

Recent Developments in Bio-Based and Antibacterial Wood Coatings: Sustainable Strategies and Future Perspective

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Abstract: Wood materials are widely used in both structural and decorative applications and engineering due to their renewable resources, low density, and environmentally friendly properties. However, these materials are highly susceptible to environmental factors such as humidity, temperature changes, harmful ultraviolet radiation from the sun, and microbial attack, and can undergo physical, chemical, and biological degradation over time. In recent years, extensive research has been conducted on bio-based, antibacterial coatings for wood surfaces. Environmentally friendly materials derived from renewable resources, such as chitin, lignin, cellulose nanofibers, natural waxes, and plant-derived polyphenols, offer high-performance protective properties. Studies on antibacterial composite coatings containing antimicrobial agents to prevent microbial-induced degradation on wood surfaces have also increased significantly. This study aims to propose a feasible and durable strategy for bio-based materials and antibacterial wood coatings used for wood surface protection.

Keywords: wood coating; bio-based materials; antibacterial coating; sustainable materials.

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1. Introduction

Wood is one of the oldest building and engineering materials used in human history and still maintains its importance today. It is widely used in the construction industry, furniture industry, interior design, packaging industry, and decorative applications due to its renewable origin, low density, high strength-to-weight ratio, ease of processing, and aesthetic appearance. It also plays an important role in sustainable material technologies due to its carbon storage capacity. Increasing global environmental concerns and efforts to reduce dependence on fossil fuels have brought wood back to the fore as an environmentally friendly engineering material [1-3].

However, the natural structure of wood has some disadvantages. Wood exhibits hygroscopic behavior due to the hydroxyl groups in its cell walls and is easily affected by changes in environmental humidity. Swelling and shrinkage events resulting from moisture absorption can negatively affect dimensional stability, leading to surface cracks and reduced mechanical properties. In addition, ultraviolet (UV) rays, temperature changes, rain, oxygen, and other atmospheric factors cause color change, lignin degradation, and surface aging on

wooden surfaces. The biodegradability of wooden materials by fungi, bacteria, and other microorganisms is one of the important factors that limit their useful life [4,5]. Various protective processes and coating systems have been used for many years to protect wooden surfaces. Traditional protection methods include solvent-based paints, varnishes, synthetic resins, and various chemical impregnations. Although these systems increase wood's resistance to environmental influences, they often contain volatile organic compounds (VOCs), toxic solvents, and petroleum-based raw materials. Increasing environmental awareness and understanding of sustainable production have made it necessary to develop alternative coating technologies with lower environmental impact [6]. In recent years, biobased materials have become an important research area in the development of environmentally friendly coating systems. These materials, derived from renewable resources, not only offer sustainability benefits but also exhibit high functional properties. Biobased components such as chitosan, lignin, cellulose nanofibers, natural waxes, and plant polyphenols can enhance the mechanical performance of coatings, provide UV protection, and help protect against biodegradation. The environmentally compatible structure and biodegradability of these materials enable them to play an important role in the coating technologies of the future [7-9]. Developments in nanotechnology have also opened up new opportunities in the field of wood protection. Multifunctional coating systems can be developed, especially as a result of the combined use of metal and metal oxide nanoparticles and biopolymers. Nanomaterials such as silver nanoparticles (AgNP), zinc oxide (ZnO), and titanium dioxide (TiO₂) show strong antibacterial properties and contribute to the prevention of microbial colonization on wooden surfaces. In addition, some nanoparticles can increase the weather resistance of coatings by absorbing or reflecting UV rays [10,11]. Antibacterial wooden coatings have attracted great attention in recent years, especially in healthcare buildings, educational institutions, public areas, and interior applications. Bacterial adhesion and biofilm formation on wooden surfaces can cause various problems both aesthetically and hygienically. For this reason, wood protection systems are not only expected to provide physical and chemical resistance, but also have properties that inhibit microbial growth. Hybrid systems that combine biobased materials and antibacterial nanoparticles offer effective solutions to this need [12].

