

Role of Nanoparticles for Wood Protection from Decaying Microorganisms and their Enzymes: A Review Study

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The growing need for sturdy lumber in many applications has made wood preservation more crucial. Nanoparticles (NPs) have been considered to improve the functionality of wood. This review article focuses on how NPs can be used to enhance the qualities of wood and wood-based products and provide them with anti-microbial protection. The ability of nano-based substances to permeate deeply into wood surfaces, which in turn causes a shift in their exterior chemistry, is the primary driver behind the nanotechnology application in lumber development. The microbial enzymes secreted by microbes is a major factor that can alter the structure of wood, especially during storage before use. This review illustrates various examples of microorganisms which secrete enzymes which impact wood structure through various mechanisms. The increased interface region created by the treatment serves as the reason for any prospective changes in the wood's characteristics *via* NPs application. To a certain extent, the NPs change the original characteristics of wood, thus improving its qualities. There are challenges and limitations for using NPs in wood preservation. The potential effect of NPs on human health and the ecosystem should be considered using techniques such as life-cycle evaluations to avoid harmful consequences.

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INTRODUCTION

A vital component of human industry and daily life, wood-based products are susceptible to environmental elements including water, chemicals, germs, insects, and so on. These elements may cause products to deteriorate and decay, reducing their lifespan, raising safety concerns, and wasting money (Cao *et al.* 2025). Wood's remarkable qualities, including its impressive strength-to-weight ratio and appealing appearance, make it a great element for construction of buildings, ships, furnishings, and wood siding for both interior and exterior applications. Outstanding wood qualities make it an adaptable substance (Papadopoulos *et al.* 2019). The primary cause of wood degradation is fungi, particularly filamentous basidiomycetes and, to a lesser extent, ascomycetes. In addition to fungi, bacteria can also break down wood. Bacterial decomposition becomes

more significant in environments where fungal potential (apart from soft rot fungi) is inhibited by limited availability of oxygen, for instance buried wood or submerged under water, even though fungi dominate the decomposition of wood above ground or in soil contact (Schrader *et al.* 2025). The breakdown of cellulose involves the production of enzymes such as β -glucosidases, cellobiodydrolases, and endoglucanases; hemicelluloses require a diverse range of enzymes, namely β -mannosidase, endomannanase, and endoxylanase because of their structural diversity, and lignolytic systems include enzymes that produce hydrogen peroxide, oxidases, and peroxidases (Arieny and Kuswytasari 2025).

To extend the useful life of wood-based substances, effective methods of conservation become essential. This has been accomplished either by applying various barrier coatings to the wood's exterior or by alleviating it with additives that seep into the wood and shield it from microbes that break it down (Teng *et al.* 2018). However, there are several troublesome issues with timber preservation techniques, such as the leaching of wood-preserving agents from processed lumber, the use of hazardous chemicals in numerous wood preventive formulas, and the issue of how to dispose of treated wood after it is no longer needed. The earth is eventually at risk, since many wood varnishes employed in the industry employ solvents that release toxic organic molecules. Consequently, there is a growing demand for substitute solutions that emphasize environmentally benign and non-biocidal wood treatment technique (Jasmani *et al.* 2020).

Nanoparticles (NPs) can be classified according to their size and shape. Additionally, NPs could be metal based, organic-based, or inorganic-based, as well as composite-based (Al-Rajhi *et al.* 2022; Alghonaim *et al.* 2024). Using various metal NPs offers excellent defense towards termites and other wood-decaying microbes. Multiple forms of NPs have been often studied and shown to be efficient in previous and updated research (Mantanis *et al.* 2014; Lykidis *et al.* 2016; Bansal *et al.* 2024) (Table 1).

