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Recent Developments Studies on Wood Protection Research in Academia: A Review

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The wood preservation industry has taken large leaps to develop and produce chemicals that protect wood from microorganisms and weathering degradation with no or low environmental impact. These improvements occurred after concerns of federal and public agencies about the release of toxic components into atmosphere, soil, and water. These days, reduction in use of non-renewable resources is a crucial concern. Wood and wood-based products are generally low in CO_2 emissions and can be gained from sustainable forest resources. Therefore, they can play a significant role as renewable resources. In comparison to other building materials, wood has numerous advantages, such as suitable thermal insulation, high strength to weight ratio, easy machinability, and attractive esthetics. Wood as a valuable building and industrial material requires to be protected due to its biodegradable properties especially when it is submitted to harsh conditions. Wood durability can be improved through wood protection which include wood preservatives and modification systems. Wood protection should be safe to use, efficient, cost-effective, permanent, and should not corrode metal or degrade wood components. Numerous reviews of wood protection can be found in the scientific literatures, but until now a review of a combination of wood preservation and wood modification has not been studied. It should be considered that the latest research projects in wood protection in academia not always reflect the most current developments in the industry due to exclusive rights. The findings reported in academia contribute to the safe use of preservatives, advancement of wood modification techniques, as well as recycle and disposal of treated material. Therefore, in this study, the most current research and advancements promoted in the wood protection in academia are discussed which including an overall summary of the recent developments on wood preservatives, different types of preservatives, natural preservative compounds, and modification technologies in academia.

Keywords: wood preservation, wood protection, wood modification, preservatives, environmental impacts, durability

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Abbreviations: ACA, Ammoniacal copper arsenate; ACQ, alkaline copper quat; ACZA, ammoniacal copper zinc arsenate; APB, ammonium pentaborate; ARS, Agricultural Research Service; ATFB, ammonium tetrafluoroborate; AWPA, American Wood Protection Association; BA, boric acid; BMPS, best management practices; CA, copper azole; CCA, chromated copper arsenate; CCAP, counter-current attrition process; CCB, Chromated copper borate, CHTM, hydro-thermomechanical wood modification; CM, chemical modification; CuN, copper naphthenate; DCOI, 5-dichloro-2-N-Octyl -4-Isothiazolin-3-One; IPBC, 3-iodo-2-propynyl-butylcarbamate; LG, Liquid glass; MOR, Moduli of rupture; PAC, polycyclic aromatic compounds; PAH'S, polycyclic aromatic hydrocarbons; PCP, pentachlorophenol; PFOTS, perfluorooctyltriethoxysilane (PFOTS); TiO_2, titanium dioxide; TM, thermal modification; TMM, thermo-mechanical modification; U.S. EPA, United States Environmental Protection Agency; USDA, U.S. Department of Agriculture; UV, ultraviolet; ZnB, zinc borate.

INTRODUCTION

Wood and wood products are present in different forms in building construction sector namely beams, cabinets, ceiling, flooring, and interior paneling. When wood and wood products are exposed to abiotic or biotic agents such water, heat, microorganisms, ultra-violet (UV) rays, and corrosive chemicals, they tend to deteriorate which may ultimately result in lack of safety for building occupants and economic losses. The service life of wooden products mainly depends on wood natural durability, design, and protection system. If wood is properly processed, it can last for a long time which can be demonstrated on historic buildings, utility and artistic objects, musical instruments, and other wood products.

In wood protection there are mainly two methods to preserve wood: wood preservation (chemical protection) and wood modification (modifying protection). While chemical protection is performed with preservatives, modification is done by activation of chemical components present in wood cell walls using high temperatures. In one hand, in wood preservation, traditional wood preservatives and methods employ chemicals that are considered toxic and can adversely affect human health and environment. Based on the impact of chemicals to the environment and human health, preservative restrictions have been established in the United States (U.S.) and some European countries. Additionally, serious efforts are being made globally to develop alternative preservatives based on natural products with low or no toxicity. Due to certain limitations which include different results between laboratory and field performance of natural products, difficulties in putting a united agreement globally on setting standards defining the quality of natural products' performance, and the efficacy of these natural compounds when expose to environmental conditions, the progress of the new technologies has been slow. On the other hand, these days the modified wood is produced throughout Europe and other parts of the world. However, in wood modification technologies, the process of transforming from the laboratory phase to production level has been started from the last decades, it is still growing slowly. Higher prices in both special equipment for wood modification process and final wood products, the lack of experience of using the material, consumer perceptions about new materials can be the possible reasons. Thus, the aim of this review is to summarize and cover recent developments studies in different categories of wood preservatives and different process in wood modification. It should be mentioned that this review is not aiming to comprehensively list every study in the field but highlight the trends in contemporary wood science that focus on these areas.

WOOD PRESERVATION

There is a long history of using preservatives to protect wood and wood products. The benefits of using preservatives are restricted not only to extend service life of structural materials but also to reduce costs and pressure on timberlands by decreasing the number of repairs and replacement of wood products. Wood preservatives provide resistance against insects, fungi, marine borers, bacteria, fire, weathering, and aggressive chemical effects.

According to the Market Research Report (2020) the value of the wood preservatives market is estimated to be $1.7 billion by 2025. North America represents the largest portion of the wood preservatives market in 2020 (Market Research Report, 2020). Global wood preservative manufacturers such as Koppers, BASF Wolman GmbH, Borax, KMG Chemicals, Kop-Coat, and Arxada are putting continuous efforts to develop new chemicals in compliance with rules and regulations of environmental agencies. The choice of treatment is made based on the use defined by internally recognized associations or agencies such as American Wood Protection Association (AWPA) or European Standards for Structural Use (EN 335) (Reinprecht, 2016). This part covers wood preservation system in the last twenty years, how preservatives have been used in new engineered wood products, and how new products are being developed to replace inorganic oil-based preservatives. Historically, wood preservatives mainly included creosote, pentachlorophenol (PCP), and water-based arsenical (Barnes et al., 2001a). The most common first and second generation of preservative systems are the following, Chromated Copper Arsenate (CCA), Creosote, PCP, Ammoniacal Copper Zinc Arsenate (ACZA), Alkaline Copper Quat (ACQ), and Copper Azole (Groenier and Lebow, 2006).

Oil Borne Preservatives

Heavy duty organic-type (oil-borne) wood preservatives such as creosote and PCP have been extensively applied in the treatment of poles, timber bridge and railway crossties (sleepers) in North America and Europe. Decades ago, the European Union has banned the use of PCP and creosote. Creosote was allowed a 5-year reprieve from its original cancelation date in 2018 (Brient et al., 2020). These two systems have been nominated as Restricted Use Pesticides by the United States Environmental Protection Agency (U.S. EPA) because of disposal concerns (Barnes, 2002). Consequently, current research involving both creosote and PCP are more likely to include best management practices, disposal, recycling, and remediation of treated wood and/or cleaning of contaminated soil.