The published studies have investigated bio-based wood preservation systems, self-healing coatings, and sustainable coating technologies. However, a comprehensive review integrating both bio-based coating materials and antibacterial wood preservation strategies is limited. In this review study, biobased materials used in advanced wood coatings and current developments in antibacterial wood coating technologies have been comprehensively evaluated. First, the properties and application areas of biobased components commonly used in wood protection applications are discussed, followed by an examination of the different materials and approaches used in antibacterial coating systems. Additionally, an up-to-date perspective on sustainable wood preservation technologies is presented by discussing current research trends, technological limitations, and future areas of work.

2. Bio-Based Materials Used in Wood Coatings

Sustainability in the chemical industry is achieved through various efforts such as minimizing volatile organic compound emissions, reducing toxicity, and enhancing sustainability and recyclability. These efforts accelerate green technology innovation and enhance the global competitiveness of industries and economies by firmly establishing green sustainability as a cornerstone of future development. Bio-based coating materials derived from

renewable biomass through chemical or physical evaluation are obtained from sustainable raw materials, exhibiting low environmental impact and biodegradability [13,14].

2.1. Chitosan-based wood coatings.

The chitin (chitosan) biopolymer, obtained by deacetylation, is one of the most researched materials in bio-based coating technologies due to its functional properties. Chitosans release non-toxic byproducts such as amino sugars, CO₂, and H₂O during degradation. Due to their antibacterial and biodegradable properties, chitosans have gained importance in environmentally friendly applications because of their biocompatible, biodegradable, and non-toxic structure. The amino and hydroxyl functional groups in the chitosan molecular structure allow it to form strong interactions with a wide variety of surfaces. These properties offer excellent film-forming ability and improved adhesion performance in surface coating applications. Research indicates that chitosan-based composite coatings have highly beneficial, non-toxic properties for the environment. They derive these properties from the fact that their positively charged amino groups interact with the negatively charged microbial cell membranes, altering membrane permeability and inhibiting microbial growth. These hybrid formulations have shown significant potential to improve mechanical properties, provide controlled release, and ensure long-term protection [15,16]. A schematic chitosan coating on the wood surface is given in Figure 1.

