Advances in Wood Preservation Technology: A Review of Conventional and Nanotechnology Preservation Approaches

Zhexun Ong,[a] Mohammad Nasir Mat Arip,[b] Shahlinney Lipeh,[c] Arnaud Besserer,[d] Nicolas Brosse,[d] Emmanuel Fredon,[d] G. Veera Singham,[e] Kah Hay Yuen,[f] and Hooi Ling Lee [a,]*

*Corresponding author: hllee@usm.my

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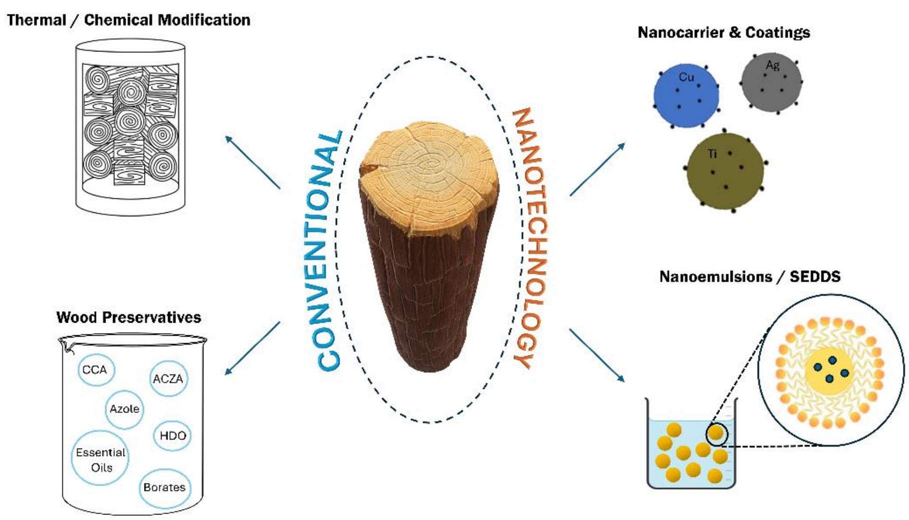
GRAPHICAL ABSTRACT



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While wood has been a renewable and versatile material for centuries, its susceptibility to biotic and abiotic degradation remains challenging. Traditional preservation methods, though effective, raise increasing concerns about environmental and health toxicity, cost, and post-consumer fate of the treated wood products. To address these issues, more sustainable and effective preservation methods have emerged. This review examines the latest innovations, particularly nanotechnology and self-emulsifying drug delivery systems (SEDDS), highlighting their applications, advantages, challenges, and research gaps. It focuses on literature from 2019 to 2024, exploring advancements in wood preservation. It also discusses the potential of these technologies to revolutionize wood preservation, offering promising and innovative solutions for the future.

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*Contact information: a: Nanomaterials Research Group, School of Chemical Sciences, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia; b: Research Planning Division, Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia; c: Forest Products Division, Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia; d: Université de Lorraine, INRAE, LERBMAB, GP4W, F 54000 Nancy, France; e: Centre for Chemical Biology, Universiti Sains Malaysia, 10 Persiaran Bukit Jambul, 11900 Penang, Malaysia; f: School of Pharmaceutical Sciences, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia; *Corresponding author: hllee@usm.my*

INTRODUCTION

Wood is a natural, renewable, and versatile material that humans have utilised for centuries. Wood and wood products have been used in different areas of construction, and furnishing, while also serving as a significant carbon storehouse. However, one of the biggest challenges wood faces is its susceptibility to decay and degradation by biotic and abiotic factors (Dimou *et al*. 2017; Ewart and Cookson 2014; Marais *et al*. 2020). Degradation would affect the structure, usability, and integrity of wood (Woods and Watts 2019). By improving its durability and performance against biotic and abiotic damage, wood can be a reliable resource that can be used in many fields. Throughout history, numerous preservation technologies and techniques have been developed and employed to protect wood from deterioration, to mitigate the effects of various biodegradation agents, and to enhance the longevity of wood products (van Niekerk *et al*. 2021).

In the field of wood preservation, methods including chemical treatments, thermal modification, and biological control agents have been used to protect and prolong the service life of wood (Bi *et al.* 2021; Hill *et al.* 2021; Kirker and Lebow 2021). Although effective, there are certain limitations, which include wood species, environmental implications, toxicity concerns, decreased mechanical strength, or changes to the inherent properties of wood. Such issues have hindered the use of wood preservatives (Irbe *et al*. 2020; Bi *et al*. 2021; Hill *et al*. 2021; Yan *et al*. 2021). As preservation technology grows slowly, other concerns have arisen, including economic costs, preservative sustainability, and production compatibility at the industry level (Dong *et al*. 2020; Akpan *et al*. 2021). Also, recyclability and lifecycle concepts are growing consumer concerns and must be considered in emerging solutions (Järvinen *et al*. 2022). Thus, modern preservative products should solve the shortcomings of their predecessors: they should be environmentally friendly and be capable of being upscaled to industry standards. In addition, it will be necessary to improve the solubility and usability of the preservative in practical applications.

As mentioned, traditional preservation methods have been effective, but they often come with environmental, practical, and health concerns, prompting a global shift towards more efficient solutions. Mitigating the shortcomings of past preservatives can be done through the application of nanotechnology, which stands out as a promising approach. Nanotechnology is a familiar subject that revolves around materials on a nanoscale. Nanotechnology has recently grown in many different disciplines, and it has started to see an emergence in application in wood preservation. The main characteristics of nanomaterials are having high surface area, good dispersion, and good penetration, which have been applied widely in medicinal and electronic fields and can similarly be applied to the wood preservation process (Shiny *et al*. 2019; Osman *et al*. 2020; Bi *et al*. 2021). Studies have shown that nanoparticles have the unique ability to penetrate the wood substrates due to the porosity of the wood cell wall (Papadopoulos 2019; Papadopoulos and Taghiyari 2019), thereby allowing preservatives to take action to alter wood cell chemistry and subsequently, quality and performance of the wood. Nanosized carriers can be used to improve the delivery efficiency of wood preservatives that are traditionally difficult to dissolve in water or other solvents, while also offering controlled release of preservatives to improve the stability and efficiency of preservatives (Teng *et al*. 2021; Amorim *et al*. 2023; Ong *et al*. 2023). Nanosized carriers can be prepared *via* multiple approaches (nanoprecipitation, vapour deposition, sol-gel), which makes them attractive and robust (Fernando *et al*. 2020; Bokov *et al*. 2021; Gautam *et al*. 2021; Yuan *et al*. 2022). Hence, nanotechnology offers promising possibilities for developing new and efficient wood preservation techniques.

This review paper explores and summarises the wood preservation technologies and techniques from 2019 to 2024, including nanotechnology and SEDDS applications in the wood preservation field, and discuss their potential for future developments.

PAST AND CURRENT PRESERVATION METHODS

In early times, wood degradation due to moisture, insects, and fungi, encouraged the demand to develop preservation methods. Early methods of wood preservation have used natural substances such as tar, pitch, and oil to apply to the surface of the wood to create a protective barrier against moisture and insects. These techniques were labour-intensive and caused many environmental and health problems, but they displayed the recognition of wood protection against natural factors (Kirker and Lebow 2021). Historical methods perceived the concept of reducing the moisture content of the wood, and although it has yet to be realised in the past, these concepts paved the way for modern methods.

Two main categories of wood preservation methods exist, which are wood modification and wood preservation (Järvinen *et al*. 2022). Wood modification focuses on making chemical and physical changes to the properties of wood to enhance its resistance against decay and insect damage or enhance its performance for service and application. Modifications mainly affect the hydroxyl groups in the wood, as it is the active site for wood-water interactions. Depending on the treatment method, lignin, and cell walls can also be modified, which will have different preservation effects (Hill *et al*. 2021). On the other hand, wood preservation involves treating the wood often with chemicals to prevent or hinder fungal decay and insect infestation (Kirker and Lebow 2021). Chemicals penetrate the timber at different depths depending on the treatment method, from the surface to the sapwood. This approach allows chemical action to offer protection against fungi and insects due to their toxic nature and ability to disrupt the biological processes of these organisms instead of altering the timber's physical or chemical state (Teaca *et al*. 2019). These techniques aim to extend the lifespan of wooden structures by enhancing their durability and protection against biological degradation. The wood treatment and modification approaches are distinct and will be discussed in the following section.

Thermal Modification

Thermal modification is a method that utilises heat to alter the wood structure and composition. The treatment temperature for thermal modification typically falls within the 160 to 240 °C range, as temperatures exceeding this limit may lead to excessive wood degradation (Goli *et al*. 2022). Thermal modification is conducted in dry (vacuum, nitrogen) or wet media (saturated steam, water bath, oil bath), and modifications towards the methods can adjust the water content in wood to be partially retained or totally dry (Goli *et al*. 2022). During thermal modification, degradation of amorphous polysaccharides, carbohydrates, and hemicellulose occurs, which results in a decrease in the hydroxyl groups present in the wood, thereby reducing its affinity for water. Insoluble hydrophobic compounds, such as phenolic compounds and furfural derivatives, are formed, further reducing water intake and the flexibility of the wood matrix (Hill *et al*. 2021). Other observable, significant changes include weight loss and reduced moisture content. Thermal modification is an attractive modification method for improving the durability and longevity of wood without toxic concerns. Such benefits come at the cost of increasing the brittleness and reducing the mechanical strength of wood. In addition, heat treatment affects the appearance of the wood, as high temperatures can cause discolouration, and to a certain extent will cause the release of volatile organic compounds (VOCs) (Gaff *et al*. 2019; Xu *et al*. 2019).

Industry thermal modification has matured, which includes many established modification processes, which are summarised well by Jones *et al*. (2019). High TRL level processes include ThermoWood® which has been studied to reduce thermal conductivity, improve dimensional stability, and improve durability against decay. Related methods include Retification and Bois Perdure methods (Bytner *et al*. 2021), which involves subjecting the timber to thermolysis in an inert gas environment using nitrogen, which prevents wood combustion and allows for controlled degradation of the wood's chemical structure (Kapidani *et al*. 2019). Also, there is the Plato process from the Netherlands, and the oil-heat treatment from Germany (Hill *et al*. 2021; Platowood 2024). More recent and medium TRL levelled processes include hydrothermal pressurised closed systems such as

WTT or IWT, dry vacuum-heat open treatment like Thermovuoto® (Meija-Feldmane *et al*. 2019) and SilvaPro™, another vacuum-thermal combination process (Sandberg *et al*. 2021). Thermal modification heavily depends on the desired end product, as the methods and conditions of treatment are responsible for changes in physical properties. Many wood species from hardwoods and softwoods can be thermally modified, establishing it as a versatile modification approach. The key markets for thermally modified wood are cladding, decking, and flooring. Such applications have reached commercial success in Europe, but it has competition with other processes that outweigh their added value to the finished products in terms of aesthetics and stability. Current developments of thermal modifications are combining techniques with chemical modifications or materials (wax, glycol) to further improve performance and value to the final product, mainly to improve stability as well as aesthetics, since thermally modified wood often has a darkened appearance compared to other modifications. Table 1 summarises the modern thermal modifications available.