Creosote

Creosote is a general term that designates coal tar creosote, coal tar, and coal tar pitch. Creosote is applied to railroad ties, utility poles, pilling, and timber bridge to provide biodegradation protection. The primary chemicals in creosote composition are polycyclic aromatic hydrocarbons (PAHs) (85%) and phenols (2–17%) (Bedient et al., 1984). Approximately, 20–40% of creosote total weight is attributed to sixteen PAHs, which are major pollutants and potential carcinogens (Goldmark, 2013).

In the United States 70% of all produced creosote is used to impregnate railway sleepers and crossties. Approximately its 20% is impregnated to utility poles and their cross arms (United States Environmental Protection Agency [U.S. EPA], 2008). Since creosote has been used for more than two centuries, the literatures have numerous research papers and studies that report its efficiency in protecting wood products

(Chow and Bajwa, 1998; Barnes et al., 2001b; Slahor et al., 2001; Freeman et al., 2005; Webb et al., 2009; Clausen et al., 2014; Lebow et al., 2015). However, in the last decade the number of studies covering the performance of creosote has significantly decreased. The most current publications include post service activities related to environment protection. Furthermore, in this section the recurrent research from (2016-2021) involving all the aspects of creosote post service has been covered.

Over 95% of railroad ties produced in the United States are impregnated with creosote (Railroad Ties Association [RTA], 2014). Jones et al. (2019) predicted that in 2030 most of the disposed railway ties (>99%) and poles (53%) will be impregnated with creosote. Although creosote does not interact with water and therefore has limited leachability without best management practices (BMPs) during and after treatment. More specifically in preservation facilities, leaching of creosote and consequent soil contamination may occur. Konkler and Morrell (2019) investigated the use of post-treatment steaming to decrease migration of creosote components. The authors concluded that prolonged steaming times after treatment decreased initial losses of creosote components from treated wood.

In older wood preserver's sites, there is widespread soil, sediment, and sludge contamination produced by process, practices, equipment, storage, and waste treatment of chemicals present in creosote composition (Sudell et al., 1992). Consequently, the matrix of organic and inorganic contaminants with very distinct physical-chemical properties makes the remediation of these sites more challenging (Madrid et al., 2019). Larsson et al. (2018) investigated the occurrence of polycyclic aromatic compounds (PAC) on soil and concluded that PAC existed in all investigated areas but in different concentrations.

One of the most practical ways of recovering creosote is to use it as energy by high temperature incineration. On the other hand, operating costs of an incinerator may be relatively high (Magdouli and Foudhaili, 2020). Numerous techniques involving biological, physical and chemical, and thermal processes have been developed with the idea of remediating contaminated sites (Kim et al., 2016; Simpanen et al., 2016; Trine et al., 2019). For instance, Bezza and Chirwa (2016) used a biosurfactant to enhance biodegradation of PAHs. The biosurfactant produced *in situ* promoted desorption and emulsification of hydrophobic contaminants.

Several cleaning up methods have been applied to either mitigate the consequences of the disposal or to recycle the creosote treated material. Konkler and Morrell (2019) studied the use of standard soil to capture heavy metals and PAHs. They reported that the soil in heated-sealed and permeable plastic mesh sachet was able to deflect heavy metals and PAHs migrating from the posts. Covino et al. (2016) investigated the feasibility of decontaminating creosote-treated wood by co-composting with agricultural wastes. The removal rate of polycyclic aromatic hydrocarbons (PAH) ranged from 81 to 97% based on the compost type after 240 days. Abouelela and Hallett (2021) investigated the use of protic ionic liquid media to decontaminate creosote treated wood. They reported that the non-hydrophobic protic ion liquid was highly effective on removing PAHs from the creosote impregnated in the wood.

Creosote is an important preservative that prolongs the service life of industrial wood products. As for research, numerous techniques have been investigated and implemented to recycle treated wood, and to remediate contaminated areas. The challenges with these methods are related to costs and time.

Pentachlorophenol

Pentachlorophenol (PCP or simply penta) is a polychlorinated phenol extensively used as a wood preservative, mostly in industrial applications such as hydro poles, cross poles, and railway ties (Butler and Frank, 1991). PCP was introduced as a wood preservative in the 1930's and since then it has been used as a heavy-duty preservative (United States Environmental Protection Agency [U.S. EPA], 2008). It is a widespread environmental pollutant that brings concerns in terms of toxicity to humans and wildlife (Wang et al., 2001). Despite restrictive policies in the use of PCP and other chlorophenols, there was not a substantial decrease in their amount in the environment (Niesler and Surmacz-Górska, 2018). Penta is mixed with petroleum oil, usually diesel or similar oil cuts, and impregnated under pressure into the wood products. The AWPA defines penta-treating as appropriate for round poles used for utility service (American Wood Protection Association [AWPA], 2019a). Currently, few investigations cover the efficiency of penta protection against microorganisms. The most recent research paper by Schauwecker et al. (2020) reported that low level of preservative, decreased moduli of rupture (MOR), and presence of decay in five penta-treated Douglas-fir crossarms after 45–60 years of service. Although penta remains as an important preservative for the wood products industry, it may solubilize if the treated wood materials enter in contact with water raising concerns to the environment (Crosby, 1981; Konkler and Morrell, 2019). According to Erickson (2021) by the end of 2021 the U.S. EPA proposes to ban all uses of wood treated with PCP. The decision was made based on the termination of production by the only manufacturer of the chemical in North America. Research in penta follows the same pattern seen on creosote, less investigation of its protection efficiency and more studies on recycling, decontamination, and disposal. Techniques to remove and remediate the extension and number of contaminants in the environment have been studied over the years as penta has continuously contaminated soil and water (Hechmi et al., 2016; Hung et al., 2016; Rao et al., 2017; Muhamad et al., 2020). For example, Stratton and Stokes (2016) determined the concentration of chlorinated metabolites 15 years after contamination and sequential remediation. They concluded that the levels of chlorinated phenolic compounds generated by PCP were below detection threshold. Guemiza et al. (2017) investigated the use of counter-current attrition process (CCAP) to remove contaminants from soil including PCP. The CCAP treatment achieved a removal rate of 49% for PCP and was considered a suitable solution for industrial applications. In Japan, crossarms, timber, utility poles, and ties were surveyed for reuse and/or disposal (Koyano et al., 2019). In the recycle material, the highest residue concentration detected was PCP with 3.0 mg/kg. In the waste timber, only 0.20 mg/kg of PCP was detected. Although the concentrations did not exceed the amount allowed by the Japanese regulations, they provide important information on how to separate treated timber and other industrial wood products. Kraševec et al. (2021) studied non-destructive detection of penta on historical wooden objects. They observed that the level found in the depot air would have low health risk to humans exposed to them.

Research in PCP has been conducted to reduce its impact on human health and environmental pollution. Even though there are regulations in place to terminate the use of penta, the forest products industry still depends on it, due to its role in extending the service life of poles, ties, and cross arms. More research is needed to determine the efficiency and leaching properties of diluted versions of penta.