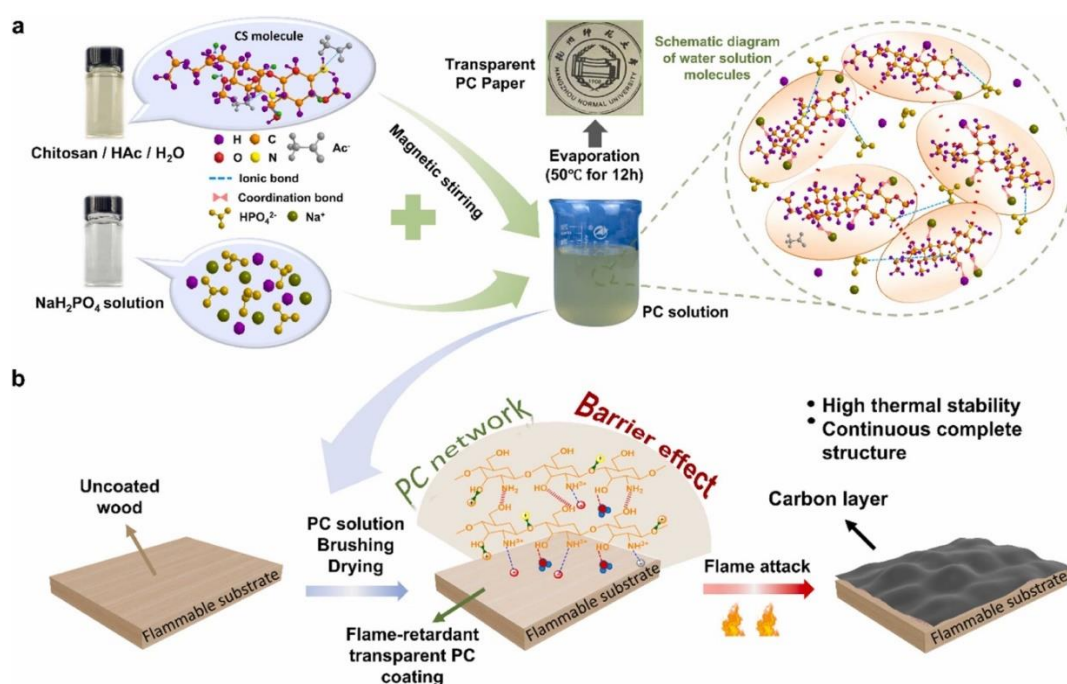


Figure 1. Schematic diagram of transparent coating using chitosan/NaH₂PO₄: (a) preparation of coating materials; (b) coating on a flammable substrate (Reproduced from Ref. [15] with permission. Copyright (2025) Publisher).

2.2. Lignin-based wood coatings.

Lignin is one of the essential structural components of plant cell walls and is considered the second most abundant biopolymer in nature after cellulose. Lignin's aromatic structure gives it the ability to absorb ultraviolet (UV) rays and neutralize free radicals. Therefore, lignin-based coatings are effective in reducing discoloration and surface deterioration on wood surfaces exposed to sunlight. Furthermore, thanks to its strong antioxidant properties, lignin

increases the resistance of coating systems to oxidative aging. Recent research has shown that lignin nanoparticles can serve as carrier materials and, when combined with antibacterial components, enable the development of multifunctional coating systems. With these properties, lignin is considered not only a sustainable and environmentally friendly biomaterial but also an important functional additive that improves coating performance [17,18].

2.3. Natural waxes and hydrophobic bio-based additives.

Natural waxes and oils are among the most effective hydrophobic protective coating materials known in bio-based coating systems for increasing water repellency. Derived from plant and animal products, waxes and oils provide strong water repellency to coated surfaces thanks to their low surface energy. These coating materials reduce the tendency of wood surfaces to absorb water, increase their resistance to water, and contribute to maintaining dimensional stability without the need for chemical treatment. Furthermore, their biodegradability makes them attractive for environmentally friendly, sustainable coating technologies. Recent studies have shown that combining natural waxes with cellulose nanofibers and various biopolymers can yield more advanced hybrid coating systems. These hybrid coatings increase resistance to environmental effects while improving long-term protection, thereby extending the lifespan of wood surfaces [19,20].

3. Antibacterial Wood Coatings

Biological degradation processes on wood surfaces are among the most important factors limiting the material's lifespan. In particular, bacteria, fungi, and other microorganisms can form colonies on wood surfaces, causing both aesthetic and structural problems. Biofilm formation, which begins with microorganism adhesion to the surface, can lead to changes in surface properties, discoloration, and a loss of mechanical performance over time. Therefore, in recent years, coating systems with antibacterial properties have become an important research area in wood protection technologies. The main purpose of antibacterial coatings is to prevent microorganisms from adhering to the surface or to reduce biological degradation by preventing the multiplication of adhering microorganisms. Antibacterial systems used today generally consist of metal nanoparticles, metal oxide nanoparticles, biopolymer-based materials, and combinations thereof. In particular, advancements in nanotechnology have enabled high antibacterial efficacy with small amounts of additives [21,22].

3.1. Coatings containing silver nanoparticles.

Silver nanoparticles (AgNPs) are one of the most commonly used nanomaterials in antibacterial applications. Although the antimicrobial properties of silver have been known for many years, reducing it to nanoparticle size has significantly increased its surface area and further enhanced its antibacterial efficacy. AgNP-containing coatings can directly affect the cell membrane of bacteria, disrupting cellular integrity. In addition, the released silver ions inhibit cellular metabolism, suppress enzyme activity, and negatively affect the functions of genetic material. As a result of these mechanisms, bacterial cells cannot multiply and are quickly rendered ineffective. Many studies in the literature have reported that AgNP-doped coatings exhibit over 99% antibacterial efficacy against common bacteria, including *Escherichia coli* and *Staphylococcus aureus*. However, high cost and potential environmental impacts are among the factors limiting the use of silver nanoparticles [23].