Table 1. Summary of Thermal Modification Methods

Method	Temperature Range (°C)	Medium	Key Characteristics
Thermowood®	190 to 240	Superheated steam	Reduces thermal conductivity, improves decay resistance, decreases dimensional stability. Produces Thermo-S and Thermo-D wood types.
Rectification	200	Nitrogen	Prevents wood combustion, controls chemical breakdown. Applied under nitrogen atmosphere to inhibit combustion.
Bois Perdure	200 to 230	Steam	Like Rectification but utilizes moisture in the wood to generate steam. Controlled breakdown of wood structure and energy recycling through steam circulation.
Plato	150 to 190	Saturated steam	Two-stage process: first heating at low temperatures, followed by dry curing. Low energy consumption and dimensional stability improvement.
Oil-Heat Treatment	180 to 220	Saturated / unsaturated oils	Wood is immersed in high-temperature oil, consuming less energy due to oil's high latent heat.
WTT 2.0	170	Nitrogen	Applies high steam pressure to induce higher relative humidity and softens wood cell wall polymers
Thermovuoto®	160 to 220	Autoclave	Combining vacuum drying and heating to reduce overall process energy consumption
SilvaPro™	180 to 220	Vacuum	Longer heating and drying times but greater resistance to natural pests

Chemical Modification

Chemical modification of wood involves chemicals to enhance wood properties such as durability, mechanical strength, and insect and water resistance. This process alters the chemistry and the internal structure of wood, often interacting with the wood cells as they have reactive sites such as hydroxyl groups. Some of the key commercial methods include acetylation, furfurylation, the use of 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU), thermosetting resins, and monomers. These methods exhibit distinct interaction mechanisms; some form crosslinks within the wood structure, whereas others involve direct reactions with the wood cell walls. Chemical modification can increase durability, enhance mechanical strength, and hydrophobicity of wood without expending high-energy processes such as thermal modifications.

Grafting monomers

Monomers have been of the materials for treating wood to fill in the cell wall structure, resulting in less availability of their hydroxyl groups. Acetylation is a matured high TRL level process that involves treating wood with acetic anhydride (AA) or acetic acid to introduce acetyl groups into the cell wall structure. The acetylation reaction occurs when the acetic anhydride or acetic acid reacts with the hydroxyl groups on the wood polysaccharides, resulting in the substitution of the hydrogen of the hydroxyl group with an acetyl group, which restricts the access of water towards the hydroxyl group (Ringman *et al*. 2019; Bi *et al*. 2021). The process usually involves vapour-phase or liquid-phase treatment, where wood is immersed in the anhydride or exposed to its vapour under controlled pressure around 120 to 180 °C (Sandberg *et al*. 2021b). Milder conditions can be achieved with acetic anhydride compared to using acetic acid, as acetic acid typically requires higher temperatures above 200 °C and strong acid catalysts to overcome the higher activation energy (Bi *et al*. 2021). Vinyl acetate (VA) has also been a popular alternative for the process, but the difference in starting chemicals will result in subtle variations in final products depending on the catalyst used. Acetylation produces wood acetate, acetic acid, and water as byproducts, which are biodegradable and environmentally friendly (Hasegawa *et al*. 2020). Studies have shown that a weight gain of 18 to 20% achieved by acetylation can fully protect against fungal decay and provide good resistance against brown rot and white rot fungi (Zelinka *et al*. 2020). Similarly, carboxylic acid monomers can react with the hydroxyl groups in the wood to form ester linkages, improving dimensional stability, water resistance, and durability; however, esterification often result in low yields due to the equilibrium involved. This is primarily attributed to the limited accessibility of the hydroxyl groups and the lower reactivity of carboxylic acids compared to their functional derivatives (Teacă and Tanasa 2020). To overcome this, activating agents such as tosyl chloride (TsCl) and N,N-dimethylacetamide (DMA) enhance the reaction efficiency. Polycarboxylic acids have multiple carboxylic acid groups and can demonstrate unique performance compared to single-function saturated or unsaturated carboxylic acids when applied in wood modification.

Cross-linking thermosetting agents

Cross-linking thermosetting agents are extensively used in wood chemical modification to enhance properties such as dimensional stability, mechanical strength, and resistance to biological degradation. These resins form a rigid, three-dimensional network upon curing, effectively reinforcing the wood structure. The furfurylation technique uses thermosetting furfuryl alcohol to impregnate and polymerise within the wood structure.

The reagent subsequently undergoes polymerisation of furan polymers that fill the cell lumina within the wood structure under heat, with the presence of acid catalysts (Vani *et al*. 2022). Studies have noted that the technique mechanism of the furan polymer link does not interact with the hydroxyl bonds in the wood cells but provides a physical barrier to water ingress and fungal decay through the filled cell lumina, which is different from acetylation (Ringman *et al*. 2019; Thygesen *et al*. 2021). Furfurylation improves wood durability against fungal decay as the polymer network created within the wood structure restricts fungi and other biodegrading agents from interacting with the cell wall (Yang *et al*. 2022). However, one drawback of furfurylated wood is the potential for increased brittleness, which may compromise its mechanical performance and workability (Shen *et al*. 2020). Furfurlylation also causes darkening, which may not be ideal for wood treatment that is used in furniture making or interior finishing (Martha *et al*. 2021; Shen *et al*. 2020).

Another cross-linking agent is 1,3-dimethylol-4,5-dihydroxyethyleneurea (DMDHEU). DMDHEU is a methylol compound that has been widely utilised in the textile industry for wrinkle resistance (Papadopoulos 2019; Bi *et al*. 2021). DMDHEU reacts with the hydroxyl groups in the cell wall, forming covalent bonds that decrease swelling and increase resistance to biological degradation (Emmerich *et al*. 2019). Unlike acetylation and furfurylation, DMDHEU does not significantly alter the colour of the wood. Thus, it is suitable for applications where aesthetic appeal is essential. In addition to its protective properties, DMDHEU-treated wood has shown promising results in terms of mechanical performance, maintaining its strength and flexibility. Figure 1 describes the different modification reactions available to wood, which mainly exploit the hydroxyl groups for chemical reactions.

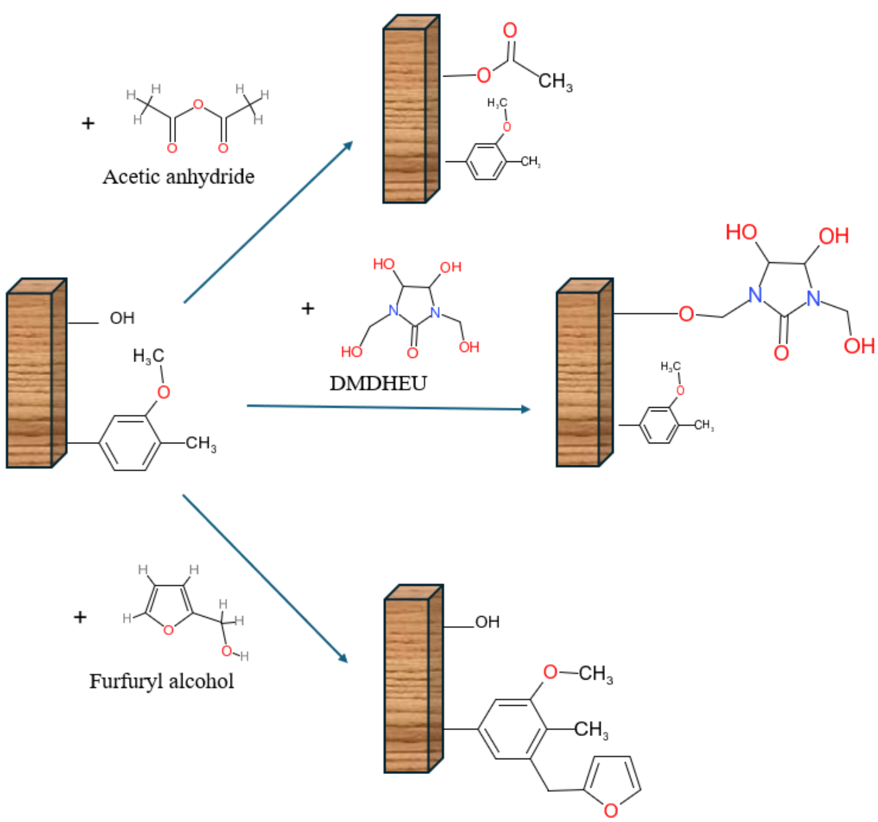

Fig. 1. Various chemical modification reactions with wood and its available functional groups

The emission of formaldehyde from DMDHEU is a potential risk, although it is quoted to be more environmentally friendly than urea formaldehyde resin (Emmerich *et al*. 2021; Rosli *et al*. 2024). Application of ether-modified DMDHEU (mDMDHEU) can lower formaldehyde emissions, however it also decreases its cross-linking reactivity to form ether bonds (Emmerich *et al*. 2020).

Bio-based polymers

During the last decade, the study of polyester treatments for wood preservation has emerged. The process consists of wood impregnation with water-soluble polyesters' precursors, monomers, namely polyacids and polyol monomers. Such reagents are subjected to a curing step that ensures the polymerisation and fixation of the esterified chemicals.

Soluble water-based polyols for impregnation include sorbitol (Mubarok *et al*. 2020; Treu *et al*. 2020), glycerol (L'Hostis *et al*. 2020), polyglycerol (Flaig *et al*. 2023), and butanediol (Chabert *et al*. 2022). These polyols can be fixed in the wood only if polyacids are combined giving in-situ polyesters. Citric acid is one of the main polyacids studied (Kurkowiak *et al*. 2022b; Hötte and Militz 2024). It is a natural chemical found in citrus fruits, industrially produced by a fermentation pathway (Reena *et al*. 2022). Other authors have also explored malic acid (Chabert *et al*. 2024), maleic anhydride (Mubarok *et al*. 2022), and succinic anhydride (L'Hostis *et al*. 2020) in combination with glycerol. Lactic acid is a hydroxyacid that condenses on itself and has been explored by Grosse *et al*. (2019). Flaig *et al*. (2023) explored a large panel of some already mentioned polyacids and including 1,2,3,4 butanetetracarboxylic acid (BTCA), L-glutamic acid, tartaric acid, and itaconic acid in combination with polyglycerol. Amongst these formulations, the treatment associating sorbitol and citric acid is currently on the way of industrial development (Hötte and Militz, 2024) in Germany (SorCA) and Norway (trademark CIOL®). Mechanisms of polycarboxylic acids and polyols have been well documented (Kurkowiak *et al*. 2022a; Shao *et al*. 2019), noting polyols in general dehydrate to anhydrides and subsequently esterify with the cellulose -OH groups, establishing the polymer network; the sorbitol/citric acid polymerisation mechanism occurring during the thermal step has also been proposed by Kurkowiak et al. (2023). Reactions can be driven without a catalyst, but Guo *et al*. (2019) have highlighted the use of sodium hydrogenophosphite (SHP) to induce "cell wall bulking," causing swelling because polyesters occupy water sorption sites.