Table 1. Studies that Illustrate the Roles of Nanoparticles in Wood Preservation

Function	Type of Nanoparticle	Reference
Protect from bacteria and UV radiation	TiO ₂	Sharma and Gaurav (2025)
Protect from UV radiation	NPs of acrylate	Karbalaei <i>et al.</i> (2022)
Longevity	ZnO	Nagraik and Shukla (2025)
Physical Characteristics	NPs of ceramic	Mahlitig <i>et al.</i> (2005)
Toleration to fire	SiO ₂	Teizer <i>et al.</i> (2012)
Protect from brown-rot fungus (<i>Coniophora puteana</i>)	Soybean oil polymer containing Ag NPs	Can <i>et al.</i> (2019)
Protection from fungi causing wood decay	Polystyrene-ricinoleic acid copolymer with Ag NPs	Can <i>et al.</i> (2022)
Protect from brown-rot fungus <i>C. puteana</i>	ZnO, TiO ₂ , Al ₂ O ₃ , MgO	Holy <i>et al.</i> (2022)
Increased the rot resistance of beech wood to white rot fungus <i>Fomes fomentarius</i>	Ag and Cu	Piętka <i>et al.</i> (2022)
Reduced water absorption and volume swelling properties. Protect from natural weathering	Cu and Zn	Nataraja <i>et al.</i> (2025)

NPs can readily enter through the cracks of wood because of their tiny dimensions, which might enhance the substance's qualities and produce a high-quality, high-performing item (Aguayo *et al.* 2021). When contrasted to their mass equivalents, these substances' substantial surface area-to-volume ratio gives them more responsiveness in surface-related incidents, which is their primary characteristic. Making sure that NPs are uniformly distributed is necessary to improve the properties of timber and wood-based materials as well as prevention from biodeterioration (Ayyoob *et al.* 2024).

In addition to testing in the lab, outdoor studies have demonstrated NPs' effectiveness in protecting wood. They outperformed the traditional preservation agents for wood employed as controls in certain instances. It may be possible to increase wood's physiological durability against molds and decomposing fungi. Additionally, it was discovered that nano-metals offer efficient defense against the development of *Aspergillus brasiliensis* (Huang *et al.* 2015).

One common issue with wood manipulation or ways to preserve it is the fixing of the chemicals employed to enhance the desired wood qualities. This issue is also relevant for NP procedures. The NP interventions, information on both high as well as low leaching levels can be found in the research that is currently available. The recent findings indicate that NP formulations are resistive to leaching when combined with surfactants or emulsifiers (Bak *et al.* 2024). The present review discusses the numerous investigations documented the roles of NPs protection in wood deteriorating especially from microbes secreting enzymes leading to wood degradation. The various kinds of NPs for inhibition of microbial growth as well as limitations were applied in wood preservation.

Utilized Methods in Review Preparation

For the current investigation, a thorough research technique was used for querying numerous databases, particularly PubMed, Scopus, Embase, and Web of Science, for pertinent material up to 2025. EndNote (version 19) was used to find and eliminate redundancies (Fig. 1). The data extraction was carried out separately by three scientists. Conflicts were debated and resolved by consensus. The main consequence that was important was the safeguarding provided by nanoparticles (NP) and the microbial deterioration of wood; 495 research studies in all that met the defined research parameters and were considered for inclusion were examined as full-text publications. Investigations on natural items, publications written in languages other than English, and articles with additional uses for NPs were not included in the selection process (Li *et al.* 2022).

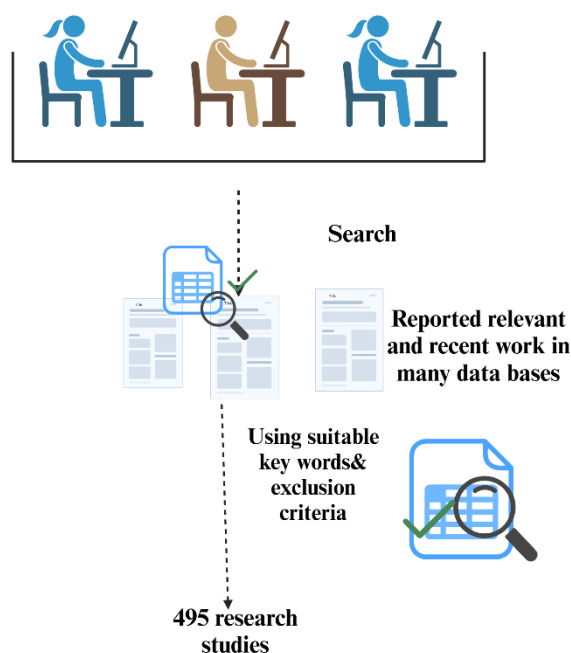


Fig. 1. Search strategy by three independent researchers to collect suitable articles for review article preparation