Copper Naphthenate

Copper naphthenate (CuN) has been used as a preservative since the beginning of the 20th century. Commercially, CuN was first developed in 1940 (Groenier and Lebow, 2006). With the regulatory efforts to restrict the use of penta in 1980, the public interest for CuN was leveraged (Morrell, 2018). Copper naphthenate belongs to the copper carboxylate group and is found in both oil and water-borne systems (Barnes et al., 2005). Copper naphthenate is generated by reacting copper with naphthenic acid, which is a byproduct of oil refining. Copper naphthenate tends to be slightly less effective than penta, however, it is around 10 times less harmful to humans. Because of the regulation's restrictions applied to penta, the interest in copper naphthenate has grown over the years (Morrell, 2018).

From the late 90's to 2000's numerous studies were published on decay, fire and termites' protection, and strength performance of wood treated with CuN by both Mississippi State University and Michigan State University (Dawson-Andoh and Kamdem, 1998; Kamdem et al., 1998; Kamdem and Chow, 1999; Barnes et al., 2001a, 2002; Kirkpatrick and Barnes, 2006). For instance, Barnes et al. (2005) investigated the performance of copper naphthenate during field testing in comparison to other copper carboxylate preservative systems using water-borne, oil-borne, and water dispersible formulations. The authors found that heavy oil carriers outperformed organic solvent and water carriers. In the last five years, few studies were conducted in academia involving performance of CuN during service. Recently, a field test performed in Canada showed that all untreated control either failed or presented severe decay after 10 years in ground contact exposure, while the copper naphthenate (2% Cu in mineral spirits) specimens displayed only low degree of decay on a few occasions. Above ground contact, the samples remained without damage whereas the untreated exhibited high degree of decay (Stirling and Wong, 2019). Lebow et al. (2017) studied the used non-pressure wood preservatives for military applications and used CuN as reference. Wood treated with CuN had the lowest weight loss during termites' non-choice test. Most of the research involving development of formulations and concentration of preservatives are restricted to the industry which is constantly seeking for cost effective solutions to prolong the useful life of wood products. Although CuN has environmental advantages and has shown great performance against decay, creosote and penta still are the most used oil-borne preservatives.

Water Borne Preservatives

Water-borne chemicals were introduced into the market in the 1950s (Smith, 2019). Their carrier is cost-effective, safe, and normally provides a clean surface on the treated wood (Schultz and Nicholas, 2004). Preserved wood with water-borne chemicals can be painted post-treatment and can also be used to a wider range of applications such as utility poles, residential lumber, and timber as well as for protection of wood composites (American Wood Protection Association [AWPA], 2019a). Water-borne treatments include arsenical, non-arsenical copper, and non-metal preservatives. Numerous studies were conducted on the fungicide, bactericide, insecticide, algaecide, and moldicide performances of water-borne chemicals.

Copper Systems

Copper is an essential micronutrient for the development of plants and animals. In higher doses, copper may act as a preservative against decay, bacteria, mold, inset, and algae. The use of copper in the preservation industry dates from over hundred years (Freeman and McIntyre, 2009). Lebow (2007) stated that, although the use of borates and other organic biocides have increased over the years, copper is still the most important biocide component used to protect wood. Preston et al. (2008) recognized the most general types of copper-based wood preservatives. One of them is the system that uses chromium as a corrosion inhibitor, fixation agent, and co-biocide, for instance CCA, and copper naphthenate. Another type is copper preservatives that contain nitrogen base as solubilizer, fixation agent and corrosion inhibitor, exemplified by ammoniacal copper arsenate (ACA), ammoniacal copper zinc arsenate (ACZA), ammoniacal copper citrate, copper azole (CA), copper HDO, and alkaline copper quat (ACQ). Numerous manuscripts and research papers have been published in the last decade on the use of copper-based systems to extend the usability of wood and wood-based products in different parts of the world for distinct applications.

The most important wood preservatives in the last 70 years have been water-borne metallic arsenicals, such as CCA and ammoniacal copper arsenate (ACA) (Smith, 2019). In the literatures, there are a wide range of research paper in the topics of degradation, durability, chemical migration, leaching, remediation, recycling, and disposal (Srinivasan et al., 1999; Clausen, 2000; Zaidon et al., 2003; Townsend et al., 2004; Virkutyte et al., 2005; Lin et al., 2009; Zelinka and Rammer, 2009; Temiz et al., 2014; Lebow et al., 2015). In New Zealand, Singh and Page (2016) evaluated the service life of CCA-treated pine based on decay progression. The authors concluded that both treated stakes and poles in ground contact with 1.65% of retention would achieve service life of more than 100 years based on decay progress.

Chromated copper arsenate and other copper-based preservatives have been in the market for many years, consequently their disposal brought many challenges which promoted the studies in the area of recycling, recovery, and remediation of copper-treated wood (Humar et al., 2004;

Sierra-Alvarez, 2009; Kartal et al., 2015; Parker, 2017; Akgul and Akgul, 2018). In a study by Tascioglu et al. (2016) the biological, physic-mechanical, and thermal properties of wood-plastic produced from recycled CCA treated wood were assessed. They found higher strength, dimensional stability, and biological resistance against termites and decay in treated samples. In Brazil, where there are no restrictions in the use of CCA (Vidal et al., 2015), Ferrarini et al. (2016) investigated the use of acid leaching to decontaminate CCA-treated eucalyptus wood. They concluded that hot water with sulfuric acid was effective in removing CCA from treated wood.

Chromated copper arsenate and ACA contain substances that are harmful to the environment, other copper-based preservatives were developed to serve as an alternative for external applications namely copper azole (CA) and alkaline copper quaternary (ACQ). According to United States Environmental Protection Agency [U.S. EPA] (2021) copper azole is a water-based preservative used to protect wood from decay and insect attack, and its uses include millwork, shingles and shakes, siding, plywood, structural lumber, fence posts, building and utility poles, land and freshwater piling, composites, as well as above-ground, ground-contact and fresh and saltwater applications. ACQ is also used to prevent decay and insect attack and has been registered to treat lumber, timbers, landscape ties, fence posts, building and utility poles, land, freshwater and marine pilings, sea walls, decking, wood shingles, and other wood structures (United States Environmental Protection Agency [U.S. EPA], 2021).