After impregnation, the wood undergoes a crucial curing step with a minimum temperature of 120 °C to properly fix the chemicals within the wood and enhance its performance (Kurkowiak *et al*. 2023). Driving the curing step at 140 °C allows the achievement of polycondensation reactions. Comparing the treatments, it ensures almost no water leaching according to EN 84, with glycerol/succinic anhydride (L'Hostis *et al*. 2020), rather low (8%) using sorbitol/citric acid (Kurkowiak *et al*. 2023), and higher in the case of polyglycerol (Flaig *et al*. 2023). Greater wood percentage gains (WPG) result in good anti-swelling efficiency (ASE), typically achieving between half and two-thirds the effectiveness of polyester treatment. This efficiency further improves as the curing temperature increases from 120 to 160 °C (L'Hostis *et al*. 2020; Kurkowiak *et al*. 2022b; Chabert *et al*. 2024). Chabert *et al*. (2022) observed that malic acid/glycerol treatment made beech wood more hydrophobic, reducing its equilibrium moisture content (EMC) by at least 50% compared to untreated wood. This reduced moisture uptake is likely due to fewer accessible hydroxyl groups, possibly from hydrogen bonding or chemical grafting.

It is also worth noting that higher curing temperatures (*e.g.*, 160 °C) in acidic media can degrade hemicelluloses, which in turn significantly lowers the wood percentage gain (WPG) (L'Hostis *et al*. 2020). Decay tests show that glycerol-based polyesters need a 160 °C treatment to achieve good durability against white rot and brown rot. In contrast, using a SorCA-140 °C treatment, real improvement in fungi decay protection up to DC1 could be achieved by providing a WPG threshold of 50%, which is much better than thermal treatment or polyacid treated wood (Kurkowiak *et al*. 2023).

However, chemical distribution and mechanical properties are questionable. First, X-ray densitometry shows that these chemicals are unequally distributed, showing higher concentrations at the edges (Kurkowiak *et al*. 2022b; Chabert *et al*. 2024), as already described concerning dry-cured thermosetting resins. Hardness and compression strength are improved from the increase in density, especially at the surface, but these gains come at the cost of becoming brittle, with an increase in modulus of elasticity (MOE) and a decrease in modulus of rupture (MOR) and impact strength. There have been several explanations for this behaviour, such as elasticity or rigidity increases due to densified network and entanglement of microfibrils. Reduction of plasticity fits well with the reduction of free movement of macromolecules. Lower MOR may arise from high curing temperature in an acidic medium, which hydrolyses wood polysaccharides (Kurkowiak *et al*. 2022b; Chabert *et al*. 2024). Promising performances of such treatments, which deserve more research dedicated to the area of thermal properties, will aim to improve uniform distribution and mechanical properties (Kurkowiak *et al*. 2023)

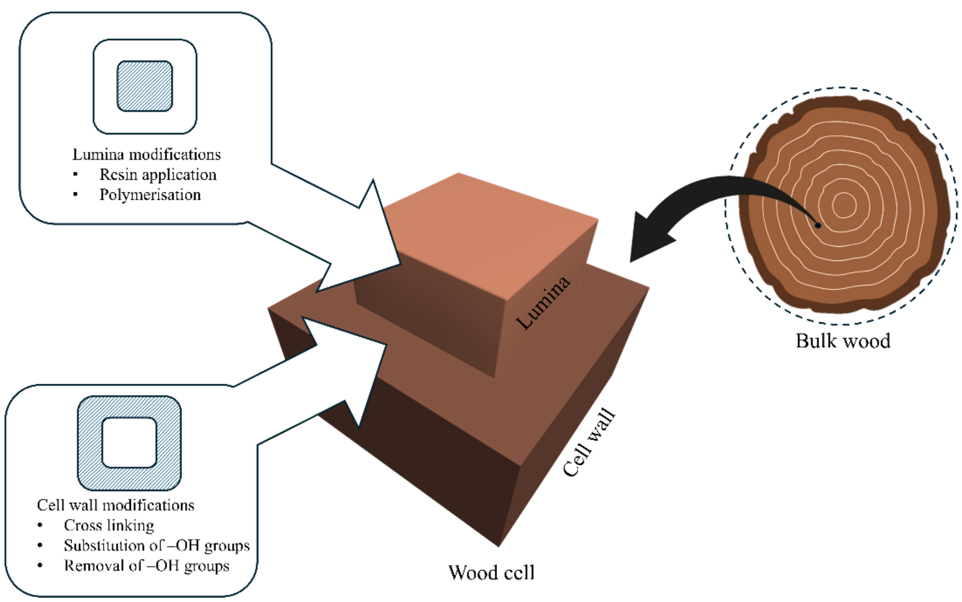

Fig. 2. Bulk wood and wood cell modifications

Current Wood Preservative Systems

Preservative systems are based on chemicals added to wood to protect against biodeterioration. They are designed to combat the effects of moisture, fungi, insects, and other environmental factors that can lead to wood degradation. Preservatives added to wood do not change the internal structure but work by targeting the external deterioration factors. Deciding the right preservative and treatment is crucial to ensure the protection and longevity of the wood and the safety of the wood and the environment.

Wood preservatives can be divided into two main types: oil-borne preservatives (creosote and pentachlorophenol (PCP)) and water-borne preservatives (chromated copper arsenate (CCA), and ammoniacal copper zinc arsenic (ACZA)). Oil-borne preservatives have caused toxicity and environmental concerns. This has led to ongoing research on their impact and potential recovery methods, and many countries have been phasing out the use of oil-borne preservatives (Brient *et al*. 2020; Paul *et al*. 2023). Their high stability can result in stubborn contamination in water systems and soil, and due to their popularity in the decade before using newer preservatives, removal studies are in the spotlight (Ma *et al*. 2019). Transitioning into water-borne preservatives, many current treatments incorporate copper as the main active ingredient, but they also contain other heavy metals such as chromium and arsenic, which have been restricted in many regions due to concerns over arsenic leaching and its potential health risks for residential application (Morais *et al*. 2021).

In some cases, co-biocides are added to enhance the efficacy of wood preservatives. Nitrogen-based compounds are added to form copper preservatives, including copper azole (CA), alkaline copper quaternary (ACQ), and copper hydroxide dimethyl dithiocarbamate (HDO), which do not contain arsenic and chromium and can achieve similar performance to older chromium-based systems without the environmental risks (Bao *et al*. 2022; Pandharikar *et al*. 2022). These copper preservatives with co-biocides are designed to be less toxic and suitable for residential, recreational, commercial, and industrial structures (Khademibami and Bobadilha 2022). However, the common issues with the alternatives are corrosivity and leaching, as CA and ACQ are more corrosive to fasteners than CCA, and copper HDO's borate component can leach relatively quickly compared to copper, which remains more stable. Additionally, their production and application can be more expensive than traditional oil-based preservatives. In extreme environments such as high humidity or severe UV exposure, additional treatments or protective coatings may be necessary for long-term durability (Papadopoulos and Taghiyari 2019).

Subsequently, other non-copper wood preservatives have also been studied to counter different biotic damage. Azoles are organic compounds that are widely utilised for their potent antifungal properties. The primary mechanism of triazoles involves blocking the enzyme lanosterol 14α-demethylase, which is responsible for converting lanosterol into ergosterol during fungal cell membrane synthesis, thereby deterring fungal growth (Houšť *et al*. 2020). Azoles that have found use in wood preservation include propiconazole, tebuconazole, cyproconazole, fluconazole, and benzimidazole, which are all commonly effective against fungi (Ahuja *et al*. 2020; Schoknecht *et al*. 2020; Verderosa *et al*. 2022). However, environmental persistence and the development of resistance from fungi are some issues for application. Leaching can also cause subsequent pollution and negative environmental impact. Hence, the application should be limited to high-deterioration areas (Schoknecht *et al*. 2020). Pyrethroids are synthetic insecticides derived from natural pyrethrins used in wood preservation for their potent insecticidal properties. They target sodium channels in insect nervous systems, causing neurotoxicity and disrupting muscle excitability (Hołyńska-Iwan and Szewczyk-Golec 2020; Ahamad and Kumar 2023). Common pyrethroids in wood preservation include permethrin, bifenthrin, and deltamethrin, which are valued for their termite resistance and repellent properties. Permethrin acts as both a contact insecticide and repellent, effectively deterring wood-destroying termites (Kadir *et al*. 2023). Bifenthrin, which is often combined with pyraclostrobin, offers an environmentally friendly alternative with low mammalian toxicity (Ahamad and Kumar 2023). However, health concerns such as neurotoxicity, endocrine disruption, and immunotoxicity have been linked to pyrethroid exposure in humans (Hołyńska-Iwan and Szewczyk-Golec 2020). Their high leaching potential, short residual effectiveness, and regulatory restrictions limit their widespread use in wood preservation. Higher interest in pyrethroids can only be achieved when there is more research to mitigate their acute health risks to humans, as well as addressing stability and pest resistance issues.

Recent Preservatives and Systems

Wood preservative technology has undergone significant advancements, with recent developments focusing on sustainability and effectiveness. While traditional preservatives protect against decay and pests, they present environmental and health drawbacks. Consequently, there is an increased demand to retain the protective properties of previous iterations of wood preservatives but also cater to the environmentally friendly and less detrimental options. The emergence of these newer preservatives in the following sections will have to be evaluated for their long-term efficacy, potential trade-offs, and the challenges they present in replacing well-established methods.

One of the newer classes of preservatives is borates, which are highly soluble with low mammalian toxicity. In addition, they are suitable for wood species that are hard to penetrate. Borates such as copper borates, disodium octaborate tetrahydrate (DOT), and sodium tetraborate are common formulas used that are effective against fungi and insects. Used in pressure or surface treatments, borates are employed for interior wood structures to avoid high humidity conditions that lead to leaching (Khademibami and Bobadilha 2022). Research is being carried out to improve its fixation through complex formulations, such as a one-step impregnation of DOT/acrylic polymer formulation to reduce leaching in high humidity environments (Ibañez *et al*. 2021). Borates have also been used to treat railroad ties as an alternative to creosote, and pre-treatment with borates can eliminate decay in service or when air-drying (Lloyd *et al*. 2020). This preliminary study confirms the need for additives to fixate boron-based preservatives, which requires more concrete research on reducing leaching for it to achieve large-scale application and increase its TRL. Quaternary ammonium biocides (quats) are also considered new preservatives, characterized by a central nitrogen atom bonded to four organic groups, resulting in a positively charged molecule. Didecyldimethylammonium chloride (DDAC), 3-iod-2-propynyl butyl carbamate (IPBC), and polymeric xylenol tetrasulphide (PXTS) belong under quats. They have good antimicrobial activity and good efficacy against fungi and termites (Kirker and Lebow 2021; Raimond *et al*. 2022). They are mostly applied in above-ground components, as they are often found in paints and coatings. Its poor wood penetration only allows it for surface applications (Raimond *et al*. 2022), so further research is required to allow better efficacy for vacuum application of quats.