3.2. Zinc oxide nanoparticles.

Zinc oxide (ZnO) nanoparticles have attracted significant attention in recent years due to their high antibacterial performance and economic advantages. One of the most important advantages of ZnO is that it not only exhibits antibacterial properties but also provides UV protection and photocatalytic activity. ZnO nanoparticles damage bacterial cell membranes by causing the formation of reactive oxygen species on the surface. Furthermore, the release of zinc ions negatively affects microbial metabolism. This dual effect results in broad-spectrum antibacterial performance. It has been reported that ZnO-modified systems used in wood coatings increase biological resistance while also providing resistance to external environmental conditions. Therefore, ZnO nanoparticles are among the most promising additives for sustainable antibacterial coating systems [24,25].

3.3. Titanium dioxide-based systems.

Titanium dioxide (TiO₂) is another nanomaterial widely used in antibacterial coating technologies due to its photocatalytic properties. TiO₂, activated under UV light, damages the cellular structure of microorganisms by generating high amounts of reactive oxygen species. Thanks to its photocatalytic mechanism, it is possible not only to neutralize bacteria but also to break down surface-accumulated organic pollutants. Therefore, TiO₂-doped coatings can exhibit self-cleaning behavior in addition to their antibacterial properties. However, the fact that the effectiveness of TiO₂ largely depends on the presence of light is considered a significant limitation. In recent years, studies have been conducted on modified TiO₂ systems that can also be activated under visible light [23-25].

3.4. Hybrid antibacterial wood coating systems.

Currently, research is shifting from single-function coatings to multi-function systems. In this context, hybrid systems are being developed that combine biopolymers, metal nanoparticles, and water-based resins. These systems not only provide antibacterial protection but also offer additional benefits, including UV and moisture resistance, mechanical strength, and long-term environmental stability. It is reported that ZnO and AgNP additives dispersed within water-based polyurethane matrices create high-performance wood protection systems. Hybrid coatings developed in recent years are considered among the wood protection technologies of the future due to their ability to combine sustainability and high performance on the same platform [26,27]. Qi *et al.* [26] have developed antibacterial AgCu nanoparticles coating on the wood surface (Figure 2) and characterized its crystal, morphological, and structural properties.

4. Future Perspectives and Challenges

Studies on bio-based wood coatings show that sustainable materials not only offer environmental advantages but also provide high-performance protective properties. Bio-based materials such as chitosan, lignin, cellulose nanofibers, and plant-derived polyphenols have become key components of advanced coating systems. In addition, antibacterial systems supported by nanoparticles such as AgNP, ZnO, and TiO₂ contribute to the effective protection of wood surfaces against biological degradation. Future research is expected to focus entirely on bio-based resin systems, smart surfaces, controlled release mechanisms, and

environmentally friendly nanoparticle technologies. Furthermore, AI-assisted material design and data-driven optimization methods are projected to play a significant role in the development of next-generation coatings. The development of industrially applicable, economical, and long-lasting bio-based antibacterial coatings will remain a key research area in future wood preservation technologies.