The scientific community in the wood protection field has studied the penetration properties, retention, leaching, and resistance to fungi and termites of softwood and hardwoods treated with CA and ACQ (Slahor et al., 1997; Morris et al., 2002; Temiz et al., 2004; Arango et al., 2006; Humar et al., 2006; Yildiz, 2007; Ma et al., 2013). In a study conducted in the Chinese Academy of Forestry, the biological and termiticidal performance of CA and ACQ as surface treatment were investigated for either remedial or supplemental application (Ma et al., 2013). The results showed that the efficacy of the preservative was linked to surface retention, for this reason wood species with low permeability had significant mass losses caused by either termites or white-rot fungus. In a more recent study, Sivrikaya et al. (2017) studied the weathering performance of wood treated with copper azole in combination with water repellents. The results showed that wood treated with CA and water repellents improved the leaching characteristic and inhibited color change. Copper ammonium acetate complex commercially known as COMPTEC^{TM} was developed by Chemical Specialties Inc., with the objective of incorporating a drying oil to a copper preservative to resist biological action and water uptake (Roos and Archer, 2004). According to González-Laredo et al. (2015), the drying oil in the wood decreases water absorption and increases dimensional stability, which preserves the wood mechanical strength. Also, the copper ammonium acetate-oil complex may be added to green wood either in solid or flaked form.

Alkaline copper quat (ACQ) is a combined formulation that contains 50–67% of copper oxide and 33 to 50% of quaternary ammonium compound with multiple variations on its composition namely ACQ-A, ACQ-B, ACQ-C, and ACQ-D (Kirker and Lebow, 2021). ACQ is one of the several preservatives that were developed to be an environmentally friendly substitute for CCA. Lebow (2007) pointed out that ACQ can penetrate into wood species that are classified as hard to treat. For instance, Pang et al. (2017) investigating the effect of incising on the resistance of ACQ concluded that the service life of ACQ treated wood be more than 50 years based on leaching test results. More recently, Adnan et al. (2021) investigated the impact of ACQ treatment on surface quality and bonding performance of hardwood and CLT elements. The results showed that ACQ treatment does not affect block shear and strength of hardwoods and CLT samples. Copper HDO (CX-A or copper xyligen) is an amine copper-based wood preservative that has been utilized in Europe for over 30 years. The active ingredients are copper oxide (61.5%), boric acid (24.5%), and copper-HDO (Bis-(N-cyclohexyldiazeniumdioxy copper) (14.0%) (Lebow, 2013). According to Schultz and Nicholas (2007), copper HDO is stable, but the borate is leached relatively quickly, and the non-complexed copper also can also leach. This system has shown satisfactory aboveground performance in research tests, but low efficacy in ground-contact in areas where copper-tolerant fungi were present. Kim et al. (2010) evaluated HDO's ability to protect pine samples from termites' attack. The results indicated not only protected the samples, but their performance was comparable to CCA-C. Barnes et al. (2009) observed that southern pine pressure treated with copper HDO had similar properties to untreated southern pine and therefore it could be used in structural applications.

Copper has also been applied in fine particles in the form of basic $CuCO_3Cu(OH)_2$ for wood protection (Cookson et al., 2010; Civardi et al., 2015). These wood preservatives commonly referred as micronized copper was approved by the International Codes Council Engineering Service (ICC ES) and started being applied after 2010. In terms of performance efficiency, micronized copper systems have either similar or superior results when compared to ionic copper-based systems for protecting wood from biodegradation (Pantano et al., 2018). According to Schmitt et al. (2014), micronized copper formulations have lower production costs, higher resistance to both leaching and corrosion of stainless steel and hot-dipped galvanized fasteners. Additionally, since particulate formulas are more concentrated in copper, they have lower shipping costs (Freeman and McIntyre, 2009; Freeman et al., 2013). Micronized copper azole, micronized copper quat, and nanoparticle formulations of copper oxide and zinc oxide have been applied into many wood and wood-based products (Lim et al., 2020a,b; Shiny and Sundararaj, 2021). Because of their leaching resistance, they have shown excellent durability performance (Kartal et al., 2009; Ozgenc et al., 2012; Nguyen et al., 2013). Copper preservatives prolong the service life of wood products which has a positive impact on the conservation of timberlands and forests. However, the disposal of copper-treated wood may pose a challenge to manufacturers and users.

Borates

Borate preservatives are highly soluble and easily leached. Borate treated wood is recommended only for above ground applications protected from liquid water. Borates have low mammalian toxicity but are sufficiently effective against wood-destroying insects and fungi (Williams, 1996). Because of its solubility and mobility, borates can be applied to wood species that are classified as hard to treat. Borate formulations include boric acid, or, usually, disodium octaborate tetrahydrate (DOT), sodium tetraborate and sodium pentaborate (Freeman et al., 2013). The AWPA P25-16 standard recommends a retention of 2.7 kg/m^3 for pretreatment of crossties and 4.5 kg/m^3 for applications above ground contact and protected from liquid water (American Wood Protection Association [AWPA], 2019b).

The use of borates has been extensively investigated nationally and internationally in the last 25 years as a preservative and fire retardant (Thevenon et al., 1997, 1998; Baysal et al., 2006; Lyon et al., 2007; Yuksel et al., 2014; Gillenwaters et al., 2018; Yan and Morrell, 2019). Copper chromium boron (CCB) preservatives is an alternative to CCA and has been widely used in Europe (Icimoto et al., 2013). The disadvantage of using CCB and other preservatives is high leachability when expose to high humidity (Koch and Sheard, 1991). The restriction for indoor applications was lifted through the developments of complex formulations (James and Edwin, 2019). The wood preservation industry has investigated and developed solutions to either decrease or improve the leachability of boron-based preservatives. For example, Lloyd et al. (2005) developed a leach-resistant borate preservative that provided resistance against insect and fungal attack in ground contact and exterior applications.

Mohamad-Nasir et al. (2019) investigated the durability of Malaysian timber species treated with DOT. Results indicated that the preservative protected all samples against termites and white-rot fungi. In fire protection, Yu et al. (2017) studied the effects of boric acid and borax on fire resistance of bamboo filament. The results showed that borax had a better performance on restraining the heat release than boric acid. Borates have also shown satisfactory preservative performance when used in combination with fast releasing DOT and less soluble zinc borate (ZnB) (Uysal et al., 2018). Uysal (2016) examined the efficiency of borate mixtures with different levels of solubility to provide threshold levels of boron into wood samples. The author concluded that boron levels were distinct in the outer zone and all the mixtures provided high protection against internal decay in the outer zone.

In France, Lyon et al. (2009) tested the resistance of wood treated with ammonium borate oleate to fungi decay. The four solutions investigated exhibited efficiency against fungi, except for pine samples exposed to the brown rot fungus (*Coniophora puteana).* In the case of surface protection, Fogel and Lloyd (2002) found that borate-containing products significantly decreased in mold growth compared to construction products without borates. In Turkey, Kucuktuvek et al. (2020) evaluated the weathering performance of wood impregnated with ammonium tetrafluoroborate (ATFB), ammonium pentaborate (APB) and boric acid (BA) and coated with a layer of liquid glass (LG). The authors concluded that samples impregnated with borate solutions were more color stable than the controls.

Borates have also proved to be an efficient ingredient for dual protection. Lloyd et al. (2018) studied the application of dual borate and CuN treatment of timber bridges. The authors pointed out that the addition of borate to protect heartwood provided significant increase in bridge tie useful life, therefore it can be used either with creosote or copper naphthenate.

