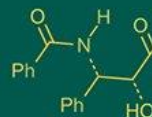


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(9): 508-512
www.biochemjournal.com
Received: 01-06-2026
Accepted: 03-07-2026

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Green solutions: Eco-friendly wood preservatives for improving wood durability

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i9Sg.9873>

Abstract

Wood remains an indispensable material across construction, packaging, infrastructure, and furniture sectors due to its favourable strength-to-weight ratio, workability and renewable origin. However, its susceptibility to biodegradation by fungi, insects, moisture and ultraviolet (UV) radiation intensifies the global demand for effective preservation systems. Conventional chemical preservatives-especially creosote, pentachlorophenol (PCP) and chromated copper arsenate (CCA)-have historically provided long-term protection but pose significant ecological and human-health risks due to toxicity, bio-persistence and leaching potential. Consequently, the transition toward green, non-toxic, biodegradable and sustainable preservatives has become scientific priority.

This review synthesizes recent advancements in plant-based extracts, essential oils, mineral-derived preservatives, bio-polymers, nanomaterials and biological control agents. Case studies (tobacco waste extract, Ginkgo biloba leaf extract, mimosa/quebracho extracts, mistletoe and lichen extracts, and essential oils) are critically analysed for their antifungal efficacy, mass-loss reduction and overall durability performance. Innovative technologies such as nanotechnology, plasma treatment, thermal modification, genetic improvement and biocontrol strategies are also evaluated. Collectively, the reviewed evidence suggests that eco-friendly wood preservatives show substantial potential, particularly for indoor applications, although challenges remain in outdoor durability, long-term performance, cost-effectiveness and regulatory acceptance. The review underscores the need for further research into synergistic formulations, nanostructured carriers and fixation technologies to enhance environmental safety while ensuring robust wood protection.

Keywords: Plant extracts, nanotechnology, essential oils and bio-based preservatives

Introduction

Wood is an essential material in construction, furniture manufacturing and various other industries due to its strength, versatility and natural aesthetics. However, it is highly susceptible to degradation caused by fungi, insects, moisture and UV radiation. Over time, these factors compromise the structural integrity and longevity of wood, making preservation techniques necessary to enhance its durability (Liu *et al.*, 2024) [8]. Traditionally, chemical preservatives have been the primary solution, providing significant protection against biological and environmental threats. These treatments extend the lifespan of wood by 20 to 40 times, making them indispensable in various applications (Schmidt, 2006) [13].

In 2020, North America led the wood preservatives industry, with the market expected to reach \$1.7 billion by 2025 (Khademibami and Bobadilha, 2022) [5, 6]. This growth reflects the increasing demand for durable and long-lasting wood products across industries. Chemical preservatives, such as chromated copper arsenate (CCA) and creosote, have been widely used for their effectiveness in protecting wood against decay and insect infestations. However, concerns over their potential health and environmental impacts have led to increased scrutiny. These chemicals can leach into soil and water, posing risks to ecosystems and human health, prompting regulatory restrictions and a search for safer alternatives (Richardson, 2002) [12].

In response to these concerns, the development of eco-friendly wood preservatives has gained momentum. Green solutions prioritize sustainability by reducing toxicity while maintaining the protective qualities of traditional preservatives. These alternatives include natural oils, bio-based compounds, and heat treatments that enhance wood durability without harmful effects.

For instance, plant-based preservatives, such as essential oils from neem and eucalyptus, have shown promise in repelling insects and fungi (Morrell *et al.*, 2010) ^[10]. Additionally, modified wood treatments, such as thermal modification and acetylation, alter the wood's structure to improve its resistance to decay, making them viable non-toxic options (Hill, 2006) ^[12].

Eco-friendly preservatives not only minimize environmental harm but also contribute to a circular economy by utilizing renewable resources and reducing reliance on hazardous chemicals. Many sustainable treatments involve biodegradable or naturally derived compounds that do not release toxic residues into the environment. Furthermore, green wood protection methods align with global efforts to reduce carbon footprints and promote sustainable construction practices (Temiz *et al.*, 2013) ^[17]. As consumer awareness grows and regulations tighten, the demand for safer and more sustainable wood preservatives is expected to increase, driving innovation in the field (Schultz and Nicholas, 2002) ^[14].

The shift toward eco-friendly wood preservatives marks a crucial step in balancing durability with sustainability. As industries seek effective yet responsible solutions, ongoing research and technological advancements continue to enhance the performance of green preservatives. By adopting environmentally friendly alternatives, the wood industry can reduce its ecological impact while ensuring long-lasting and high-quality wood products (Jones *et al.*, 2019) ^[4]. The transition to sustainable wood protection methods is not just a trend but a necessary evolution in response to environmental and health concerns, paving the way for a greener future in wood preservation.

