Outdoor Wood Finishing: A Review on Making Wood Resistant to Moisture, Ultraviolet Light, and Degradation

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This article reviews published literature related to the coating of wood surfaces for external applications. Research has shown that a wide range of procedural steps and components in coating formulations can contribute to increasing the effective service life of the coating as well as to maintaining the quality of the coated wood surfaces. Published findings support the idea that the commonly observed service life of painted wood surfaces exposed to outdoor weather can be significantly increased by dedicated application of such measures as optimized sanding, the use of an effective primary coat, the type of resin in the finish coat, increasing the number of layers of the finish coat, and a wide range of issues related to formulation of the finish coat. Even if a majority of contractors and homebuyers continue to prefer such options as vinyl or aluminum siding, the market opportunities remain very large for clients who prefer to rely on coatings and wood products for exterior surfaces of buildings and other exterior wood items.

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INTRODUCTION

According to the National Association of Home Builders, most single-family houses in the US are being sided (or "clad") with such products as vinyl siding (25.6%), fiber cement (21.7%), or brick-like materials (18.5%), leaving only about 5% of wood-clad houses (NAHB 2024). Back in 2000, wood comprised about 13% of the share. For the wood industry and the paint industry, this circumstance highlights both a challenge and an opportunity. On the one hand, many builders and homeowners have come to the conclusion that non-wood siding represents a better investment than painted wood exteriors. But on the other hand, painted wood still represents a major category that can offer attractive prices, workability, and a sense of familiarity. This review article considers factors affecting the durability of outdoor-applied finishes for wood surfaces.

Goal: Protection of Exterior Wood

The damage that can happen to wood that is exposed to outdoor weather, including mold and insect attack, has been covered in earlier review articles (Feist 1996; Kropat *et al.* 2020). For instance, it is well known that exposure of wood to ultraviolet light, in combination with periodic rain, will result in weathered wood, which involves depletion of lignin in the outermost layer (Williams *et al.* 1996; Kropat *et al.* 2020; Gurleyen 2021). Cycles of repeated wetting and drying of wood that is exposed outdoors can be expected to develop periodic cracks, which are known as checking (Nejad and Cooper 2011; Lestari *et al.* 2020). Boards exposed to periodic rain, followed by drying, also can develop cupping, in which the last-dried side may shrink in comparison to the rest of the material, leading to a concave shape exposed outwards (Fufa *et al.* 2012).

In cases where wood remains moist for a long time, or if it is near to soil, mildew and rot may proliferate (Bjurman 1992; Brischke *et al.* 2006; van Meel *et al.* 2011). Fungal species typically play a leading role in the decay of wood (Goodell 2003; Cogulet *et al.* 2018a), though bacteria also are expected to be involved (Clausen 1996). Wood that is near to soil also can be subject to attack by termites, which chew tunnels into the wood and build nests (Remadevi *et al.* 2015). In cases where the wood surface has been covered by a coating layer, exposure to outdoor conditions may eventually lead to flaking (Williams and Feist 1993), after which at least a portion of the wood becomes directly exposed to the weather.

Hypotheses

For the purpose of focusing attention on some important issues, a series of hypotheses, as follows, will be considered in this article (Fig. 1):

1. The durability of the coating layer itself, including its resistance to cracking, flaking, and peeling, is of paramount importance, since without such strength and adhesion to the wood surface, it will not remain present to provide its other functions.
2. Finish formulations for outdoor application need to contain a component capable of absorbing ultraviolet light, so as to protect the lignin in the outermost wood layer (about 1 mm) from photochemical degradation (Williams *et al.* 1996).
3. Finish formulations for outdoor application need to contain sufficient hydrophobic resin component to prevent liquid water (from rain) from contacting the wood directly.

4. Biocidal, including antifungal, antibacterial, and insect-resistant treatments can play significant roles in extending the useful lifetime of wood finish in outdoor applications.
5. The formulation of a wood coating for outdoor applications can significantly affect its outward appearance both initially and during its period of use.
6. By investing more in the quality of wood preparation and in the composition of the coating layer formulations, there is potential to greatly increase the length of time during which a wood coating can effectively protect wood that is exposed outdoors.

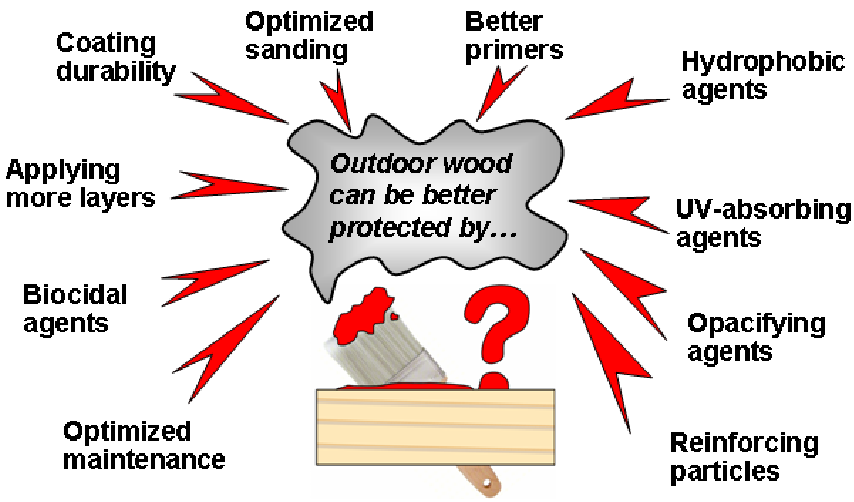

Fig. 1. Some hypotheses regarding how exterior wood can be better protected by improvements involving coating technology and its optimized application

Published Reviews: Finishing for Wood Protection

Table 1 lists some key themes of review articles and books that have dealt with various aspects of outdoor wood finish applications.

Table 1. Review Articles and Books Dealing with Aspects of Outdoor Wood Coatings

Themes of Publications	Citation
External wood finishing & water-repellent coatings	Feist & Mraz 1978
Durability of external wood finishes	Feist & Mraz 1980
Selection, application, & maintenance of coatings	Cassens & Feist 1986
Water-repellent preservatives for wood pre-coating	Feist 1990
Painting and finishing of exterior wood	Feist 1996
Finishes for external wood usage (book)	Williams *et al.* 1996
Guide for selection of finishes for various applications	Bonura *et al.* 2004
Acetylation of wood, followed by its coating	Rowel & Bongers 2015
Exterior wood coatings	Nejad & Cooper 2017
Clear coatings to protect against wood weathering	Cogulet *et al.* 2018b
Bio-based finishes for exterior wood	Teaca *et al.* 2019
Nanomaterials & antimicrobial paints	Ganguli & Chaudhuri 2021
Multifunctional wood coatings with nanomaterials	Wang *et al.* 2023
Principles and mechanisms of wood coating systems	Hubbe and Laleicke 2025

The first six items listed in Table 1, covering a period from 1978 through 1996, all were written by researchers at the Forest Products Research Laboratory of the Forest Service, a division of US Department of Agriculture. Review articles from other sources dealing with outdoor application of wood coatings did not begin to appear until 2004, though there has been an acceleration in the most recent decade.

BACKGROUND OF DAMAGE TO OUTDOOR WOOD

Overview of Wood Weathering and Decay

Within the category of wood weathering, this review article will be ultimately concerned with what has been called "natural weathering" of coated wood, *i.e.*, that which occurs under typical outdoor conditions (Feist 1982a, 1983, 1988, 1994). This is an important distinction, since many similar effects can be achieved by artificial or "accelerated" weathering and by various approaches intended to simulate the effects of weathering relative to the outward appearance of wood surfaces (Kropat *et al.* 2020). The purpose of accelerated weathering is to enable more rapid and reproducible testing, especially in the case of newly developed coatings for outdoor applications of wood.

Natural weathering

As noted by Cogulet *et al.* (2018b), wood weathering can be attributed to the combined effects of light irradiation (especially the ultraviolet component), water, oxygen, temperature, and the colonization of wood by fungi. Striking photographs of weathered wood have been presented by Williams *et al.* (1996). One of the most noticeable effects of weathering is a change of color. Often the color undergoes a two-stage transition, initially acquiring a redder tone, and thereafter tending to become grayer and bluer (Kropat *et al.* 2020). The first part of this transition is understood to involve changes in the molecular structure of the lignin component of wood, such that the absorption of light in the visible range is increased in transient ways. The second part has been generally attributed to the gradual depletion of lignin in the outermost 1 mm or so of wood, due to its photochemical breakdown, followed by the leaching action of water. The color of weathered wood usually is also affected by the colonization of the surface by blue-stain fungus, which takes its name from the color of the fungal hyphae.

Artificial weathering

Although resistance to genuine outdoor conditions is the true test of a wood finish, weather conditions are subject to huge variability. Artificial weathering equipment and procedures can overcome such problems, but the outcomes can be expected to show some characteristic differences from natural weathering. In particular, wood that has been exposed to cycles of ultraviolet light and water spray in a chamber generally will not experience any fungal infestation (Kropat *et al.* 2020). On the other hand, artificial weathering tests have made it possible to evaluate a wide range of wood coatings under controlled conditions (Cogulet *et al.* 2019). For instance, Cogulet *et al.* (2019) were able to demonstrate that ultraviolet light plays a critical role in the weathering of wood. Likewise, de Mesquite *et al.* (2020) were able to document changes in lignin structure, by means of infrared spectrometry, following artificial weathering. Hinderliter and Sapper (2015) used accelerated weathering tests to show differences in the permeability of wood coatings, thus affecting the rates of migration of moisture. Podgorski *et al.* (1994, 1996) used artificial weathering as a means of studying the changes in glass transition temperature of alkyd resins of wood coatings in the course of exposure.

Simulated weathering

By means of staining, mechanical abrasion, and other such treatments, it is possible to render wooden surfaces more suitable for certain kinds of displays, which may or may not resemble genuinely weathered wood. For example, wood pieces subjected to simulated weathering may help to establish a mood or a theme in an indoor setting. This type of treatment has been studied based on social media posts (Kropat *et al.* 2020).

General effects of finishes on weathering

As a general trend, the application of a conventional wood finish can be expected to greatly diminish weathering effects, at least during the recommended lifetime of the coating (Feist 1982a, 1983, 1988, 1990, 1994). In addition to the effects of weather on exposed wood, the term weathering also can be applied relative to changes in the coatings itself in the course of exposure to weather. A prime example is the depletion of binder, *i.e.* "chalking," in certain wood finishes over the course of exposure to ultraviolet light, rain, and general exposure (Allen 1984; Miklecic and Jirous-Rajkovic 2011; Nguyen *et al.* 2018). This phenomenon and its most likely causes are illustrated in Fig. 2. As noted, ultraviolet (UV) light is expected to gradually break down the binder. The "chalk" that tends to come off onto one's fingers when inspecting the surface likely comprises mineral components of the coating, *e.g.* TiO_2 or $CaCO_3$. In addition, depending on the porosity of the wood, some of the binder may have immediately migrated into pores of the wood (*i.e.* vessels or tracheids), thus leaving an insufficient amount of binder within the coating layer.

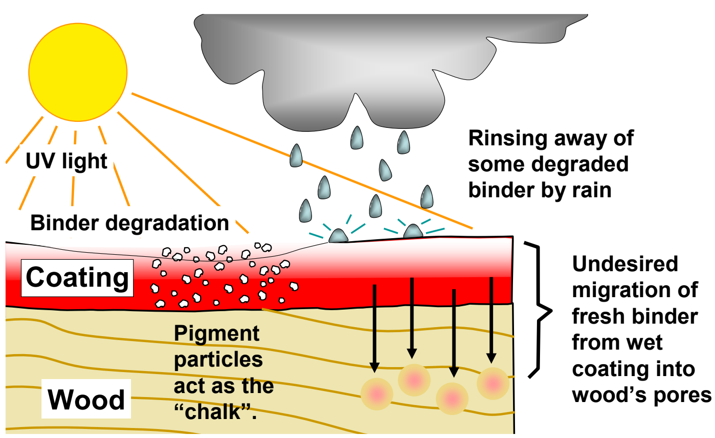

Fig. 2. Illustration of some contributions to chalking of paint layers exposed to weather

Overview of Wood Decay

What would happen if wood didn't decay? According to Schwarze *et al.* (2000), there is a dynamic balance between the growing amount of woody biomass and its breakdown in the natural environment. Decomposing communities (Kahl *et al.* 2017) of biotic agents such as fungi, bacteria, and insects are the main decay agents that decompose holocellulose and lignin. By breaking down these main chemical components of the woody structure, the nutrients are made available to other organisms, eventually allowing new growth of plants. In the built environment, however, the decay of wood affects the longevity of wood structures and requires protection of the wood by physical and chemical means. Table 2 lists review articles dealing with various aspects of wood decay.

Table 2. Review Articles and Books Dealing with Aspects of Wood Rot and Decay

Themes of the Publications	**Citations**
Fungal decay of wood: soft rot – brown rot – white rot	Goodell *et al.* 2008
Wood microbiology: decay and its prevention (book)	Zabel & Morrell 2012
Microbial & enzymatic degradation of wood (book)	Eriksson *et al.* 2012
Delignification by wood-decay fungi	Blanchette 1991
Bacterial associations with decaying wood: A review	Clausen 1996
The bacterial factor in wood decay	Greaves 1971
Wood deterioration by insects	Pournou & Pournou 2020
Wood destroying insects: Wood borers and termites (book)	Creffield 1996

Upon the inspection of wooden structures, such as a fence pole, an attic, or a standing tree, one can come across three different types of rot: brown rot, white rot, and soft rot (Worrall *et al.* 1997). Different decay fungi cause them, each with their individual types of chemical and enzymatic degradation (Veloz Villavicencio *et al.* 2020), conditions of the remaining wood, and impacts on its mechanical strength. The main reason for this multiplicity of enzymes is that cellulose, hemicellulose, and lignin require different degradation pathways. Different fungal species prefer specific hosts due to their differences in composition, such as the types of lignin in softwoods *vs*. hardwoods (Tuor *et al.* 1995). For fungi to thrive on a digestible substrate, they require a suitable combination of moisture (Thybring 2017), temperature, oxygen, and pH. According to Zabel and Morrell (2012), fungi need free water, some atmospheric oxygen, and temperatures between 15 and 40 °C. This is supported by a review of the degradation mechanisms of brown rot by Ringman *et al.* (2019), who describe how enzymatic degradation requires water for transportation of important metabolites.

Soft rot

Soft rot is caused by deuteromycetes, a.k.a. Fungi Imperfecti and Ascomycetes (Goodell *et al.* 2008, Schwarze *et al.* 2000, Lee 2000, Worrall *et al.* 1997). This type of decay occurs in wet or aquatic environments (Hale 1986). The fungi cause decay at the cellular level and attack the S2 layer of a cellulosic fiber, thus creating a chain of cavities along the hyphae in a helical microfibrillar angle. Upon microscopic observation at the longitudinal face, cavities appear diamond-shaped (Anagnost 1998). Soft rot fungi degrade cellulose and hemicellulose and rarely the lignin (Schwarze *et al.* 2000).

According to Anagnost (1998) there are three types of soft rot: regular type 1, diffuse type 1, and type 2. Not all types are caused by the same soft rot fungi. Type 1 was observed only on pine and birch, whereas type 2 was limited to pine. Major differences are related to location and types of cavities and erosion caused by the fungus in the wood. While type 1 describes the regular progression of hyphae and cavities within the S2 sublayer of the cell wall, diffuse type 1 accounts for a more diffuse and irregular structure. Type 2 describes soft rot in hardwoods, in which the hyphae penetrate the lumen with significant damage of the cell wall (Anagnost *et al.* 1994).

Brown rot

Brown rot is the most common and most destructive of the three types of rot (Green and Highley 1997). It is more commonly found in softwood stands and therefore predestined for the decay of structural softwood wood products (Arantes and Goodell 2014). The result of brown rot is a brown, wood-structured residue that has lost all of its holocellulose. The remainder are mostly modified lignin residues and extractives (Arantes and Goodell 2014). The main mechanism consists of the degradation of polysaccharides as well as partial oxidation of the lignin (Worrall *et al.* 1997; Jensen *et al.* 2001).

Brown rot causes weight and strength loss. The decay process commences with the degradation of the cellulose, resulting in significant strength loss (Arantes and Goodell 2014; Curling *et al.* 2002). Subsequent weight loss can be observed at later stages of the decay process. Curling *et al.* (2002) showed that even at low weight losses, specimens of southern pine exposed to brown rot quickly lost their resistance to plastic deformation in bending at a rate of 3.6% per day. The onset of decreasing modulus of rupture (1.6% per day) and modulus of elasticity (0.6 % per day) were delayed.

White rot

White rot fungi primarily degrade the lignin, but they can also degrade the cellulose (Worrall *et al.* 1997). For visual identification, the leftover residue has a bleached look (Goodell 2008). Some white-rot fungi are better at removing just the lignin, as mentioned by Blanchette (1991) in his review article about the delignification by wood-decay fungi.

