e-planet **23** (1): 01-14 (June 2025)

Eco-toxicological impact of wood preservatives and its sustainable mitigation strategies: A review

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Date of receipt: 16.01.2024 Date of acceptance: 04.05.2025

ABSTRACT

Wood preservatives are both organic and inorganic additives which are extensively utilized to improve the longevity and resilience of wooden products. Nonetheless, their usage causes considerable environmental threats. Wood preservatives, such as creosote and chromated copper arsenate, zinc and copper compounds have the potential to leach into soil and water, causing toxicity in aquatic ecosystems and possible bioaccumulation within food chains. Furthermore, these preservatives may also pollute water sources, negatively impacting microbial communities and aquatic life. This paper investigates the harmful effects of these preservatives on the ecosystem. The study highlights the necessity for sustainable alternatives and regulatory measures to reduce the ecological impact of wood preservatives, stressing the significance of environmental safety in choosing and application of these chemicals.

Key words: Chemicals, ecosystem, environment, preservation, wood preservatives

INTRODUCTION

In earlier times, people relished the benefit of having plentiful high-quality wood sourced from natural forests. The wood, possessing excellent inherent qualities, was typically a ‘ready to use’ raw material that required minimal processing. However, the availability of these wood raw materials has diminished, similarly with scarcity of water resources (Panda et al., 2023) and little significant supply is anticipated from natural forests in the future (Dubey, 2010). The reliance of wood industries on fast-growing plantation wood as the primary raw material is expected to markedly increase in the coming years (Carle and Holmgren, 2008; FAO, 2009). Public awareness regarding the effects of human actions on the environment is rising, and environmental factors are altering how materials are used. Therefore, it is crucial to create products that have a minimal impact on the environment (Dubey, 2010).

Wood is a globally essential and economically significant material (Emenike et al., 2024). It is extensively utilized because of its beneficial properties, including low density, high impact strength, low thermal conductivity, and a strong strength-to-weight ratio (Winandy and Rowell, 2005; Cardarelli, 2018). The Forest Service and various government organizations frequently utilize pressure-treated wood for building highway bridges, foot bridges, wetland boardwalks, and other instances where the wood is installed in or above water (Lebow et al., 2002). It is a primary product that is renewable and sustainable, and it continues to be utilized to produce timber and various secondary products. However, since wood being a lignocellulosic material composed of lignin, cellulose, hemicellulose, and trace amounts of pectin, it is vulnerable to biodegradation by various organisms such as fungi, insects, and termites, which decompose the polymers in plant cell walls using cellulases and hemicellulases

(Eaton and Hale, 1993; Papola et al., 2025). Due to its complex and recalcitrant structure, of lignin its degradation is primarily carried out by specific groups of microorganisms, notably certain fungi and bacteria (Hatakka, 2005). As a result, it is necessary to shield wood using eco-friendly and biodegradable materials that can guarantee an extended lifespan and safe disposal of wooden items (Mishra et al., 2022).

Wood treatment is an essential process that is used to increase the longevity of wood and wood products to keep them unaffected by insects, marine borers, and decay (Li et al., 2017). In the protection of wood, there are different approaches to preserve it such as wood preservation (using chemicals for protection), thermal modification (heating wood at high temperatures (typically 160/260°C), bio based treatments (natural compounds like tannins, chitosan, lignin derivatives, essential oils), nanomaterials like metal nanoparticles (Ag, Cu, ZnO), nano-cellulose, and nano-silica and wood modification (altering its properties for protection) (Hill, 2006; Singh and Singh, 2012; Schubert et al., 2020; Khademibami and Bobadilha, 2022). Treatment of wood using chemical and biological substances to protect its integrity from decay caused by living organisms like insects, fungi, bacteria, mildew, algae, and other microbes known as wood preservation (Ryszard and Małgorzata, 2016). Nevertheless, they can cause considerable harm to the environment. The traditional chemical methods for wood preservation rely on a wide range of biocide formulations, including copper or organic biocides, copper-organometallics, and preservatives that are metal-free (Hughes, 2004). The most frequently used wood preservatives include chemicals such as arsenic, copper, chromium, and creosote. These compounds have the potential to seep into nearby soil and water systems, resulting in contamination (Bates et al., 2000; Hingston et al., 2001b).