Environmental impact of chemical-based wood preservatives

Chemical-based wood preservatives, such as chromated copper arsenate (CCA), creosote, and pentachlorophenol, have been widely used to protect wood from decay and pests. However, these preservatives pose significant environmental risks, particularly due to their toxicity and persistence in ecosystems (Richardson, 2002) ^[12].

One major concern is soil and water contamination. Chemicals from treated wood can leach into surrounding environments, introducing toxic substances like arsenic, chromium, and polycyclic aromatic hydrocarbons (PAHs). These compounds have been found to persist in soil and groundwater, affecting plant growth and aquatic life (Lebow *et al.*, 2004) ^[10]. Creosote, in particular, has been linked to long-term water pollution, leading to fish mortality and biodiversity loss (Weis and Weis, 1995) ^[18].

Wildlife is also at risk from chemical preservatives. Birds, amphibians, and soil organisms can suffer from exposure to toxic compounds, leading to reproductive and developmental issues. Creosote-treated wood, often used in outdoor structures, has been associated with harmful effects on amphibians and soil microbes, disrupting natural ecosystems (Eisler, 1989) ^[1].

Additionally, human health risks arise from exposure to wood preservatives. Workers in wood treatment industries and individuals handling treated wood may experience respiratory problems, skin irritation, and long-term neurological effects. Burning treated wood can release hazardous substances like dioxins and volatile organic

compounds (VOCs), further contributing to air pollution (McLean *et al.*, 2009) ^[9].

Given these concerns, regulatory restrictions on chemical preservatives have increased, driving interest in eco-friendly alternatives. Sustainable solutions such as bio-based preservatives and heat treatments offer effective protection while minimizing environmental harm. As awareness grows, the transition to greener wood protection methods becomes essential for long-term ecological balance and human safety.

Eco-friendly wood preservatives

Eco-friendly wood preservatives are non-toxic and biodegradable solutions that offer effective protection for wood without causing harm to human health or the environment. These alternatives utilize natural or low-impact compounds to enhance durability while minimizing contamination. Unlike traditional chemical preservatives, which can leach harmful substances into soil and water, eco-friendly options provide a sustainable way to extend the lifespan of wood products.

The adoption of these innovations plays a crucial role in supporting global environmental goals. By shifting towards sustainable practices and effective wood protection methods, eco-friendly preservatives contribute to reducing ecological damage and promoting environmental stewardship. Their development signifies a growing awareness of the need for safer alternatives in the wood industry, ensuring long-term sustainability without compromising performance (Singh and Singh, 2012) ^[15].

Characteristics of eco-friendly wood preservatives

The characteristics of eco-friendly wood preservatives emphasize sustainability and safety. These preservatives are designed with low toxicity, ensuring they do not pose significant health risks to humans or the environment. Their biodegradability allows them to break down naturally over time, reducing long-term contamination and minimizing their ecological footprint. Additionally, human safety is a key advantage, as these preservatives do not release harmful chemicals, making them safer for workers and end-users.

Another crucial characteristic is environmental safety, as eco-friendly wood preservatives prevent soil and water pollution, preserving ecosystems. They also promote recycling and reuse, allowing treated wood to be repurposed without generating hazardous waste. By incorporating these features, eco-friendly wood preservatives contribute to sustainable development while ensuring long-lasting protection for wood materials (Lebow *et al.*, 2004) ^[10].

Types of eco-friendly wood preservatives

There are various types of eco-friendly wood preservatives available on the market, each offering unique benefits and applications depending on the type of wood and intended use. The main categories include plant-based preservatives, mineral-based preservatives, and innovative green chemicals.

Plant-Based Preservatives

Plant-based preservatives include essential oils and plant extracts. Essential oils, such as linseed oil, tung oil, and soybean oil, penetrate deeply into wood fibers, forming a protective barrier against moisture and insects without harmful chemicals. These oils enhance the natural beauty of the wood while providing a durable finish.

Plant extracts are also used as wood preservatives due to their antimicrobial, antifungal, and insect-repelling properties. These extracts contain bioactive compounds such as tannins, flavonoids, alkaloids, and essential oils that protect wood from decay and pests. Common plant extracts used include tannin extracts from oak, chestnut, and mimosa, as well as *Azadirachta indica* (neem), eucalyptus, clove, and pine resin extract (Liu *et al.*, 2024) ^[8].