There are two types of white rot: Simultaneous white rot and selective white rot. The first enables the simultaneous degradation of cellulose, hemicellulose, and lignin. The latter is the case when only lignin and hemicellulose are degraded and the cellulose remains untouched (Goodell 2008). Therefore, the residues have a white appearance.

Bacteria

Based on thorough reviews of the roles of bacteria in wood decay by Johnston *et al.* (2016) and Clausen (1996), fungal decay has been much more explored than bacterial decomposition. Clausen (1996) dates the initial recognition of a relationship between wood and bacteria back to the 1950s and 1960s. Bacteria play an important role in the decay of wood and often work in conjunction with fungi. Johnston *et al.* (2016) describe the dynamics and complexity of the types and numbers of bacteria throughout the decay process. The number of bacteria, for example, increases as the wood decays.

Greaves (1971) grouped wood-inhabiting bacteria into four main groups. The groups and their characteristics are shown in Table 3.

Table 3. Grouping of Wood-decaying Bacteria and their Characteristics

Group	Affect Permeability	Affect Strength	Contribution towards Breakdown
1	Yes	No	
2	Yes	Yes	
3			Active
4			Indirect

Groups 1 and 2 impact the permeability of the wood for liquids to more easily move through the wood, with Group two degrading the cell walls. The strength, however, is only impacted by bacteria in Group 2. Bacteria in the third group contribute to the overall decay of the wood as part of the total amount of microorganisms. Bacteria in the 4th group are passive and support other organisms in the wood with no direct contribution to the decay.

Overview of Insect Damage

Live and dead wood can provide a habitat for many insects. In the natural environment, so-called xylophagous insects are part of the lifecycle of trees and woody biomass.

Table 4. Common Wood Deteriorating Insects and their Damages (Amburgey 2008)

Wood Attacked			**Recognition of Damage**			
Type of borer	**Part and type**	**Condition**	**Exit holes**	**Galleries (tunnels)**	**Frass**	**Re-infested**
Anobiid powerderpost beetles	Sapwood of hard-woods and soft-woods; rarely in heartwood	Seasoned	Circular, 1/16 to 1/8 in diameter	Circular, up to 1/8 in diameter; numerous; random	Fine powder with elongated pellets conspicuous; loosely packed	Yes
Bostrichid powderpost beetles	Sapwood of hardwoods primarily; minor in softwoods	Seasoning and newly seasoned	Circular, 3/23 to 9/32 in diameter	Circular 1/16 to 3/8 in diameter; numerous; random	Fine to coarse powder; tightly packed, tends to stick together	Rarely
Lyctid powderpost beetles	Sapwood of ring- and diffuse-porous hardwoods only	Newly seasoned, with high starch	Circular 1/32 to 1/16 in diameter	Circular, 1/16 in diameter; numerous; random	Fine, flour like, loose in tunnels	Yes
Roundheaded borers (general)	Sapwood of softwoods and hardwoods; some in heartwood	Un-seasoned, logs and lumber	Oval to circular, 1/8 to 3/8 in long diameter	Oval. Up to ½ in long diameter, size varies with species	Coarse to fibrous; may be mostly absent	No
Old house borer	Sapwood of softwoods, primarily pine	Seasoning to seasoned	Oval, ¼ to 3/8 in long diameter	Oval, up to 3/8 in long diameter; numerous in outer sapwood, ripple marks on walls	Very fine powder and tiny pellets; tightly packed in tunnels	Yes
Lat oak borer	Sapwood and heartwood of hardwoods, primarily oak	Seasoning and newly seasoned	Slightly oval; 1/16 to 1/12 in diameter	Oval, up to 1/12 in long diameter	Fine granules	No
Flat-headed borers	Sapwood and heartwood of softwoods and hardwoods	Seasoning	Oval, 1/18 to ½ in long diameter	Flat oval, up to 3/8 in long diameter; winding	Sawdust-like, may contain light and dark portions of under bark: tightly packed	No
Bark beetles	Inner bark and surface of sap-wood only	Un-seasoned under bark only	Circular 1/16 to 3/32 in diameter	Circular, up to 3/32 in diameter; random	Coarse to fine powder, bark-colored, tightly packed in some tunnels	No
Ambrosia beetles	Sapwood and heartwood of hardwoods and softwoods	Un-seasoned, logs and lumber	Circular, 1/50 to 1/8 in diameter; stained wall	Circular same diam. as holes; across grain; walls stained	None present	No
Wood boring weevils	Sapwood and heartwood of hardwoods and softwoods	Slightly damp, decayed	Raggedly round or elongate, 1/16 to 1/12 in diameter	Circular, up to 1/16 in diameter	Very fine powder and very tiny pellets, tightly packed	Yes

They consume wood at some or all of their life stages. Other insects use wood as a temporary or long-term habitat, rather than feeding on the wood substrate. Sometimes, during imbalances in forest systems, one can observe calamities in which growing populations of insect species can affect, destroy, and eventually help renew large-scale forests. In the built environment, the presence of insects can cause damage to wooden structures and objects.

It is possible to distinguish three main groups of wood-destroying insects: Coleoptera (beetles), Hymenoptera (bees, ants, wasps), and Isoptera (termites) (Unger *et al.* 2001; Amburgey 2008). Table 4 provides an overview of some common wood-boring beetles. Individual species prefer specific substrates and leave characteristic boring and frass patterns. Unlike in the case of fungi, the wood does not have to have elevated moisture content for some insects. Dry-wood insects, for example, are known to infest in-service furniture, building components, and artifacts used in dry, interior environments.

Seasoning, *i.e.* the exposure of wood to elevated temperatures, typically achieved during kiln drying, is known to prevent initial and subsequent infestations with some species. As early as 1921, Craighead and Loughborough investigated the fatal temperatures for red-headed ash borers infested ash. The experiments showed that the effectiveness of kiln drying depends on RH, temperature, and time. Temperatures could range from 105 to 135 °F (40 to 57 °C) and eliminate all larvae within an hour at low RH. Heat treatment at even higher temperatures is also discussed in a later chapter, in which the purpose was to improve the dimensional stability of the wood. So-called phytosanitation is commonly practiced to control the spread of plant diseases, including insects, in commercial goods. Invasive alien species (IAS) have damaged and can create significant damage to ecosystems and the built environment (Ormsby 2022). Treatments, per national and international regulations, may involve individual methods or combinations of heat, fumigation, and chemical applications (Leal *et al.* 2010; Allen *et al.* 2017). Payette *et al.* (2015), for example, studied the efficacy of microwave irradiation in the context of packaging materials. Slahor *et al.* (2005) assessed the efficacy of hot water baths. Sohi *et al.* (2016) used ultrasonic energy to generate heat at temperatures near 70 °C in pine wood. An abundance of literature sources focuses on traditional and alternative methods to balance the effectiveness of treatments, cost, and environmental concerns.

Termites

Termites are commonly found in subtropical and tropical regions, as they prefer relatively warm environments (Kalleshwaraswamy *et al.* 2022). They can be found throughout the United States, except for Alaska (Peterson 2006). They are divided into five different groups: subterranean, soil-feeding, dry wood, damp wood, and grass-eating (Olaniyan *et al.* 2015). All of them feed on lignocellulosic materials (Scharf 2020). Subterranean and drywood termites are efficient agents in wood decay, and they can cause significant damage to wooden structures. In the US, only drywood, dampwood, and subterranean termites can be found (Peterson 2006). Infested wood will sound hollow and dull when hit with a hammer (Gouge *et al.* 2009).

Drywood termites

Drywood termites live in the southern parts of the United States, between North Carolina and the Gulf Coast, as well as the coastal areas of California (Gouge *et al.* 2009). As their name suggests, they live in sound, dry wood. Their excrement is dry pellets, a common form of identification as they accumulate outside of their entrances. They feed on early and latewood, following the grain of the wood. Their major feeding source is the cellulose in the wood.

Dampwood termites

Dampwood termites are more adapted to colder climates (Lacey *et al.* 2010). This relatively small group of termites lives in galleries of moist and decaying wood (Harris 1955) of living and dead trees (Haverty 2003).

Subterranean termites

Subterranean termites live in underground nests. A typical identifying feature is so-called run-ways made of carton material used for transporting food (Harris 1955). Similar to ants, termites form colonies with large numbers of workers, from less than a thousand to 2,500,000 (Ewart and Cookson 2014). According to Scharf (2020), most termites feed on dead wood, and only a few prefer living trees.

Identifying the types of wood that are resistant to termite infestations, construction principles, and treatments is a major focus in the termite-related literature. To prevent subterranean termites, which live underground, from entering structures, preventing access is a major strategy. Ghaly and Edwards (2011) propose the use of rammed sand and soil, concrete and steel to harden the exterior structures of homes against termite infestations and to create impenetrable barriers. This is in line with Peterson (2006), who describes the construction of a home as the best time to prevent future infestations. Chemical prevention, however, is an important factor in mitigating the immense damage of termite attacks.

Wood Treatment Options to Guard Against Rot and Insects

While the present article focuses on the role of wood coatings, it is important not to overlook measures involving impregnating of the wood or otherwise treating it as a means to control against various forms of rot, termites and other wood-attacking insects. Table 5 lists some review articles and chapters that have covered those areas.

Table 5. Review Articles and Books Dealing with Wood Treatments to Resist Rot Organisms, Termites, and Other Insects

Themes of Publications	Citation
Wood modification by chemical, thermal, *etc.*, processes (book)	Hill 2006
A review of wood preservation	Schultz *et al.* 2007
Natural products for wood protection	Singh & Singh 2011
Non-toxic methods to enhance resistance against fungi	Ringman *et al.* 2013
Brown-rot biodegradation mechanisms	Arantes *et al.* 2014
Thermal treatment and its impacts	Candelier *et al.* 2016
Wood modification technologies reviewed	Sandberg *et al.* 2017
Thermal treatments of wood against termites & fungi reviewed	Lee *et al.* 2018
Conventional & nano wood preservation technologies reviewed	Teng *et al.* 2018
Chemical treatments for decks, railroad ties, *etc.* reviewed	Lebow *et al.* 2019
Natural compounds for wood protection reviewed	Broda 2020

FACTORS AFFECTING WOOD FINISHING FOR DURABILITY

Homeowners who are faced with the prospect of repeatedly repainting exterior wood have a strong motivation to invest in some form of siding or cladding, such that they can greatly extend the time before further repair is needed. According to Williams *et al.* (1996), a typical wood coating, applied outdoors, will last two to eight years, depending on many factors. The goal of this section is to examine such factors.

Weather Severity

Climate clearly can play an important role relative to the rate and extent of weathering of wood. Grüll *et al.* (2013) found that a site in the United Kingdom that was known for wet weather gave more rapid degradation of coated pine panels compared to four other European sites. Creemers *et al.* (2002) carried out matched sets of weathering tests at nine different locations in Europe. They found that the general effects could be simplified by defining a climate index, which was a function of the amount of irradiation, total precipitation, and number of days with more than 0.1 mm of precipitation. Likewise, Bobadilha *et al.* (2021) found that wood finishes failed more quickly in Mississippi than in Wisconsin, which they attributed to greater decay. Davis *et al.* (2022) carried out matched weathering tests of coated wood in a warm-summer Mediterranean location and in a semi-arid climate of eastern Oregon in the US. Fungal growth was much more prominent in the wetter site. Dawson *et al.* (2005) compared weathering of matched pine wood specimens in Germany and New Zealand. As in the previous example, it was found that mold growth played a major role in the degradation of the coated wood specimens. It was found that a higher amount of treatment to suppress mold was required at the New Zealand site, which was the wetter site. Bratasz *et al.* (2012) compiled maps based on projected climate change, in future years, to be able to estimate the risks to painted wood items.

Wood Selection

Wood species

Several studies have revealed differences in coating performance on different species of wood. Some key findings are highlighted in Table 6.

Table 6. Effects of Wood Species on the Performance of Outdoor Finishes

Themes of Publications	Citation
The service life of the finish was found to be affected by growth rate, density, knots, extractives, juvenile wood, grain orientation, and weathering characteristics.	Williams *et al.* 2000
Differences in susceptibility to color change were observed for five tropical wood species that had been coated with transparent finishes.	Silva *et al.* 2007
Different color changes were observed for ash and for oak in the course of conventional accelerated weathering tests.	Nzokou *et al.* 2011
European larch gave higher durability of 20 commercial transparent and semi-transparent coatings compared to Siberian larch.	Simunková *et al.* 2019
Coated Norway spruce heartwood exhibited lower moisture content and equal or lower fungal infestation compared to the sapwood.	Sjökvist & Blom 2019; Sjökvist *et al.* 2020
Teak enabled better performance of wood coatings in comparison to pine in Indonesia based on microbial infestation.	Lestari *et al.* 2020
Results from five wood species all showed loss of the protective effects of 12 exterior coatings within 1 year.	Davis *et al.* 2021
Water-based acrylic paint was more durable on spruce than oak.	Dvorák *et al.* 2023

Notably, certain species such as teak are known to have greater natural resistance to decay (Lestari *et al.* 2020). However, color change is a priority for many users, who are not pleased in cases where an expensive, reddish-colored wood tends to become gray during exposure to weather (Williams *et al.* 1996). Feist (2002) provides a broad discussion of how not only the species of wood but also differences between the wood of individual trees can affect the performance of coatings. For example, it has been found that wood having a large proportion of latewood can give rise to adhesion failure of the coating after extensive weathering. The cited article provides a table with ratings of different wood species with respect to paint-holding ability for oil-based and latex paints.

Wood's inherent antimicrobial performance

Some wood species are inherently more resistant to biological decay. This characteristic often has been attributed to the presence and levels of wood extractives (Kirker *et al.* 2013). The cited work showed that after extraction of such compounds from the tested wood species, the rates of attack by fungi and termites were higher in nearly all cases. Similar results had been obtained earlier by Taylor *et al.* (2006), but the correlations were low. Further confirmation of these effects comes from studies in which the extracts from resistant wood species were used to treat non-resistant species, such as pine. Thus, Syofuna *et al.* (2012) found that certain wood extracts could protect pine wood against termites. Sablík *et al.* (2016) found related effects when extracting the heartwood of black locust and then impregnating non-resistant beech wood, which then showed resistance against fungal decay.

Wood density

Sjökvist *et al.* (2019) reported correlations between the density of Norway spruce wood and the tendency of the coated wood to develop cracks during three years of outdoor exposure. The lower-density specimens exhibited higher moisture contents. However, the higher-density specimens showed a higher number of cracks. Follow-up work showed the unexpected effect of higher water uptake into coated high-density wood, compared to coated low-density wood (Sjökvist *et al.* 2020). Williams *et al.* (2000) noted that high-density woods tend to swell and shrink to a greater extent than lower-density woods, and that this tendency can lead to a higher rate of checking. It makes sense that checking will hurt the performance of coatings. Strikingly different effects were found in a study of surface-densified wood (Cheng *et al.* 2024). Such densified surfaces showed superior paint film adhesion, hardness, and resistance to impacts, and these were applied to a range of tropical hardwoods.

Grain coarseness

Better performance has been reported for wood coatings on fine-grained woods. Thus, de Windt *et al.* (2014) found the lowest degradation rate of coatings on fine-grained wood. The coatings ranged from clear stains to opaque stains. There appears to be a need for more research in this area, not only to confirm the reported observations, but also to seek a mechanistic explanation.

Heat-treatment of wood

The heat-treatment of wood can be regarded as an additional option related to the kiln drying of wood, as illustrated in Fig. 3. Kiln drying, meaning the heating in air for many hours or a few days at about 50 to 90 °C for most hardwoods and above 100 °C for softwoods, is applied to most commercial lumber as a means to stabilize the dimensions of the wood. Due to increased danger of fire, as well as to minimize undesired chemical changes, such as oxidation, technologists use various ways to exclude oxygen when using higher temperatures, often in the range 180 to 220 °C, to heat-treat the wood. Details and options for the procedures and conditions of heat-treatment of wood have been reviewed (Esteves and Perera 2009; Cao *et al.* 2022; Hubbe and Laleicke 2025).

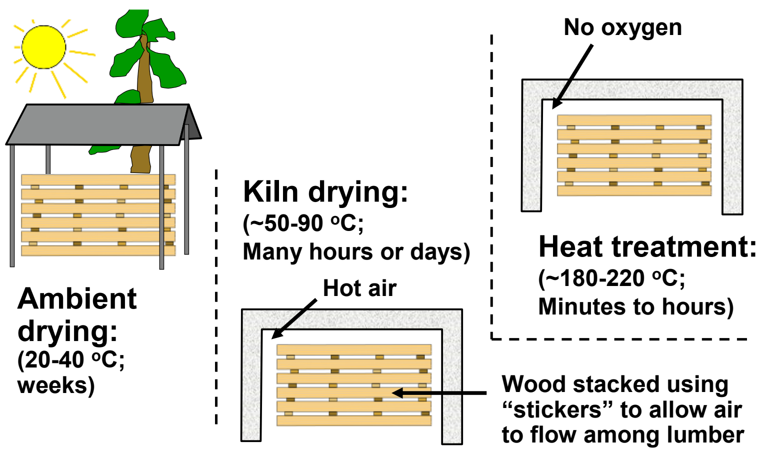

Fig. 3. Simplified comparison of conditions typically used in ambient drying, kiln drying, and heat treatment

The effects of high-temperature treatment already were considered in a companion article (Hubbe and Laleicke 2025), where the emphasis was on adhesion between the coating and the wood. Heat-treated wood is also of importance in the present context, since it is a known strategy to increase resistance to decay. Here the emphasis is on whether the combination of heat treatment, followed by coating of the heat-treated wood, renders the surface more durable in a practical sense. The highlights listed in Table 7 are focused on such issues.