MICROBIAL ENZYMES AND THEIR RELATION TO WOOD DEGRADATION

The cellulose fibrils contained in the lignin matrix provide the cell walls of woody plants with a highly strong framework for support (Sivan *et al.* 2025). Certain fungi and a number of bacterial species are responsible for the breakdown of lignin. Bacteria delignify lignin more slowly and with less resources than fungi, which disintegrate the substance more effectively (Zhou *et al.* 2025).

Despite evidence suggesting bacteria being able to fragment degrade lignin, the microbe-mediated breakdown of lignin in microorganisms aside from fungi has not been thoroughly investigated. The three primary classes of lignin-degrading bacteria are Actinomycetes, α -Proteobacteria, and γ -Proteobacteria (Huang *et al.* 2013). *Rhodococcus jostii* and *Streptomyces viridosporus* as actinomycetes are known for producing catabolic enzymes (Tian *et al.* 2014). Different strains of *Streptomyces thermoviolaceus* possess high lignocellulolytic enzymes such as laccase, LiP, and MnP, which are able to remove more than 53.0% of lignin. Therefore, these strains are recognized as lignin degradation agents (Jing and Wang 2012; Priyadarshani *et al.* 2025).

It is unknown how many fungal species are able to break down lignin. The sole group of microbes that can mineralize lignin, a ubiquitous plant product that makes up around 20% of the biosphere's transportable biological content, are wood-rotting fungus, which are typically the main lignin degradation agents (Wang *et al.* 2025). Three primary kinds of saprophytic fungi have been identified based on the specific morphology of wood breaking down (Fig. 2).

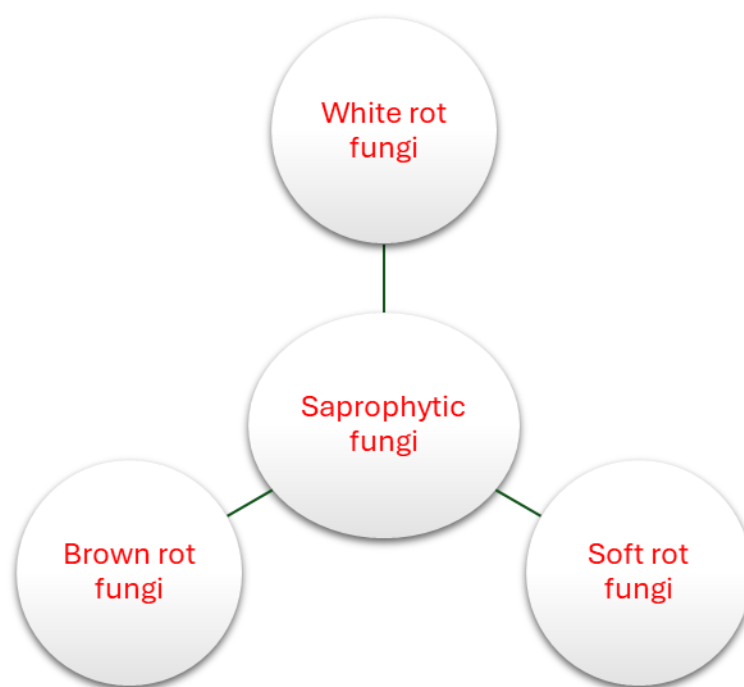


Fig. 2. Kinds of saprophytic fungi

According to Liers *et al.* (2011), these taxa can be further divided into (a) fungi that break down litter and (b) fungi that live in manure and also break down lignin. While lignin can be broken down by all of these fungi, only white rot fungi can fully break it down into CO₂ and H₂O (Al-Rajhi *et al.* 2023; Al-Rajhi *et al.* 2024a).