Preservative manufacturers such as Nisus, Koppers and Ko-Coat have developed new borate formulations with the objective of protect wood in ground above contact (Marks et al., 2002; Lloyd, 2013; Zhang et al., 2014). For instance, Zhang et al. (2012) created a micronized boron preservative that had both wood preservative and flame retardant composition with low leachability. In Uruguay, the developed micronized zinc borate inhibited mold growth and prevent leachability while maintained protection against decay fungi (Ibañez et al., 2019).

Borates have a great performance in interior applications, but its fixation problem restrain its use in outdoor exposure. Although fixation of boron compounds has been extensively studied (Huang et al., 2018; Murthy et al., 2019; Verly Lopes et al., 2020; Bhatt and Tripathi, 2021; Ibañez et al., 2021), it is still recommended only for interior purposes by AWPA (American Wood Protection Association [AWPA], 2019c). As mass timber products become more popular in North America, borates may serve as a great preservative as well as fire retardant. More research needs to be done to determine the application of borates for engineered wood products.

Natural Wood Preservatives

Traditional preservatives including CCA have been banned in many European countries as well as the United States due to the toxic components including chromium and arsenic. It is well documented that a common wood preservative, for example, CCA contains considerable level of arsenic after its disposal resulting in the soil and groundwater contamination. This has led to a ban on its use by several countries in response to CCA toxicity (Khan et al., 2006; Hawley et al., 2009). Thus, there is an ongoing need of non-toxic preservatives to improve wood preservation technology to replace synthetic and inorganic compounds with organic biocides or natural wood preservatives (Broda, 2020). Environmentally friendly wood preservative has recently emerged as a common acceptable alternative for wood preservation industry. This becomes more important since the demand for environmentally friendly wood preservative has been shown to increase by environmental organizations, consumers, and authorities (Alfredsen et al., 2004).

Depending on the origin of the compounds, natural wood preservatives can be categorized into different sections such as plant extracts, essential oils, waxes, resins and tannins from bark, heartwood extractives, chitosan, etc. The antimicrobial agents which are aromatic and non-aromatic compounds are produced by plants. Some of these products include phenols, terpenoids, alkaloids, lectins and polypeptides and they can be used in different applications (Broda, 2020). In several studies, derivatives from various plant parts including bark, wood, leaves, seeds, and fruits, have been investigated for their wood protection properties (Yang, 2009). In different studies, extracts from cinnamon leaves have been effective against wood decay fungi and termites (Wang et al., 2005; Cheng et al., 2006; Lin et al., 2007; Maoz et al., 2007). Matan and Matan (2007), also investigated the highly effective of cinnamon oil and clove oil against mold growth on the surface of rubber wood. Lemon grass, rosemary, tea tree and thyme also contain essential oils which are effective against mold on wood (Yang and Clausen, 2007). **Table 1** which has prepared by Singh and Singh (2012) categorized the natural preservatives, especially essential oils with details. One of the essential oils as an effective organic biocide, particularly when used in combination with other organic products is Linseed oil. Linseed oil can be used as protective coatings for a long-time protection. Linseed oil-boron and tall oil-boron combination treatments have given very effective results against fungi and termites (Lyon et al., 2007; Temiz et al., 2008). The heartwoods of durable species such as black locust (*Robinia pseudoacacia L.*) and African padauk (*Pterocarpus soyauxii Taub.*) contain natural extractive compounds which have antifungal activities (Sablik et al., 2016). The bark extract from mimosa (*Acacia mollissima*) and quebracho heartwood extract (*Schinopsis lorentzii*) contains condensed tannins (proanthocyanidins or polyflavonoid tannins). These condensed tannins are so effective against both white and rot fungi (Tascioglu et al., 2013; González-Laredo et al., 2015) especially in indoor applications (Tascioglu et al., 2012). Other extractive compounds from plants, such as diols, may be effectively used as coatings for wood protection in outdoor applications (Teacă et al., 2018). Chitosan which is a 1-4-linked polymer of 2-acetamido-2-deoxy-β-D-glucose derived from chitin has also antimicrobial and antifungal properties. Chitosan has been raised the attention of several scientists during the past decades as an excellent environmentally friendly wood preservative agent (Eikenes et al., 2005a,b; Torr et al., 2005; Hussain et al., 2013; Khademibami et al., 2020a). Factors that impact the antifungal activities of chitosan are the molecular weight, degree of deacetylation, and source of chitosan as well as fungi or bacteria that interact with chitosan and its derivatives (Xu et al., 2010; Ing et al., 2012). The antifungal activity of various concentrations of Low molecular weight chitosan (0.25, 0.50, and 0.75%) in three active strains of fungal (Aspergillus niger, Aspergillus flavus, and Penicillium chrysogenum) in wooden artifacts samples was also reported by El-Gamal et al. (2016).

It is well observed that replacement of effective preservatives such as CCA is the time-consuming process (Schultz and Nicholas, 2007). Finding effective bioactive sources, development of formulation and treatment processes in which how target natural compounds eliminate wood deteriorating organisms including fungi, bacteria and termites are needed more investigations and considerable exploration. Furthermore, suitable formulations and treatment methods should be applied to achieve the significant biocides penetration within wood cell walls in order to increase their efficacy and decrease the cost. There are two main issues that can be addressed for natural products as wood preservatives. Firstly, retention of organic biocides into impregnated wood particles, and secondly, susceptibility of natural wood preservatives to biodegradation (Singh and Singh, 2012). Unlikely, the exposure of treated wood to moisture has been shown to result in a significant increase in leaching and decrease in antifungal activity or prevention microbial attack organic biocides on wood products (Larnøy et al., 2006; Treu et al., 2009; Khademibami et al., 2020b). It is well documented that certain additive in combination with organic biocides resulted in an increase the functionality of biocides and their retention rate into wood cells (Schultz et al., 2006; Torr et al., 2006). The efficient way retaining biocides within the impregnated wood is to use co-impregnate agents for fixation of organic biocides which is facilitated by cross link biocides to polymers in the wood cell walls. Suitable refinements as well as cost-effective treatments are facilitated by appropriate understanding of the mode of action of different natural compounds. The aforementioned results can be used to select fit-to-purpose agents and develop tools for possible integrated approaches linked to natural compounds and other agents, including antagonistic fungi.