Table 7. Overall Effects of Heat Treatment of Wood, Followed by Coating, Relative to its Durability

Themes of Publications	Citation
Adding TiO_2 nanoparticles to the polyacrylate clear coating helped to protect the heat-treated beech wood.	Miklecic *et al.* 2017
Heat-treatment yielded inconsistent effects on the weathering of uncoated and coated woods.	Jirous-Rajkovic & Miklecic 2019
Overall resistance to weathering increased with increasing temperature and time of wood treatment. Two kinds of varnish were applied after heat treatment.	Kart *et al.* 2019
Coated heat-treated pine and spruce had lower moisture uptake and better appearance after weathering compared to coated untreated wood.	Nejad *et al.* 2019
Coatings on heat-treated short-rotation teak wood showed better performance than on untreated short-rotation teak wood.	Pratiwi *et al.* 2019
Coatings that contained nano TiO_2 were effective in reducing color change of heat-treated wood with olive leaf extract in a polyacrylate coating.	Nowrouzi *et al.* 2021a,b

Mechanical Processing of Wood for Adhesion of Finish

There is much evidence that the performance of wood coatings can be improved by appropriate preparation of wood surfaces. Aspects to be considered here include the freshness of the wood surface (*i.e.* how recently the surface has been machined or sanded), the planing of wood surfaces before coating, and aspects of sanding prior to coating application.

The importance of freshness of the wood surface

Articles cited by Hubbe and Laleicke (2025) showed that fresh removal of the outermost layer of wood is a reliable way to achieve improved adhesion of coatings on wood. Wood extractives are expected to gradually migrate to exposed surfaces of wood over time. The migration is motivated by a minimization of surface free energy when a surface becomes covered by nonpolar compounds. Such compounds, which include fatty acids and resin acids, can be expected to inhibit wettability of the surface by some coatings, especially water-borne formulations. In addition, the monomeric compounds, due to their lack of covalent bonding to the surrounding material, will not be able to provide firm anchoring of the coating. In principle, such problems can be minimized if the outermost wood is removed shortly before coatings are applied.

Adverse effects of weathering of bare wood on subsequent coating performance

Severely adverse effects on coating performance have been reported in cases where the uncoated wood surfaces have already been exposed to outdoor weather (Williams *et al.* 1987a,b; Williams and Feist 1993, 1994, 2001). To some extent, such problems can be overcome by selecting a specialized finish formulation, such as with 10% linseed oil and 11% acrylic resin (Williams *et al.* 1999).

Some challenges in the application of coatings on top of weathered wood are highlighted in Fig. 4. As shown by articles cited in an earlier review article (Kropat *et al.* 2020), one of the major changes resulting from exposure to weather, *i.e.* combinations of ultraviolet (UV) light exposure and periods of rainfall, is a loss of lignin from the outermost 1 mm or so of the wood. On the one hand, the loss of lignin results in a relatively loose layer of cellulose fibers, which might be regarded as a weak layer. However, the cited research suggests also that there is an inherent incompatibility between the generally hydrophilic nature of cellulose and hemicellulose (after the loss of lignin) and the more hydrophobic nature of typical resins used in wood coating formulations. A study by Kanbayashi *et al.* (2023), based on Raman spectrometry, showed that lignin degradation can take place even below both penetrating and film-forming coatings. As outlined in another earlier review article (Hubbe and Laleicke 2025), the strength of adhesion between two materials, depending on various process details, is often governed by how similar the two materials are in terms of cohesive energy density, polarity, and capacity to form hydrogen bonds. Further challenges, from the standpoint of establishing lasting adhesion to a coating layer, may be associated with the tendency of lignin-free cellulose fibers to swell a lot when then imbibe water and then to shrink a lot when dried (Hubbe *et al.* 2024). Depending on the flexibility of the dried and cured coating, such dimensional changes can be expected to induce strong shearing forces at the interface. The presence of lignin, when the fibers are within a sound wood structure, tends to restrain such dimensional changes. Since the lignin is the most hydrophobic of the three main chemical components of wood, and thereby the most similar in terms of wetting properties to the resins used in coating formulations, its presence seems to be important when the goal is to achieve strong adhesion of a coating.

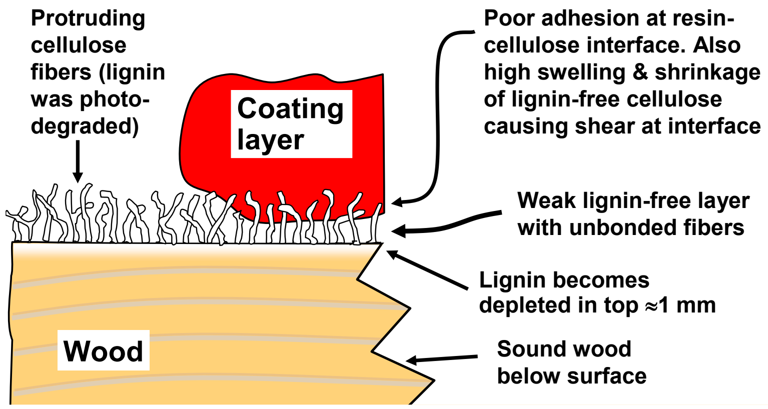

Fig. 4. Idealized illustration of weathered wood surface and its ineffective adhesion to a coating

Figure 5 illustrates the role of fresh mechanical treatment of a surface, as in the case of planing or sanding. The mechanical action appears to have three main objectives, the first of which is to achieve a specified level of smoothness. The second objective, which is sometimes overlooked, is that there ought to be an optimized level of roughness of the surface in order to be able to interact in a three-dimensional manner with the coating layer. Third, the fresh mechanical action can remove any accumulation of waxy substances, which otherwise could impede spreading of the adhesive and development of effective bonding with such wood components as lignin, cellulose, and hemicellulose.

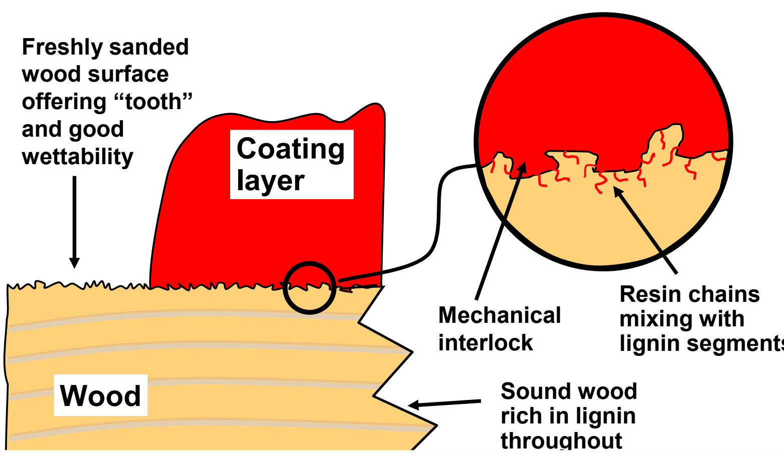

Fig. 5. Schematic description of mechanisms by which fresh sanding can provide stronger adhesion of coatings to wood

As illustrated in Fig. 6, the planing of wood employs a blade to improve the smoothness of a sawn lumber piece. Studies by de Moura and Hernández (2005) showed that improved adhesion of wood coatings could be achieved by peripheral knife planing before high-solids polyurethane coating. The wood surface after planing was described as "undamaged". Planing to achieve a fresh surface is commonly done during the assembly of Cross-Laminated-Timber, a structural wood panel. Some adhesive manufacturers require a timely planing step prior to the application of the primer (Miyamoto 2024).

Cool and Hernández (2016) compared oblique cutting, face milling, and helical planing as alternative preparations of spruce wood immediately before application of exterior acrylic water-based coating. Helical planing achieved superior results, including better adhesion of the coating and resistance to weathering. The worst results were with the face milling, which gave an uneven coated surface and poor adhesion. Follow-up work showed best results with peripheral planing of red oak wood at a rake angle of 25 degrees (Ugulina and Hernández 2017). The authors attributed the superior adhesion of the wood coating to the fibrillation of the surface in the course of the planing. Altun and Esmer (2017) likewise achieved good adhesion of varnish to iroko wood that had been planed.

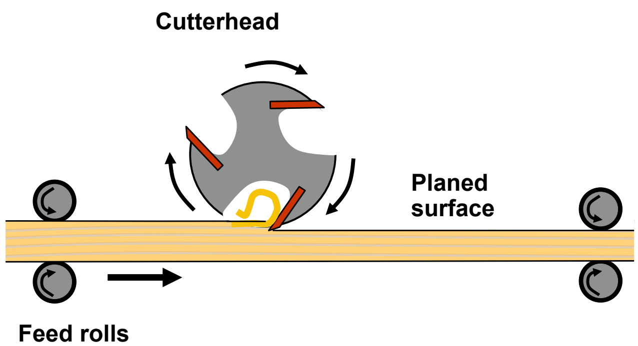

Fig. 6. Simplified diagram of a rotary planing operation

Though a state-of-the-art planing treatment carried out recently before application of coating might be favorable for the overall goals of a project, it is important to note that a roughly sawn surface may provide superior adhesion of a coating. Thus, Nussbaum *et al.* (1998) reported superior adhesion of alkyd and linseed oil finishes onto sawn and rough surfaces.

Sanding

It is notable that de Moura and Hernández (2005), even when showing positive effects on coating adhesion after planing of the wood surface, found even better results following sanding. When using sanding to prepare a wood surface for application of a coating, the general recommendation is to start with a level of grit suitable to remove the largest features of roughness, such as grooves created by previous sawing or planing actions (Allen 1984; Flexner 1994). Detailed measurements of the features left behind by sawing have been quantified by Singh and Dawson (2006) and Singh *et al.* (2007). Subsequently, the sanding is repeated with successively finer (higher number) sandpaper but not continuing past what is needed. Thus, Allen (1984) recommends starting with 100 grit and proceeding up to 150 grit for routine house painting or 220 grit for varnish applications. Table 8 lists articles dealing with the role of sanding is preparing durable external wood coatings.

Figure 7 illustrates the point made by Landry and Blanchet (2012a) regarding optimization of sanding practices in the case of typical outdoor wood coating projects. As shown, it has been recommended that a medium coarseness sandpaper such as 160 grit may be a good choice for such projects as the final sanding before application of a primer coat. When such sandpaper is replaced with sufficient frequency so that it will be sharp and not filled with wood particles, it can be expected to provide enough fibrillation and microscopic tearing of the wood surface to provide strong adhesion at the wood-coating interface.

Table 8. Sanding Used as a Means to Improve the Performance of Wood Coatings for Outdoor Applications

Themes of Publications	Citation
This review article provides recommendations for routine sanding procedures.	Allen 1984
The author recommends 220 grit as the finest sandpaper to use.	Flexner 1994
Sanded surfaces enabled good results even with low quality paint and low-grade wood	Richter *et al.* 1995
Overly aggressive sanding or too fine a grit can hurt coating adhesion.	Cox 2003
A sanded surface gave better anchoring of wood coatings.	de Moura & H. 2005
Two-stage belt sanding is recommended with 17 m/min speed.	Cool & H. 2011
180-grit sandpaper gave good wetting & adhesion of wood coating, whereas 150-grit have poor results.	Landry & B. 2012a
Adhesion strength on sanded ash and birch woods sometimes increased with increasing roughness.	Vitosyte *et al.* 2013
Smoother sanded surfaces before painting resulted in higher resistance against cracking due to weathering.	Panek & R. 2016
The feed speed of belt sanding could be optimized to achieve the highest pull-off strength for the coating.	Ugulino & H. 2018
Surface roughness decreased with increasing fineness of the final sandpaper employed.	Liu *et al.* 2020
Sanding of hornbeam and ash woods increased adhesion.	Miklecic *et al.* 2022
Sanding tended to make the wood more wettable.	Yu *et al.* 2023

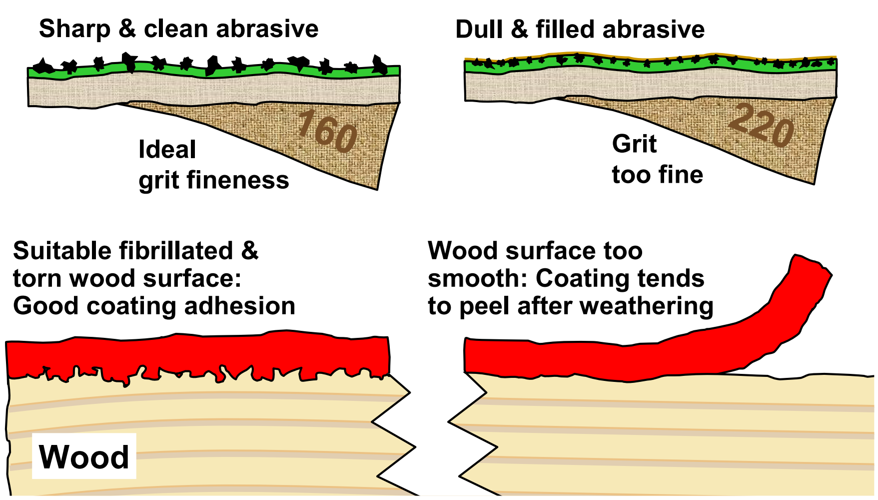

Fig. 7. Schematic illustration of the importance of selecting a sufficiently coarse sand paper and replacing it often enough as a means to achieve good long-term coating adhesion

One of the commonly repeated points of advice regarding the sanding of wood is to use fresh sandpaper that is replaced with suitable frequency (Flexner 1994). In addition, as noted by Allen (1984), it can be helpful to periodically slap the paper on a hard surface to dislodge wood particles and expose the sharp mineral grains. Such practices are consistent with the idea that loose material left on the wood surface might not be helpful for developing strong adhesion to a coating. Conversely, a sharp sandpaper sheet may be helpful in creating fibrillation or minor tearing of the wood surface in such a way as to achieve better mechanical interlocking at a suitable length scale, such that the coating becomes well attached, but the surface of the coating does not become rough.

Chemical Treatment of Wood for Finish Durability

Though it has not become a common practice, there has been some research related to potential chemical treatments of wood surfaces in advance of coating application. These can range from bleaching to extraction of the wood surfaces, to plasma treatments, and finally to chemical derivatization of the wood surface.

Bleaching

Bleaching of wood surfaces provides a means to achieve a lighter appearance of wood, when that is desired. Atar *et al.* (2004) compared a series of different bleaching treatments, all based on hydrogen peroxide, for beech wood in preparation for varnish application. All of the treatments decreased the hardness of the unfinished wood surface, but after varnish application, the initial hardness had been restored in all cases. Budakçı (2006) showed that bleaching treatment can be effective for restoration of wood's color after weathering of clear-coated wood.

Going another step beyond conventional bleaching treatments, Dawson *et al.* (2008a,b) explored the feasibility of intentionally removing lignin from the outermost 2 or 3 mm of the wood surface before application of a clear coat. The idea was to preemptively remove the component of wood that is susceptible to photodecomposition in the presence of ultraviolet light and thereby stabilize the system. The desired delignification was achieved by means of oxidation with peracetic acid. The resulting surface was judged to still have sufficient strength to work well with the coating. It is worth noting, however, that surface delignification also can be achieved by natural or conventional weathering, the results of which are often unfavorable to the adhesion of wood coatings (Kleive 1986; Hubbe and Laleicke 2025).

Extraction of wood

Ghofrani *et al.* (2016) showed that stronger adhesion of varnish to wood could be achieved by removal of extractives. Alder and ironwood were compared, and the extractive media were either hot water or ethanol. The extracted surfaces showed superior wettability to the two-part waterborne urethane-alkyd varnish formulations, as well as showing higher pull-off strength. The authors attributed the improvements to avoidance of the blocking action of the wood extractives. The extractives would have prevented direct contact between the coating and the polymeric components of the wood. Wu *et al.* (2020) used nanoindentation to show that a waterborne formulation achieved higher hardness after extractive removal from a wood surface. The benefit was attributed to the better wettability of the surface by aqueous media.