Mineral-Based Preservatives

Mineral-based preservatives include borates and silicates. Borates (boric acid & borax) are effective in preventing fungal growth and insect infestations, while being non-toxic to humans and having a low environmental impact. Silicates (sodium silicate) create a protective layer on wood surfaces, enhancing durability and resistance to moisture. They act as a physical barrier against pests and decay without harmful chemical residues (Liu *et al.*, 2024) ^[8].

Innovative Green Chemicals

New advancements in wood preservation have introduced organic acids, bio-based polymers, and nano-preservatives as eco-friendly alternatives. Organic acids, such as citric acid, acetic acid, lactic acid, and oxalic acid, help inhibit microbial growth and protect wood from rot without leaving toxic residues.

Bio-based polymers, derived from renewable resources, can be used to coat wood surfaces, improving resistance to water and pests. Examples include starch-based polymers, polylactic acid (PLA), chitosan, and lignin-based resins.

Nano-preservatives employ nanoparticles that penetrate deeply into the wood, offering long-lasting protection. Common nanoparticles used include silver (AgNPs), copper (CuNPs), zinc oxide (ZnO), titanium dioxide (TiO₂), and silica nanoparticles. These innovative solutions ensure enhanced wood protection while remaining environmentally friendly (Liu *et al.*, 2024) ^[8].

Benefits of eco-friendly wood preservatives

Eco-friendly wood preservatives offer numerous benefits, contributing to a healthier indoor and outdoor environment. These preservatives help maintain the integrity of wood while eliminating the risks associated with toxic chemicals. By using eco-friendly alternatives, the woodworking industry promotes sustainable practices that reduce environmental impact. Additionally, these products provide durability by acting as a protective barrier against insects and rot. They are also non-toxic, ensuring safety for both humans and nature. Water-based formulations with low VOCs (volatile organic compounds) further enhance environmental friendliness. Furthermore, these preservatives support cleaner air quality, reducing harmful emissions and fostering a greener future (Singh and Singh, 2012) ^[15].

Challenges for eco-friendly wood preservatives

Eco-friendly wood preservatives come with several challenges despite their benefits. One major drawback is their higher initial cost, as they tend to be more expensive than traditional chemical-based alternatives. Additionally, their effectiveness and longevity can be a concern, as some natural preservatives may not last as long as synthetic options. Limited availability poses another issue, as these products are not as widely accessible in all regions compared to conventional treatments (McLean *et al.*, 2009) ^[9].

Application and maintenance can also be more demanding, requiring frequent reapplication or special techniques for effective use. Regulatory approval is another hurdle, as newer eco-friendly formulas may undergo strict testing and approval processes before reaching the market. In harsh conditions, such as extreme weather, heavy moisture, or termite-prone areas, these preservatives may not offer the same level of durability as chemical treatments (Jang and Kang, 2024) ^[3]. Lastly, consumer awareness and adoption remain low, with many people unfamiliar with or skeptical about the effectiveness of eco-friendly wood preservatives.

Innovative Technologies for Natural Wood Preservation

Nanotechnology in wood preservation involves manipulating materials at the nanoscale to achieve desirable properties and functions. Some applications of nanotechnology include the use of nanoparticles, nanocellulose, and coatings/films.

Metal nanoparticles, such as silver and copper nanoparticles, have shown antimicrobial properties and can be incorporated into wood preservatives to enhance their effectiveness against decay-causing fungi and insects. Nanocellulose, derived from wood fibers, can be used to reinforce wood composites and improve their mechanical properties. Additionally, nanocoatings and thin films can be applied to wood surfaces to provide barriers against moisture, UV radiation, and biological degradation (Khademibami and Bobadilha, 2022) ^[5, 6]. Plasma technology for wood treatment involves the use of ionized gases to modify the surface properties of materials. This technology has gained attention as a potential method for wood treatment and preservation. Heat and thermal modifications include subjecting wood to high temperatures in controlled conditions to alter its structure and properties. These treatments can enhance the durability, dimensional stability, and resistance of wood to decay and insects.

Other innovative approaches include genetic modification and biological control agents. Genetic engineering techniques aim to develop genetically modified trees with enhanced natural resistance to pests and decay fungi. By identifying genes responsible for wood defense mechanisms, scientists can transfer them to economically valuable tree species. Biological control agents, such as beneficial microorganisms like bacteria and fungi, can be used to inhibit the growth of decay fungi and protect wood from degradation (Liu *et al.*, 2024) ^[8].