The two primary categories of enzymes that contribute to the breakdown of lignin are lignin-modifying enzymes along with lignin-degrading ancillary (LDA) enzymes (Fig. 3). Although they are required to finish the degradation process, LDA enzymes cannot break down lignin on their own (da Silva Coelho-Moreira *et al.* 2013). Heme-thiolate haloperoxidases are another class of enzymes that are currently being considered to play a part in the breakdown of lignin. With the gradual acting of many proteins, including the oxidative production of H₂O₂, auxiliary enzymes facilitate the breakdown of lignin (Janusz *et al.* 2017).

The carbohydrate active enzyme collection according to Zerva *et al.* (2021) classifies the enzymes needed for lignocellulosic biomass degradation into simpler forms as carbohydrate-active enzymes (CAZymes). The family classification of CAZymes in a continuously updated format is accessible online through the CAZy database (Drula *et al.* 2022). Metagenomics, proteomics, and transcriptomics research are examples of omics technologies that can be used to find new CAZymes without requiring the isolation and culture of microbes for the manufacture of enzymes. A variety of CAZymes were identified according to Parushi *et al.* (2023), such as lytic polysaccharide monooxygenases, multicopper oxidases, and esterases. In a metagenomic analysis of an enriched rumen consortium made from bagasse from sugar cane, Tomazetto *et al.* (2020) identified 41 metagenome-assembled genomes, some of which showed minimal sequence resemblance to known sequences and contained CAZymes.

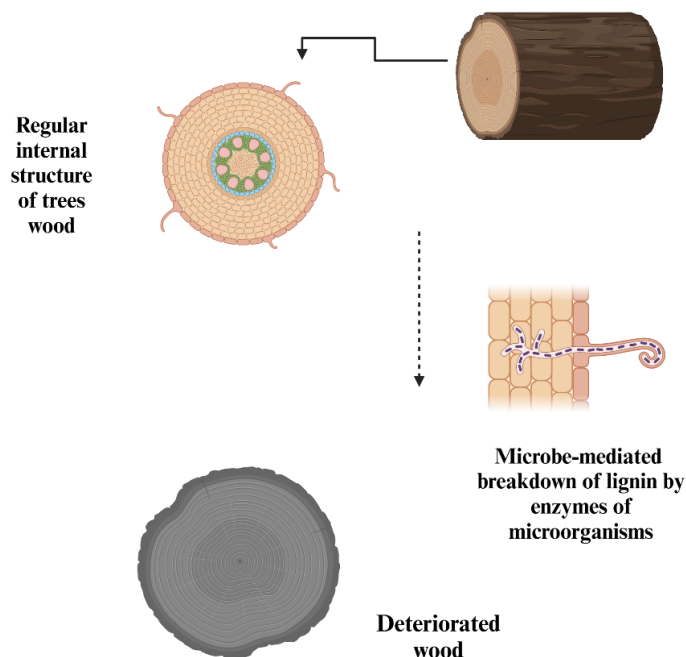


Fig. 3. Degradation of wood by enzymes of microbes causing infection

Inhibition of Woods Decaying Enzymes by Nanoparticles

Three main processes including physical, chemical, and biological have been applied to wood modification to improve the decay resistance *via* microorganisms and insects. Several forms of wood modification have been applied commercially (Fig. 4).