Plasma pretreatment of wood

As discussed in recent review articles (Klébert *et al.* 2022; Hubbe and Laleicke 2025), treatment of a wood surface with plasma, especially the so-called corona treatment that involves relatively low energy plasma in air, can be used as a way to increase adhesion, especially in the case of water-borne coatings. As illustrated in Fig. 8, some of the potential beneficial effects of corona treatment, possibly in preparation for the coating of wood, can include the cleaning of waxy substances from the surface, the etching of the surface on a microscopic level, and oxidation of the surface, leading to good wettability by aqueous formulations (Klébert *et al.* 2022; Zigon *et al.* 2022). Here the emphasis is on developing resistance to outdoor exposure. Reinprecht and Somsák (2015) and Reinprecht *et al.* (2020) showed that plasma treatment aided the stability of clear acrylic and alkyd coatings on spruce specimens that were exposed to artificial weathering. Gholamiyan *et al.* (2022) compared plasma treatments with air, nitrogen, and carbon dioxide media on the performance of waterborne and solvent-borne coatings on fir. They found increased weather resistance of both waterborne and solvent-borne coatings. Even though the plasma treatment rendered the wood surface more hydrophilic, the final result achieved greater hydrophobic character of the coated surface. Kettner *et al.* (2020) pointed out that resinous woods, including pine, are often preferred for outdoor applications, in recognition that the hydrophobic nature of wood resins can help resist water, but that the same resins can hurt the performance of coatings. They were able to overcome the adverse effects by a specialized plasma treatment involving chemical vapor deposition. Blue-stain fungal infestation was effectively suppressed by the treatment before application of a glaze or lacquer coating.

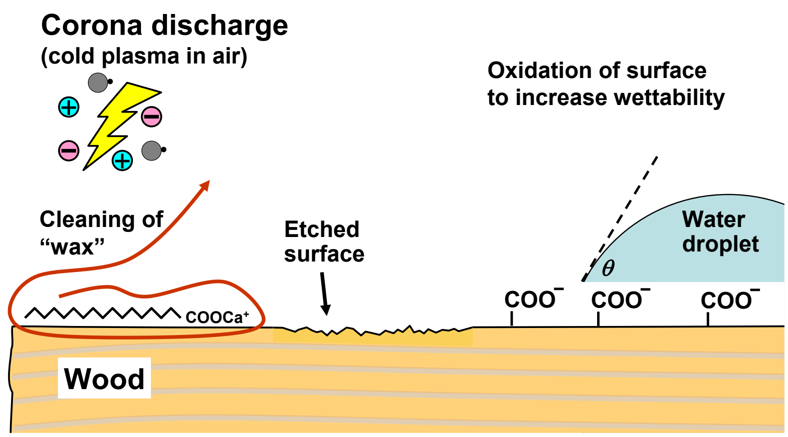

Fig. 8. Reported effects of corona treatment, a relatively inexpensive cold plasma treatment using air, for preparation of a wood surface to receive a coating

Czarniak *et al.* (2022) found better wettability of common wood finishes after corona treatment; however, there was no corresponding improvement in adhesion of the coating layer. Thus, it makes sense in practical cases to determine whether or not plasma treatment is either needed or beneficial, depending on various details.

Acetylation of wood

By treatment of the wood surface with acetic anhydride, some of the -OH groups that are prevalent especially within the hemicellulose and cellulose components can be converted to their acetylated forms. Such an operation is illustrated schematically in Fig. 9. This kind of treatment can be interesting from a wood protection standpoint, since acetylated wood is much more resistant to wetting and swelling in water (Rowell and Bongers 2015). The cited authors explained that the improved dimensional stability of the wood, relative to changing moisture conditions, reduces the stress at the coating-wood interface, such that less there will be less tendency for peeling of the coating over time. Studies have shown that acetylated wood is more resistant to weathering (Beckers *et al.* 1998; Fodor *et al.* 2022). Beckers *et al.* (1998) showed furthermore that acetylated pine wood still adhered well to a variety of different wood primers, including waterborne and solvent-borne. Fodor *et al.* (2022) reported decreased absorbance of pigmented stains into acetylated hornbeam wood, though the acetylated wood was more durable and dimensionally stable under outdoor conditions. Although acetylation has been shown to increase the service life of exterior wood, as in the case of wood siding on houses, it does not prevent color change due to weathering (Sandak *et al.* 2021). The cited authors showed that so-called hybrid processing, using a range of commercially available treatments, all of which were coatings. Nagarajappa *et al.* (2020) showed that the photostability of acetylated wood could be improved by adding an ultraviolet light absorber, ZnO, to the coating formulation.

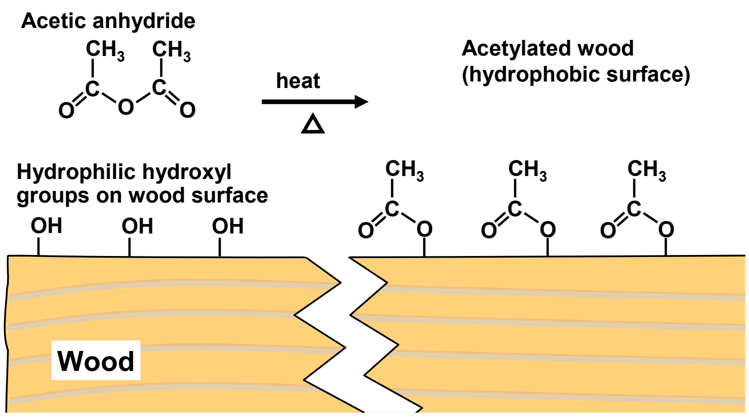

Fig. 9. Surface acetylation of wood, using acetic anhydride

Wood Impregnation and Wood Finish Performance

Resin impregnation

Wood impregnation has become a popular way to improve its weathering characteristics, especially with respect to attack by fungi and termites. As illustrated in Fig. 10, such treatment can be achieved by first immersing the lumber pieces in a solution or suspension of the material to be impregnated, then applying vacuum, and then releasing the vacuum. The evacuated pores of the wood then suck the impregnating fluid into the pores of the wood, including vessels and fiber lumens. Subsequently, the suspending medium is expected to evaporate.

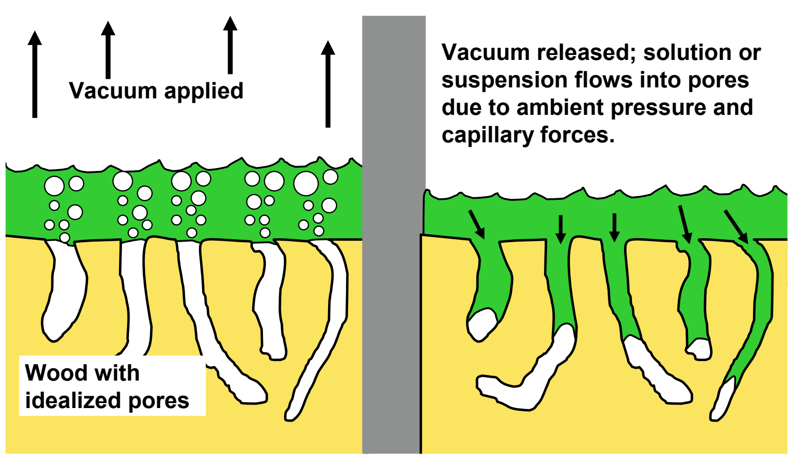

Fig. 10. Schematic diagram of steps in a process of impregnating wood by use of application and release of vacuum

Table 9 highlights some work that has been carried out to find the impact of such impregnation on the performance of coatings. The most commonly studied impregnants have been copper-based antimicrobial treatments and formaldehyde resin formulations. In a majority of cases, the impregnation resulted in better resistance to weathering.

Table 9. Effects of Wood Impregnation on the Performances of Exterior Wood Finishes

Themes of Publications	Citation
The authors of a review article state that impregnation with chromated copper arsenide will enhance the durability of finish applied later to the wood.	Williams *et al.* 1996
Impregnation of pine, spruce, oak, and Douglass fir wood with melamine resin before varnish coating provided protection against photochemical degradation of the wood by weathering and resistance against blue-stain fungus, but it did not protect against cracking and the effects of high moisture content.	Rapp & Peek 1999
Impregnation of pine and chestnut woods with chromium-copper-boron before application of either polyurethane varnish or an alkyd varnish, followed by outdoor exposure, stabilized the surface color, but the adhesion of the coating was adversely affected.	Yalinkilic *et al.* 1999a,b
Impregnation with two commercial formulations, one waterborne and one solvent-borne, including sodium chromate, copper sulfate, and hydrogen borate, had little effect on the hardness after waterborne varnishing.	Atar *et al.* 2004
Impregnation of *Pterocarbus marsupium* wood with ammoniacal copper ferricyanamide and related agents before three commercial wood finishes increased water repellency and dimensional stability during weathering, thus giving longer service life of the coatings.	Upreti & Pandey 2005
Impregnation with boron compounds before varnishing decreased surface roughness.	Örs *et al.* 2006
Modification of the wood with N-methylol compound improved the adhesion of both waterborne and solvent-borne finishes.	Xie *et al.* 2006
Weathering resistance was increased following the combination of impregnation with copper-chromated boron and then either polyurethane or alkyd varnish.	Baysal 2008
Both copper-based wood preservative impregnation and varnish coating improved the surface characteristics of pine specimens after accelerated weathering.	Baysal *et al.* 2014
Impregnation of pine and beech woods before two kinds of varnish and 3 months of natural weathering that surface hardness values decreased in all cases, especially for the impregnated wood.	Turkoglu *et al.* 2015a,b
Impregnation with phenol-formaldehyde resin improved the performance of clear coatings on oak and pine.	Evans *et al.* 2016
Impregnation with copper monoethanolamine solutions enhanced the durability of semitransparent penetrating stains on larch wood.	Isaji & Kojima 2017
Impregnation with copper-based chemicals resulted in more stable color after varnishing and accelerated weathering.	Gunduz *et al.* 2019a
Impregnation with copper-based chemicals resulted in increased surface hardness and gloss after varnishing and accelerated weathering.	Gunduz *et al.* 2019b
Wood specimens impregnated with ammonium tetra-fluoroborate, ammonium pentaborate, and boric acid were covered by liquid glass. Good resistance to weathering was observed, except for a pronounced reddening and yellowing.	Kucuktuvek *et al.* 2020
Impregnation of pine wood with three commercial copper-based	Türkoglu *et al.* 2020

products, followed by waterborne varnish and six months of natural weathering resulted in less loss of lightness.	
Impregnation with copper-based chemicals increased the surface roughness of pine even after coating with varnish. Adhesion strength after weathering was decreased by the impregnation.	Baysal *et al.* 2021
Impregnation of pine sapwood with phenol-formaldehyde resin before painting decreased discoloration associated with resin exudation after exposure to artificial weathering.	Karlsson *et al.* 2022
Sealing of oak with an epoxy resin enhanced the durability of several exterior paint systems exposed to outdoor weathering.	Dvorák *et al.* 2023

Even in the absence of biocidal treatment, it has been shown that various clear and tinted coating formulations can provide resistance against mildew for 12 months or so, followed by a decline (Morrell *et al.* 2001). After 21 or 39 months of weathering, the coating surfaces on western red cedar were generally found to be hydrophilic and in poor condition.

Primer Coats and Finish Performance

Why apply a primer?

The most important aim of applying a primer coat to a wood surface is to provide strong adhesion to the wood and thereby achieve reliable anchoring of subsequent coating layers. The practice of employing a primer layer for this purpose is consistent with an expectation that the wood-coating interface is likely to be a point of failure, including eventual peeling of coating from the wood (Knaebe *et al.* 1996; Williams *et al.* 1996). Another part of this general expectation is that adhesion between successive layers of coating is likely to be relatively strong, especially if only hours or days have separated application of the different layers. A further role of the primer coat, especially when covering resinous wood species, is to act as a sealant against permeation of wood extractives into the final layers of coating (Cassens and Feist 1986). As was illustrated in Fig. 2, excessive migration of resin from freshly applied coating into the pores of the wood can contribute to chalking; it follows that one of the roles of the primer, in addition to other intermediate coating layers, is to reduce such undesired depletion of binder from the top coating layer when it is still wet. According to the USDA Forest Products Laboratory (1972), “The fist, or prime coat of paint, is the most important coat to be applied to wood.” Despite this assertion, the literature search carried out in preparation of this article found that relatively little research has been carried out relative to the performance of primers.

Figure 11 illustrates the concept of using a primer. As shown, the low viscosity and relatively low solids content of a primer allows it to penetrate deeply into vessel openings, lumens, and fiber-level tear-out defects near to the wood’s surface, thus achieving good chemical and mechanical bonding. Achieving such a beachhead of good adhesion can be very important, especially if the wood-finish interface later becomes the critical site for initiation of peeling.

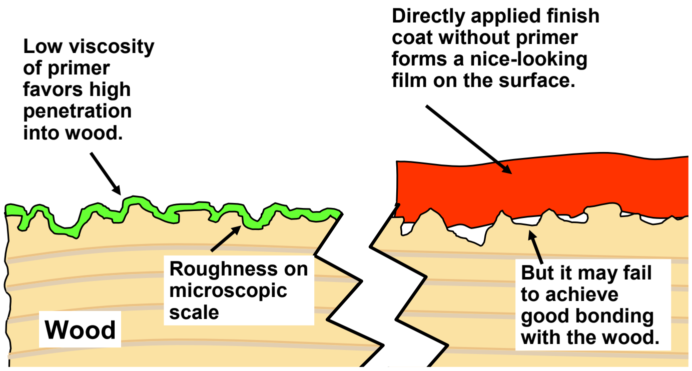

Fig. 11. Schematic diagram contrasting the deep penetration to be achieved by an idealized primer coat, *vs.* a typical film-forming finish coating formulation

Typical primer formulations

Consistent with the goal of penetrating well into the pores of the wood surface, primers are generally formulated with a relatively high content of liquid medium (Hubbe and Laleicke 2025). The USDA Forest Products Laboratory (1972) has recommended usage of an alkyd oil-based formulation, with inclusion of TiO_2 particles as a preferred primer choice. Liu *et al.* (2021) suggested using a polyurethane sealing primer on poplar wood. However, the main reported benefit was a higher gloss, not resistance to weathering.

In cases where resistance to discoloration of coatings by wood resins is a priority, Coniglio (2023a,b) have recommended using a water-borne primer, followed by a solvent-borne subsequent coating layer. This combination was reported to be very effective in protection against the bleeding of extractives from knots. Pánek *et al.* (2017) advocated priming oak wood surfaces with a transparent, hydrophobic coating to prolong the service resistance of coatings the undesired bleeding of tannins.

Considering the widespread agreement among experts that primer application should not be skipped, it seems remarkable how few times the formulation of primer coatings was found in the literature search for this article. It follows that the formulation of primer coatings, relative to such factors as coating adhesion, wood resin migration, and resistance to weathering effects, can be regarded as priority topics for future research.

Water-repellent preservative

Several articles have described the application of formulations called water-repellent preservatives, which appear to play a role analogous to that of a primer, or maybe as an impregnation treatment preceding usage of a primer coating. Highlights from such publications are provided in Table 10.

It is notable that Williams *et al.* (1996) disclosed the usage of wax, which appears to have been the main hydrophobic ingredient in the formulations being recommended in a series of articles and publications coming from employees of the USDA Forest Products Laboratory. However, the application of wax prior to coating prompts the following question, which might be considered in future research: Are there circumstances under which the wax itself may play a role as a weak boundary layer, thus increasing the likelihood of future peeling of a coating layer at its interface with the wax or within the wax layer? That question does not appear to have received an answer in the published literature.

Table 10. Effects of a Water-repellent Preservative, as a Primer Coating, on the Performances of Exterior Wood Finishes

Themes of Publications	Citation
Recommends using a commercially available water-repellent preservative solution before painting. The composition is not described.	USDA Forest Products Laboratory 1972
Water-repellent preservatives are described as containing a fungicide, wax, resin or drying oil, and either solvent or water. Such treatment is recommended before applying exterior coatings.	Williams *et al.* 1996
Recommends first treating with either a water repellent or a combination of water repellent and a preservative, before painting of outdoor wood surfaces. The hydrophobic component(s) is not mentioned in the article.	Williams & Feist 1999
A double-vacuum pressurized treatment was used to apply hydrophobic coatings based on polyurethane or acrylic resin to achieve resistance to weathering.	Bahchevandziev & M. 2022

Primer coats acting alone, vs. weathering effects

Though primer coats are not usually envisioned as acting by themselves, without at least one subsequent coating layer, there are some special circumstances under which this may happen. For instance, there might be a change of weather that delays the application of the intended subsequent coats. Ahola (1995) has reported that under such conditions, application of a pigmented stain (which essentially would be serving as a primer coat) made it possible to minimize adverse effects of leaving the wood exposed.