Newer Preservative Systems

Currently, because of concerns with the potential contamination of air, soil, and water by heavy duty treatments, the wood preservative market is constantly developing new solutions that address the degradation problem using environmentally friendly ingredients (Marx, 2013; Mars et al., 2015; Richardson and Hodge, 2016; Warburton et al., 2017; Hughes et al., 2018; Arumugam et al., 2021). Newer preservative systems are only marketed for above ground exposure. They do not include metal in their compositions. These preservatives rely solely on organic pesticides for wood protection including triazoles, benzimidazoles, isothiazolones, sulfamides, carboxamides, or 3-iodo-2-propynyl-butylcarbamate (IPBC) and 4,5-dichloro-2-N-Octyl- 4-Isothiazolin-3-One (DCOI) (Reinprecht, 2016). All these synthesized organic biocides are efficient against numerous wood damaging fungi, and they may also offer protection against termites (Bota et al., 2010; Nicholas, 2018; Singh and Page, 2020; Mehramiz et al., 2021). **Table 2** shows the most common wood preservatives and their respective efficacy against fungi and insects. Cost effective and durable water-borne organic systems are difficult to develop in some applications, especially in areas of high deterioration hazards or for ground contact uses (Schultz et al., 2014). Therefore, traditional first- and second-generation preservatives will still be applied for heavy duty applications in order to prolong the service life of wood structures and materials. Continuous research in recycling and disposal are necessary to protect health and the environment.

Wood Coatings

Wood coatings are used to protect the surface of wood against biotic and abiotic factors. In the case of exterior wood coatings, they are primarily designed to resist weathering effects. Coatings are also designed for esthetic purposes where the wood is exposed without compromising its service-life. The mechanism of action of wood coatings is divided in two categories namely film forming and penetrating (Williams, 1999). Film forming such as paints and solid-body stains contain pigments that protect wood from discoloration caused by sunlight (Feist, 1990). Penetrating coatings consist of water repellents, clear stains, preservative, and surface treatments. They usually contain oil or resin in their composition to seal the wood surface and a solvent to facilitate absorption into the cells (Daniel et al., 2004).

The efficiency of a surface treatment in protecting the wood substrate is highly attributed to its ability to cover and adhere to

TABLE 1 | Summary of natural compounds.

	Natural wood preservatives	Uses	References to work done
Essential oils	Essential oil from cinnamon leaves	Wood decay fungi (nutrient medium)	Wang et al. (2005)
	Essential oils from Japanese ceder (*Cryptomeria japonica*) heartwood	Wood decay fungi (nutrient medium)	Cheng et al. (2006)
	Anise oil, lime oil, and tangerine oil	Molds on rubberwood (dip treatment on wood)	Matan and Matan (2008)
	Essential oils from lemongrass, rosemary, tea tree, and thyme	Mold growth on yellow pine (dip and vapour treatment on wood)	Yang and Clausen (2007)
	Cinnamon oil	Ponderosa pine (dip treatment on wood)	Li et al. (2008)
	Essential oil compounds and plant extracts; cinnamaldehyde, cinnamic acid, cassia oil, and wood tar oil	Brown, white rot decay fungi and termites (pressure treatment on wood)	Kartal et al. (2006)
	Essential oil from fruit peel of citrus	Fungi and termite (nutrient medium)	Macias et al. (2005)
	Essential oils from Japanese ceder (*Cryptomeria japonica*) heartwood	Wood decay and tree pathogenic fungi (nutrient medium)	Cheng et al. (2005)
	Cinnamon (*Cinnamomum osmophoeum*)	Wood decay fungi (nutrient medium)	Cheng et al. (2006)
	Cinnamon and clove oils	Mold fungi on rubberwood (nutrient medium and dip treatment)	Matan and Matan (2007)
	Hinau (*Elaeocarpus dentatus*) leaf extract	Brown rot fungi (nutrient medium)	Rickard et al. (2009)
	Cinnamaldehyde in combination with antioxidants propyl gallate, octyl gallate, quercetin, and eugenol, catechin	White rot and brown rot fungi (nutrient medium)	Hsu et al. (2007)
	Cinnamaldehyde, eugenol	White rot and brown rot fungi (nutrient medium)	Cheng et al. (2008)
	Twelve essential oils screened, including eugenol and oil from cinnamon leaf and germanium	Mold, sapstain and decay fungi (nutrient medium and radiata pine pressure treatment)	Singh and Chittenden (2008a)
	Plant-derived oils (almond bitter, anise, basil, bay, caraway, cardamom, cedar, celery, chamomile, cinnamon, citronella, clove, coriander, cumin, dill, eucalyptus, fennel, ginger, grapefruit, lemon, lime, mint, parsley, peppermint, pepper, rose, spearmint, sweet orange, thyme, turmeric, juniper, winter green, tall, and pine oils in combination with silicone-based polymer	Mildew, termites and insects on wood (the method of treatment not disclosed)	Glassel and Mellema (2006) US patent no. US 200601 23341A1
	Oxygenated aromatic essential oil compounds-22 essential oil phenols, phenol ethers, and aromatic aldehydes	White rot and brown rot (nutrient medium)	Voda et al. (2003)
	Boron-linseed oil combination treatment	Japanese cedar, beech and pine against termites (pressure treatment)	Lyon et al. (2007)
Waxes, resins and tannins from bark	Tannins from the bark of Southern pine	Brown and white rot fungi (pressure treatment)	Laks et al. (1988)
	Aleppo pine leaves and bark	Dip treatment	Passialis and Voulgaridis (1999)
	Bark from six species of wood	Mold, stain, brown and white rot fungi (nutrient medium)	Yang et al. (2004)
	Guayule (*Parthenium argentatum* Gray)	Decay fungi, termites and marine borers (pressure treatment)	Nakayama et al. (2001)
	Pinus bruita bark extracts	Brown and white rot (pressure treatment)	Nemli et al. (2006) Extractives
Extractives	Extractives of *Milicia excelsa* and *Chlorophora excelsa*	Fungi, insects and marine borers (pressure treatment)	King and Grundon (1949)
	Heartwood extract of *Milicia excelsa* and *Erythrophleum suaveolens*	Brown and white rot fungi (pressure treatment)	Onuorah (2000)
	Extract from Taiwania (*Taiwania cryptomerioides*)	White and brown rot fungi (nutrient medium) Termite	Chang et al., 2001, 2003
	Lignans and glycorides from *Gmelina arborea* hertwood	White rot (nutrient medium)	Kawamura et al., 2004; Kawamura and Ohara, 2005
	Heartwood extractive of *Thuja plicata* and *Chamaecyparis nootkatensis*	Termite and brown rot (pressure treatment)	Taylor et al. (2006)
	Valonia extract, sumac leaf extract and pine bark extract	White and brown rot fungi (pressure treatment on wood)	Sen et al. (2009)
	Extract of herbaceous plant, *Inula viscose* in combination with cinnamon oil, carvacol or thymol	White and brown rot fungi (pressure treatment on pine wood)	Maoz et al. (2009)
	Heartwood extractive of *Prosopis juliflora*	White rot, brown rot, mold and termite (durability test without pressure treatment)	Sirmah et al., 2009a,b
	Australian native tree (*Eremophila mitchelli*)	Termites	Scown et al. (2009)
	Extract from white cypress pine	Termites	French et al. (1979) Miscellaneous
Miscellaneous	Chitosan	Sapstain, mold and wood decay fungi (nutrient medium and dip and pressure treatment on wood)	Kobayashi and Furukawa (1996) and Chittenden et al. (2004) Maoz and Morrell (2004), Eikenes et al., 2005a,b, and Torr et al. (2005) Singh et al. (2008a)
	Silicon compounds	Decay fungi	Weigenand et al. (2008) and Panov and Terziev (2009)
	Trichoderma extracts	Sapstain and basidiomycetes	Bruce and Highley (1991)
	Lactobacillus extracts	Sapstain	Singh and Chittenden (2008b)

TABLE 2 | Efficacy of biocides against fungi and insects.