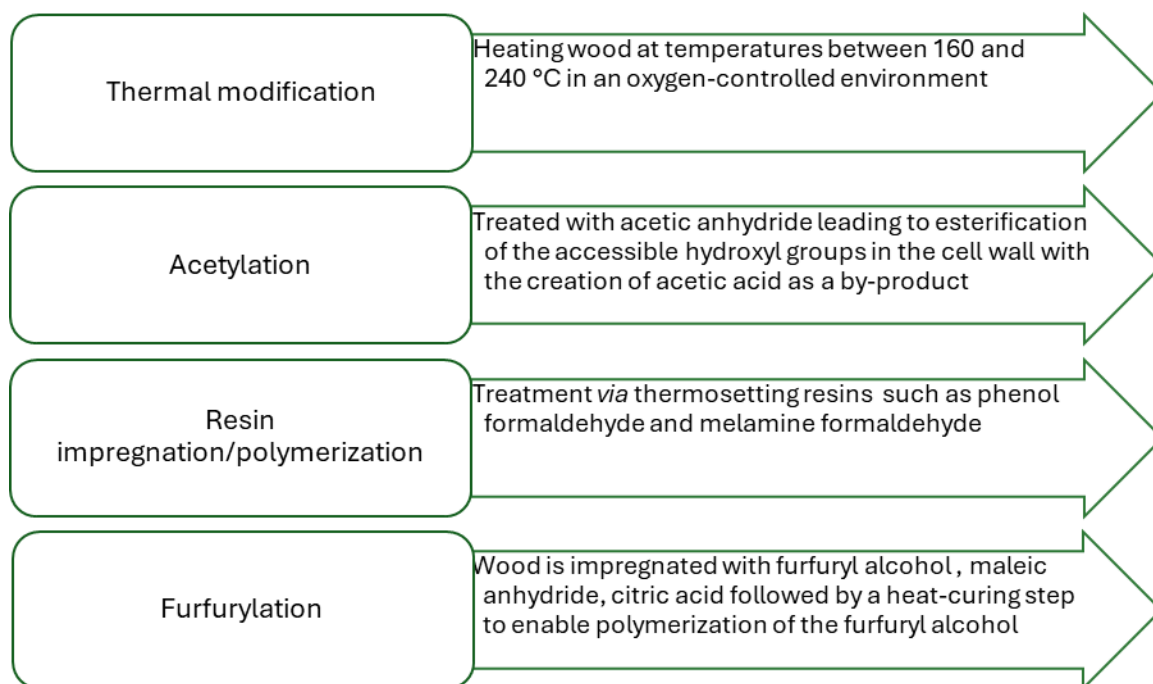


Fig. 4. Commercial forms of wood modification

These days, nanotechnology is being used more and more in several economic sectors, notably the conservation of wood (Pulit-Prociak and Banach 2016; Al-Rajhi *et al.* 2024b). According to Choat *et al.* (2003), most nanoparticles (under 100 nm) can more easily penetrate wood cell walls and are harder to leach out than traditional compounds, as the pore sizes in the wood cell wall membrane range from 5 to 95 nm.

Researchers have examined the micro-distribution of stabilizers inside the cell wall, which determines their level of leachability and effectiveness (Piętko *et al.* 2022). The usage of various nanoparticle forms as preservers for wood conservation (Fig. 5) and the susceptibility of wood rot fungi and termite attacks as well as other ecological stressors to NPs have made the subject of numerous experiments (Teng *et al.* 2016; Jasmani *et al.* 2020; Evans *et al.* 2022; Nataraja *et al.* 2025).

Several studies have demonstrated that in some situations, NPs were totally useless towards the fungi that cause wood rot. According to Moya *et al.* (2017) and Bak and Németh (2018), some tropical wood species have a reduced resistance to the brown rot fungus *Leptocorisa acuta* and a higher resilience to the white rot fungus *Trametes versicolor*. Moreover, it was found that AgNPs failed to protect *Tectona grandis* from *L. acuta* and *Chromolaena odorata* from *T. versicolor*. Broda (2020) mentioned that these variations in decay susceptibility are probably caused by the mechanisms that brown rot and white rot fungi employ. Due to the varying enzyme functioning of these fungi, they are classified according to their capacity to break down lignin in addition to cellulose and hemicellulose.

Casado-Sanz *et al.* (2019) showed that AgNPs with diameters from 10 to 30 nm have antimicrobial properties at very low doses of 5 to 20 ppm. Akhtari and Arefkhani (2013) found that AgNPs with sizes ranging from 10 to 80 nm, but with an elevated level of 400 ppm, had a comparable high preventive impact. The extracellular enzymes found in brown rot and white rot fungus are inhibited by silver ions (Pařil *et al.* 2017).