One of the main worldwide issues are the presence of heavy metals, which are naturally occurring in the environment and are transported into water bodies, through air, soil and by human activities (Rehman et al., 2021; Mitra et al., 2022). The negative effects of inorganic preservatives are widely noticed which occure due to the presence of heavy metals in other context, some heavy metals, are necessary micronutrients needed by plants and animals for a variety of physiological and biochemical processes. However, when their concentrations beyond physiologically safe thresholds often because of human activities like mining, industrial waste, and excessive pesticide use-problems occur (Alloway, 2013). The primary heavy metals include copper, chromium, zinc, and others (Xing et al., 2020b). The pollution by heavy metals poses a significant threat to both environment and human health threating the balance of ecosystems and long-term ecological health (Raina and Sharma, 2024). According to the environmental risk assessment and review of preservative-treated wood and wood products, the Scientific Committee on Toxicity, Ecotoxicity, and the Environment of the European Commission concluded that treated wood and wood products pose risks to human health, presents significant danger to children's health (Mohajerani et al., 2018). The wood preservatives may circulate between living organisms via the food chain. This transfer can occur through ecological models in both terrestrial and aquatic environments. These pathways are widely documented in existing research, pinpointing the main exposure route along with a multi-pathway risk assessment (Xing et al., 2020a).

TYPES OF WOOD PRESERVATIVES

Wood preservatives are categorized into various generations based on their chemical makeup and effectiveness. Below is a concise summary of the primary types:

First generation wood preservatives

Creosote

A wood preservative sourced from coal tar, it is effective against fungi and insects but raises environmental issues. It has been used as a wood preservative for many years. Due to the presence of known cancer-causing chemicals, its use became restricted or banned (JORF, 1992).

Applications

Used for railroad ties, utility poles, marine pilings, and bridge timbers due to strong water and insect resistance. Not suitable for residential use due to toxicity.

Pentachlorophenol (PCP)

This preservative works well against wood decay and insects, but it faces regulations due to its toxic nature and environmental effects.

Applications

Applied to utility poles, fence posts, foundation timbers, and industrial lumber. Its use is now restricted to industrial settings.

The two main oil-based preservatives, creosote and pentachlorophenol, have been widely utilized for many years in the preservation of timber, ties, poles, and piling (Lebow et al., 2002).

Second generation wood preservatives

Chromated Copper Arsenate (CCA)

A commonly used preservative that combines copper, chromium, and arsenic, efficient for structural uses but has been banned for residential applications due to health risks (Preston, 2000). When CCA is applied to wood, chromium reacts chemically with both copper and arsenic, binding them to the wood's cellulose, hemicellulose, and lignin components. This reduces leaching of toxic elements, particularly arsenic, by forming insoluble complexes within the wood matrix (Cooper and Ung, 1992). However, over time and under certain environmental conditions (e.g., acidic soils), chromium and arsenic may still leach, leading to environmental concerns (Hingston et al., 2001a).

Applications

Formerly used in residential decks, playgrounds, fences, and marine structures. Now banned in residential uses in many countries due to arsenic toxicity. Still used for industrial and agricultural purposes.

Alkaline Copper Quaternary (ACQ)

A less harmful substitute for CCA that effectively protects against fungi and insects, frequently applied in residential settings (Morrell and Lebow, 2005a). ACQ is a second-generation, arsenic-free wood preservative. It replaces arsenic with quaternary ammonium compounds (quats), which are effective fungicides and insecticides. Copper remains the primary biocide, but quats enhance its spectrum by targeting organisms that might be copper-tolerant. This formulation maintains high biocidal efficiency while eliminating the toxicity and environmental persistence associated with arsenic (Lebow, 2004; Morrell and Lebow, 2005a, b).

Applications

Commonly used in residential decking, fencing, play structures, and outdoor furniture. Safer alternative to CCA.

Third generation wood preservatives

Copper Azole (CA)

A more environment friendly option compared to CCA and ACQ, it offers robust protection against decay and insect damage. There are two variants of Copper Azole: type A (CBA-A) and type B (CA-B). Copper Boron Azole type A is composed of the following elements: copper (49%), boron present as boric acid (49%), and azole in the form of tebuconazole (2%). Copper Azole type B contains copper (96.1%) and azole as tebuconazole (3.9%) (EPA, 2011). Boron compounds highly are effective against fungi and insects (Freeman et al., 2006), they are typically utilized in scenarios where leaching is not a concern.