Table 11. Effects of the Choice of Finish Type on Resistance to Weathering

Themes of Publications	Citation
25 different paint systems were compared on five different wood types. The major factors governed weathering effects: wood species, location, and surface roughness. Different coating types (lacquer, oil-based, dispersion) showed similar trends to each other.	Bottcher 1975
Several coatings were evaluated on rough-sawn and smooth-planed aspen in three locations of natural weathering. The best results were obtained with acrylic paints (two coats) over an oil-based primer.	Feist 1994
Data are tabulated for several commercially available paints exposed on wood surfaces in the US and Europe for five years.	Kropf *et al.* 1994
Eight different varnish products were compared, some of which performed better than others, as evaluated on pine and iroko under accelerated and natural weathering conditions.	Custodio & E. 2006
Varius exterior coatings, including alkyd primer followed by either alkyd paint or resin varnish exposed to natural weathering were compared. A stain decreased the total color change.	Sivrikaya *et al.* 2011
Various coatings were evaluated on pine sapwood panels exposed to natural and artificial weathering. Pigmented (“opaque”) coatings greatly exceeded the durability of clear coatings. For instance, even after 60 weeks of artificial weathering, three such systems were so durable that they had not yet met the failure criteria for that study.	Grüll *et al.* 2014
Eight transparent or pigmented coating systems, including oil, acrylate, alkyd, and urethane alkyd on oak wood were exposed to natural and acerated aging. Oil coatings minimized color change. Acrylate coatings minimized changes in gloss and wettability.	Oberhofnerová *et al.* 2019

Coating Type

When considering different options to achieve resistance to weathering, one of the important questions is whether the type of coating, *i.e.* the main resin ingredients, makes a difference in terms of its effectiveness and service lifetime. Table 11 highlights studies that shed light on such issues. A notable point about this collection of cited work is that there have been relatively few reported studies comparing completely different wood coating types under matched weathering conditions. In addition, none of these cited reports gave persuasive evidence that any particular type of wood coating ought to be completely avoided for outdoor applications. On the other hand, to help answer questions regarding weathering issues, it would make sense to carry out a systematic study involving a large number of coating types, some involving use of a primer coat, all on the same wood and with the same weathering conditions. An interesting research question to consider is whether or not a wide range of commercially available formulations intended for outdoor use all show comparable resistance to color change, cracking of the coating, checking of the wood, or peeling when subjected to the same weathering conditions.

Finish Coat Application Factors and Durability

Another kind of question to consider is whether the results of coating performance, especially in exterior applications, depend on such factors as the application method, the number of coats, the total coat weight, the method of application, the time passage between applications of successive coats, or the weather conditions (*e.g.* humidity or rain) during or immediately before the application. Here, attention will be paid to the finish coats, *i.e.* the coating layers that follow the primer coat.

Application methods, brushing, rolling, wiping, and spraying,

In principle, coating formulations can be applied to wood surfaces by brushing, rolling, wiping, dipping, and spraying (Williams *et al.* 1996; Landry and Blanchet 2012a). These four systems are illustrated in Fig. 12.

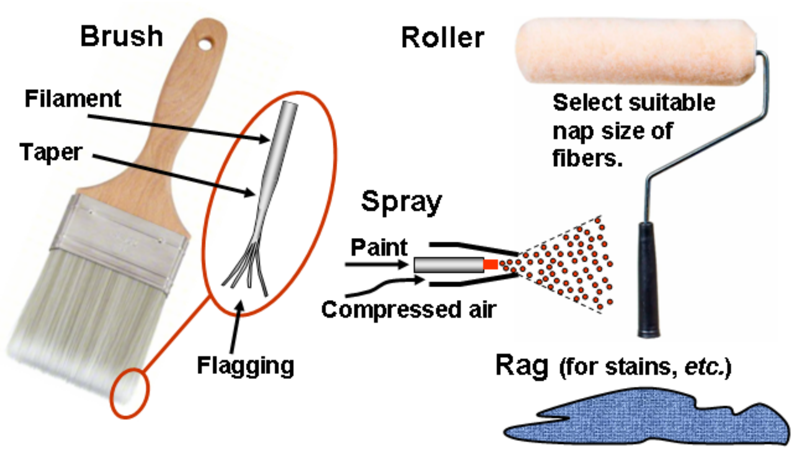

Fig. 12. Common systems for application of wood coating formulations

Of these, brush painting is the most common for coating of wood in external applications. Flexner (1994) provides a detailed description of the most popular type of paintbrush, which typically has a chisel-shaped tip and taper bristles that are flagged into multiple filaments near their tips. The flagging provides some extra capacity to hold wet coating formulation. In the case of roller application, which is widely used for applying paint to gypsum board (drywall), the fineness of the pattern has been shown to depend on the nap (meaning the size of the filaments in the felt-like material). In addition, there has been some work on the relationship between spattering of paint during roller application and the rheological properties of the formulation (Chaudhary *et al.* 2020). However, the literature search carried out for this article did not discover any scientific study to compare different application methods with each other with respect to outcomes such as the quality and service life of the resulting coating.

Number of coats

Several studies have considered issues related to the number of coats that should be applied to wood for exterior usage. Key findings or recommendations of those studies are highlighted in Table 12. In terms of effects on weathering, the most pertinent findings were from the 1972 USDA Forest Products Laboratory publication, since it basically predicted an increased service life of about 7 years due to application of a second finish coat. These findings are reinforced by work of Grüll *et al.* (2014). The results of Hysek *et al.* (2018) provide circumstantial evidence that a higher number of coatings has the potential to achieve a more uniform final effect.

Table 12. Findings from Studies Considering the Number of Coating Layers for External Wood Applications

Themes of Publications	**Citation**
The recommendation is to apply two finish coats (or “topcoats”) on top of a primer coat. The system with just a primer and one topcoat was estimated to last 3 years, whereas the application of the second finish coat extended the estimated time to 10 years.	USDA Forest Products Laboratory 1972
The durability of external coats was found to increase with an increasing number of layers.	Boxall 1981
Recommends using multiple coats, with sanding in between. These were general recommendations, not specific to external wood applications.	Flexner 1994
Increasing the number of applied coatings from 1 to 2 to 3 yielded large increases in the time to failure according to both artificial and natural weathering tests of various acrylic, alkyd, and polyurethane-acrylic coatings.	Grüll *et al.* 2014
Best results were achieved with two pigmented acrylate coating layers and a final transparent hydrophobic (water-repellent) layer.	Panek & R. 2016
The total waterborne acrylic coating thickness was found to correlate strongly with resistance to permeation of moisture through the total layer; but the correlation was affected by the number of coating layers. Four-layer coatings gave stronger correlations of water absorption rate *vs*. net thickness than 3-layer coatings.	Hysek *et al.* 2018
Gloss of a surface coated with a waterborne transparent formulation increased with the number of layers, but it decreased when sanding was done after coating.	Slabejová *et al.* 2016
Plywood was coated with either one, two, or three layers of solvent-based, waterborne, and hard wax layers. The authors were mainly interested in roughness and gloss effects, not weathering. Quality increased with increasing numbers of layers.	Slabejová & S. 2022

Figure 13 illustrates some reasons to expect that multiple layers of a finish coating ought to have a more durable effect than just one. If it is assumed that each coating will have defects, such as gaps or thin spots, the next layer can be expected to fill in such defects. If such defects are assumed to be random, then the application of multiple layers decreases the probability that inadequately covered areas will remain. Finally, multiple coatings allows for a greater overall thickness, while avoiding such problems as sagging of wet coating on vertical surfaces, which might be expected if excessive amounts are used in individual layers.

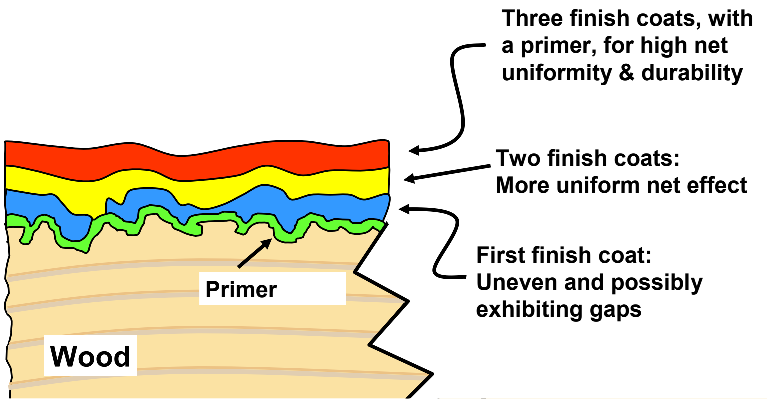

Fig. 13. Illustration of how the usage of multiple coatings may be able to compensate for un-evenness of individual coating layers, leading to a thicker and more durable combined coating

Net coating weight

Grüll *et al.* (2014) found that higher total film thickness led to greater resistance to the effects of weathering. Liu and Xu (2022) found that there was an optimum layer thickness when implementing a three-layer system in which a sealing primer was covered by a default primer and then a polyurethane topcoat. The sealing primer layer thickness did not show any significant effects. Best performance, in terms of adhesion and gloss were achieved with wet layer thicknesses of 60 g/m^2 for the sealing primer, 100 g/m^2 for the waterborne primer, and 120 g/m^2 for the self-made topcoat formulation.

Given the finding that coating performance often has been correlated with increasing total coat weight, it is worth considering whether it is feasible to increase the thickness of individual layers. Allen (1984) states that excessive layer thickness is likely to give rise to wrinkling. Such an effect might be expected on vertical surfaces in the case of coatings having a tendency to form an outer skin in the early stages of drying due to evaporation from the surface. A high thickness would imply a large amount of wet, low-viscosity material persisting long enough below the surface to allow the outer skin layer to sag, possibly in an uneven manner, giving rise to wrinkles. Cox (2003) recommended an ideal layer thickness of 4 wet milli-inches (equal to a total of about 0.1 mm) for a primer layer and 3 wet milli-inches (~ 0.075 mm) for a topcoat.

Time between coating applications

In principle, it is expected that there should be an optimum window of time during which to apply a second or layer coating layer to wood. Cox (2003) pointed out that sufficient time must have passed in order to allow the previous layer to have dried. The USDA Forest Product Laboratory (1972) and Cassens and Feist (1986) recommend applying each layer within two weeks of application of the preceding layer. As illustrated in Fig. 14, presumably with the further passage of time, the polymer segments within a coating layer become increasingly difficult to mobilize, thus limiting the amount of mixing of polymer segments at the interface between layers when applying the next coating.

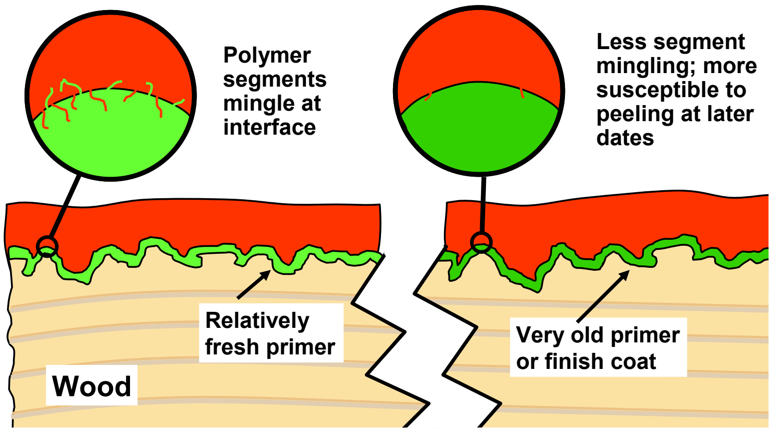

Fig. 14. Schematic illustration of an effect of time between application of successive coating layers on the development of polymer segment mixing at the interface

Sanding between coats

It makes logical sense that abrading a layer of coating with a suitable fine sandpaper ought to increase its adhesion to the next layer, due to mechanical interlocking, but the questions to consider is whether or not such improvements are needed and whether the effects are large enough to be worth the effort. As already was shown in Table 12, Flexner (1994) recommends sanding between layers of coating when there is a need to improve adhesion between them. Liu *et al.* (2021) reported improved bonding of a nitrocellulose transparent coating to a nitrocellulose transparent primer on poplar wood. However, the application was antique furniture, not exterior wood. It would be interesting to test this approach for systems that are subsequently exposed to weathering.

Weather conditions during application

Though it is reasonable to discontinue exterior painting well before the onset of a rainstorm, the weather circumstance most often mentioned by experts is almost the opposite – the warming of previously cold wood by sunlight (Ulfvarson and Pattyran 1972). A likely cause of this problem is illustrated in Fig. 15.

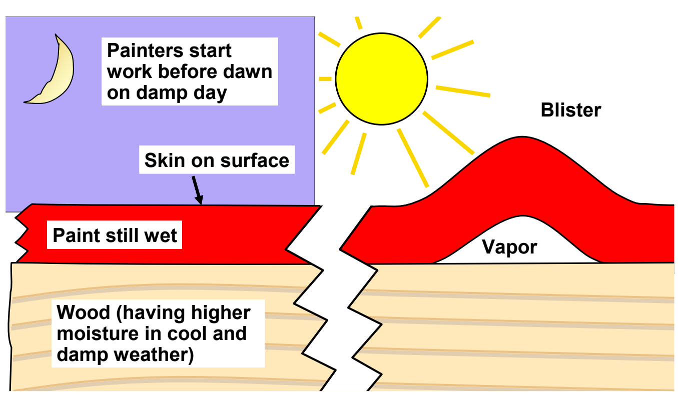

Fig. 15. Schematic illustration of what can happen when a fresh coating is applied to cool, damp wood not long before the rising of the sun, thus allowing a skin to form on the surface of the wet coating layer, followed by buildup of vapor pressure from the evaporation of water in the wood

When cold wood is coated, and when the sun subsequently is able to heat the surface before drying of the coating, it is likely that substantial liquid (water or solvent) may still be present underneath a skin of cured resin. Such a situation can give rise to blisters (USDA Forest Product Laboratory 1972; Williams *et al.* 1996; Cox 2003).

Moisture Control and Finish Durability

Water, together with ultraviolet light, can be regarded as a key enemy to the preservation of exterior wood. In particular, multiple episodes of wetting and drying will give rise to periodic vertical cracks, *i.e.* checking (Feist 1982b; Kropat *et al.* 2020). The wood swells each time that it is wetted, and it shrinks each time that it is dried. Steep moisture gradients can arise, for instance when wet wood is exposed to strong sunlight. It follows that the wood will experience shear stresses periodically during such moisture cycling (Flexner 2005). These shear stresses can result in check formation.

To combat the effects just described, an effective wood finish for exterior use needs to do two things.

- First it needs to block liquid water (from rain, dew, *etc.*) from entering the pores of the wood.
- Second, it needs to have sufficient vapor permeability to allow any water that might be trapped below the finish to gradually diffuse out. If not, there is a danger that the wood may decay (van Meel *et al.* 2011).

Hydrophobic character of finish

During rainstorms, as well as morning dew, coated wood surfaces are periodically exposed to liquid water. Many studies have been carried out to evaluate different additives that might act as hydrophobic agents, often with the goal of decreasing the amount of water that might permeate through the coating. Figure 16 highlights three classes of hydrophobic agents that can be components of various exterior coating formulations for wood. The main findings of such studies are highlighted in Table 13. As shown, the studied treatments have been highly diverse. Though the concept of using hydrophobic additives in wood coatings appears to be widely shared, no particular type of treatment has achieved a large proportion of research attention.

Though research into hydrophobic additives has shown that the contact angle of water on wood coatings can be increased, it is worth keeping in mind that the initial hydrophobic charter of such a surface can be expected to change over time due to the gradual oxidation of coating layers, the build-up of dirt, and any biological growth, such as mildew. Though it is possible, in the lab, to prepare surfaces so hydrophobic that drops of water just roll off of them (Huang *et al.* 2022), it is realistic to expect that coating wood surfaces exposed to rain will soon become completely wetted by water.

Even if the outside surface of a coating layer becomes completely wetted by water, especially with continued rainfall, that does not necessarily mean that the hydrophobic nature of a wood coating does not play a role in keeping the underlying wood dry. Suppose, for instance, that the coating layer has capillary pores within it; a hydrophobic nature of the walls of such pores will be expected to resist penetration by water (Lucas 1918; Washburn 1921). Such a mechanism can become important in cases where there are pinhole-like features in a coating layer.