Silver ions are created when metallic silver oxidises in humid environments. Although the process of oxidation is a sluggish reaction, NPs' tiny dimensions increase the area of their surface and, consequently, the amount of area that may be oxidized compared to larger compounds (Bak and Németh 2018). Furthermore, (Can *et al.* 2022) reported that polystyrene-polyricinoleic acid copolymer with AgNPs for protection from brown rot fungi, termites and insects. In the Kartal *et al.* (2009) investigation, copper, and boron NPs prevented *T. versicolor*-induced wood deterioration but did not preserve southern yellow pine wood from *Antrodia* sp. *Gloeophyllum trabeum*, the third fungus examined in this investigation, showed no sensitivity to boron and zinc NPs. Zinc oxide NPs were unsuccessful against *Poria placenta*; however, they prevented *Serpula lacrymans* from decomposing Scots pine wood.

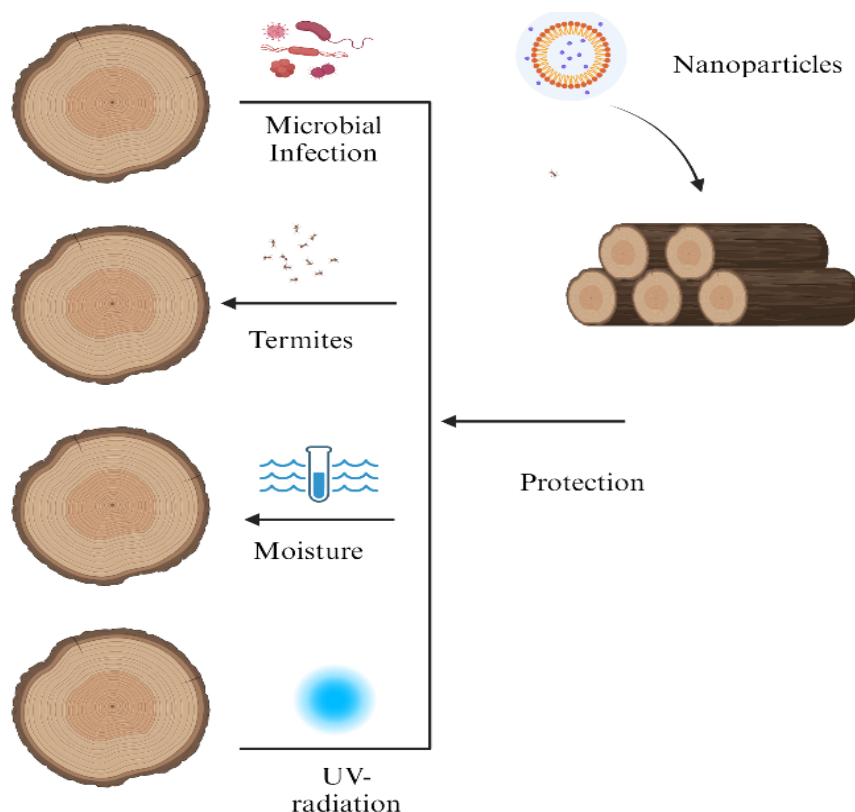


Fig. 5. Applications of various types of nanoparticles for wood protection from microbial enzymes and other environmental factors

Copper is harmful for many fungi, even at low levels, which is why copper-based biological agents have been applied to shield wood from rotting fungi (Jasmani *et al.* 2020). At the same time, copper is a metal that is required for fungal growth. White rot fungi produce three primary types of ligninolytic enzymes. According to some research, millimolar levels of copper promote the formation of these enzymes by the fungi, but at greater levels, copper is extremely poisonous to microbial cells. Probably, the copper from the CuNPs of *F. fomentarius* was employed to enhance the development rate and the generation of enzymes, thereby raising the level of wood rot. However, larger quantities than those utilized should be explored. Nevertheless, researchers think that CuNPs are appropriate for protecting beech wood against molds. CuNPs could not prevent wood from decomposing, may possibly have been caused by variations in fungal species' susceptibility to heavy metals, particularly copper, as well as between strains of a similar species (Vrsanska *et al.* 2016). On the other hand, Wang and Qi (2022) illustrated that CuNPs could be released in the dust through processing of treatment of preserved wood which might impact the ecosystem.