CA-A (Copper Azole Type A) and CA-B (Copper Azole Type B) are both wood preservatives that utilize copper as the primary biocide along with tebuconazole as a secondary fungicide. The inclusion of boron (in the form of boric acid) in CA-A broadens its antifungal capabilities, making it especially effective against a wider variety of wood-destroying organisms in controlled indoor environments. Nevertheless, the solubility of boron in water makes it susceptible to leaching in situations with high moisture or outdoors, which diminishes its long-lasting effectiveness in wet or humid climates (Freeman and McIntyre, 2008). On the other hand, CA-B does not contain boron, instead opting for a stronger concentration of copper and tebuconazole. This formulation exhibits better resistance to leaching, rendering it more appropriate for outdoor and ground-contact uses, such as decks, fences, and landscape timbers (EPA, 2011).

Applications

Decking, fencing, landscaping timbers, patios, gazebos, and outdoor furnitures.

Fourth generation wood preservatives

Micronized copper preservatives (MCP)

Utilizing tiny copper particles, they preserve wood while enhancing safety and minimizing environmental effects without sacrificing effectiveness (Hasanagić et al., 2023).

Applications

Sill plates, joists, and beams, especially in moisture-prone or insect-exposed areas.

EMERGING TECHNOLOGIES

Nanotechnology, the chemical alteration of wood using nanoparticles, and plasma technology are innovative wood protection techniques for the future. Plasma technology mainly serves as a technique for modifying surfaces to improve the functionality and lifespan of wood. It entails treating wood with a cold plasma field, which consists of an ionized gas made up of electrons, ions, and reactive species like oxygen or nitrogen radicals. This method changes the chemical and physical characteristics of the wood surface while leaving the bulk material unaffected, resulting in increased hydrophobicity, better adhesion for coatings, and enhanced resistance to microbial threats (Mishra et al., 2022).