Ionic liquids (IL) are promising for wood preservation due to their high absorption capacity and effective penetration into wood structures. They are organic salts composed of organic cations (alkylimidazolium, 1-alkyl-1methylpiperidinium) and anions (PF_6^-, Br^-, Cl^-, BF_4^-); they are known for their ionic nature and unique physicochemical properties such as low volatility, high thermal stability, and good conductivity (Croitoru and Roata 2020; Woźniak 2022). It is theoretically feasible to create an ionic liquid tailored for a specific use or characteristic, as it has "high synthesis versatility" for them to be applied as selective dissolution solvents or carriers (Croitoru and Roata 2020). Research has observed that ILs can be used as preservatives or chemical modifications as they can exhibit antifungal activity, or they can double as a swelling agent (Haron *et al*. 2021). Antifungal properties of ILs are decided by the types of cations and anions they contain, with alkyl-substituted cations being essential in their ability to combat a wide range of fungi present in wooden materials (Kaczmarek *et al*. 2022). Their capacity to expand wood cell walls makes them effective as preservatives against fungi such as *Basidiomycetes* and *Fungi imperfecti* (Szalaty *et al.* 2020). IL treatments show limitations due to elevated viscosity, leaching issues, possible adverse effects on human health, and high cost (Flieger and Flieger 2020; Cho *et al*. 2021; Magina *et al*. 2021).

Table 2. Essential Oils Used for Wood Protection and their Respective Antifungal Species (Broda 2020)

Essential Oil	Effective against	Main Active Compound
Anise	*Coniophora puteana, Trametes versicolor*	Thymol, Carvacrol, Trans-anethole, Cuminaldehyde
Oregano	*Coniophora puteana, Trametes versicolor, Laetiporus sulphureus*	Carvacrol, Thymol
Thyme	*Coniophora puteana, Trametes versicolor, Aspergillus niger*	Thymol, Carvacrol
Cinnamon	*Oligoporus placenta, Coniophora puteana, Antrodia xantha*	Cinnamaldehyde, Eugenol
Geranium	*Oligoporus placenta, Coniophora puteana, Antrodia xantha*	Citronellol, Geraniol
Clove	*Serpula lacrymans, Trametes versicolor, Coniophora puteana*	Eugenol
Lemongrass	*Laetiporus sulphureus*	Citral, Citronellol
Cassia	*Tyromyces palustris, Trametes versicolor*	Cinnamaldehyde, Cinnamic acid
Rosemary	*Aspergillus niger, Trichoderma viride, Penicillium chrysogenum*	1,8-Cineole, Camphor

Extracted from various plants, herbs, and spices, essential oils (EO) contain bioactive compounds such as terpenes, phenols, and aldehydes that work as natural wood preservatives (Broda 2020). These components exhibit antimicrobial properties, making them effective against fungi, insects, and bacteria responsible for wood deterioration (Hou *et al*. 2022). Eucalyptus oil, tea tree oil, and clove oil are commonly used in wood preservation because they inhibit the growth of decay fungi and termites (Antonelli *et al*. 2020; Broda 2020). Regarding their mechanisms of action, studies report that EOs can disrupt cell membranes and enable easier permeability and subsequently promote cell leakage (Mutlu-Ingok *et al*. 2020; Hou *et al*. 2022). For example, linseed oil can also provide long-term weathering protection, and combined with boron, it can also be effective against fungi (Hassan *et al*. 2021). As antifungal properties are common, current researchers are more invested in novel properties and synergistic applications of essential oils to investigate more specific uses against specific fungi. However, from a practical standpoint, the large-scale use of EOs faces several challenges, including high costs, volatility, biodegradability, and potential human health risks (Khademibami and Bobadilha

2022). In above-ground applications, issues such as strong, persistent odours and potential irritation may further limit their use for indoor materials. These obstacles keep such technology at low TRLs, but further studies may reveal more potential uses that come with co-biocides to improve retention. Table 2 compiles the essential oils that have been studied and showed antifungal properties, showing that essential oils are a pool of untapped potential for future studies against fungi deterioration.

Chitosan, a natural biopolymer derived from chitin, can be sourced from crustaceans. Chitosan is increasingly recognised for its potential in wood preservation due to its excellent biodegradability, biocompatibility, and antimicrobial properties (Saberi Riseh *et al*. 2024). Extracted chitosan contains glucosamine and N-acetyl glucosamine units, which are biodegradable. Its application in wood preservation is part of a broader trend toward utilising natural products to develop environmentally friendly and sustainable wood treatments (Teaca *et al*. 2019). The primary mechanism of chitosan preserving wood is by disrupting the cell membranes of a wide range of microorganisms, which is effective against decay fungi such as brown rot, white rot, and soft rot fungi, as well as penetrating the cell wall to resist swelling and shrinking (Alorbu and Cai 2022; Saberi Riseh *et al*. 2024; Zhang *et al*. 2024). Chitosan has a polycationic nature, allowing it to bind easily to the negatively charged cell walls of microorganisms, enhancing its inhibition efficacy (Zhang *et al*. 2024). Additionally, chitosan can chelate metal ions, which are essential for the enzymatic activities of many wood-degrading organisms, thereby inhibiting their growth and metabolic processes (Mesas *et al*. 2021; Verma and Quraishi 2021). Previous studies have confirmed the antifungal properties of chitosan in solution form, and recent research has highlighted the potential of chitosan in the form of films and coatings, which have been applied to post-harvest food products (Mondéjar-López *et al*. 2022). However, it has lesser commercial success as wood preservatives, as there is limited raw material and seasonal supply for crustacean chitosan, and limited quantity and expensive cost for producing fungal chitosan to be applied for large volumes of wood treatment, as compared to drug synthesis (Huq *et al*. 2022). Chitosan needs a breakthrough for wood preservation, as current applications are small-scale and are limited to its functions and solubility. Investigating cost reduction and expanding other forms of treatment with chitosan (co-biocides, improving solubility) will allow larger scale applications.

NANOTECHNOLOGY IN WOOD PRESERVATION

Nanotechnology is involved in many scientific fields that are pioneers in providing new possibilities to current studies, and this applies to the application of wood and wood preservation. Nanotechnology involves the manipulation of matter at the atomic and molecular level, usually working with structures that are less than 100 nanometres in size (Khan *et al*. 2022; Yusuf *et al*. 2023). Materials at this scale demonstrate traits such as increased reactivity and strength and innovative optical and electronic behaviours (Khan *et al*. 2022). By utilising these distinctive attributes, nanotechnology enables innovation for a wide range of applications such as medicine, electronics, and environmental science (Xu *et al*. 2020; Saravanan *et al*. 2021; Afzal *et al*. 2022; Samuel *et al*. 2022)

In the context of wood preservation, nanotechnology introduces innovative solutions to longstanding challenges associated with protecting wood from biological degradation and environmental damage. Nano-based materials allow for deeper penetration of preservatives or materials into the wood structure, ensuring more comprehensive protection (Papadopoulos and Taghiyari 2019; Rahayu *et al*. 2023). Furthermore, nano-based materials' high surface area-to-volume ratio enhances their reactivity and efficacy against biological threats (Cruz-Luna *et al*. 2021). By incorporating nano-based materials into wood preservatives, researchers can improve these treatments' durability, efficacy, and environmental friendliness (Vargas-Hernandez *et al*. 2020). This technological advancement holds the potential to innovate wood preservation methods, offering superior protection with reduced ecological impact. Interest in nanotechnology has been present in the past (De Filpo *et al*. 2013; Kartal *et al*. 2014; Weththimuni *et al*. 2016; Goffredo *et al*. 2017). Still, it has been rising in the past decade, which has advanced the understanding of nanotechnology's potential uses in wood science.

This section discusses several approaches for applying nanotechnology in wood preservation. They can be divided into different categories: nanosized biocide (metals and non-metals), polymeric nanocarriers of wood preservatives, and wood coatings, as presented in Fig. 3. Each category has unique characteristics that allow a variety of applications and come with advantages.

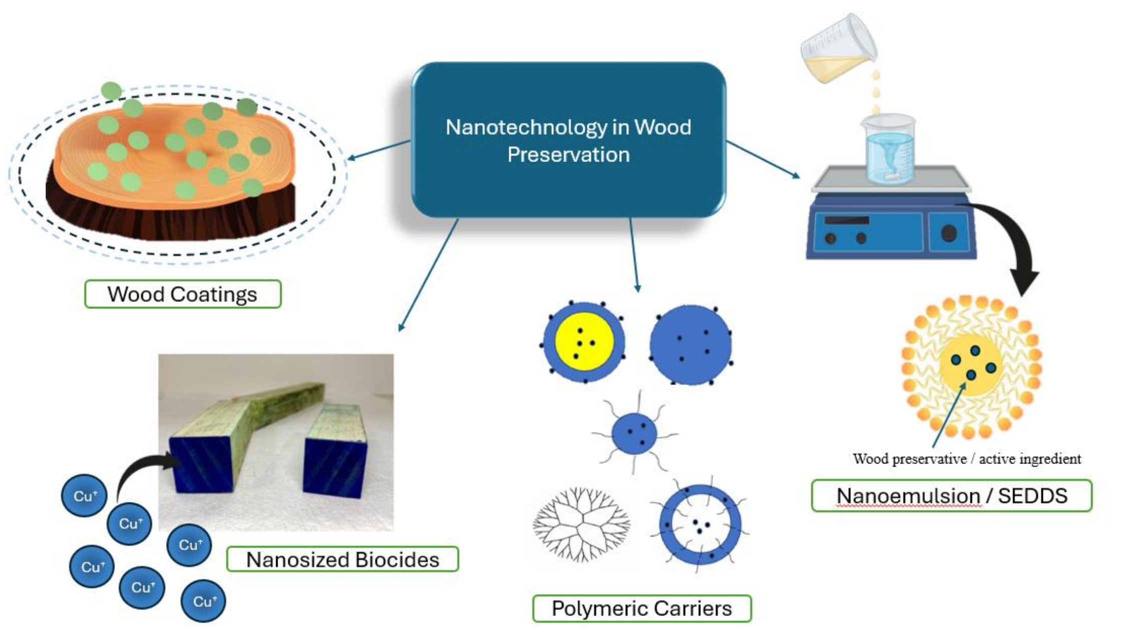

Fig. 3. Nanotechnology and its approaches in wood protection (Aguayo *et al*. 2022)

Current Nanotechnology Approaches in Wood Preservation

Nanosized biocides

Nanosized biocides provide biocidal or protective properties that can be single-occurring elements, metals, or non-metals. Metal-based preservatives can find application in their nano form and provide similar or better performance. This allows deeper and more homogeneous penetration and improved distribution compared to water-borne preservatives (Papadopoulos *et al*. 2019). Nanometals reported for biocidal purposes include copper, silver, zinc, and titanium. Nanometal biocides exhibit antimicrobial and antifungal activities, generally with less leaching than conventional metal-based preservatives. This allows broad applicability for long-term retention in outdoor wood where high exposure occurs.