Inhibition Mechanisms for Microbial Growth and Their Enzymes by Nanoparticles

The mechanisms of microbial inhibition by NPs may differ according to kind of NPs, the microorganisms responsible for the wood decay, the resistance ability of microorganisms, virulence factors, and environmental conditions. Therefore, the rising prevalence of NPs in treatment of microbes causing wood decay has contributed to a rising number of investigations evaluating putative antimicrobial properties of NPs.

Metal NPs, for instance, have the ability to alter bacterial metabolic processes (Hong *et al.* 2025).

To treat microbial infections, this ability is a big advantage. A useful technique to prevent the development of biofilm that uses NP-inhibited gene expression is also made possible by NPs' capacity to penetrate biofilms. To have antimicrobial properties, NPs must come into communication with pathogenic cells. Electrostatic enticement, van der Waals actions, receptor-ligand connections, and hydrophobic bonds are among the recognized methods of connection. After passing the NPs through the membrane of the microbe (Luan *et al.* 2016), it congregates throughout the path of metabolism, changing the form and functionality of the cell membranes. After that, NPs connect with the fundamental elements of the microbes' cell, including DNA, lysosomes, ribosomes, and enzymes. This results in oxidative stress, heterogeneous modifications, altered permeability of the cell membrane, problems with electrolyte equilibrium, limitation of enzymes, suppression of proteins, and modifications in gene expression. The main pathways are the most commonly reported in existing investigation: oxidative stress, metal ion discharge, and non-oxidative processes (Xu *et al.* 2016).

Metal oxides release metal ions gradually, and these are then taken up *via* the cell membrane and engage directly with the carboxyl (-COOH) and mercapto (-SH) functional chains of proteins and nucleic acids. This alters the framework of the cell, damages enzyme function, interferes with common physiological functions, and eventually inhibits the microorganism. Nevertheless, metal ions have little effect on the pH within lipid vesicles and exhibit minimal antimicrobial action when used in metal oxide suspension for antimicrobial purposes. Thus, the primary antimicrobial action of metal oxide NPs is not dispersed metal ions (Depan and Misra 2014).

Oxidative stress brought on by ROS is one of NPs' key antimicrobial mechanisms. Multiple types of NPs create different kinds of ROS through the reduction of oxygen molecules. ROS is a general term for molecules and intermediates that react with a strong positive redox potential. The four kinds of ROS, which have varying degrees of dynamics and action, are hydrogen peroxide (H₂O₂), singlet oxygen (O₂), hydroxyl radical (·OH), and superoxide radical (O⁻²). In microbes, ROS generation and clearance comes to an equilibrium under normal conditions. On the other hand, oxidation is preferred by the cell's redox status when the release of ROS is overwhelming. Oxidative stress, which results from an out-of-balance condition, harms the separate parts of microbial cells (Li *et al.* 2012; Peng *et al.* 2013).

In the non-oxidative process, researchers reported that *E. coli* responds well to the antibacterial properties of three different kinds of MgO NPs when exposed to UV light or total darkness. According to the three subsequent arguments, these NP antibacterial methods have nothing to do with the oxidative stress-induced membrane lipid peroxidation: 1) MgO NPs are not seen in the bacterial cell when the membrane is ruptured and surface holes are plainly evident. Thus, the cell membrane is harmed by MgO's inhibitory action. 2) Only one kind of MgO NP is able to identify trace levels of ROS. 3) MgO NP administration had no discernible effect on lipopolysaccharide and in the cell wall, suggesting that MgO does not suppress peroxidation (Leung *et al.* 2014; Wang *et al.* 2017). On the other hand, Kartal *et al.* (2015) reported the role of fungi in bioremediation of preserved wood containing NPs for protection of environment. Some inhibition mechanisms of NPs are summarized in Fig. (6).