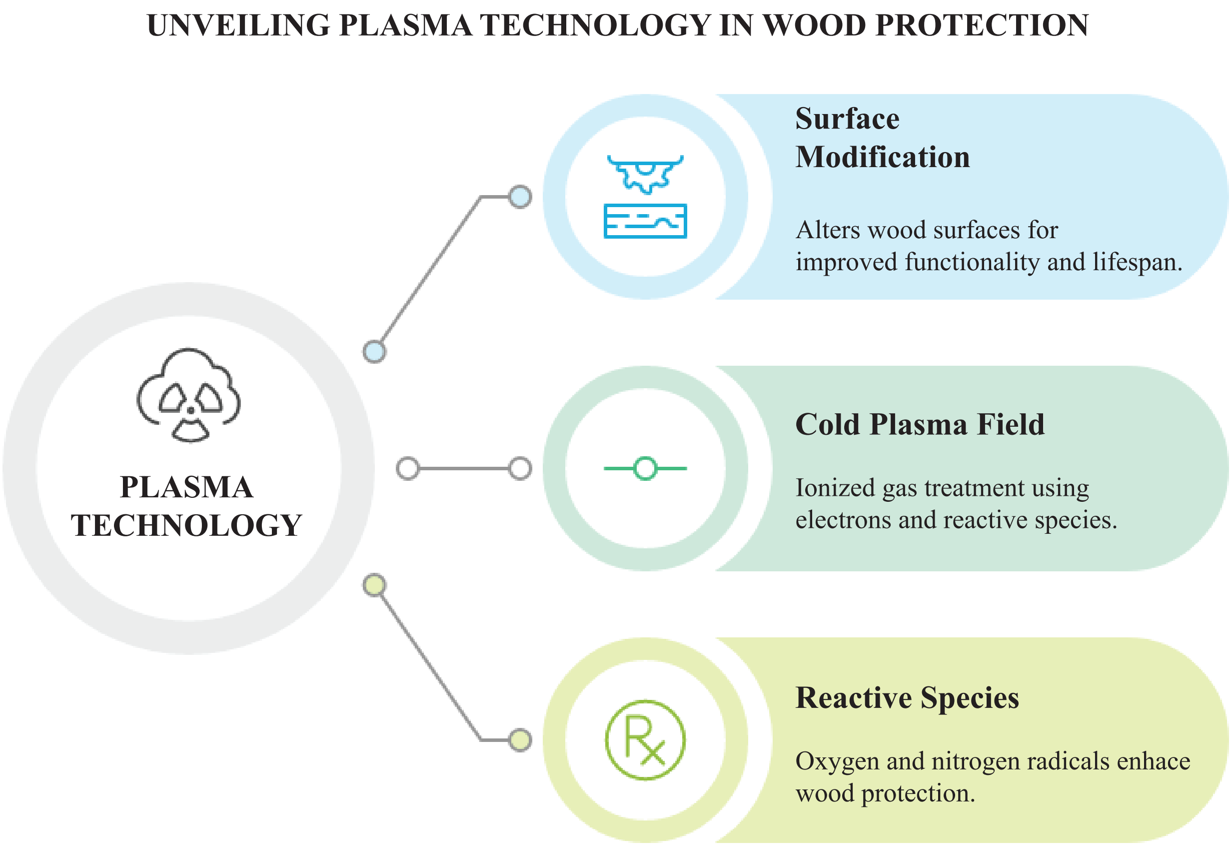

Fig. 1. Plasma technology in wood protection

Table 1. Different types of wood preservatives

Generations	Preservative Type	Description	Advantages	Limitations/ Concerns	References
1st Generation	Creosote	Coal tar-derived oil-based preservative effective against fungi and insects	Long history of use; good protection	Carcinogenic PAHs; environmental restrictions	Lebow et al. (2002)
	Pentachlorophenol (PCP)	Chlorinated phenol compound used for utility poles and ties	Effective against fungi and insects	Toxicity; environmental persistence; regulatory bans	Lebow et al. (2002)
2nd Generation	Chromated Copper Arsenate (CCA)	Inorganic compound of copper, chromium, and arsenic	Strong structural protection	Arsenic toxicity; banned for residential use	Preston (2000)
	Alkaline Copper Quaternary (ACQ)	Copper-based with quaternary ammonium compounds	Safer than CCA; widely used in residential settings	Higher copper content may increase corrosion of fasteners	Morrell and Lebow (2005 a, b)
3rd Generation	Copper Azole (CA-A, CA-B)	Copper combined with azole fungicides (e.g., tebuconazole)	Highly durable and environmentally friendlier	Costlier than earlier generations	EPA (2011)
	Boron Compounds	Inorganic borates used mainly indoors	Effective, low toxicity	Leaching in wet conditions	Freeman et al. (2006)
4th Generation	Micronized Copper Preservatives (MCP)	Submicron copper particles fixed in wood matrix	Less leaching; high efficacy; safer for workers Submicron copper particles fixed in wood matrix	Newer, cost implications	Hasanagić et al. (2023)
Emerging technologies	Nanotechnology	Incorporates nanoparticles (e.g., ZnO, CuO) for protection	Deep penetration; antimicrobial; UV-resistant	Long-term impacts under study	Mishra et al. (2022)
	Plasma Technology	Uses cold plasma for surface modification	Improves hydrophobicity and coating adherence	Experimental; industrial scaling challenges	Mishra et al. (2022)

ENVIRONMENTAL ISSUES

The environmental pollution worldwide causes global human health problems due to exposure to toxic substances (Jan et al., 2024). The environmental issues associated with organic, inorganic and nano-based wood preservatives have been described here under.

The wood preservative chemicals such as ammoniacal copper arsenate (ACA), ammoniacal copper zinc arsenate (ACZA), creosote, methyl arsenic (MA), chromated copper arsenate (CCA), copper dimethyl dithiocarbonate (CDDC), pentachlorophenol (PCP) and chromated copper borate (CCB) can lead to chemical spills and leaching from woodpiles, resulting in the contaminations of soil and water bodies (Miranji et al., 2022). Creosote which is a by-product obtained from the distillation of coal tar, which is further processed with sodium hydroxide, re-acidified, and re-distilled, comprising a diverse mixture of polycyclic aromatic hydrocarbons (Xing et al., 2020a). It primarily contains polycyclic aromatic hydrocarbons (PAHs), many of them are classified as carcinogenic to humans and as pollutants in the environment (U.S. EPA, 2008). These PAHs tend to decompose into their elemental parts, particularly at lower concentrations (Smith, 2023). The surface soils at the American creosote works site, covering roughly eight acres of main processing and drip tracks, are predominantly made up of sands and silts, which have been contaminated by creosote, PCP, and dioxin (Bates et al., 2000). Furthermore, the toxicity to humans and animals, the potential environmental risks, and the surface leaching of these treated materials are significant disadvantages associated with creosote treatment (Gallacher et al., 2017).