Nanometal biocides

Nano-copper has been effective against termite attacks given with co-biocides such as azoles and borates, whereas nano-CuO has been used to treat various fungi and moulds (Shiny *et al*. 2019; Crisan *et al*. 2021). Aguayo *et al*. (2022) studied micronized copper (MC) and copper NP on radiata wood and its effects on mechanical properties. They confirmed the effectiveness against wood rot fungi with high copper retention. Mass loss was close to 10% even for leached samples, which means that further studies to move away from traditional copper preservatives that are leachable. Ag NP is also effective as a coating to improve UV protection and fire retardancy. A study by Dai *et al*. (2022) further established the use of nano-Ag on anti-mould efficiency against *Aspergillus niger*, *Penicillium citrinum,* and *Trichoderma viride*, for which the effectiveness reached 80, 75, and 80%, respectively, given the surface retention of 0.324 gm^{-2}. Ag-Cu alloy has been suggested for antibacterial effectiveness against *Escherichia coli* and *Staphylococcus aureus*, which lowers overall cost and overcomes Cu-resistant fungi (Dai *et al*. 2022). Studies have also found that nano Cu provided anti-termite properties to wood samples against *Odontotermes horni*, *Odontotermes obesus*, *Odontotermes redemanni*, and *Microtermes obesi* for up to six months (Shiny *et al*. 2019). Zinc nanoparticles, particularly nano-zinc oxide, are highly effective against a wide range of wood-decaying fungi such as *Aspergillus niger*, *Gleophyllum trabeum*, and *Trametes versicolor*. Combined treatment with zinc and silver NPs has been able to provide UV protection on wood, and ZnO gave the most negligible colour change compared to other metallic NP treatments (Wang *et al*. 2021). Along with its good chemical stability, it is US FDA-approved for human and environmental safety (Rohani *et al*. 2022). Treating wood with nano-ZnO NPs with PEG 6000 followed by heat treatment also resulted in high antifungal activity (Reinprecht *et al*. 2022)*,* Wood preservative interactions may correlate with treatment conditions, which should be considered. Ti and TiO_2 are generally suitable for antimicrobial activity, and a thorough study on Ti has allowed cheap and easy synthesis methods to prepare (Amiri *et al*. 2022; Ansari *et al*. 2022; Luo and Zhang 2022).

Non-metal nanosized biocides

Non-metal nanosized materials also have been discussed in wood protection, as they also provide various protection properties to their metal counterparts. Silica nanoparticles have been explored for their potential to mainly improve durability and water resistance, which can deter fungi and termite damage to wood (Jeer 2022; Rahayu *et al*. 2023). A study stated that fluorinated silica NPs improved overall dimensional stability in European beech and Scots pine with an 18.0% to 28.7% decrease in moisture due to inducing secondary surface roughness that reduced hygroscopicity and raised dimensional stability (Bak *et al*. 2023). Other studies find different silica forms for wood protection purposes, such as nano-silica sol to improve hydrophobicity in Chinese fir (Xu *et al*. 2020). Silica can improve water resistance, which indirectly helps maintain the effectiveness of other biocide protection on wood.

Chitosan, used in chemical modification, can also treat wood in NP form, as studies have claimed its antifungal properties at low dosages. Studies have demonstrated that chitosan oligomer nanoparticles can be used alone or in combination with silver nanoparticles (Spavento *et al*. 2023). Its application on poplar wood showed a significant decrease in weight loss from brown and white rot fungi test assays. Chitosan chelating and reducing properties work well with Ag to avoid agglomeration, allowing better wood distribution (Cheng *et al*. 2020). Carbon in the form of nanotubes and graphene has been applied to wood as fire retardants; recent research has demonstrated that carbon nanoparticles can be formulated into coatings that exhibit self-cleaning, scratch-resistant, and weathering-resistant capabilities, substantially improving the structural integrity and aesthetic appearance of wood (Pandit *et al*. 2020; Łukawski *et al*. 2023; Wu *et al*. 2023).

Recent advancements include reduced graphene oxide (RGA), prepared with Ag NP applied to poplar wood to provide photo-absorbing properties and antibacterial activity against *Staphylococcus aureus* (Ebrahimi *et al*. 2022). Overall, nanosized biocides are a very versatile and blooming field in wood protection with their potential. The possibility of combining different materials to enhance performance among metal and non-metal materials reveals promising advancements and further studies, such as understanding the compatibility between nanobiocides with other materials, such as binders and polymers.

Polymeric carrier

Wood preservatives may be poorly water-soluble, which hinders their application using conventional water-based wood treatments, such as vacuum pressure treatment or spraying. Polymeric nanocarriers can mitigate wood preservatives that have solubility, stability, or aggregation issues in different media or have difficulty penetrating wood. Nanocarrier systems can enhance the impregnation of wood preservatives, facilitating more efficient and uniform delivery of the active ingredients throughout the wood structure by encapsulating biocides to deliver into wood (Nair *et al*. 2022; Paul *et al*. 2023; Athulya *et al*. 2024). Research has shown that encapsulating active ingredients in polymeric nanocarriers can protect them from environmental degradation, thus prolonging their efficacy (Sánchez-Hernández *et al*. 2022; Athulya *et al*. 2024). Polymeric nanocarriers can also facilitate the controlled release of wood preservatives, which helps maintain a consistent protection over time (Beckers *et al*. 2021; Machado *et al*. 2022). The colloidal stability of polymeric nanocarriers dictates their ability to transport and distribute preservative compounds through the vascular system of wood. Colloidal stability is influenced by factors such as the nanocarrier's chemical design, use of surfactants, and surface charges that interact with the complex plant environment (Beckers *et al*. 2021; Bi *et al*. 2021). The release rate is also inversely proportional to polymer polarity; being more polar will result in a slower release rate (Bi *et al*. 2021). Different mechanisms of polymeric nanocarriers include nanocapsules, nanospheres, and micelles (Jiang *et al*. 2020; Primaningtyas *et al*. 2020; Andeme Ela *et al*. 2021; Yan *et al*. 2021; Yang *et al*. 2023). Each form is dependent on the biocide used and the target wood. Fabrication techniques include emulsion techniques, solvent evaporation, nanoprecipitation, spray drying, ionic gelation, milling techniques, and more (Bossert *et al*. 2020; Teng *et al*. 2021; Baldelli *et al*. 2022; Shilova *et al*. 2022; Zikeli *et al*. 2023). Natural (chitosan, lignin, silica) and synthetic (polyvinylpyridine, polylactic acid) polymers have been studied and may be used for specific process requirements (Chauhan 2020; Maluin and Hussein 2020; Hussin *et al*. 2022; Bak *et al*. 2023).

Nanocarriers have been increasingly discussed and applied, and different polymeric carriers and biocide combinations have been discovered in newer literature. Chitosan NPs loaded with permethrin were successfully produced using the nanoprecipitation technique. When *Hevea brasiliensis* wood samples were treated with a 0.0025% w/v aqueous suspension of these nanoparticles, the weight loss in termite testing was reduced from 7.35% to 1.20%, demonstrating the enhanced protective efficacy of the nano-enabled wood preservation approach (Kadir *et al*. 2023). Another study used chitosan NPs to encapsulate antifungal garlic essential oil (GEO) *via* a two-step process (Gong *et al*. 2021), namely

O/W emulsification followed by ionic gelation method. By modifying the chitosan and using a GEO ratio from 1:0 to 1:1, the size distribution of the nanoparticles fabricated fell within the range of 200 to 400 nm, and the amount of the encapsulated GEO was quantified, yielding an encapsulation efficiency of approximately 32.8% (Mondéjar-López *et al*. 2022). Lignin NPs were also interesting as nanocarriers for thyme EO, which was previously reported to work well in protecting from brown and white rot fungi (Vettraino *et al*. 2023). Lignin benefits from antioxidant properties, which protect EO from UV degradation and fast evaporation (Zikeli *et al*. 2022). Hydrophobic biocides triclosan and 4-hexylresorcinol were entrapped using cellulose acetate NPs as nanocarriers fabricated *via* nanoprecipitation (Cordt *et al*. 2020). The diffusion mechanism allowed the biocides and cellulose acetate to form due to the hydrophobic nature of the biocides. Triclosan-loaded NPs were effective against *Bacillus subtilis* with controlled release, suggesting long-term biocidal activity (Cordt *et al*. 2020). A study by Liu *et al*. (2023) developed phosphate-modified cellulose microspheres with chitosan to load emamectic benzoate (EB). Loading capacity was as high as 50.8% and improved against UV degradation, as EB is susceptible to degradation under UV light. Poly(lactide-co-glycolide) (PLGA) biodegradability has attracted use to lessen environmental impact for nanocarrier purposes (Beckers *et al*. 2021). A novel copolymer, polylactic acid-co-polyethylene glycol (PLA-PEG) NP, successfully incorporated chlorothalonil used to treat rubberwood (Teng *et al*. 2021). The amphiphilic block polymer was able to accommodate the hydrophobic chlorothalonil in the polymer block core and improve solubility and delivery efficiency, resulting in high wood retention at 8.5 kgm^{-3}. The chlorothalonil-PLA-PEG NP worked well against brown and white rot fungi by reducing weight loss by 25.7 % and 19.7%, respectively (Teng *et al*. 2021).

Nanocarriers significantly improve wood preservation by enhancing delivery efficiency and reducing the required dosage against termites and fungi. Their effectiveness largely depends on the compatibility between the nanocarrier material and the wood preservative. Understanding various materials and their compatibility is crucial for application and also for development to align with sustainable practices for a greener, safer approach. By adapting strategies from drug delivery, there is potential to improve biocide solubility, encapsulation efficiency, nanoparticle-wood interactions, and economic viability. Future research is particularly promising for greener materials like carbon nanotubes, halloysite, nano-clay, metal alloys, silica, proteins, and lipids, which can enhance overall wood preservation approaches (Chaud *et al*. 2021).

