause rot. Some nanomaterials and wood degrading fungi were organized in Table 1.

Table 1. Nanomaterials and Wood Degrading Fungi

NPs	Function	References
Al ₂ O ₃	Inhibition white-rot fungus (<i>Trametes versicolor</i>) and brown-rot fungus (<i>Gloeophyllum trabeum</i>).	Acosta <i>et al.</i> 2022
Se	Against the brown-rot <i>Serpula lacrymans</i>	Gablech <i>et al.</i> 2022
Silver	Antifungal particularly against mildew fungi and Inhibit <i>Trametes versicolor</i> of Populus wood	Huang <i>et al.</i> 2022
Zn oxide and/or polyethylene glycol 6000	Inhibit brown-rot fungus <i>Rhodonia placenta</i> and the white-rot fungus <i>Trametes versicolor</i> of beech wood	Reinprecht <i>et al.</i> 2022
ZnO NPs, TiO ₂ NPs Al ₂ O ₃ , MgO NPs	Physical properties, thermal and fungal resistance of Scots pine wood	Holy <i>et al.</i> 2022
CuO NPs	Inhibit the proliferation of wood-decaying fungi <i>Trametes hirsuta</i> (white rot) and <i>Oligoporus placenta</i> (brown rot).	Shiny <i>et al.</i> 2022
Zinc-oxide, zinc borate, copper, titanium, cerium, and boron)	Suppressing wood– degrading fungi	Terzi <i>et al.</i> 2019
ZnO-PVAc	Inhibition <i>Trametes hirsute</i> and <i>Oligoporus placentus</i> of <i>Populus deltoides</i> wood	Nagraik and Shukla 2025
Organosilica NPs and carbon quantum dots	Inhibition Brown rot fungus (<i>Gloeophyllum trabeum</i>)	Wang <i>et al.</i> 2023
Magnesium and calcium fluorides NPs	Inhibition White rot fungus: <i>T. versicolor</i> Brown rot fungus: <i>R. placenta</i> . Termite species- <i>C. formosanus</i>	Usmani <i>et al.</i> 2022
TiO ₂	Inhibition brown rot fungus (<i>Postia placenta</i> and <i>Mucor circinelloides</i>) and white-rot (<i>Hypocrea lixii</i>)	Zanatta <i>et al.</i> 2022

Influence of Metal Nanoparticles on Ligninolytic and Cellulolytic Enzymes in Wood-Degrading Fungi

Wood's cell walls are crucial components for its structural integrity. In contrast to the lumen, which is a space, the cell wall itself has a fairly regular structure throughout species, cell types, and even between hardwoods and softwoods (Schmitt *et al.* 2021). The primary wall, secondary wall, and middle lamella are the three principal areas that make up the cell wall. The three main components of the cell wall in each area are cellulose microfibrils (which have distinct distributions and organization), hemicelluloses, and a matrix or encrusting substance, usually lignin in secondary walls

and pectin in primary walls (Dong *et al.* 2022). The complicated and resistant lignin polymer is broken down by ligninolytic enzymes. Because of their extreme versatility, this set of enzymes is used in many different sectors. The growing importance of enzyme biotechnology has significantly increased the demand for these enzymes in recent years. However, producing enzymes and metabolites from microbial sources remains costly, making the use of low-cost raw materials essential to lowering production expenses (Fasim *et al.* 2021).

Three oxidative enzymes are primarily included in the term “lignin-degrading enzymes,” namely laccase, manganese peroxidase (MnPase), and lignin peroxidase (LiPase). Because of their prospective uses in a variety of biotechnological fields, these enzymes have become more and more in demand in recent years. Lignin-degrading enzymes are widely used in pollution control, especially for treating industrial effluents containing harmful substances such as dyes, phenols, and other xenobiotics. Numerous studies have investigated their role in the decolorization of textile dyes and the degradation of both phenolic and non-phenolic aromatic compounds (Jasińska *et al.* 2024). The effectiveness of five distinct NPs zinc oxide, zinc borate, silver, copper, and copper borate in protecting beech and pine sapwood against *Coniophora puteana* and *Coriolus versicolor* was investigated by Bak and Németh (2018). The treatments with borate NPs were the most successful. Only the copper, silver, and zinc oxide NPs, however, demonstrated a significant level of leaching resistance. As a result, only the zinc oxide at the highest concentration studied (5% m/m) effectively protected both of the fungus under investigation following leaching. At larger concentrations, the copper NPs also demonstrated promise as an efficacious treatment.

CONCLUSIONS

1. Recent studies have demonstrated that nanotechnology, and especially the use of metallic NPs such as silver, copper, and zinc oxide, holds promising potential for enhancing wood durability and resistance to biological agents such as fungi and termites. Certain NPs have also shown effectiveness in modifying the chemical composition of wood and improving its physical properties, such as reducing water absorption. However, further applied research is needed to understand long-term effects, optimize dosages, and ensure environmental safety. Based on the discussions presented in this article, nanoscience is emerging as an innovative and effective approach for improving wood preservation and performance, provided it is supported by additional scientific and experimental evidence.
2. Nanotechnology offers promising potential for enhancing wood preservation through the use of metal-based NPs. While current studies demonstrate their antifungal and insecticidal properties, further research is needed to better understand their penetration behavior and long-term efficacy in wood matrices. Future investigations should focus on optimizing NPs concentration, delivery methods, and evaluating their impact under real world environmental conditions.

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