Pentachlorophenol is a solid compound formed from the reaction between chlorine and phenol (Xing et al., 2020a). Phenol undergoes stepwise electrophilic chlorination to produce a mixture of chlorinated compounds including pentachlorophenol depending on reaction conditions and temperature. The hydroxyl group in phenol activates its ring to electrophilic substitution at the ortho and para positions. Initially, monochlorophenol forms when exposed to chlorine then further chlorine addition produces di- tri- and tetrachlorophenols ultimately leading to PCP when chlorine is in excess. However, this reaction does not produce the desired product only as the chlorine attaches in a non-selective order. Unwanted by-products resulting from this non-selective chlorination process include lower chlorinated phenols and potentially hazardous chlorinated dioxins and furans in high temperature and poorly controlled industrial conditions (Bevenue and Beckman, 1967; HSDB, 2021). One organochlorine substance that has been utilized as a disinfectant and insecticide is pentachlorophenol. It is an artificial compound produced by the catalytic chlorination of phenol at 191°C. This is the standard industrial synthesis method for PCP. However, the process is not perfectly selective, and it often yields a mixture of chlorinated phenols and toxic by-products, such as dioxins and furan (PubChem, 2018).

One of the most widely used wood preservatives, is pentachlorophenol, which is currently considered to be a potential pollutant. It poses a risk to human health and the environment (Emenike et al., 2024). The aquatic environment is particularly vulnerable to PCP and its derivatives, which is a general environmental problem. Environmental elements like concentration, pH, and adsorption to suspended solids, temperature, rate of biodegradation, and rate of photodecomposition significantly impact the hazardous nature of PCP (AEOC, 1980). Their bioaccumulation potential in aquatic organisms is quite substantial owing to their high levels of toxicity and relatively high-water solubility (Muir et al., 1999). When aquatic species are exposed to PCP, they may suffer from short-term or long-term harmful consequences. 68 $\mu g\ L^{-1}$ for chinook salmon, 52 $\mu g\ L^{-1}$ for rainbow trout, 205 $\mu g\ L^{-1}$ for fathead minnow, 68 $\mu g\ L^{-1}$ for channel catfish, and 32 $\mu g\ L^{-1}$ for bluegill sunfish are the lethal concentration 50 (LC50). LC50 stands for lethal concentration 50%, which is the concentration of a substance, e.g., a wood preservative or nanoparticle, in water that is expected to cause death in 50% of a test population of aquatic organisms-typically within a specified time period, such as 96 hours for fish) values (Johnson and Finley, 1980).

The amount of chemical needed to kill the organism within a set amount of time is known as the lethal concentration, and it is 50. PCP alters numerous enzymes involved in glycolysis and the citric acid cycle, partially uncoupling phosphorylation and boosting oxygen consumption, which impacts fish energy metabolism (Weinbach et al., 1954; Boström and Johansson, 1972).

The compounds containing hexavalent chromium (47.5%), copper (18.5%) and inorganic arsenic (34%) are combined with water to develop a wood preservative called chromated copper arsenate (Coles et al., 2014; Chen and Olsen, 2016). Wood products that have been treated with CCA have demonstrated negative effects on both the environment and human health, primarily because of the leaching and build-up of metals/metalloid, particularly arsenic, from the wood into the surrounding environment (Morais et al., 2021). Traditional wood preservatives like CCA have been commonly utilized, but their continued use has been prohibited since January 2004 because of environmental issues (Freeman et al., 2006). The release of water-soluble CCA from treated wood leads to problems with groundwater and soil (Babaee et al., 2018). Concerns regarding contaminants seeping from the product into the soil below and the possible health risks associated with arsenic exposure through skin contact have led to an agreement between the US EPA and the treated wood industry to gradually discontinue the product's use in most residential settings by 2004 although it remains permissible for specific marine and industrial uses (US EPA, 2002).