Studies on Green Wood Preservatives

Tobacco Waste Extract

Liu *et al.* (2024) ^[8] investigated the antifungal potential of tobacco waste extracts prepared using water, 50% ethanol, and absolute ethanol as eco-friendly wood preservatives. Among the tested fractions, the water extract exhibited the highest antifungal efficacy against the brown-rot fungus *Gloeophyllumtrabeum* and the white-rot fungus *Trametes versicolor*, particularly at concentrations ranging from 40 to 80 mg mL⁻¹. Chemical characterization revealed nicotine and neophytadiene as the principal bioactive compounds responsible for fungal inhibition. Wood samples of *Pinus yunnanensis* and *Hevea brasiliensis* treated with these extracts showed a significant reduction in mass loss compared to untreated controls, confirming enhanced resistance to decay. The study highlights the possibility of valorizing tobacco agricultural waste into a sustainable, low-

toxicity wood preservative, especially suitable for indoor applications where environmental and human safety are critical.

Ginkgo biloba Leaf Extract

The preservative efficacy of *Ginkgo biloba* leaf (GBL) extract was evaluated by Jang and Kang (2024) ^[3] using *Pinus koraiensis* wood exposed to the white-rot fungus *T. versicolor*. GBL-treated wood samples recorded only 9.9 percent mass loss, in contrast to 34.1 percent in untreated controls, demonstrating substantial improvement in decay resistance. According to the Korean Standard KS F 2213, the treated wood was classified as “resistant,” indicating performance comparable to commercial preservatives. Notably, GBL treatment preserved the natural colour and appearance of wood, unlike conventional alkaline copper quaternary (ACQ-2) preservatives, which often cause discoloration. These findings suggest that *G. biloba* leaf extract represents an aesthetically acceptable and environmentally benign alternative for green wood preservation.

Mimosa and Quebracho Extracts

Tascioglu *et al.* (2013) ^[16] assessed the decay resistance of Scotch pine treated with tannin-rich extracts derived from Mimosa (*Acacia mearnsii*) and Quebracho (*Schinopsis* spp.). At treatment concentrations of 9-12 percent, both extracts resulted in less than 5 percent mass loss when exposed to major wood-decaying fungi, including *T. versicolor*, *Pleurotus ostreatus*, *Fibroporia palustris*, and *G. trabeum*. The high antifungal efficacy was attributed to the presence of condensed tannins, which interfere with fungal enzyme activity and cell wall integrity. The biodegradable nature and renewable origin of these tannins indicate strong potential for their integration into sustainable wood preservative formulations.

Lichen (*Usnea filipendula*) and Mistletoe (*Viscum album*) Extracts

Yildiz *et al.* (2020) ^[19] explored the antifungal performance of lichen (*Usnea filipendula*) and mistletoe (*Viscum album*) extracts prepared using hot water and methanol solvents. The extracts were applied to wood at different concentrations and their retention and decay resistance were subsequently evaluated. In all treatments, mistletoe extracts exhibited higher retention levels compared to lichen extracts, indicating better fixation within the wood matrix. The lowest mass loss values were observed at concentrations of 15 percent for water extracts and 18.75 percent for methanol extracts, suggesting optimal antifungal performance at these levels. The study demonstrated that these plant taxa possess natural bioactive compounds capable of inhibiting fungal degradation, supporting their suitability for use in natural antifungal wood protection systems.

Essential Oils

Panek *et al.* (2014) ^[11] evaluated the antifungal efficacy of ten essential oils as potential green preservatives for wood protection. Among the tested oils, thyme (*Thymus vulgaris*), oregano (*Origanum vulgare*), sweet flag (*Acorus calamus*) and clove (*Syzygium aromaticum*) exhibited the strongest inhibitory effects against the brown-rot fungus *Coniophoraputeana* and common mould fungi. An effective

concentration of approximately 3.5 percent was sufficient to significantly suppress fungal growth. Although treated wood developed a mild yellowish coloration, the colour remained stable after artificial ageing, indicating acceptable long-term aesthetic performance. These essential oils are particularly suitable for indoor wood preservation, while further improvements in fixation and leaching resistance could enhance their applicability for outdoor conditions.

Conclusion

Eco-friendly wood preservatives represent a promising and increasingly necessary alternative to conventional toxic preservative systems. Plant-derived extracts (tobacco waste, *Ginkgo biloba*, mimosa, quebracho, lichen, mistletoe) and essential oils demonstrate significant antifungal performance and clear environmental advantages. Mineral-based systems, nanotechnology-enhanced coatings, and thermal or plasma treatments further expand the portfolio of sustainable wood protection technologies. However, while these green preservatives are suitable for indoor use, improvements in fixation, long-term stability, and cost-efficiency are essential for outdoor applications. With continued research and technological innovation, eco-friendly wood preservatives have the potential to redefine the global wood protection industry towards a more sustainable and biologically compatible future.

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