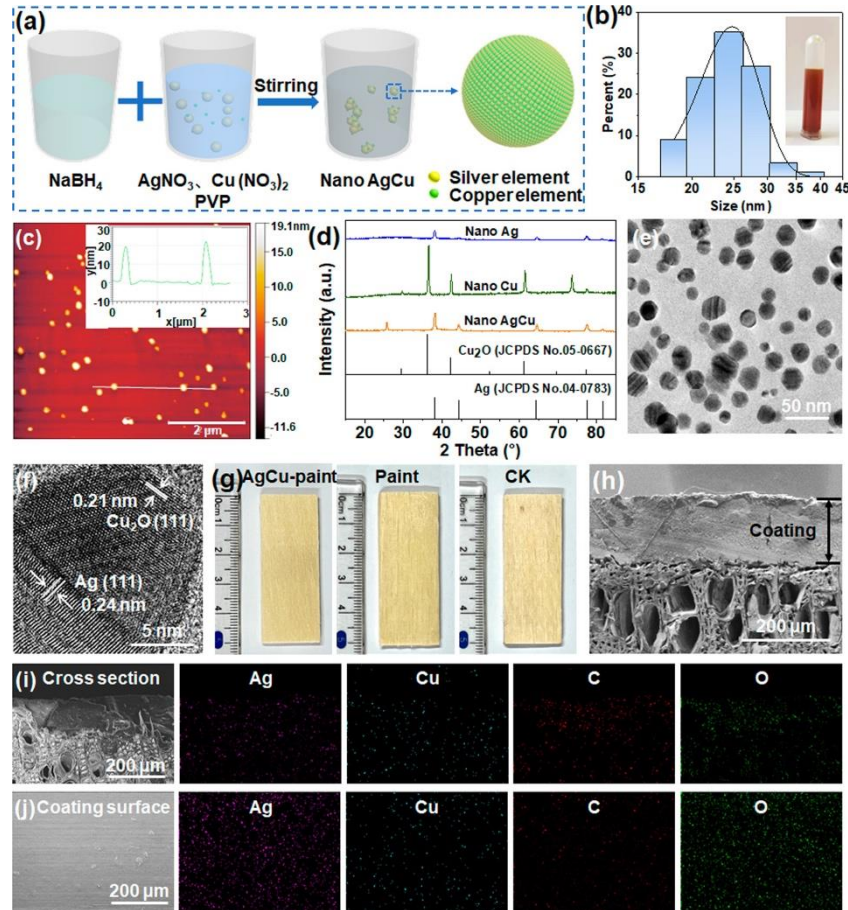


Figure 2. Antibacterial AgCu nanoparticles hybrid coating: (a) schematic preparation of AgCu nanoparticles; (b) size distribution; (c) AFM image of AgCu; (d) XRD pattern of AgCu; (e,f) TEM images of AgCu; (g) hybrid coated wood photos; (h-j) SEM image of coated wood surface with EDX analysis (Reproduced from Ref. [26] with permission. Copyright (2024) Publisher)

Author Contributions

Conceptualization, A.Y.; methodology, A.Y.; formal analysis, A.Y.; investigation, A.Y. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest

References

1. Calovi, M.; Coroneo, V.; Rossi, S. Antibacterial efficiency over time and barrier properties of wood coatings with colloidal silver. *Appl. Microbiol. Biotechnol.* **2023**, *107*, 5975–5986, <https://doi.org/10.1007/s00253-023-12710-1>.
2. Chang, Y.; Liu, E.; Wu, Z. Constructing chitosan microcapsules using hydroxypropyl methylcellulose for self-healing antibacterial wood coating. *Int. J. Biol. Macromol.* **2025**, *308*, 142300, <https://doi.org/10.1016/j.ijbiomac.2025.142300>.
3. Zou, Y.; Zhang, Y.; Li, P.; Qiao, J.; Wu, Y.; Li, X.; Zuo, Y. Water-resistant, transparent, and highly efficient flame-retardant wood coating. *Ind. Crops Prod.* **2025**, *223*, 120061, <https://doi.org/10.1016/j.indcrop.2024.120061>.
4. Sharma, T.; Manik, G. Sustainable UV-resistant and anti-bacterial wood coating reinforced with cellulose nanofibers (CNF) and titanium dioxide nanoparticles: Synthesis, characterization and properties. *Int. J. Biol. Macromol.* **2025**, *303*, 140533, <https://doi.org/10.1016/j.ijbiomac.2025.140533>.
5. Liang, Y.; Zuo, H.; Wen, M.; Shi, J.; Park, H. Self-healing, flame retardant and UV resistant lignin-derived epoxy wood coating with a Schiff base structure. *Int. J. Biol. Macromol.* **2025**, *286*, 138393, <https://doi.org/10.1016/j.ijbiomac.2024.138393>.
6. Yan, C.; Fang, Y.; Yang, R.; Yan, M.; Wang, W.; Song, Y.; Wang, Q. A novel organic-inorganic hybrid ceramicizable intumescent coating for wood fire protection. *Prog. Org. Coat.* **2025**, *200*, 109037, <https://doi.org/10.1016/j.porgcoat.2024.109037>.
7. Jirouš-Rajković, V.; Miklečić, J. Heat-Treated Wood as a Substrate for Coatings, Weathering of Heat-Treated Wood, and Coating Performance on Heat-Treated Wood. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 8621486, <https://doi.org/10.1155/2019/8621486>.
8. Kúdela, J.; Liptáková, E. Adhesion of coating materials to wood. *J. Adhes. Sci. Technol.* **2006**, *20*, 875–895, <https://doi.org/10.1163/15685610677638725>.
9. Rowell, R.; Bongers, F. Coating Acetylated Wood. *Coatings* **2015**, *5*, 792-801, <https://doi.org/10.3390/coatings5040792>.
10. Sykam, K.; Hussain, S.S.; Sivanandan, S.; Narayan, R.; Basak, P. Non-halogenated UV-curable flame retardants for wood coating applications: Review. *Prog. Org. Coat.* **2023**, *179*, 107549, <https://doi.org/10.1016/j.porgcoat.2023.107549>.
11. Chang, Y.; Yan, X.; Wu, Z. Application and prospect of self-healing microcapsules in surface coating of wood. *Colloid Interface Sci. Commun.* **2023**, *56*, 100736, <https://doi.org/10.1016/j.colcom.2023.100736>.
12. Kassaun, B.B.; Fatehi, P. Solvent-Free Lignin-Silsesquioxane wood coating formulation with superhydrophobic and Flame-Retardant functionalities. *Chem. Eng. J.* **2024**, *493*, 152582, <https://doi.org/10.1016/j.cej.2024.152582>.
13. Calovi, M.; Zanardi, A.; Rossi, S. Recent Advances in Bio-Based Wood Protective Systems: A Comprehensive Review. *Appl. Sci.* **2024**, *14*, 736, <https://doi.org/10.3390/app14020736>.
14. Wang, F.; Morsali, M.; Rižikovs, J.; Pylypchuk, I.; Mathew, A.P.; Sipponen, M.H. Fully bio-based water-resistant wood coatings derived from tree bark. *Mater. Horiz.* **2024**, *11*, 6504-6515, <https://doi.org/10.1039/D4MH01010H>.
15. Lv, P.-Y.; Feng, X.-L.; Shi, Q.; Wan, J.-J.; He, S.-Y.; Kong, D.-M.; Li, Y.; Cao, C.-F.; Gao, J.-F.; Wang, W.; Zhang, G.-D.; Tang, L.-C. Chitosan-based transparent and flame-retardant bio-composite coatings for wooden materials with rapid fire monitoring response. *Constr. Build. Mater.* **2025**, *491*, 142765, <https://doi.org/10.1016/j.conbuildmat.2025.142765>.
16. Cho, W.; Shields, J.R.; Dubrulle, L.; Wakeman, K.; Bhattarai, A.; Zammarano, M.; Fox, D.M. Ion – complexed chitosan formulations as effective fire-retardant coatings for wood substrates. *Polym. Degrad. Stab.* **2022**, *197*, 109870, <https://doi.org/10.1016/j.polymdegradstab.2022.109870>.
17. Sreejaya, M.M.; Jeevan Sankar, R.; K, R.; Pillai, N.P.; Ramkumar, K.; Anuvinda, P.; Meenakshi, V.S.; Sadanandan, S. Lignin-based organic coatings and their applications: A review. *Mater. Today: Proc.* **2022**, *60*, 494-501, <https://doi.org/10.1016/j.matpr.2022.01.325>.