Table 13. Studies Evaluating the Addition of Hydrophobic Components to Coating Formulations for External Applications

Themes of Publications	**Citation**
Water repellents, for the treatment of wood, keep the wood dry, whereas water repellent preservatives also control fungus. They can be used as a pretreatment before other coatings.	Williams & Feist 1999
Wax esters are used as hydrophobic components in industrial wood coatings. Life cycle impacts of the products were compared.	Gustafsson & B. 2007
Hydrophobic fumed silica was added to transparent UV-curable coatings. The additive improved scratch resistance.	Nkeuwa *et al.* 2014b
A top-applied water protective coating delayed the degradation of paint on spruce wood exposed to three years natural weathering.	Panek & R. 2014
Nanoparticles comprising poly(styrenemaleimide) with optional vegetable oil were used to coat high-density and low-density wood surfaces. The combination of both additives achieved hydrophobic surfaces.	Samyn *et al.* 2014
Beech and fir wood specimens were thermally treated in oil and then covered with poly-dimethylsiloxane. The hydrophobicity persisted after weathering.	Saei *et al.* 2015
A commercial hydrophobic topcoat provided limited durability against artificial weathering. Failure was due to micro-crack formation and the adverse effects of oak tannins and large vessels.	Pánek *et al.* 2017
Bark extracts from red cedar and lodgepole pine were evaluated for usage in primer and topic coatings.	Huang *et al.* 2019
Polymeric films were prepared based on natural latex and rosin as waterproofing coatings for bamboo particleboards. Latex formed a smooth hydrophobic film, whereas the rosin did not.	Nakanishi *et al.* 2019
Hydrophobic oils were added to either synthetics or waterborne acrylate with wax additive for oak wood. The hydrophobic treatment increased resistance to accelerated weathering.	Pánek *et al.* 2019a
Shellac was used to increase the hydrophobicity of bamboo. Its effectiveness was shown by contact angle tests.	Acarali & Demir 2021
Post-application of hexadecyltrimethoxysilane, *etc.*, reduced water permeation.	Yona *et al.* 2021b
Lignin-based polyurethane contributed to the hydrophobic character of a wood surface, but it promoted crack development.	Bergamasco *et al.* 2022
Jatropha curcas seed oil and vegetable resins contributed to the hydrophobicity of a bio-based varnish formulation.	Bessike *et al.* 2022
Application of waterborne (acrylic) and solvent-borne (polyester) coatings greatly increased the hydrophobicity of fir wood after plasma treatments with air, nitrogen, and carbon dioxide gases.	Gholamiyan *et al.* 2022
Thyme essential oils were added to solvent-borne or waterborne polyurethane coatings. Biocidal effects were found, especially when the oils were encapsulated. Hydrophobicity was not considered.	Tari *et al.* 2022
Hexadecyltrimethyoxysilane and related hydrophobic agents were used with vegetable-oil-based thermoset coatings.	Husić *et al.* 2023
Melamine was added to a polyurethane/acrylic dispersion to achieve hydrophobic character or a fire-resistant wood coating.	Puyadena *et al.* 2024

The next topic to consider is factors affecting the rate of diffusion of water monomers (*i.e.* water vapor) through the coating itself, regardless of whether or not the external surface has a low contact angle with liquid water.

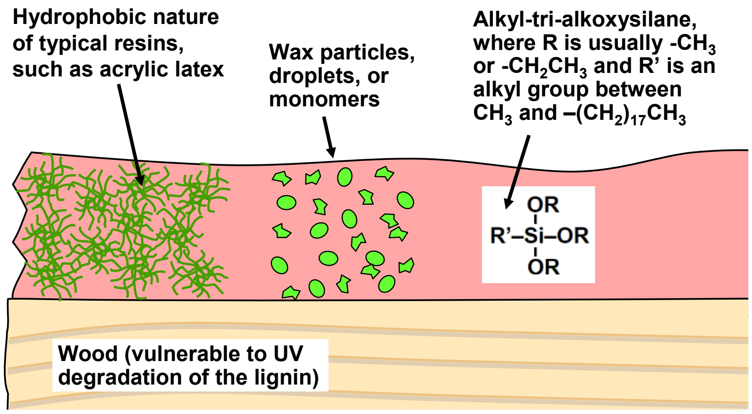

Fig. 16. Three classes of hydrophobic agents that may be present in coating formulations

Moisture barrier issues

Table 14 highlights key findings from studies that have considered the rate of permeation of water vapor and other monomeric substances through layers of wood coatings. Of particular note is the point that waterboard coatings, which involve the coalescence of polymer segments on adjacent latex particles during evaporative drying and curing, are known for providing greater breathability, meaning that their water vapor transmission rate is higher (Allen 1984). Another key point is the finding that defects such as cracks in a coating layer can be expected to have a disproportionately large effect on the overall protective ability of a coating (Williams *et al.* 1996). For example, interfacial incompatibility between a kind of particle and a kind of resin within a coating layer has potential to yield air gaps, which can serve as a conduit for water vapor transport (Donkers *et al.* 2013).

Table 14. Studies Considering Rates of Diffusion and Factors Affecting Rates of Diffusion of Water Vapor and Other Monomers through Wood Coatings

Themes of Publications	Citation
Increased water vapor absorption can be a sign of deterioration of the paint. This was shown in a study of 28 paint systems on fir and oak woods.	Botcher 1975
Waterborne coatings for wood tend to be more breathable, meaning that the moisture vapor transmission rate is higher.	Allen 1984
Moisture transported into pine and spruce was affected by the presence of any of nine different joinery paints. Absorption of water also was affected by weathering and the type of wood. Many of the coatings showed much higher transport of water vapor or liquid water after three years of weathering. Stain was not effective as a moisture barrier. Acrylic resin was less effective than other coating types at slowing water vapor transmission.	Ahola 1991
Air leaks tend to be more important than diffusion issues; thus, any vapor retarding treatment must form a continuous film.	Williams *et al.* 1996
Moisture diffusion coefficients were calculated from rates of weight gain after abrupt changes in relative humidity. These values were affected by both the coating system and the wood.	de Meijer & Militz 2001
Nuclear magnetic resonance (NMR) spectrometry was used to quantify moisture permeation into wood. Diffusion was the dominant mechanism of transport. An acrylic resin was more effective at inhibiting oxygen transport compared to an alkyd resin.	van Meel *et al.* 2011

The effect was attributed to closure of pores during resin drying.	
Though it makes sense to consider using minerals to block moisture absorption, what appears to happen in some cases is that the moisture shows enhanced moisture permeability near to the surface of the mineral, which suggests the presence of air gaps.	Donkers *et al.* 2013
Addition of 0.5% hydrophobic nano-silica together with 1% of nano-clay gave the best results on birch wood with respect to barrier properties and adhesion strength.	Nkeuwa *et al.* 2014a
Water vapor resistance was evaluated for four commercially available coating systems. Systems based on alkyd resins were effective at blocking water transmission. Mineral addition tended to make the coatings more permeable.	Volkmer *et al.* 2015
Permeability decreased with increasing coating layer thickness, with the number of coats, and was affected by coating composition. Certain pigment types affected permeability. Water vapor absorption dominated over permeability of liquid water. The rate of desorption from the coated wood was half the rate of water uptake.	Hysek *et al.* 2018
Moisture content of coatings was highly correlated with their water vapor permeability. A water-based acrylic coating showed lower water uptake compared to a solvent-based alkyd and a waterborne alkyd coating.	Gezici-Koç *et al.* 2019
Penetrating coatings provided little resistance against water vapor diffusion into larch and ash woods. Film-formers were much more effective.	Miklecic & Jirous-Rajkovic 2021
Nanofibrillated cellulose was added to acrylic resin to form a film on wood panels that decreased oxygen gas permeation and increased film strength.	Shimokawa *et al.* 2021
Differences in permeation of water vapor through various coatings were attributed to open pores in formulations including silicon-based components. Post-treatment with alkyltrialkoxysilanes reduced water vapor permeability.	Yona *et al.* 2021b
Spruce wood absorbed more water than larch, independent of whether or not it had been charred or coated with a waterborne acrylic high-build stain.	Zigon & Pavlic 2023

Ahola (1991) compared nine different joinery paints with respect to their rates of water vapor and liquid water transport on pine and spruce woods. Tests were done in outdoor conditions for a year. One of the biggest contrasts was the much slower flux of water into wood when using film-forming coatings (typically about 1 to 1.5 kg/m^2s) rather than a stain (about 5 kg/m^2s). Surprisingly, three years of weathering did not have a large effect on the transmission rate, with a few exceptions. Follow-up work showed that the absolute rate of water permeation through the finish did not depend on the underlying wood species (Ahola *et al.* 1999). Williams *et al.* (1996) mention a commercial “vapor retarder” product having the purpose of slowing down the diffusion of water into wood through the coating layer. However, the note was made that in many cases air leaks through cracks or other defects in a coating may have a more important effect than the rate of diffusion through unblemished parts. Allen (1984) noted that oil-based primers tend to be resistant to vapor diffusion, whereas water-based primers can be generally described as breathable. Gezici-Koç *et al.* (2019) found a correlation between the amount of water present in a coating, on the wood surface, and its rate of diffusional transport of water vapor. Similar results were obtained for two alkyd coatings (one solvent-borne and one waterborne, and a water-borne acrylic formulation).

Excessive resistance to water vapor diffusion can be a problem in cases where the wood tends to retain too much moisture after rainfalls and a coating slows subsequent transport and evaporation of that moisture (Bronski and Ruggiero 2000). The cited authors pointed out that surface-sealing barrier coats may tend to entrap moisture within a wall system.

Rapp and Peek (1999) likewise blamed a varnish layer for long-lasting periods of high moisture content during natural weathering of spruce, oak, and Douglass fir specimens. On the other hand, as noted by van Meel *et al.* (2011), a coating also can reduce the amount of moisture taken up by the wood during rain events, leading to net positive results in typical cases.

Binder Attributes and Durability

The question considered here is whether certain attributes of the binder, *i.e.*, the softness or stretchability of the polymer used in different wood coating formulations, has been found to correlate with its performance in external wood coating applications. Thus, de Meijer and Nienhuis (2009) considered the susceptibility of different coating formulation to develop internal stresses and compared those findings to cracking and flaking results.

It was found that high levels of stress were developed when there were large differences in swelling between the wood and the coating. Results were compared with accelerated and natural weathering test results, and a good correlation was found. Best results were found with those primers (especially solvent-borne) having less swelling tendency and therefore less stress development at the interface.

According to Baumstark and Tiarks (2002), an ideal resin for exterior wood coatings ought to be non-tacky, hard, resistant to blocking, but also very flexible, such that it will be resistant to cracking. They found that those criteria were best met, in the case of acrylic binder systems, by using multi-phase acrylic emulsions. A combination of a soft hydrophobic monomer (2-ethyl hexyl acrylate) and methyl methacrylate gave the best resistance to weathering, including the least uptake of water by the wood. Rather than try to achieve a uniform or random copolymer, it was found that particles with soft and hard phases performed best. A particle size of about 100 nm was recommended, such as to allow good penetration and distribution.

Silicones for durability

Silane and silicate-type coatings appear to offer a wide range of possibilities for such purposes as cross-linking and the development of hydrophobicity in wood coatings. Highlights from related studies are provided in Table 15. As indicated by the table contents, the properties provided by these treatments were quite diverse, such that time and effort will need to be devoted to formulation of the best ratios of additives in various cases. Alkyltrialkoxysilanes and related chemicals were effective both as crosslinking agents and as hydrophobizing additives (Husić *et al.* 2023). Systems based on precipitation of water glass (a highly alkaline solution of silicate) tended to be brittle, but suitable as a pre-coating treatment; film-forming additives can be employed to overcome the brittleness (Tshabalala *et al.* 2011).

Table 15. Studies of Effects of Different Formulations of Silane-type or Silicate-type Components in Exterior Wood Coatings

Themes of Publications	Citation
A radiation-curable coating based on two acrylate monomers was supplemented with a silane coupling agent.	Landry *et al.* 2008
Wood veneers were dipped into mixtures of alkyltrimethoxysilanes and aluminum isopropoxide precursors as an aqueous sol with an acrylic self-crosslinking binder formulation to provide effective weathering resistance.	Tshabalala *et al.* 2011
Organosilane nanoparticles in nitrocellulose and polyester lacquer coating formulations formed a uniform layer on poplar wood, providing weathering resistance. The hydrophobic particles reduced wettability of the surfaces.	Gholamiyan & T. 2018
The authors describe a final coating with "liquid glass," which was described as a two-part waterproofing system. Further information is not provided, but the name suggests silicon-type chemistry.	Kucuktuvek *et al.* 2020
Silicate treatments could be prepared on wood surfaces, especially following pre-mineralization (highly alkaline water-glass silica solution followed by either boric acid or sodium bicarbonate). Cracking problems could be overcome by careful formulation.	Yona *et al.* 2021a
The silicate-based coatings tended to be porous to water permeation, but also quite hydrophobic. Post treatment with alkyl-trialkoxysilane reduced liquid water permeation and increased durability.	Yona *et al.* 2021b
Incorporation of alkyltrialkoxysilanes was able to achieve highly durable brass-containing coatings for fine art on wood.	Han & Yan 2023
Hexadecyltrimethoxysilane and related agents provided increased hydrophobicity. The balance between hydrophobicity and physical strength could be balanced by the selection of different monomers.	Husić *et al.* 2023
Fast-growing wood was hydrophobized and rendered weather-resistant by dip-coating with methyltriethoxysilane and silica particles.	Qu *et al.* 2023

UV-cured finishes and durability

Decker (1996) appears to have been the first to describe the development of a UV-cured coating for exterior application of wood. A large increase in weatherability of the wood specimens was observed in comparison to uncoated wood. No pigmentation or absorbers for UV light (beyond the photosensitizer for curing of the resin itself) was employed. Gurleyen (2021) improved weathering performance by application of UV-cured varnishes for flooring applications. Again, no additional UV-absorbing materials were employed. Weichelt *et al.* (2010) developed a UV-cured coating for outdoor wood application. This was done with the addition of nano-sized ZnO particles to protect against ultraviolet light. Vardanyan *et al.* (2015) showed that adding cellulose nanocrystals to a UV-curing polyurethane acrylate transparent coating formulation decreased color change during accelerated weathering. Irmouli *et al.* (2012) found that adding UV absorbers having different absorbance spectra compared to the photoinitiator did not provide any improvement in resistance to artificial weathering of UV-cured clear finishes on oak and spruce woods. Dixit *et al.* (2021) did not consider weathering effects, but they formulated a UV-cured wood coating system to have antimicrobial properties. Because UV-curing coating formulations already have to contain an initiator that absorbs UV light, there is reason to suspect that there might be a significant contribution of that additive to later protecting the coating and the wood during outdoor exposure. However, there does not appear to have been a study addressing such a contribution to the performance of UV-cured coatings.

Reinforcing Particles and Durability

Many coating formulations that are intended for external usage on wood are filled with particles. Often it is possible to classify such particles based on certain roles that they play with respect to the performance of the coating product. For instance, the word “filler” can be used in cases where a prime consideration is to decrease the overall cost of the formulation. But in addition, it is possible to utilize solid additives for the purpose of enhancing the hardness or other strength properties, and such components can be regarded as reinforcing particles. Another category is particles that have a propensity to impede diffusion of such items as water vapor or air. Finally, it makes sense to consider the extent to which special advantages might be achieved by the addition of particles that interact with light. The refractive index of TiO_2 particles is high enough (2.55 to 2.7) so that there is a large contrast with the typical refractive index of binders (often 1.5 to 1.6), which can give rise to strong scattering of light if the particles are in the diameter range of about 0.2 to 1 µm. Adding such particles to a coating formulation contributes to opacity. When the goal is to achieve high absorption of UV light, one option is to use nano-sized TiO_2 particles. For example, the tendency for particles to contribute to the scattering of visible light, leading to increased opacity, decreases more and more with decreasing diameter below about 200 nm (Jalava 2006). The cited article quantifies how decreases in particle size of TiO_2 particles in the range 237 down to 166 nm tend to shift the interactions with light more and more into the ultraviolet region.

Fillers

According to Flexner (1994) a filler in a wood coating is just a binder with a mineral particle inside. To the extent that such a description is valid, it underscores the idea that some minerals might be regarded as merely occupying space. Yan *et al.* (2018) used inexpensive talcum powder or calcium carbonate particles and achieved good hardness, adhesion, and impact strength. Relatively inexpensive mineral particles can be obtained, for instance from calcination of rice husks; Guo *et al.* (2019) found that such material could be added to waterborne acrylic coating recipes. But even in that case, substantial benefits were observed, including increases in tensile strength, elastic modulus, and pencil harness of the coating. Likewise, Meng *et al.* (2020) added silica particles, but the source of the material was a combination of sol-gel and thiol-ene reactions. The particles were added to a castor-oil-based waterborne acylate formulation. Again, increases in Young’s modulus and hardness of the resulting coatings were observed. Thus, even when considering examples from the literature that would best correspond to the idea of merely filling the coating film with an inexpensive kind of mineral, many researchers have reported reinforcing effects as well. None of the articles cited in this paragraph had anything to report with respect to weathering, however.

Reinforcing particles, including nanocellulose

In principle, when the goal is to increase the strength or elastic modulus of a coating film, three attributes to look for in a particle are its interfacial compatibility with the resin, an elongated or even fibrillar character, and an inherent strength that is sufficiently high. These three attributes, ideally, would allow each of the particles to interact with multiple resin particles, for instance in a typical latex formulation. As an example, Yan *et al.* (2019) employed glass fiber powder in waterborne coatings at levels ranging from 1 to 7%. The best overall performance was found at a 3% level. A key benefit was in preventing decoloration of a thermochromic ink in the formulation. However, strength benefits were not observed in that study.