It protects wood from the damage caused by termites, insects, decay bacteria, and other organisms that degrade wood. The Cu^{2+}, Cr^{6+}, and As^{5+}, the three primary active components of CCA, chromium, and arsenic are one of the most hazardous heavy metals chromium can also induce bronchitis, pharyngitis, and other similar symptoms produce neuritis and harms the skin. Since 2004, there have been risks and pollution issues with CCA preservatives in the US and Europe. The use of CCA preservatives has been steadily prohibited by many countries. The growing apprehension regarding the application of CCA in the treatment of lumbar due to the potential for hazardous metals to seep into the soil and eventually into water systems (Liu et al., 2020).

At present, most wood preservatives available in the market are water-based and primarily based on copper, which poses possible risk to the environment (Xing et al., 2020b). With the introduction of water-based preservatives which exhibit significant surface properties and enhanced performance, oil-based preservatives have slowly been phased out, leading to increased exploration of water-based preservatives across different applications (Xing et al., 2020a, b). The growing concern about azoles and their effects on human health relates to their possible function as endocrine disruptors (Connell, 1999; Taxvig et al., 2007). There are worries about exposure to agrochemical azoles for farmers, consumers, and employees of pesticide companies.

Typically, exposure levels are quite minimal and are regulated by stringent laws that establish an Admissible Daily Intake for each chemical (Giavini and Menegola, 2010). Ramwell et al. (2005) pointed out that agricultural workers might encounter epoxiconazole residues on the outer surfaces of spraying equipment. Miconized copper azole, considered as the fourth generation of copper-based preservative are nowadays in trend Hasanagić et al. (2023). The vulnerability of copper particles to oxidation and biodegradation, the possible release of copper nanoparticles into the environment, and the absence of standardization and regulation regarding their quality and performance have been studied by Hasanagić et al., 2023. However, the primary drawback of borate-based formulations is their propensity to leach when subjected to outdoor environments (Yamaguchi, 2003). Boron is not chemically bonded to wood, and it can be washed away if the wood is exposed to a moist environment while in use (Caldeira, 2010).

Nanotechnology-based treatments are often promoted as eco-friendly treatments. Some studies suggest that nanoparticles (e.g., copper or silver nanoparticles) may leach into the environment and pose ecological risks leading to potential toxicity.

The bioavailability and unknown long-term effects may provide serious health hazards. A variety of published studies have raised concerns about the health risks linked to nanoparticles (Lee et al., 2010). The extensive use of synthetic nanomaterials have raised safety concerns and prompted an evaluation of the risks associated with nanotechnology, from production to degradation (Athulya et al*.,* 2024). Risk control (RC) methodology is one of the models that is used to examine life cycle assessment. It was shown in case studies of industrial i) nano-enabled products, such as basic copper carbonate ($Cu_2(OH)_2CO_3$) and nano-scale copper oxide (CuO), which are commonly used as antifungal coatings on treated wood, and ii) nanoscale pigments, such as carbon black and red organic pigment, which are used to color plastic automotive parts (Athulya et al., 2024). The nanoCu-treated wood could potentially disperse into the environment and be inhaled, posing risks to human health (Civardi et al., 2015). Exposure to nano-Cu, especially via inhalation, is associated with several potential health risks such as respiratory toxicity: Inhaled nano-Cu can penetrate deep into the lungs, causing inflammation, oxidative stress, and potential damage to alveolar cells. Animal studies show lung tissue damage and immune responses after nano-Cu exposure (Karlsson et al., 2008). It is recommended to enhance research aimed at assessing toxicity and interactions in environmental exposure (Anjum et al., 2015).

The silver, copper, and zinc oxide are examples of nanosized metallic wood preservatives which are employed in wood protection by the application of nanotechnology. Better and more adequate preservative/metal retention in wood would result from the nanometal treatment, which would the wood against wood degradation (Taghiyari et al., 2014; Harandi et al., 2016). In comparison to the traditional formulations such as CCA, PCP etc, they show a high degree of penetration and are uniformly absorbed into the wood (Matsunaga et al., 2009). Künniger et al. (2013) examined the functionality and environmental effects of metallic nanoparticles of silver (Ag) and observed that the overall release of silver from nano Ag products was directly related to the extent of coating erosion. Additionally, there were signs that metallic nano Ag undergo transformation into Ag complexes which are less toxic than ionic silver (Borges et al., 2018). The growing application of nano-sized CuO and $Cu_2(OH)_2CO_3$ as wood protectants has led to worries regarding the possibility of these materials causing negative effects on human health (Hristozov et al., 2018).