Wood coatings

Modifying wood surfaces with nanotechnology can improve protection against moisture, UV radiation, biological organisms, and mechanical wear (Sandberg *et al*. 2021a; Landry *et al*. 2023; Saberi Riseh *et al*. 2024; Laleicke and Hubbe 2025). Wood coatings can offer innovative solutions for both wood preservation and aesthetics (Spear *et al*. 2021; Landry *et al*. 2023). Coatings provide versatility for specific wood applications and environmental conditions, have a large surface-to-volume ratio, and are easy to apply, which is a crucial advantage (Jirouš-Rajković and Miklecić 2019; Jasmani *et al*. 2020). However, the shortcomings are its limited flexibility and susceptibility to substrate adhesion variations, which may affect the coating performance (Taghiyari *et al*. 2020; Blanchet and Pepin 2021). By incorporating nanotechnology, coatings can enhance their performance and provide additional properties. This is achieved by incorporating nanomaterials into a solvent or synthesising nanomaterials *in situ via* sol-gel or hydrothermal method, followed by homogenising the solution to be applied to wood *via* spraying, dipping, or brushing (Papadopoulos *et al*. 2019; Bi *et al*. 2021; Qu *et al*. 2021; Sun *et al*. 2023)

Coatings can be equipped with different protective traits, which commonly include UV resistance to protect against ultraviolet (UV) rays, which damage wood structure, stability and colour change (Bansal *et al*. 2022; Wang *et al*. 2022; Zhu *et al*. 2023), antimicrobial effects to counter fungi growth (Broda 2020; Tang *et al*. 2021; Calovi *et al*. 2024), flame retardancy to improve utilisation on fire safety (Taghiyari *et al*. 2019; Kačíková *et al*. 2021; Mali *et al*. 2022), and hydrophobicity to discourage biodegradation and fungi growth (Xu *et al*. 2020; Wang *et al*. 2022).

UV-resistant coatings

UV-resistant coatings have included ZnO, TiO_2, and CeO_2 NPs, as they are suitable protectors against UV irradiation. They can disperse or absorb UV, which is further enhanced with the NP large surface area distribution (Janesch *et al*. 2020; Zhou and Fu, 2020; Yang *et al*. 2021; Muzata *et al*. 2023). Recent studies highlight different media used in conjunction with nanoparticles. A layer-by-layer self-assembled chitosan/ZnO antichromatic coating was prepared by Luo and Zhang (2022) for application on dyed wood. The ZnO concentration influenced the loading and UV absorption effect and resulted in a smoother surface on dyed wood after deposition from the interaction of chitosan with wood, effectively reducing colour difference by 56.4%. Yi and Morrell (2023) treated radiata pine sapwood with water dispersions of *α*/*γ*-iron oxide (Fe_2O_3) or zinc oxide (ZnO) that provided UV protection. This interesting study used a zinc nitrate ($Zn(NO_3)_2$) solution precursor to deposit ZnO coating *via* an atmospheric pressure plasma jet (APPJ) approach to generate fine NPs, further improving surface area coverage of the UV coating (Jnido *et al*. 2021). Hydrothermal synthesised TiO_2 NPs have been studied in water and oil-based varnish for mangium wood, which shows effectiveness against UV irradiation (Rahayu *et al*. 2023). TiO_2 synthesis *via in situ* hydrolysis with tetrabutyl titanate (TBT) in an acidic solution (CH_3COOH) was applied to delignified wood, achieving a key precursor to obtain transparent wood with UV shielding qualities. Fan and Xing (2024) developed Ce/TiO_2 anti-UV coating through a sol-gel method, applied *via* brush coating. This method creates a uniform, stable coating that effectively adheres to the wood surface.

Antimicrobial coatings

Coatings can be applied to deter the growth of microorganisms and fungi with the addition of antimicrobials. Notable NPs with antimicrobial properties include Ag, ZnO, and TiO_2 NPs (Salem 2021; Amiri *et al*. 2022; Rohani *et al*. 2022). The antimicrobial mechanism works in several ways: NPs can attach to microbial cell membranes to cause structural damage and leakage of cellular contents.

Silver NPs (Ag NPs) are particularly prominent due to their broad-spectrum antimicrobial activity, high stability, and low volatility. Ag^+ ions produced from Ag NPs provide stable bactericidal properties and high effectivity (Fan *et al*. 2021; Ganguli and Chaudhuri 2021; Parmar *et al*. 2022). Ag NP coatings are commonly applied as paints and can be synthesized through various methods, including eco-friendly approaches that use natural sources such as leaf extracts or are surfactant-free (Parmar *et al*. 2022; Saada *et al*. 2021; Widatalla *et al*. 2022). Studies reported that Ag NP coatings work against fungi such as *Chaetomium globosum*, *Alternaria alternata*, *Aspergillus niger*, *Aspergillus flavus*, *Chaetomium globosum*, *Stachybotrys chartarum*, and *Mortierella alpine* (Ganguli and

Chaudhuri 2021). Past studies utilised Ag NPs in hydrogels, containing fillers such as ZnAl layered double hydroxide (LDH) and sodium alginate (SA), that show antibacterial and antifungal properties (Lestari *et al*. 2020; Porter *et al*. 2021). A recent study by Feng *et al*. (2022) employed soy protein isolates to stabilise and disperse Ag NPs by leveraging the strong affinity between the isolates' amino and the silver ions' amino and carboxyl groups. *Escherichia coli* and *Staphylococcus aureus* were successfully inhibited directly proportional to the nano-Ag concentration. Ag NP also improved elastic modulus and tensile when prepared in film, acting as a reinforcing agent, which could be beneficial for various wood applications. Zou *et al*. (2023) synthesised urea-formaldehyde resin-coated nano-Ag nanocapsules to address the reduced activity of Ag NPs when exposed to air. This approach improved the controlled release of Ag NPs without affecting the original substrate structure and effectiveness. When treating agar plates with 5% of the AgNPs@UF nanocapsules, an 82.1% antibacterial efficacy against *Escherichia coli* was achieved.

Research reported significant antibacterial capabilities of TiO_2 nanoparticle coatings applied to wood surfaces. Incorporating TiO_2 nanoparticles into wood coatings was found to improve antibacterial activity against pathogens such as *Bacillus subtilis* (Anaya-Esparza *et al*. 2020; Ganguli and Chaudhuri 2021). Combining TiO_2 nanoparticles and reduced graphene oxide on wood has shown high antibacterial efficacy against *Staphylococcus aureus*, with specific nanocomposites exhibiting the greatest effectiveness (Bharat *et al*. 2023; Turu *et al*. 2023). Another study reports TiO_2/wood composites synthesised *via* solvothermal methods providing excellent antibacterial properties against both Gram-positive and Gram-negative bacteria (Ahmad *et al*. 2020). Overall, it is favourable to use TiO_2 NPs as they have targeted fungicidal properties and can avoid harming non-target organisms (Jasrotia *et al*. 2022).

Flame resistant and moisture resistant coatings

Addressing wood's inherent flammability and fire safety is crucial for various applications. Coatings with flame-retardant properties mitigate these limitations by lowering wood's combustibility. Recent studies indicate that nanocomposites containing nanoparticles can improve fire retardancy, making them suitable for protective coating applications (Wang *et al*. 2021; Mensah *et al*. 2023). Nanoparticle coatings for flame resistance have a few advantages: nanoscale size and high surface area allow coatings to be effective at lower concentrations compared to other conventional compounds (Kačíková *et al*. 2021; Nair *et al*. 2022). Metal NPs provide fire retardancy by being able to provide a thermal barrier on the wood surface, which can reduce thermal degradation and oxidation (Jin and Chung 2020; Fu *et al*. 2023). This barrier creates a dense char layer, lowering the ignition probability and suppressing smoke generation during combustion. Several studies have highlighted the fire-retardant properties of TiO_2, ZnO, and SiO_2 nanoparticles, attributed to their high thermal stability (Kačíková *et al*. 2021; Desai *et al*. 2023). Emerging nanomaterials used in fire-resistant wood coating include mineralisation utilising silica NP, nano clay, and carbon-based nanomaterials such as graphene and carbon nanotubes (CNT) (Esmailpour *et al*. 2020; Xu *et al*. 2020; Kawalerczyk *et al*. 2023). Carbon-based nanomaterials can provide excellent mechanical strength and high thermal stability, and studies have shown applications in fabrics and wood composites, with their ability to form a barrier to quench ignition can be helpful to be applied to wood substrates (Xu *et al*. 2022; Zhou *et al*. 2021).

Another major contributor to wood degradation is moisture, which promotes not only biodegradation and fungal growth, but also leads to dimensional instability (Brischke and Alfredsen 2020; Wang *et al*. 2021). While wood contains internal water and retains its structure when submerged, it becomes susceptible to attack during cyclic wetting and drying. This process leads to physical degradation of the wood surface. Recent innovations in coatings, including the incorporation of water-repellent particles and the development of superhydrophobic coatings, can substantially improve wood's hydrophobic characteristics. Silica nanoparticles are versatile materials known for their high thermal stability and ability to form rough surface textures at the micro- and nanoscale. By modifying the availability of hydroxyl groups on their surface, silica nanoparticles functionalized with agents such as fluoroalkoxysilane, chloro-trimethyl silane, or polymethylsiloxane can create hydrophobic surface chemistry and roughness, thus contributing significantly to water repellence (Gaff *et al*. 2019; Jirouš-Rajković and Miklecić 2019; Sharma *et al*. 2022). TiO_2 nanoparticles can create self-cleaning surfaces that prevent water absorption (Xing *et al*. 2020; Yang *et al*. 2021). Similarly, ZnO nanoparticles can form a protective barrier that reduces water absorption and enhances weather resistance (Jnido *et al*. 2021; Wang *et al*. 2021). Graphene oxide and CNTs, due to their high surface area and hydrophobicity, create a rough surface texture that leads to hydrophobic properties (Łukawski *et al*. 2023).

Superhydrophobic wood coatings have been gaining interest, as they can self-clean and resist corrosion. Achieving superhydrophobic surfaces typically involves constructing micro-nanoscale surfaces and applying low surface energy coatings to the modified surface (Han *et al*. 2019; Sharma *et al*. 2020; Gao *et al*. 2023). The addition of cellulose nanofibers (CNFs) into hydrophobic silica nanoparticles can promote the formation of covalent bonds, enhancing the integration of the two components, resulting in a dispersible superhydrophobic coating solution (Chen *et al*. 2022). The solution precursor plasma spraying (SPPS) process generated ZnO NPs depositions on wood, achieving hydrophobicity, UV resistance, and a water contact angle (WCA) of 120° (Jnido *et al*. 2021).

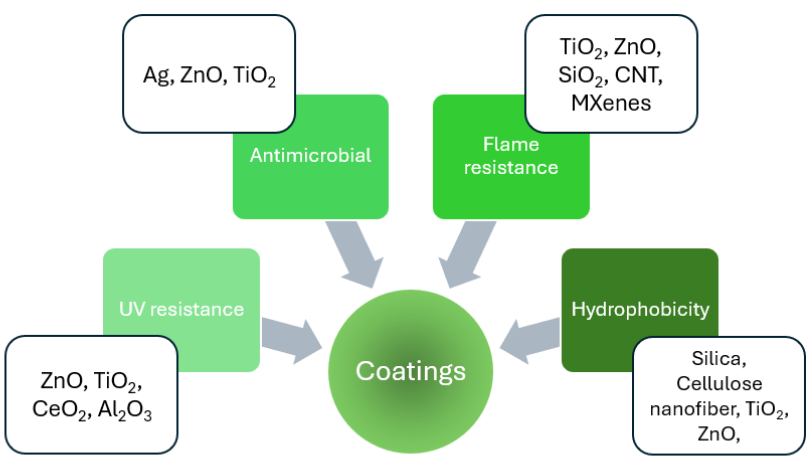

Fig. 4. Various wood coatings and its materials

Coatings offer a straightforward and efficient method to enhance the performance and longevity of various wood products, given their direct application to the wood surface. They serve as a viable alternative when pressure treatment is not feasible, and can improve durability, mechanical properties, and scratch/abrasion resistance. However, a more comprehensive and holistic approach to wood preservation and enhancement may necessitate additional treatments. Hence, coatings may not be the ultimate solution to all wood treatments. Combining them following pressure treatments may give the best results, depending on the situation, most importantly, the wood preservative used. Figure 4 gives a summary of different categories of coatings and their additives.