Biocide	Efficacy	
	Fungicide	Insecticide
Boron compounds (boric acid, borax. . .)	+	+
Carbamates (IPBC. . .)	+	
Copper inorganic compounds (copper oxide, . . .)	+	
Copper naphtenates and citrates	+	
Creosotes	+	+
Isotiazolones (DCOIT,)	+	
N-organodiazeniumdioxy-metals (Cu-HDO,.)	+	(+)
Quarternary ammonium compounds – QAC (DDAC,.)	+	(+)
Sulfamides (dichlofluanid, tolylfluanid,.)	+	
Triazoles (propiconazole, tebuconazole,.)	+	

Modified from Reinprecht (2010). +, basic biocidal activity; (+), additional biocidal activity.

the wood surface. A high-performance coating should repel water without trapping it into the wood. If a finish traps water in the wood, it can lead to fungal development. Lu (2019) developed an exterior wood coating with crosslinking polyvinyl acetate technology intended to improve water resistance. Pandit et al. (2020) studied the use of titanium dioxide (TiO_2) nanoparticles and perfluorooctyltriethoxysilane (PFOTS) to improve water repellency on wood surface. The authors pointed out that the method not only promoted excellent water repellency but also increased thermal and chemical stabilities.

Although coatings are not intended to protect wood from decay, there are some formulations include biocide in their composition to inhibit fungal growth (Bobadilha et al., 2020; Mustata et al., 2021). Stirling et al. (2011) investigated the biocidal performance of various wood coating formulations. The authors concluded that combinations of propiconazole with 3-iodo-2-propynyl butylcarbamate (IPBC), as well as propiconazole, IPBC, and thiabendazole were the most effective treatments against fungal growth. In Australia, Moon et al. (2014) developed a light organic solvent preservative (LOSPs) product with a new composition that used acrylic as resin. The invention allowed the application of other protective coating without penetration of the preservative.

The wood protection industry has developed surface treatments to protect timbers and wood-based materials from weathering and mechanical degradation (Costin and Costin, 2009; Kingma et al., 2010; Kuang and Zhang, 2018). They may be used for temporary protection of wood elements specifically during construction. When pressure treatment is not a practical solution, coatings may be applied to protect wood and wood-based products from deterioration. The combination of pressure treatment and finishes are also desired to extend service of structures.

WOOD MODIFICATION

During the last few years, the environmental pressures have been increasing which have led to significant changes in the field of wood protection. Thus, modern technologies performing by either thermal or chemical modifications have programmed according to ban of biocide products.

In addition, wood modification has become new alternative for wood preservation to change the properties of wood material by describing the application of chemical, mechanical, physical, or biological methods. Modification is emerged to increase the quality of wood materials associated with the moisture sensitiveness, low dimensional stability, hardness and wear resistance, low resistance to bio-deterioration against fungi, termites, marine borers, and low resistance to UV irradiation. Currently, wood modification is applied to enhance the physical, mechanical, or esthetic properties of the sawn timber, veneer or wood particles that can be used in wood composites production. Disposal materials that produce as a result of above process at the end of a product's life cycle have been shown to exhibit no environmental hazards in comparison to unmodified wood. According to Hill (2006) wood modification is the process involves in the action of a chemical, biological, or physical characteristic, leading to a desired property improvement under the service life of the modified wood. The products of wood modification process have not been observed any toxicity reaction under service conditions, as well as toxic substances resulted in their release during service, end of life cycle, disposal or recycling of the modified wood. Non-biocidal mode of action should be applied when the purpose of wood modification is to increase resistance to biological attacks.

Dimensional stability, hygroscopicity, and biological resistance of wood have been observed to enhanced using wood modification because this method alters wood cell components during thermal processing (Kamdem et al., 2002). In addition, an increase in density, hardness, bending strength and stiffness, and termite durability was observed in pine wood as a result of the post heating after densification (Esteves et al., 2017). These results showed that the quality and dimensional stability of the non-durable and low durable wood species could be improved using wood modification. Therefore, weak points of the wood material that are mainly related to low dimensional stability, moisture sensitivity, hardness and wear resistance, low resistance to bio-deterioration against fungi, termites, marine borers, and low resistance to UV irradiation improve by applying modification. Three most important aspects of the entire wood modification mechanism against fungi biodegradation are: (1) modified wood has lower equilibrium moisture content, so it is harder for fungi to obtain the moisture required for decay, (2) The entrance of decay fungi is physically blocked from the micro pores of the cell walls in modified wood, and (3) specific enzymes involved in fungi growth is inhibited in modified wood (Hill, 2006, 2009; Rowell et al., 2009; Rowell, 2016). Wood modification can be done by different process such as chemical processing (acetylation, furfurylation, resin impregnation etc.), thermo-hydro processing, and thermo-hydro-mechanical processing (Sandberg et al., 2017). Chemical, thermal and impregnation modification are the three methods that used commercially (Hill, 2011). Europe has become world leader in the development of commercial wood modification technologies in the past decade. Currently, near 300,000 to 400,000 m^3 of modified wood is produced throughout Europe and other parts of the world (Militz, 2020). In this review paper, chemical, thermal, and thermo-mechanical processing are briefly discussed.

Chemical Modification

Chemical modification of wood ι has emerged since middle of the 20th century. The final use of material is the main factor to determine the objective of chemical modifications, for example these modifications in solid wood are intended to increase the dimensional stability, mechanical properties, or resistance to biodegradation, whereas modifications in divided wood are aimed to improve behaviors of particles or fibers for utilization for given applications such as composites, paper or new materials.

There are two categories for chemical wood modification technology as an active and passive modification. Chemical modification of wood is considered as an active modification because it results in a chemical change in the cell-wall polymers. Passive modification occurs when the cell walls of wood impregnate with a chemical, or a combination of chemicals, that reacts to form a material that is locked into the cell wall and there is no change in the chemistry of the material (Homan et al., 2000; Hill, 2006; Sandberg et al., 2017; Bi et al., 2021). There are different literature reviews that have been published the chemical reaction systems for chemical modification of wood (Rowell, 1975, 1983, 1991, 1999; Kumar, 1994; Hon, 1996). These chemicals include anhydrides such as phthalic, succinic, malaic, propionic, and butyric anhydride; acid chlorides; ketene carboxylic acids; many different types of isocyanates; formaldehyde; acetaldehyde; difunctional aldehydes; chloral; phthaldehydic acid; dimethyl sulfate; alkyl chlorides; β-propiolactone, acrylonitrile; epoxides, such as ethylene, propylene, and butylene oxide; and difunctional epoxides. Chemical modification methods have their own characteristics. Currently, acetylation and furfuryl alcoholization modifications' methods are using worldwide for commercial production due to the lower cost, simple manufacturing process, and excellent modification effect (Bi et al., 2021). It is also worth mentioning that the commercial chemical modification (acetylation) of wood in Europe arose from the research in the Netherlands (Hill, 2011).