The study demonstrated that life cycle risks which are associated with sanding and sawing of nano-scale copper oxide are not appropriate and would require a more effective risk control strategy, the nano-related risks associated with nanopigments could be easily controlled through specific modifications (Semenzin et al., 2019).

CHALLENGES ASSOCIATED WITH CONVENTIONAL WOOD PRESERVATIVES

The conventional wood preservatives are commonly utilized to safeguard wood from deterioration, insects, and decay. However, they present several challenges. Numerous traditional wood preservatives include harmful chemicals like chromated copper arsenate (CCA) and pentachlorophenol, which can endanger human health and wildlife. Exposure can occur during the application, utilization, or disposal of treated wood. The leaching of these conventional wood preservatives into soil and water can result in ecosystem contamination (Hingston et al., 2010). Some substances such as chromated copper arsenate (CCA), creosote, and pentachlorophenol (PCP) can remain in the environment and accumulate in organisms, leading to prolonged ecological consequences (USEPA, 2008). Growing awareness about the health and environmental dangers linked to conventional preservatives results in stricter regulations and prohibitions in various areas (European Commission, 2003). This may restrict the options available for wood treatment. Although many traditional preservatives are initially effective, their performance over time can be inconsistent. Several biotic and abiotic factors such as weathering, UV exposure, and microbial activity can diminish their effectiveness.

Some preservatives can change the appearance of wood, causing discoloration or staining, which may be undesirable for applications valuing the wood's natural aesthetics. The costs of treated wood might be enhanced due to the treatment process. Additionally, ongoing maintenance and possible replacements can contribute to long-term expenses. Certain preservatives may not be appropriate for all wood types or conditions, which can limit their application in specific situations or environments. The use of conventional wood preservatives can pose health risks to workers in handling hazardous substances necessitating the implementation of protective equipment and safety protocols. Some occupational safety organizations have set comprehensive recommendations and exposure limits to help reduce these dangers. For instance, in order to lower the risk of long-term exposure-related illnesses like cancer, respiratory disorders, and skin conditions, the Occupational Safety and Health Administration (OSHA) in the United States establishes Permissible Exposure Limits (PELs) for arsenic (0.01 mg m^{-3}), chromium VI (0.005 mg m^{-3}), and creosote (0.2 mg m^{-3} for coaltar pitch volatiles) as per the report of OSHA (2023).

REPLACEMENT OF CONVENTIONAL WOOD PRESERVATIVES

The international limitations on commonly used first-generation wood preservatives, such as creosote, oil-based pentachlorophenol, and water-based arsenicals like chromated copper arsenate (CCA), have led to the development of environment friendly, sustainable, cost-efficient, and effective methods for wood protection (Mishra et al., 2022). Growing environmental challenges in recent years have resulted in significant transformations in industrialized nations concerning sustainable development, particularly in wood preservation (Hasanagić et al., 2023). This shift has created new possibilities for developing 'non-biocidal' alternatives through chemical or thermal treatment of wood (Schultz et al., 2007). Natural materials are gaining increasing attention as a source of preservatives as they are easy to obtain, affordable, and environment friendly (Xia and Jia, 2023).

Plant extracts have attracted considerable interest as natural substitutes for chemical wood preservatives. These extracts are rich in various bioactive compounds that help in safeguarding wood against deterioration caused by fungi, insects, and other organisms. The promise of plant extracts lies in their capability to offer eco-friendly and sustainable solutions for preserving wood (Hasanagić et al., 2023). To safeguard wood against fungal and other biological harm, natural preservatives like essential oils present a promising option when compared to the highly toxic conventional wood preservatives (Kartal et al., 2006; Maoz et al., 2007). Furthermore, essential oils with fragrance, volatile compounds are obtained from plants using various extraction techniques. For centuries, they have been utilized in a range of applications, including as natural substitutes for chemical wood preservatives. They are rich in bioactive compounds, essential oils exhibit antimicrobial and insecticidal traits, making them effective in safeguarding wood against decay, fungi, termites, and other pests (Hasanagić et al., 2023).