18. Ruwoldt, J.; Blindheim, F.H.; Chinga-Carrasco, G. Functional surfaces, films, and coatings with lignin – a critical review. *RSC Adv.* **2023**, *13*, 12529–12553, <https://doi.org/10.1039/D2RA08179B>.
19. Krishnan P, S.; Rowthu, S.; Kalpathy, S.K. Durable Bio-Based Hydrophobic Recrystallized Wax Coatings. *ACS Appl. Bio Mater.* **2025**, *8*, 1437-1450, <https://doi.org/10.1021/acsabm.4c01672>.
20. Kończak, B.; Uszok, E.; Białowas, M.; Wiesner-Sękala, M.; Zawartka, P.; Klus, M.; Klus, L. Biodegradation of Hydrophobic Coatings Based on Natural Wax and Its Mixtures. *Sustainability* **2026**, *18*, 509, <https://doi.org/10.3390/su18010509>.
21. Feng, B.; Zhang, S.; Wang, D.; Li, Y.; Zheng, P.; Gao, L.; Huo, D.; Cheng, L.; Wei, S. Study on antibacterial wood coatings with soybean protein isolate nano-silver hydrosol. *Prog. Org. Coat.* **2022**, *165*, 106766, <https://doi.org/10.1016/j.porgcoat.2022.106766>.
22. Chang, Y.; Wu, Z.; Liu, E. Fabrication of chitosan-encapsulated microcapsules containing wood wax oil for antibacterial self-healing wood coatings. *Ind. Crops Prod.* **2024**, *222*, 119438, <https://doi.org/10.1016/j.indcrop.2024.119438>.
23. Jafarpisheh, F.; Kolvir, H.R.; Ghorbanpour, M. Photocatalytic self-cleaning and antibacterial activity of modified wood by Ag doped TiO₂ nanoparticles. *Next Mater.* **2024**, *4*, 100207, <https://doi.org/10.1016/j.nxmater.2024.100207>.
24. de Caro, T.; Toro, R.G.; Cassone, L.; Barbaccia, F.I.; Zaratti, C.; Colasanti, I.A.; La Russa, M.F.; Macchia, A. Functionalization of Artwork Packaging Materials Utilizing Ag-Doped TiO₂ and ZnO Nanoparticles. *Molecules* **2024**, *29*, 3712, <https://doi.org/10.3390/molecules29153712>.
25. Paul, D.; Petrič, M.; Humar, M.; Fabjan, E.Š.; Gaff, M.; Tesařová, D. Enhancing the superhydrophobicity, UV-resistance, and antifungal properties of natural wood surfaces *via in situ* formation of ZnO, TiO₂, and SiO₂ particles. *Nanotechnol. Rev.* **2025**, *14*, 20250171, <https://doi.org/10.1515/ntrev-2025-0171>.
26. Qi, Y.; Wei, L.; Dong, Y.; Gong, R.; Wang, X.; Yao, F.; Liu, Y.; Kong, L.; Dong, X.; Li, Y. AgCu Nanoparticles as an Antibacterial Coating for Wood. *ACS Appl. Nano Mater.* **2024**, *7*, 5339-5347, <https://doi.org/10.1021/acsanm.3c06115>.
27. Grigorescu, R.M.; Ion, R.-M.; Iancu, L.; Slamnoiu-Teodorescu, S.; Gheboianu, A.I.; Alexandrescu, E.; David, M.E.; Constantin, M.; Raut, I.; Damian, C.M.; Nicolae, C.-A.; Trica, B. Sustainable and Functional Polymeric Coating for Wood Preservation. *Coatings* **2025**, *15*, 875, <https://doi.org/10.3390/coatings15080875>.

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