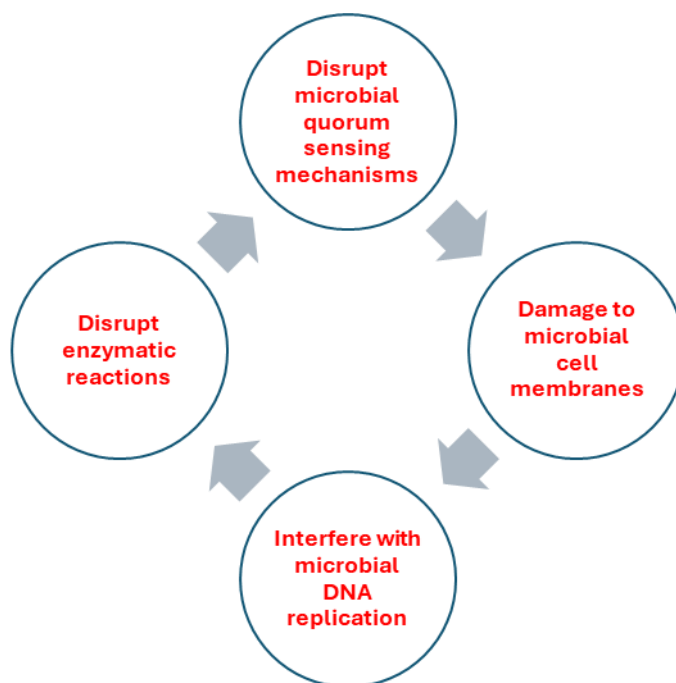


Fig. 6. Inhibition mechanisms of nanoparticles

Disadvantages and Limitations of Applied Nanoparticles for Wood Protection

The incorporation of inorganic components into organic polymers is frequently employed in wood coverings to improve mechanical characteristics; as padding, the stiffness and toughness of the inorganic substances are successfully paired with the processing capacity of the polymer; the use of inorganic elements in micron size has drawbacks, such as reducing the material's capacity to and affecting the protective system's accountability (Havrlik and Ryparová 2015), while the use of inorganic elements in nano-size boosts the amount of surface area and the proportion of the surface region, which in turn affects the raw materials characteristics (Papadopoulos and Taghiyari 2019). Tebuconazole was encapsulated by Salma *et al.* (2010) using the nanoprecipitation process. Based on the core/polymer shell proportion, hydrophilic copolymers of gelatin bonded with methyl methacrylate were used to create the polymer capsules incorporating tebuconazole. The measured dimensions of these capsules ranged from 10 to 100 nm. According to reports, enclosed tebuconazole can protect wood from a fungus that causes brown rot. However, the chemical composition system created by Salma *et al.* (2010) is adaptable and simple to alter by the copolymerisation of additional acrylic monomers, such as hydroxyethyl methacrylate. This suggests that the rate of dissolution of tebuconazole can be modified. Nevertheless, the drawback of these nanocapsules is their propensity for formation, which lowers the effectiveness of their distribution into the wood. Furthermore, determining exactly what conditions must be met in order to use NPs to accomplish an excellent degree of wood conservation is challenging. It was investigated whether NPs of various sizes and shapes, sprayed at varying levels, could protect various wood species from various fungus. Additionally, the NPs were applied in a variety of ways. Concerns over NPs' potential effects on the ecosystem is growing. Thus, more investigation ought to be carried out (Piętko *et al.* 2022).

CONCLUSIONS

Wood is an essential raw material with many applications in industry. The motivation for using nanotechnology in wood scientific and technological applications is due to its special ability to effectively and thoroughly enter wood surfaces to change the chemical composition of the wood's outer layer. Wood, as an unprocessed product, is enhanced by nanomaterials, which also somewhat changes its inherent characteristics. The characteristics of the wood are eventually improved upon treatment using various types of NPs. The increased interface area that results from treating wood with NPs is the basis for any possible changes in its characteristics. This occurs as a result of the fragments being much reduced in size.

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