Some microorganisms and the substances they produce have been studied for their potential application as wood preservatives (Hasanagić et al., 2023). Trichoderma fungi are recognized for their ability to combat wood decay. Certain species of Trichoderma generate enzymes and metabolites that suppress the proliferation of harmful fungi, positioning them as promising options for bio-based wood preservation (Ribera et al., 2017).

Currently, chitosan is regarded as a fascinating eco-friendly substance for the preservation of wood. It is utilized as a potential wood preservative either on its own or in conjunct with other biocides to combat fungi that inhabit the wood (Schmidt et al., 1995; Chittenden et al., 2004; Larnøy et al., 2006). For instance, chitosan-based coatings can be applied as films or absorbed into wooden surfaces to offer protection against fungi and microbes, frequently enhanced with natural substances or metal ions like copper or zinc. These biodegradable biopolymer coatings have demonstrated effectiveness in decreasing mold growth and decay in wood that has been treated (Fernández-Costas et al., 2017). Chitosan possess non-toxic, biodegradability and antimicrobial activity (Xu et al., 2010; Kumar et al., 2017; Ikono et al., 2019).

Wood modifications are gaining popularity as a method to boost the functionality of wood, whether it's to increase durability or enhance its performance. Wood modifications are gaining increasing popularity as sustainable, durable alternatives to traditional chemical preservatives. Driven by growing environmental awareness, regulatory restrictions on toxic preservatives, and the demand for high-performance, low-maintenance materials, modified wood offers enhanced properties through physical, chemical, or biological treatments without introducing harmful substances into the environment. Common modification techniques include thermal modification, acetylation, and furfurylation (Rowell, 2012; Zelinka et al., 2022). Thermal treatment is a highly beneficial alternative method for modifying wood, significantly enhanced its durability (Candelier and Dibdiakova, 2021). As noted by Sandberg and Kutnar (2016), heat-treated wood products, can aid in addressing climate change and fostering sustainable development by lowering energy consumption, decreasing solid and volatile emissions, minimizing pollution, and lessening harm to ecosystems (Marra et al., 2015), all while enhancing the performance of wood. The chemical alteration of solid wood is typically studied to enhance its dimensional stability by lowering its moisture affinity and to boost its resistance to biological decay. The first aspect involves altering the hydroxyl groups of wood cell wall polymers via esterification, carbamatation, or alkylation reactions; the second aspect pertains to infusing polymerizable monomers or resins into the wood matrix to create wood polymer composites after undergoing *in situ* polymerization (Gérardin, 2016).

CONCLUSION

Wood preservatives are frequently utilized to prolong the longevity of wood in both outdoor and indoor settings, and they often comprise chemicals like copper, chromium, arsenic, and various toxic substances. These compounds have the potential to leach into the soil, water, and adjacent environments, resulting in detrimental effects on ecosystems. The main harmful consequences include soil and water contamination, toxicity to aquatic organisms, disruption of microbial communities, and possible hazards to wildlife and human health. Furthermore, the bioaccumulation of these chemicals may cause long-term harm to the environment and interfere with natural processes. Meanwhile, stringent regulations on the use of toxic chemicals, rising problems with the disposal of chemically treated wood, and growing awareness of using eco-friendly preservatives have encouraged wood protection scientists to seek alternatives for traditional preservative systems. To summarize, the use of natural wood preservatives and modification techniques presents promising and environmentally friendly alternatives to traditional chemical treatments. By employing natural substances such as plant extracts, oils, resins, and other bio-based materials, these approaches not only boost wood's resistance to decay, pests, and moisture but also promote sustainability by decreasing dependence on harmful chemicals. Furthermore, wood modification methods, including heat treatment, acetylation, and furfurylation, further enhance the durability, dimensional stability, and overall effectiveness of wood in a variety of applications. A trade-off occurs with each method of modification between cost, performance, and environmental impact. High-performance options like acetylation and furfurylation come at a higher price. Thermal modification is cost-effective and eco-friendly but slightly weakens the wood.

ACKNOWLEDGEMENT

The authors are thankful to the Director, ICFRE-Institute of Wood Science and Technology, Bengaluru, India for extending necessary support during the study.

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