Greater success, in terms of strength development, has been reported for nanocellulose, which typically has a generally fibrillar character. For instance, Vardanyan *et al.* (2014) added cellulose nanocrystals (CNCs) to a UV-cured waterborne coating formulation. Increased scratch resistance, hardness, and adhesion to the wood were observed. Veigel *et al.* (2014) obtained similar results with the same additives and a waterborne wood coating. Poaty *et al.* (2014) reported follow-up work in which either alkyl quaternary ammonium bromide or acryloyl chloride was used to render the CNC surfaces more hydrophobic and thereby more compatible with an acrylic resin in the coating formulation. The presence of the compatibilized CNC particles raised the abrasion and scratch resistance by 24 to 38%. Cheng *et al.* (2016) utilized a certain kind of nanocellulose nanofibers (called TEMPO-oxidized) in a waterborne polyurethane coating. Young's modulus and hardness were increased. However, the nanocellulose at a 1% addition by mass tended to hurt the adhesion of the coating. Likewise, Kluge *et al.* (2017) added cellulose nanocrystals and nanofibrillated cellulose (NFC) at the 0.5 and 2% levels to waterborne wood coating formulation. Substantial increases in tensile strength (to breakage) and elastic modulus were found, especially at the 2% level of the NFC. Grüneberger *et al.* (2014) added NFC to eight commercial acrylic and alkyd polymeric binders; all the resulting films were stiffer, stronger, and less extensible. Pacheco *et al.* (2021) prepared a composite from SiO_2, TiO_2, and nanocellulose in waterborne varnish and improved the mechanical performance and stability. Shimokawa *et al.* 2021) showed that adding NFC to waterborne primer formulation resulted in increased breaking stress by a factor of about 1.5. Song *et al.* (2023) showed that NFC and CNC particles, prepared directly from lignocellulose, improved the hardness, abrasion resistance, and adhesion strength of a waterborne wood coating. Neelambaram *et al.* (2023) likewise found strength gains upon addition of NFC to a siloxane acrylic latex formulation. Wang *et al.* (2023) reviewed related work in which nanocellulose has been used as a reinforcement in coatings. It is notable, however, that none of the work mentioned so far in this paragraph involved analysis of the effects of weathering. A rare exception was research reported by Yoo and Youngblood (2017), who studied the effect of adding CNC to tung oil finish formulations. Greater color stability was observed due to the presence of the CNC during weathering of the coated wood. Likewise, Yuan *et al.* (2021) reported strong reinforcing effects of NFC, in the presence of carbon nitride nanosheets (as a UV absorber), which together improved the weathering resistance of a transparent coating on wood.

Though many of the studies just cited, involving addition of nanocellulose products to wood coating formulations, can seem promising in terms of developing Youngs modulus and strength attributes of the coating films, research attention will be needed with respect to the rheological behavior of such coatings. It is well known that the presence of nanocellulose in aqueous systems can greatly increase the viscosity of the mixtures (Hubbe *et al.* 2017; Li *et al.* 2020; Koo *et al.* 2021).

Tortuosity and effects on vapor diffusion

In principle and in practice, platy particles such as clays are expected to be the most effective in decreasing the permeation of water vapor or other gases through a coating film (Wolf and Streider 1990). This expectation is supported by Nkeuwa *et al.* (2014a), who considered nanoclay in transparent UV-cured coatings. In particular, multilayer coatings achieved good barrier properties. However, contrary results were observed by Donkers *et al.* (2013). The latter results raise a suspicion that there may have been poor contact within the coating layer between the resin and the mineral, thus allowing water to migrate through void spaces within the coating. For instance, a failure of the resin to wet the surface of the mineral during formulation and drying may have resulted in gaps between the mineral surfaces and the resin within the dried coatings. Again, none of the studies cited in this paragraph specifically studied weathering effects. Given that mineral particles are relatively inexpensive, as well as the potential benefits of increasing the tortuosity of exterior coating products, it is recommended that such studies be carried out as a priority.

UV Light Absorbers: Mineral

Another key purpose of adding minerals to a coating formulation, especially for outdoor applications, is for protection of both the coating and the wood against adverse effects of ultraviolet light. As noted in an earlier review article (Kropat *et al.* 2020), the combination of UV light with periodic rainfall is expected to result in degradation and removal of the lignin from the outer layer of unprotected wood.

As illustrated in Fig. 17, one can place UV-absorbers, as used in coating formulations, into three categories. When using high refractive index particles, such as conventional TiO_2 products, both visible and UV light will be impeded from transmission through the coating. When the mineral particles are very small or have a refractive index similar to that of the resins in the coating, then it may be possible to absorb the UV light without affecting the visible appearance. The third category is organic compounds having sufficient conjugation of unsaturated carbon-to-carbon bonds in their molecular structure to allow them to absorb UV light.

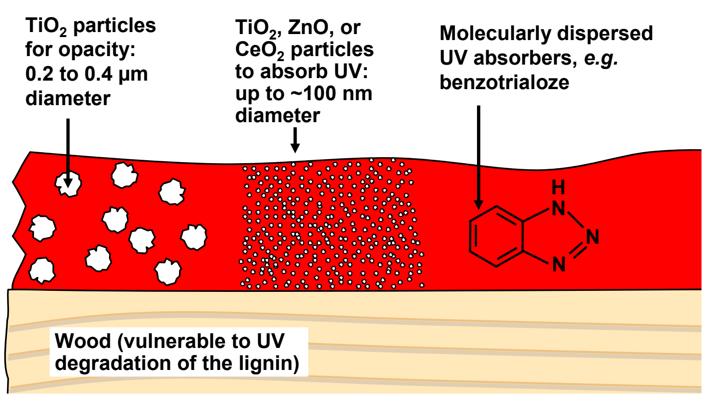

Fig. 17. Three classes of UV-absorbing components that can be used in coating formulations

TiO_2 pigment

Due to its high index of refraction (2.55 or 2.7), titanium dioxide has proven itself very effective in the scattering of light (Jalava 2006), making it a good choice for increasing the opacity of coatings. High-quality white paints are usually rich in TiO_2. Another reason to favor TiO_2 in external wood coatings is its strong ability to absorb UV light. In terms of nomenclature, many authors have used the term "nanoparticle" when describing the types of TiO_2 employed in wood coatings. It should be noted, however, that TiO_2 particles in the diameter range of about 200 to 500 nm had become well established in the paint industry long before nanotechnology had emerged as a popular topic. Thus, the term "nano" tends to be absent in much of the older literature. When formulators wish to minimize the scattering of light, which leads to opaque coatings, they need to use even smaller particles, *e.g.* with diameters less than about 100 nm (Allen *et al.* 2002). Table 16 highlights studies in which the addition of TiO_2 to exterior wood coating formulations was evaluated. Schaller *et al.* (2012) have reviewed related literature comparing TiO_2 with other light stabilizers. In addition, Ganguli and Chaudhuri (2021) have reviewed the topic of using nanomaterials, including TiO_2, to minimize biodegradation of the underlying wood.

Table 16. Studies Considering the Effects of Adding Titanium Dioxide Particles to Exterior Wood Coating Formulations

Themes of Publications	**Citation**
Ultrafine (nanoparticle) TiO_2 was added to waterborne acrylic and isocyanate-acrylic formulations. Strong UV absorption was observed. There was reduced photodegradation of the wood.	Allen *et al.* (2002)
Artificial weathering of coatings on black spruce wood showed that TiO_2 particles reduced chemical degradation of the wood.	Cristea *et al.* 2010, 2011
TiO_2 particles were added to waterborne acrylic coating formulations. Coating thickness decreased with increasing weathering time. Coatings containing TiO_2 were somewhat more effective than ZnO and an organic UV absorber in retaining the coating thickness.	Saha *et al.* 2011b,c
Adding TiO_2 articles to acrylic stain coating formulations made them less affected by accelerated weathering.	Fufa *et al.* 2012
The surfaces of TiO_2 particles were modified by deposition of an alumina or silica layer to minimize undesired photoactivity. The treatment made it easier to disperse the particles, and they achieved higher UV absorbance. The coatings also were more resistant to weathering.	Godnjavec *et al.* 2012
Adding TiO_2 particles to different coatings led to the least discoloration of beech and pine specimens, compared to some other UV absorbers subjected to artificial weathering.	Ozgenc *et al.* 2012
Adding TiO_2 particles to an acrylic clear coating formulation stabilized the coating against loss of Young's modulus and elongation to breakage, as well as color changes, upon exposure to xenon arc illumination. However, the TiO_2 catalyzed photooxidation reactions due to its photoactivity.	Forsthuber *et al.* 2013a,b
Adding TiO_2 particles to waterborne acrylic coating formulations slightly decreased degradation of the lignin in the underlying wood.	Fufa *et al.* 2013a,b
The photocatalytic activity of TiO_2 particles suppressed bacterial activity an aqueous acrylic paint in the presence of fluorescent light, rendering an antibacterial effect.	Zuccheri *et al.* 2013
The surfaces of TiO_2 particles were treated with amorphous silica to suppress the photocatalytic effects. Color change in response to UV irradiation was reduced.	Veronovski *et al.* 2013
The presence of TiO_2 particles interfered with the curing of UV-curing epoxy acrylate coatings.	Kardar *et al.* 2014
The undesired photoactivity of TiO_2 particles was revealed by a transformation of lodgepole pine wood surfaces from hydrophobic to hydrophilic. Peeling of the TiO_2 layer gave further evidence of wood deterioration upon exposure to UV light.	Zheng *et al.* 2016
Rutile TiO_2 particles in a waterborne polyacrylate coating	Miklecic *et al.* 2017

formulation improved the weathering performance. The color of beech wood was more stable. Unlike ZnO particles, there was no sign of cracking and peeling.	
Adding TiO_2 particles at the 1.5% level to waterborne varnish formulation improved the color stability of tropical wood.	Moya *et al.* 2017
Oak wood was protected by applying TiO_2 particles before coating with exterior transparent coating formulations. Resistance to weathering was best with thick waterborne acrylic coatings.	Pánek *et al.* 2019b
The presence of TiO_2 particles in waterborne acrylic paint rendered the coating more resistant to weathering.	Ling *et al.* 2020
Adding TiO_2 particles to a polyacrylate formulation resulted in less color change and crack development in the course of accelerated weathering of thermally modified *Picea* wood.	Nowrouzi *et al.* 2021a,b
Adding TiO_2 nanoparticles to transparent oil and acrylic coating formulations increased resistance to artificial weathering of spruce and beech woods. Tests also involved caffeine addition.	Pánek *et al.* 2021
The photoactivity of TiO_2 particles helped to reduce the colonization of coating surfaces with basidiomycetes fungi.	Hernandez *et al.* 2023
Lignin/TiO_2 composite nanoparticles were added to waterborne polyurethane coatings. Good color stability was observed in the course of UV irradiation.	Song *et al.* 2024

ZnO pigment

After TiO_2, the next most studied UV-absorbing additive for wood coatings has been ZnO. Especially in cases where the goal is not to increase the opacity and hiding power of a paint layer, there may not be a strong need to consider TiO_2, which has a higher refractive index (2.55 or 2.7) in comparison to ZnO (1.54). However, in common with TiO_2, ZnO is photoactive (Thi and Lee 2017), which can raise concerns about undesired generation of high-energy species such as free radicals during service life of the coating, leading to possible breakdown of the coating or the underlying wood. For instance, such effects might possibly be responsible for an observed higher frequency of crack development in some coating systems containing ZnO particles (Allen 1984). However, as in the case of TiO_2, the undesired photocatalytic effects can be reduced by coating the ZnO particles with other materials (Weng *et al.* 2014; Yin and Casey 2014).

Table 17. Studies Considering the Effects of Adding Zinc Oxide Particles to Exterior Wood Coating Formulations

Themes of Publications	**Citation**
The presence of ZnO can contribute to cracking of a coating layer.	Allen 1984
Adding ZnO_2 to a polydimethylsiloxane film, followed by plasma curing, conferred resistance to weathering, as indicated by lower weight loss.	Denes & Young 1999
Nano ZnO was shown to be an efficient UV absorber. Improved weathering resistance was shown.	Weichelt *et al.* 2010
ZnO nanoparticle outperformed CuO to reduce wood discoloration.	Auclair *et al.* 2011
ZnO was added to the formulation of an acrylic polyurethane coating. Coating thickness decreased during artificial weathering. The ZnO was less effective than TiO_2 in preventing the effect.	Saha *et al.* 2011c
ZnO did not perform as well as 2-hydroxyphenyl-s-triazine in extending the service life of waterborne coatings. Specimens were exposed to xenon illumination and color deviations were noted.	Schaller *et al.* 2012
Nanofibrillated cellulose aided in the distribution and colloidal stability of the ZnO particles in the formulation. Color stability was	Grüneberger *et al.* 2015

improved by the ZnO, as shown by artificial weathering.	
Oak wood was protected by modifying the surface with ZnO before adding a commercial hydrophobic topcoat. The protection against weathering was limited in its effectiveness.	Pánek *et al.* 2017
ZnO in combination with tannin in a coating was used to treat pine wood, which was exposed to accelerated weathering. The ZnO decreased color change. The best results were with a combination of different UV protective additives.	Tomak *et al.* 2018b
Adding Zn/ZnO particles with a cold plasma spraying process, as well as using the particle as a layer followed by sealants, provided protection against color change upon exposure to UV light. The best results were with a polyurethane coating, which appeared to be stabilized by the nanoparticles. An alkyd coating was photodegraded.	Wallenhorst *et al.* 2018
ZnO was applied to oak wood, followed by application of several coating formulations. A positive effect of ZnO, as well as of other UV absorbers, was shown by accelerated weathering tests.	Panek *et al.* 2019
Nano ZnO was added in an acrylic paint to improve weathering performance of beech wood. The particles reduced color changes and mold growth on the weathered samples.	Akbarnezhad *et al.* 2020
Acetylated wood was coated with nano ZnO particles, then exposed to accelerated weathering. The treatment reduced color change and degradation of wood polymers upon weathering.	Nagarajappa & N. 2020
ZnO particles applied with wood coating formulations were found to mostly remain associated with the wood surface in the course of one year of natural weathering.	Thornton *et al.* 2020
ZnO treatment was less effective than TiO_2 or 2-hydroxyphenyl)-benzotriazone UV absorbers to resist effects of natural weathering.	Nowrouzi *et al.* 2021b
Shellac-based varnish formulation was prepared with ZnO, which was functionalized by grafting with shellac, using an epoxy reagent. Photoprotective behavior was shown.	Weththimuni *et al.* 2021
Pine specimens were treated with ZnO particles, then coated with various formulations and exposed to natural weathering. The ZnO decreased microbial colonization as well as color change.	Hernandez *et al.* 2023

Other minerals

Table 18 lists key findings for studies that have considered the addition of other mineral types, with an emphasis on absorbance of UV light. As shown, there has been quite a lot of research done on cerium oxide (CeO_2), which has been found to be an effective absorber of UV light.

Table 18. Studies Considering the Effects of Adding Other Inorganic Agents to Exterior Wood Coating Formulations

Themes of Publications	**Citation**
Chromium trioxide was less effective as a UV absorber for protection of wood veneers, compared to PF resin and other options.	Kiguchi *et al.* 2001
CeO_2 particles were among the UV absorbents used with waterborne clear coats; however, all other systems were out-performed by 2-hydroxyphenyl-s-triazine.	Schaller *et al.* 2012
CeO_2 particles were added to an acrylic polyurethane coating formulation on thermally treated jack pine. The additive reduced the color change of the thermally treated wood during accelerated weathering.	Saha *et al.* 2013

Chromic acid pretreatment of the wood improved the performance of clear coatings. However, results also depended on the coating flexibility and its propensity to form surface defects.	Vollmer & Evans 2013
The release of CeO_2 particles from an acrylic stain was evaluated during accelerated weathering. Two kinds of release were observed, namely loose material and particles released due to gradual breakdown of the coating.	Scifo *et al.* 2018
Tannin and CeO_2 were used in coating formulations that were exposed to artificial weathering. The combination treatment was more effective than the individual components.	Tomak *et al.* 2018b
A layer-by-layer deposition process was used to apply CeO_2 particles and either chitosan or cationic starch to a wood surface with the goal of protecting wood from UV light. The amount of color change induced by UV light was decreased.	Janesch *et al.* 2020
Boric acid was used to protect pine and beech sapwood samples in various waterborne acrylic resin coating systems exposed to natural weathering. The boric acid increased the durability.	Özgenç 2020
Nano CeO_2 particles aided weather resistance when added to fire-retardant coating formulations.	Yang *et al.* 2024

Organic UV Absorbers

As an alternative to the mineral particles just considered, *e.g.* TiO_2, ZnO, and CeO_2, the other main class of candidate UV absorbers that can be used especially in exterior paints can be described as organic UV absorbers. Within that category, there are a wide range of choices. Some of the most widely studied include benzotriazole, hydroxyphenyl-s-triozine, and hindered amine light stabilizers (HALS). But in addition, studies have also considered the usage of lignin, carbon particles, dihydroxy benzophenone, stains, and various other compounds as UV absorbers for addition to external coating formulations. Figure 18 shows the molecular structures of three of the most often studied organic compounds or classes of compounds used to protect the underlying wood from UV rays.