Thermal Modification

Development in thermal modification (TM) started from the early of 20th century and it has been continuing in the U.S in 1970. In Latvia, Japan, and Canada the development and commercialization of TM happened in 1970's and 1980's. At the end of 20th century, Europe was trying to develop TM which led to approve of various laws and legislations. Currently, Finland has the highest production of the TM wood (Hill, 2011).

The dimensional stability and durability of timber has been shown to improve using TM which is a well-established commercial technology (Esteves et al., 2006; Huang et al., 2012; Hill et al., 2021). Hygroscopicity also decreases by TM (Metsa¨-Kortelainen et al., 2005; Bao et al., 2017). The optimum temperature for the commercial production of TM wood ranged usually between 160 and 240^{o}C. TM has been observed to result in a material that is darker in color, improved dimensional stability and microbial resistance of wood heated, and reduced in strength, especially fracture resistance (Bekhta and Niemz, 2003; Hill, 2006; Hill et al., 2021). The chemistry of thermal degradation has been different below and above about 150°C. Thermal modification is well defined when it was employed at above 150°C where chemistry of thermal degradation occurred (Yin et al., 2011; Ganne-Chédeville et al., 2012; Endo et al., 2016; Obataya et al., 2019). Above 240^{o}C is not recommended for TM due to severe degradation of the wood that cannot be commercially useful. Thermal modification processes have been previously established in North America. In 2012, there were 7 manufacturers of TM in Canada and 10 in the United States (Sandberg and Kutnar, 2016; Sandberg et al., 2017). Thermal modification is applied in two conditions dry and wet (Hill et al., 2021). The significant differences in the characteristics of TM wood under dry or wet conditions are the differences in weight loss, sorption behavior and dimensional stability. Thermally modified wood under dry is more common for formation of crosslinks (especially within the lignin network). The control of moisture content within the cell wall is needed to support exercising fine management over the thermal modification process that can result in an improvement in properties of interest along with minimal negative effects of thermal modification such as brittle and fracture properties (Hill et al., 2021). In order to support aforementioned hypotheses several improved products are commercially available for more in-depth related studies.

Thermo-Mechanical Modification

Mechanical modification is the compression or densification of the wood in which wood is deformed under mechanical pressure in order to increase its density (Jennings, 2003; Sandberg et al., 2013). Compreg wood, lingostone, lignofol, and staypak are different name of mechanical wood modification products (Kollman et al., 1975). However compressed wood reveals superior strength properties, wood will return to its initial dimensions when it exposes to wet conditions or soaked in water (Dwainto et al., 1997; Ito et al., 1998a,b; Kultikova, 1999; Navi and Girardet, 2000; Heger et al., 2004; Kamke, 2006). Many researchers have been successful to reduce this issue, but the weakness of densified wood was poor bio-resistance against microorganisms (Welzbacher et al., 2005). Therefore, combination of thermal modification and mechanical modification have been improved the mechanical, physical properties of wood as well as wood bio-resistance at the same time (Hakkou et al., 2006; Mohebby et al., 2009). This product also produces hydrophobic wood due to the hydrothermal modification (Rapp, 2001; Mohebby and Sanaei, 2005; Tjeerdsma and Militz, 2005). Thermo-hydromechanical process is one of the processes for manufacturing wood-based panels and an efficient way to improve the natural properties and produce stable materials (Navi and Heger, 2004; Sandberg et al., 2013).

CONCLUSION

Wood Preservation

Wood preservation research is globally focus on using natural environmentally compatible compounds, nonetheless few wood preservation industrial companies are willing to uptake of these natural compounds and their associated technologies. There is human health and environment concern in those compounds with antimicrobial activities, regardless of its origin, associated with their intrinsic biological activity, and therefore, regulatory authorities have been applied for registration of natural compound in many countries. Regulatory roles enforce that any new compound or formulation should be registered prior to manufacturing or sale in which a risk assessment associated with these compounds is determined by direct and in-direct exposures using exhaustive toxicity studies over several years, demanding considerable financial investments. Therefore, conflicts between legislation and registration of new natural compounds can be one of the possible reasons associate with limitation use of the natural preservatives in comparison to the old and toxic generation of preservatives. The other possibilities can be (1) incompatibility of results between laboratory studies and field trial as a result of impaired efficacy of organic biocides in nutrient medium in comparison to the biocide impregnated wood, and (2) limited range of activities for some of natural compounds. For the newer preservatives, the wood protection industry has developed nano and micronized preservatives with objective to improve preservative efficiency without compromising the durability of wood products. There were also recent developments on surface protection systems that not only offer weathering resistance but also inhibit fungal growth specifically mold fungi. With the popularity of mass timber buildings and other engineered wood products, in the future preservatives and coatings are going to be developed to specifically attend the needs and expectations of mass timber elements without compromising the serviceability of metal connections and fasteners.

Wood Modification

The product performance, the environment, and end-of-life aspects of different modifications are not well investigated to date. To achieve this goal, the entire value chain, from forest through processing, installation, in-service, end-of-life, second and third life, and, eventually, incineration with energy recovery has to be obtained. Modified wood and their products are mainly made in accordance with the interactive assessment of process factors, developed product characteristics, and environmental effects of the timber processing in which environmental effects is associated with amount of energy consumption. However, enhanced characteristics during the use phase could result in a reduction of environmental effects of the timber processing. Among all modification techniques, thermally modified wood can now be used in many common applications, but it has its own limitations. Thermally modified wood is suitable for various uses in both interior and exterior uses. However, they are not suitable for timber structures due to their properties and low strength. Thermally modified timber was firstly developed in order to increase the performance and durability of softwoods, and later expanded to boost the performance of hardwoods to eliminate the additional protection for outdoors materials that made by low-durability hardwoods species, for example, birch, aspen, ash, soft maple, tulipwood, and red oak.

Thus, the improvement of existing wood technology has been recently shown to be the main emphasis of wood modification technology studies. The properties of modified wood are more diversified using improved the production process, changed, or supplemented chemical reagents leading to overcoming the original defects. To sum up, economic and environmental parameters are the basis for the improvement of the modified wood properties. Without doubt that research results reporting the efficiency of wood modification in different applications are crucial to maintain and improve its use in the industry. However, there are still some challenges concerning wood modification's application in certain locations, in countries such as United States, wood modification has not been fully explored. More studies are expected to be done to determine wood modification's performance and applications.

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All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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