Nanoemulsions and SEDDS for Wood Preservatives

Emulsions are heterogeneous mixtures composed of two immiscible liquids, with one liquid dispersed as tiny droplets within the other. These mixtures are stabilised by emulsifying agents, which reduce the interfacial tension between the two liquids and prevent the droplets from coalescing (Sneha and Kumar 2022). Emulsions are broadly categorised into two types: oil-in-water emulsions, where oil droplets are dispersed within a continuous aqueous phase, and water-in-oil emulsions, where water droplets are dispersed within a continuous oil phase (Kharat *et al*. 2019). The stability and properties of emulsions are influenced by various factors, including the size of the dispersed droplets, the type and concentration of emulsifying agents, and the conditions under which the emulsion is prepared and stored (Kharat *et al*. 2019; Hidajat *et al*. 2020; Marhamati *et al*. 2021). Different emulsion possesses unique characteristics and applications, making them versatile tools in diverse industries such as pharmaceuticals, food, cosmetics, as well as wood preservation (Choradiya and Patil 2021; McClements *et al*. 2021; Chuo and Mohd Setapar 2022). By improving the solubility of hydrophobic wood preservatives, emulsions could bring great potential to wood preservation research.

Potentially, emulsions need to be able to deliver hydrophobic wood preservatives but also be able to penetrate the wood to deliver the preservatives to its active sites, penetrating wood vessels and enough surface to provide protection and avoid leaching. Nanoemulsions (NE) are stable, non-toxic systems consisting of an oil and aqueous phase that form droplets with diameters of < 200 nm and can dissolve hydrophobic active ingredients (Safaya and Rotliwala 2020). NEs can be prepared with high-energy input methods such as high-pressure homogenisation, ultrasonication, or microfluidisation to achieve the nanosized droplets (Li *et al*. 2021; Pratap-Singh *et al*. 2021; Sadeghian *et al*. 2023). In addition, low-energy methods phase inversion temperature (PIT), spontaneous emulsification, microemulsion dilution, solvent displacement or evaporation methods, can be used to produce NEs, which incorporate the active ingredient, as shown in Fig. 5 (Safaya and Rotliwala 2020; Li *et al*. 2021). NEs are thermodynamically unstable systems that can degrade due to phenomena such as flocculation, coalescence, creaming, Ostwald ripening, and other similar processes (Alhasso *et al*. 2023; Ding *et al*. 2023; Preeti *et al*. 2023).

Self-emulsifying drug delivery systems (SEDDS) are an advancement in the formulation of pharmaceuticals, designed to improve the bioavailability of compounds with poor water solubility. Initially developed within the pharmaceutical industry to optimise the delivery of hydrophobic drugs, SEDDS have shown a potential to be adapted for other applications, such as wood preservation (Cholakova *et al*. 2022; Salawi 2022; Sultana *et al*. 2022). SEDDS are isotropic mixtures of oils, surfactants, and co-surfactants that spontaneously form fine oil-in-water emulsions upon contact with an aqueous phase, such as gastrointestinal fluids in the case of drug delivery (Cholakova *et al*. 2022; Salawi 2022; Sultana *et al*. 2022). SEDDS can self-emulsify without needing external energy input, such as mechanical agitation (Kommana *et al*. 2020; Park *et al*. 2020). This property can ensure uniform distribution and penetration of active ingredients into complex substrates like wood. When SEDDS mixes with the aqueous phase, surfactants and co-surfactants reduce the interfacial tension between the oil and water phases, thereby facilitating the formation of fine droplets (Tran and Park 2021). These droplets encapsulate the active ingredients, enhancing their solubility and enabling efficient delivery to the target site. This mechanism allows the active compounds to penetrate the wood structure for wood preservatives, providing prolonged protection against decay, wood-degrading insects, and environmental degradation.

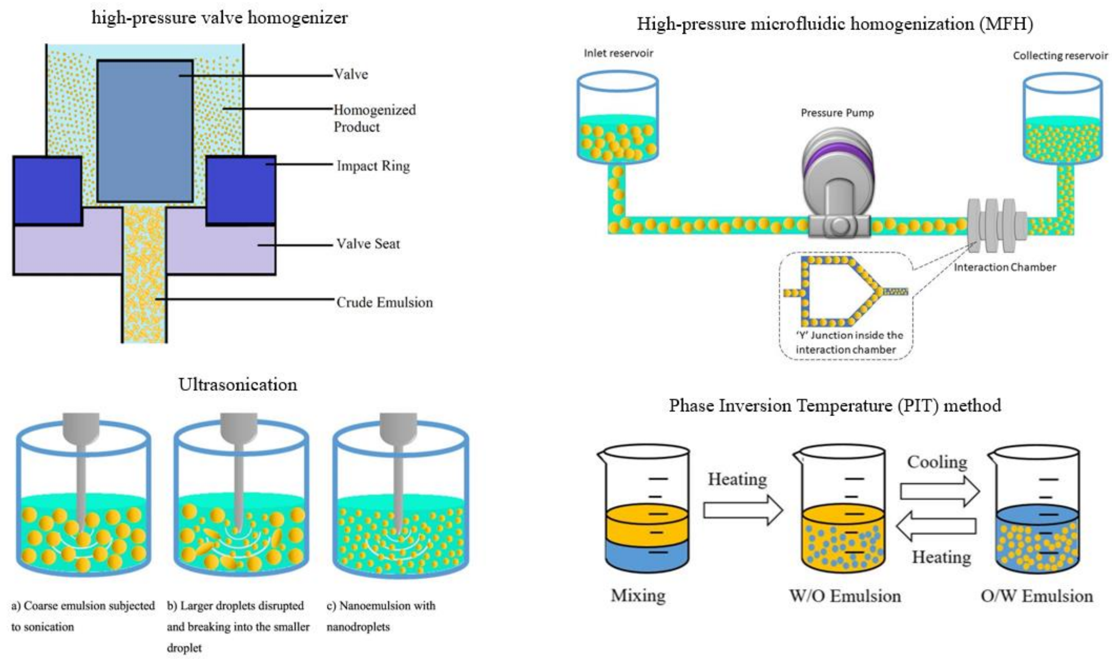

Fig. 5. Examples of high and low-energy emulsion preparations (Sneha and Kumar 2022)

Applications of nanoemulsions and SEDDS in wood preservation

NEs and SEDDS provide a new approach to applying preservatives, as they allow more extensive surface area coverage, better solubility, improved penetration of preservatives into wood, and protection from photodegradation (Mustafa and Hussein 2020). Dosage levels of preservatives can be reduced by improving bioavailability from implementing emulsion systems to limit environmental and health risks.

Applying NEs and SEDDS can also replace organic solvents and oil-borne preservatives that are detrimental to the environment (Ioan *et al*. 2023; Mondal *et al*. 2022). A recent study investigates the effectiveness of eugenol-in-water NEs loaded with tebuconazole for protecting *Populus* wood against white and brown-rot fungi (Lucia *et al*. 2021). Retention of tebuconazole was up to 40%, and it displayed good antifungal activity as the treated wood only experienced weight loss of as little as 2%. Paraffin wax that can be used directly to improve wood stability has also been studied to load CeO_2 NPs at 30% NE concentration. The average emulsion droplet size was determined at 358.6 ± 3.03 nm (Bansal and Pandey 2023). Colour change was significantly reduced compared to uncoated wood, which indicates high UV stabilisation on wood. In a similar study, linseed oil emulsion was embedded with ZnO and CeO_2 NPs for UV protection in coatings (Bansal *et al*. 2022). NE-based pesticide formulations have been discussed for their agricultural uses on crops. In such applications it possible to load different pesticides and fungicides to suit target applications, given that the fabrication methods are optimised and catered to specific uses (Mustafa and Hussein 2020). Feng *et al*. (2020) optimised a formulation including 2% abamectin, 5% castor oil polyoxyethylene (EL-40), and 7.5% hydrocarbon solvent (S-200) in deionised water. The resulting NE demonstrated good wettability and high effectiveness against *Plutella xylostella* larvae at a minimal LC_{50} of 0.0686 mg L^{-1} (Feng *et al*. 2020). This NE allows potential use on cabbage crops and may encourage application on wood with more targeted preservatives.

The oil phase itself can also be used as the active ingredient for preparing NEs or SEDDS, which can be interchangeable with essential oils (EO) that have pesticidal or fungicidal effects (Maurya *et al*. 2021; da Silva *et al*. 2022; Shehabeldine *et al*. 2023). Application of EOs can be instrumental in reducing the overall chemical accumulation within the ecosystem, supplying a greener alternative to potentially harmful chemical preservatives (Sharma *et al*. 2020; Tiwari and Dubey 2022). EOs that show fungal resistance can be prepared in NE forms to improve dispersibility, stability, and efficacy when applied to wood (Liu *et al*. 2023). Lemongrass EO NE was prepared with the stabilisation of polysorbate 80 and corn-stover-derived nanocellulose, producing a 19 nm mean droplet size emulsion with high transparency and high stability, achieving -34 mV zeta potential. The prepared NE has also effectively inhibited the growth of *Aspergillus flavus* and performed better than pure lemongrass EO, which may be attributed to the increased surface area of NE (Liu *et al*. 2023). Garlic EO and its primary compound, diallyl trisulfide (DAT), was spontaneously emulsified and tested for antifungal activity against *Trametes hirsuta* and *Laetiporus sulphureus*. Significant inhibition was observed at 20% DAT concentration with IC_{50} values of 43.2 µg/mL for *Trametes hirsuta* and 27.4 µg/mL for *Laetiporus sulphureus*. NEs with a higher concentration of DAT in their lipid component will require a smaller quantity of DAT to inhibit wood decay growth, reducing environmental impact and increasing efficacy (Gong *et al*. 2021). Eucalyptus nanoemulsion (E-NE) and nutmeg nanoemulsion (N-NE) were employed in a novel study by Nasser *et al*. (2023) to investigate their pesticidal activity against *Odontotermes formosanus*. The E-NEs proved highly effective with 100% and 99.5% termite mortality rate respectively, with significantly higher potency than the bulk EO itself. SEDDS have been used as carriers for an extensive list of antibacterials (ciprofloxacin, cephalexin, curcumin) (Asghar *et al*. 2022; de Oliveira and Bruschi 2022; Zafar *et al*. 2022) and antifungi (amphotericin B, cinnamon EO) (Kontogiannidou *et al*. 2020; Zhang *et al*. 2023) active ingredients, which can lead more researchers to discover specific applications of NE and SEDDS for wood protection.

Wood End-of-Life Management and Health Risks

Wood preservation benefits wood by enhancing durability and protection against fungi and insects, thereby extending the functional lifespan of wood products. These wood products have found many applications in our built environment. However, eventually, they will experience degradation due to weathering, decay, or wear and tear and should be removed from service. When treated wood is retired from use, it enters its end-of-life (EOL) cycle, which requires handling and disposal. Previously, wood treated with creosote, CCA, or pentachlorophenol contained compounds resistant to degradation (Smułek *et al*. 2020; Morais *et al*. 2021; Emenike *et al*. 2024). Disposing of chemically treated wood is challenging due to the potential toxicity of its chemical content to both the environment and human health. This has sparked research on properly handling, reusing, and recycling EOL wood and improving wood preservatives to make them easier to handle at their EOL phase.

Similarly, with the incorporation of nanotechnology and SEDDS for wood preservation, the same problem persists for nanotechnology-treated wood: its EOL impact on human health and the environment is largely unknown. Furthermore, the proper procedure for handling nanotechnology-treated wood has not been clearly defined. The industry must stipulate the same object assessments, regulations, and policies towards nanotechnology-treated wood to ensure the proper handling of EOL wood and be responsible for public health and environmental safety. This section will further discuss the EOL of nanotechnology-treated wood and its challenges while predicting strategies for managing EOL nanotechnology-treated wood.

Risk assessment of nanotechnology-treated wood

In the past, chemically treated wood products have been subject to regulatory controls across various regions, reflecting concerns over their potential for environmental contamination. In many areas, treated wood waste is designated as hazardous material, and disposal methods that were available, such as regulated landfilling and high-temperature incineration, have been used (Jones *et al*. 2019). Landfills may limit or restrict chemically treated wood to avoid the risk of leaching, where preservative chemicals such as arsenic and chromium from CCA-treated wood could seep into soil and groundwater over time, thereby contaminating ecosystems and potentially impacting human health (Kato *et al*. 2021; Euflosino *et al*. 2022). Incineration is restricted, as improper combustion of treated wood can release hazardous chemicals into the air, posing inhalation risks and affecting local air quality (Scussel *et al*. 2022). Currently, life cycle assessment (LCA) is one of the more applied tools that sheds light on waste management and current wood disposal practices, where it is used to evaluate the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to disposal or recycling. However, there is a need for clearer studies, specifically on end-of-life options and the impacts of nanotechnology-treated wood.

Many nanotechnological applications to wood preservation were mentioned previously, but along with them are their disadvantages and potential human and environmental hazards. Unlike conventional wood preservation methods, nanotechnology treatments incorporate various nanoparticles that can be synthesised from metals and non-metals. Nanotoxicity studies have reported effects on a wide range of biological systems, raising concerns about the safety of nano-preservatives used in wood treatment. As the application of treated wood allows it to be exposed to the environment, the nano-preservatives can affect the environment (soil and water bodies), the ecosystem, air, and humans (Chaud *et al*. 2021; Yamini *et al*. 2023). NPs can be affected by environmental modification to undergo aggregation, which in turn could affect their potent toxicity (López *et al*. 2022). Previous literature has covered nanotoxicity risks: AgNPs have demonstrated cytotoxicity and genotoxicity in human cell lines, disrupting cellular homeostasis and potentially affecting soil and aquatic ecosystems (Cypriyana *et al*. 2021). CuNPs have shown similar toxic effects, including hepatotoxicity and systemic inflammation, particularly when released into environments where organisms are exposed through ingestion or inhalation (Cypriyana *et al*. 2021).

Potential exposures are predicted from the “extraction, production, handling, usage, and disposal” phases (Jasmani *et al*. 2020). Although there is extensive information on the negative effects of nanoparticles on environmental and human health, there is insufficient data on the potential exposures and their magnitude of toxicity during these processes, especially in the EOL process. Wang and Qi (2022) studied the release of CuNP from wood sawing and the abrasion of copper-treated wood to determine the impact of processing Cu-treated wood. Heating treated wood as fuel will also release NPs. Laboratory studies have determined that 30% of released particles from burning biomass fuel were under 100 nm (Trojanowski and Fthenakis 2019), posing health risks even more in the case of burning treated wood. As conventional methods for processing nanotechnology-treated wood may contribute to human and environmental risks, more research is needed to evaluate and assess EOL handling of nanotechnology-treated wood using alternative methods, as there have been limited studies on EOL.

End-of-life strategies for nanotechnology-treated wood

Conventional EOL has three main strategies: landfilling, recycling, and energy recovery (Farjana *et al*. 2023). Generally, nanotechnology-treated wood comprises components that are nano-scaled, which is the main concern. Hence, strategic adjustments should be made to accommodate handling EOL nanotechnology-treated wood.

Landfilling is one of the direct and economical strategies for handling EOL wood. Although it is an inexpensive method for disposal, there is a risk of NP leaching from treated wood to the environment, soil, or groundwater over time. Studies have shown that the leaching of nanoparticles from treated wood can occur under various conditions, including weathering, landfill degradation, or water exposure (Gupta and Dhawan 2022). The persistent nature of nanoparticles also raises concerns about bioaccumulation and biomagnification in food chains (Malhotra *et al*. 2020; Banu *et al*. 2021; Velicogna *et al*. 2021). Conventional landfill designs may not adequately address these challenges. Therefore, containment systems incorporating nanoparticle-specific filtration or stabilisation adsorbents such as zeolites and aluminosilicates are viable options for removing NPs, similar to treating wastewater and leachates (Ahmad *et al*. 2020; Bandala *et al*. 2021; Shahrashoub and Bakhtiari 2021). Updated adsorbents include polymer-based and clay-based nano adsorbents, and in recent years, there has been increased attention on aerogel application for removing heavy metal ions (Emenike *et al*. 2024). Discovering new alternatives can substitute for expensive existing filters or adsorbents, which will encourage widespread use.

Recycling wood is another less destructive approach. It is generally more energy-conserving, minimises waste, and has a lower carbon footprint. Recycling has the potential to provide a subsequent usage of nanotechnology-treated wood when it is judged to be not structurally or mechanically suitable for service in its primary use. Possible repurposing can be in the form of particleboards, fibreboards, or wood-cement composites (Iždinský *et al*. 2020; Nuryawan *et al*. 2020; Lee *et al*. 2022). However, recycling has challenges due to the potential release and redistribution of nanoparticles during processing and reuse. Cutting, grinding, or shredding nanoparticle-treated wood for repurposing can release nanoparticles into the air as fine particulates, posing respiratory hazards to workers and contaminating the environment (Wang and Qi 2022). For example, studies have indicated that nano-silver and nano-copper particles embedded in wood treatments can become airborne during mechanical processing, increasing the risk of inhalation exposure. The environmental persistence and potential ecotoxicity of nanoparticles raise significant concerns when nanotechnology-treated wood is recycled or reused in the environment. Weathering and other environmental factors can exacerbate the leaching of nanomaterials, leading to unstudied long-term risks such as bioaccumulation and other negative impacts (Chaud *et al*. 2021). Reducing the nanotoxicity risk of recycled nanotechnology-treated wood requires consideration during processing and reapplication to ensure human and environmental safety.

Energy recovery for EOL wood involves converting EOL into some form of energy or fuel, typically *via* incineration in biomass plants, converting biomass into heat or electricity. This strategy offers efficient repurposing of EOL wood, as it reduces waste and the cost of sourcing other fuel types (Farjana *et al*. 2023; Kumar Sarangi *et al*. 2023). However, this strategy poses significant risks as burning nanotechnology-treated wood will potentially release NPs or toxic byproducts that may be formed during incineration or repurposing (Portugal *et al*. 2024). Like recycling wood, airborne NPs or ash residues may pose health risks and cause contamination if not properly monitored. Safety implications need to be implemented during and after the energy recovery process: filtration systems should be used to monitor air quality and emissions from the incineration, as well as residue treatment to stabilise the residue from contaminating air or soil after combustion (Rabajczyk *et al*. 2020).

In summary, EOL methods for wood products, particularly those treated with preservatives or nanotechnology, remain a critical area of research to improve sustainability and minimise environmental and health impacts. Researchers are increasing efforts in assessing LCA to better quantify the environmental footprint of different EOL scenarios. However, significant research gaps persist, including a lack of comprehensive understanding of nanoparticles' long-term behaviour and environmental fate, insufficient data on the cumulative health risks associated with their release, and the absence of standardised guidelines for the disposal and recycling of nanoparticle-treated wood. Additionally, the proposed EOL solutions' scalability and economic feasibility require further investigation. Future studies should focus on developing innovative nanoparticle stabilisation methods, creating alternative preservation technologies with lower toxicity, and implementing robust monitoring systems for nanoparticle emissions during recycling and incineration. Addressing these gaps and advancing safe, efficient, and sustainable end-of-life management strategies for wood products represents a critical pathway for future progress.

FUTURE OUTLOOK

Conventional wood preservatives have been the industry standard. Still, noticeable deficiencies can be observed, such as leaching hazardous and toxic pollutants harmful to humans and other living organisms, having low efficacy, and having poor distribution on wood matrices. As discussed in this review, nanotechnology provides an alternative to wood preservatives to provide improved protection for wood and its structures against various biotic and abiotic factors. Nano-based wood preservatives are effective even at low dosages and offer substantial long-term protection with insignificant environmental impact. Different nano-preservative formulations can be adopted based on specific end-use requirements, such as nanosized biocides, polymeric carriers, and wood coatings. Nanosized metal preservatives enable deeper penetration and more uniform distribution of particles within the wood, as well as controlled release and effective encapsulation, which enhance the effectiveness of wood treatments. By similar rationale, applying NEs and SEDDS can act as carriers for hydrophobic wood preservatives and enhance preservative performance by lowering the dosage and improving the surface area.

The green synthesis of nanoparticles using eco-friendly sources could aid in mitigating their negative environmental impacts. The commercialisation of nanoparticle-based wood preservatives demonstrates their wide-ranging applications in the forest products and building sectors. However, a significant need and scope remain for the continued adoption, improvement, and commercialisation of nanoparticles in the wood industry. Considerations of nanotechnology's environmental impact and potential health risks is essential and crucial to ensure a sustainable market. The long-term effects of nanotechnology-treated wood are still unknown and require research, particularly at the EOL stage. To safely apply the treated wood during their service and to manage them at the EOL phase requires thorough evaluations, or with the help of LCA, to evaluate its EOL impact on human and environmental health. As nanotoxicity is a rising concern with the development of nanotechnology applications, further steps to monitor, control, and minimise the nanotechnology footprint and impact from EOL processes should be crucial. They will be essential for raising the bar for nanotechnology applications in the wood preservation field.

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