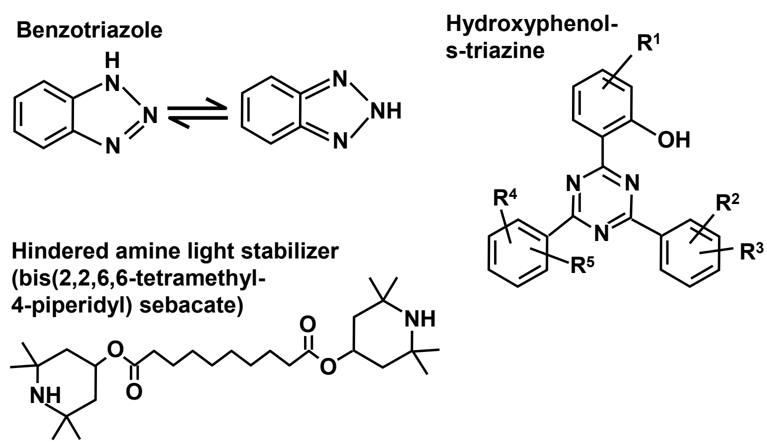

Fig. 18. Three classes of UV-absorbing components that can be used in coating formulations

Benzotriazole

As shown in Fig. 18, benzotriazole can be described based on a pair of resonance structures, one of which contains an aromatic ring. As is well known, compounds that have sufficient conjugation (double-single-double, *etc.*, carbon-carbon bonding) will absorb light of various wavelengths (Yuan *et al.* 2018). The relatively short conjugation sequences present in at least one of these structures are apparently well suited for the absorption of UV light in a range that can be effective for external coating usage. Another attribute that follows from the chemical structure of benzotriazole is a positive charge, due to the presence of a primary amine in its protonated form. The positive ionic charge can, in principle, favor association of the compound within negatively charged groups, such as the carboxylate groups present in typical acrylic latex products that utilize alkali-swellable latex products (Padget 1994; Larson *et al.* 2022).

Table 19 lists some studies aimed at evaluating the performance of benzotriazole in the formulation of external wood coatings. As shown, both benzotriazole and its derivatives (usually hydroxyphenyl-benzotriazole) were generally found to be helpful in reducing effects of weathering.

Table 19. Highlights from Studies Considering Benzotriazole as a UV Absorbing Agent in External Coating Formulations

Themes of Publications	**Citation**
UV-cured polyurethane-acrylic films were prepared with the addition of benzotriazole. Excellent resistance to weathering was reported.	Decker 1996
The performance of a benzotriazole derivative in preventing the effects of weathering was found to be almost as good as that of TiO_2. Results of natural weathering were confirmed with xenon light exposure tests.	Forsthuber *et al.* 2013a,b
Coatings that included a benzotriazole derivative were shown to be effective in protecting bamboo from UV radiation.	Li *et al.* 2015
Plasma-treated spruce specimens were protected using a benzotriazole derivative with optional hindered amine light stabilizers in a transparent acrylic or alkyd coating formulation. The color stability was improved, as shown by accelerated weathering.	Reinprecht & S. 2015
Usage of benzotriazole in an acrylate coating decreased the loss in brightness during accelerated weathering.	Oberhofnerová *et al.* 2018
A mixture of benzotriazole, hindered amine light stabilizers, and TiO_2 was the most effective in protecting oak wood with a clear exterior coating.	Panek *et al.* 2019
A combination of benzotriazole and ZnO were used as an acrylic-based coating to protect bamboo against aging by UV light exposure.	Rao *et al.* 2019
A benzotriazole derivative with optional hindered amine light stabilizers was added to transparent alkyd or acrylic coating formulations. There was no effect of the benzotriazole on adhesion strength, based on accelerated weathering tests.	Reinprecht *et al.* 2020
A benzotriazole derivative was added to a waterborne polyacrylate formulation in combination with olive leaf extract. Weathering resistance was demonstrated, especially in combination with TiO_2.	Nowrouzi *et al.* 2021b

Hydroxyphenyl-s-triazine

The generalized structure of hydroxyphenyl-s-triazine, indicating points of optional substitution of this class of compounds, is was shown in Fig. 18. Note that, like the benzotriazole just considered, this is a structure with conjugated double and single carbon-to-carbon bonds. In addition, the tertiary amines on the central ring will allow for the development of a positive charge due to protonation.

Table 20 provides some highlights of studies to evaluate the effectiveness of hydroxyphenyl-s-triazine in exterior coatings. Most notably, though it was found to be effective against weathering, the studies often found that other agents were more effective.

Table 20. Highlights from Studies Considering Hydroxyphenyl-s-triazine as a UV Absorbing Agent in External Coating Formulations

Themes of Publications	**Citation**
Hydroxyphenyl-s-triazine is described as a new UV-absorbing compound suitable for exterior wood coatings.	Schaller *et al.* 2008
Hydroxyphenyl-s-triazine was added to different coating formulations to protect beech and pine woods. Protection by hydroxyphenyl-s-triazine was almost as effective as TiO_2.	Özgenç *et al.* 2012
The authors compared several UV absorbers in waterborne coatings. The 2-hydroxyphenyl-s-triazine outperformed several other UV-absorbing compounds.	Schaller *et al.* 2012
Hydroxyphenyl-s-triazine was added to waterborne acrylic and alkyd formulations. There was reduced color change upon exposure to weathering. However, even greater protection was provided by bark extract from alder and maritime pine.	Özgenç *et al.* 2020

Hindered amine light stabilizers (HALs)

Table 21 lists highlights from studies evaluating the protective effects of HALs in coatings for exterior wood. Note that the molecular structure of one of the most widely used HALs additives, namely bis(2,2,6,6,-tetramethyl-4-poperidyl) sebacate, was shown in Fig. 18.

Table 21. Highlights from Studies Considering Hindered Amine Light Stabilizers as UV Absorbing Agents in External Coating Formulations

Themes of Publications	**Citation**
Several different UV-light absorbers were compared in waterborne coatings. The 2-hydroxyphenyl-s-triazine outperformed the hindered amine light stabilizer and other candidates.	Shaller *et al.* 2012
Color stability of spruce specimens coating with transparent acrylic and alkyd formulations was improved by the presence of hindered amine light stabilizer, as shown by accelerated weathering.	Reinprecht S. 2015
Hindered amine light stabilizer was spread on oak wood before application of a hydrophobic coating and exposure to accelerated weathering. Limited durability was achieved.	Pánek *et al.* 2017
Hindered amine light stabilizer was encapsulated in PMMA microspheres and used in clear acrylic water-based coating. Color change and photooxidation of the binder were both minimized, as shown by accelerated weathering.	Queant *et al.* 2019
Hindered amine light stabilizer was added to transparent acrylic and alkyd coatings. The additive did not affect the adhesion of the coating after accelerated weathering.	Reinprecht *et al.* 2020
The addition of hindered amine light stabilizer improved the protection of bamboo scrimber by an acrylic formulation.	Yang *et al.* 2022

Other UV absorbers

Finally, a variety of other additives have been considered in at most three published studies that were found in the literature search in preparation for this article. Highlights from these studies are given in Table 22.

Table 22. Highlights from Studies Considering Other Potential UV Absorbing Agents in External Coating Formulations

Themes of Publications	Citation
Melamine resin was added to varnish to help protect pine, spruce, ok, and Douglas fir woods from natural weathering. Protection was effective against wood degradation, but not against cracking and high moisture content.	Rapp & Peek 1999
The UV-absorber 2-hydroxy-4 (2,3-epoxypropoxy) benzophenone was added to or grafted onto wood. The grafting increased the effectiveness to decrease weight loss in the course of weathering.	Kiguchi *et al.* 2001
Bark extract was added to an acrylic polyurethane coating formulation to protect pine wood. There was less color change in the course of weathering. A combination of bark extract and lignin gave the best results.	Saha *et al.* 2011a
Opaque acrylic coatings with poly(vinylidene fluoride) (PVDF) were used to protect spruce and pine. The PVDF was shown to be effective in resisting UV light.	Landry & Blanchet 2012b
Lignin was used in combination with CeO_2 in an acrylic polyurethane formulation that was coated on pine wood and exposed to accelerated weathering. Color stability was moderately improved due to the lignin addition.	Saha *et al.* 2023
Phenol-formaldehyde and N-methyl melamine, in an addition to a dye, served the role of UV absorbers in a translucent waterborne acrylic coating to protect beech wood. Capillary uptake of water was reduced. There was less blistering and higher adhesion in the course of natural weathering due to the phenolic and melamine resins.	Kielmann & Mai 2016a
Using the same system described immediately above, the authors also showed that N-methyl melamine was the most effective for decreasing color change. There was also less flaking and cracking.	Kielmann & Mai 2016b
Beech wood was treated first with extracts of mimosa and quebracho, then coated with polyurethane, water-based, and cellulosic varnishes. Accelerated weathering tests showed higher loss of adhesion strength for the specimens with the extracts.	Yalcin & Ceylan 2017
Beech wood specimens were impregnated with aqueous solutions of tannins and then varnished. After accelerated weathering, the tannin-impregnated wood showed greater color change.	Yalcin *et al.* 2017
Condensed tannin addition to acrylic-based clear coatings gave 20% better performance than hindered amine light stabilizers for exterior exposure.	Grigsby 2018
Accelerated weathering tests showed that adding condensed tannins from tree bark and esterification or etherification of the tannins in clear acrylic or styrene-acrylic coatings resulted in longer service life.	Grigsby & Steward 2018
Tannins were added to the water-based transparent and opaque coating formulations, which were coated on pine wood and exposed to artificial weathering. Color changes were reduced at high levels of treatment.	Tomak *et al.* 2018a
Tannins were added in combination with zinc oxide and cerium	Tomak *et al.* 2018b

oxide to wood coating formulations. The presence of tannins made it possible to reduce the amounts of UV-absorbing inorganic particles to protect against weathering.	
Tree bark extract was added to acrylic and alkyd formulations in combination with other UV-absorbers to protect pine wood surface from artificial weathering. The extract was especially effective with the alkyd system.	Özgenç *et al*. 2020
Extract of Chinese fir bark was added to polyurethane-acrylate coating, which was applied to pine wood. Accelerated weathering tests showed free radical scavenging ability and protection of the wood. The phenolic compounds in the extract were converted to ketones and quinones in the process of weathering.	Peng *et al.* 2020
Lignin and cellulose nanocrystals were added to acrylic formulations to coat beech wood. CNC promoted take-up of the coating by the wood, whereas lignin did not show any benefits.	Jusic *et al.* 2021
Thermally modified wood was protected with polyacrylate coating that contained olive leaf extract. This was effective in reducing natural and accelerated weathering, especially in combination with TiO_2 and 2-(2-hydroxyphenel)-benzotriazole.	Nowrouzi *et al.* 2021a
Continuing the study introduced immediately above, the authors showed that olive leaf extract was the most effective in reducing the wettability of the coatings in the course of natural weathering. Adhesion of the coating also was improved.	Nowrouzi *et al.* 2021b
Bark extracts from various trees were used as UV-absorbers to help protect pine and beech garden furniture in waterborne acrylic coatings. The bark extracts helped to protect the wood against weathering. Some of the coatings with the extracts developed cracks with weathering.	Özgenç *et al.* 2021a,b
Caffeine was used in combination with TiO_2 to protect spruce and beech wood from UV radiation and mold. Accelerated weathering tests showed positive results in the case of acrylate coatings.	Pánek *et al.* 2021
A diglycidyl ether of bisphenol A was crosslinked with a resin acid/maleic anhydride adduct to treat pine wood with a coating. Color changes were reduced during exposure to UV radiation.	Rosu *et al.* 2021
Nanofibrillated cellulose was added to the water-based primer containing acrylic resin. The coating reduced the transmittance of UV light and oxygen permeation, as well as increasing the breaking stress of the coating.	Shimokawa *et al.* 2021
Graphitic carbon nitride nanosheets were used in a hydrophobic and transparent coating with nanofibrillated cellulose as a film-forming carrier. Spin-coating was used to apply a film on the wood. A hydrophobic coating was then applied by chemical vapor deposition. Accelerated weathering tests showed a 79.6% reduction in color change due to the carbon nitride.	Yuan *et al.* 2021
Benzoyl chloride and chromic acid were found to be the most effective treatments to reduce the effects of weathering on wetting and adhesion of solvent-based polyurethane and waterborne alkyd coating.	Kardar & Amini 2022
Lignin nanospheres were added to waterborne wood coating. The treatment blocked UV radiation and decreased color changes during exposure to UV light.	Song *et al.* 2022
Adding lignin to a solvent-based lacquer primer and to a topcoat helped to protect spruce and oak woods. Accelerated aging tests showed that the lignin addition can increase color stability.	Kudela *et al.* 2023
Up to 20% of carbon particles added to tung oil did not affect the hydrophobicity. The carbon particles at the highest level protected the coated wood against a decrease in water repellence.	Marrot *et al.* 2023

Microfibrillated cellulose was used to improve the mechanical strength and functionality of exterior coatings applied to birch veneer and exposed to natural and artificial weathering. The microfibrillated cellulose decreased discoloration in combination with the TiO_2 or when present alone. A primer was optionally coated on top of the microfibrillated cellulose.	Orelma *et al.* 2023
Nanoparticles with lignin and TiO_2 were added to waterborne polyurethane formulation, which showed good color stability on exposure to UV radiation.	Song *et al.* 2024

Clear Coats for External Application

Clear coats, which allow the user to clearly see the underlying wood, represent a particular challenge for outdoor applications (Morrell *et al.* 2001). As described in the preceding sections, many of the materials that can be used to provide protection against ultraviolet light work by scattering light aggressively, making the coating layer highly opaque. Others strongly absorb visible light, in addition to UV light, thus rendering the coating strongly colored and thereby hiding the underlying wood (Evans *et al.* 2015). This section considers studies that have addressed this set of challenges, attempting to create clear coating systems that nevertheless exhibit increased resistance to weathering.

One of the intriguing facts associated with the seven immediately preceding tables is that most of the cited studies have been concerned with clear coat applications. This is consistent with an expectation that opaque or deeply colored coatings generally do not raise concerns regarding UV protection. As shown by Oberhofnerová *et al.* (2019), pigmented coatings typically display much higher resistance to weathering in comparison to clear coatings. According to a review by de Meijer (2001), photodegradation of the underlying wood is not expected in the case of coatings that are opaque due to the presence of high refractive index mineral particles that are large enough to scatter light effectively, *i.e.* greater than 100 nm. This assertion is supported by the results of Tomak *et al.* (2018a), who found that opaque coating alone, without any UV absorbing additives, was sufficient to protect against the effects of UV light exposure. The difference can be attributed to the effective scattering of both visible and UV light by the pigments in the opaque coatings. In addition, pigments that are colored in the visible spectrum are often strong absorbers of UV light as well. Thus, the incoming UV light is scattered and absorbed before it can reach the underlying wood. Coatings having a darker color also have been shown to provide better protection of the underlying wood (Reinprecht and Panek 2013).

Biocidal Treatments in the Wood Coating

In addition to the effects of UV light and rainfall, wood products that are exposed outdoors also can be attacked by fungi, bacteria, termites, and other pests. These issues will be considered in this section.

Antibacterial agents

Compared to fungal attack, there has been less research attention to the effects of bacteria during the decomposition of external wood used in buildings. Table 23 lists some key findings from studies that have considered this topic. It is notable that several different classes of effective antibacterial components of wood coatings have been demonstrated. These include the biocides 2,3,5,6-tetrachloro-4-(methylsulfonyl)-pyridine (de Souza and Gaylarde 2002) and mono(hydroxyethoxy-ethyl)phthalate (Lu and Chang

2020). Another class of demonstrated antibacterial treatment involves metals. Thus, silver nanoparticles (Cheng *et al.* 2020) and silver-copper alloy nanoparticles (Qi *et al.* 2024) have been found effective. Another intriguing approach has been to utilize the interaction of photoactive TiO_2 particles with light as a means of suppressing bacteria (Zuccheri *et al.* 2013).

Table 23. Key Findings from Studies Considering Wood Coatings that Protect Against Bacterial Degradation

Themes of Publications	Citation
Adding melamine to wood, optionally followed by varnish, gave photochemical protection during two years of weathering, but it did not protect against bacterial attack, which was predominant on the inside of the coating layer.	Rapp & Peek 1999
The biocide 2,3,5,6-tetrachloro-4-(methylsulfonyl)-pyridine was added to the formulation of an alkyd varnish. The treatment had more effect on fungi than on bacteria.	de Souza & G. 2002
The photocatalytic behavior of TiO_2 was used in combination with visible light by its incorporation in a waterborne acrylic paint. Fluorescent light activated antimicrobial effects against *E. coli*, *S. aureus*, and *Pseudomonas aeruginosa.*	Zuccheri *et al.* 2013
Silver nanoparticles were supplemented with cellulose nanocrystals in waterborne polyurethane coatings. Antibacterial effects were observed.	Cheng *et al.* 2020
Various antimicrobial agents based on mono(hydroxyethoxy-ethyl)phthalate (M(HEEP)(2)) with different metals ("M") were added to waterborne urethane formulations. The treatment was effective against *E. coli* and *S. aureus.*	Lu & Chang 2020
Nanosilver particles were shown to be effective in water-borne formulations as microcapsules to protect against bacterial attack. Results were maximized at an HLB value of 1.97 of the emulsifier.	Pan & Yan 2023
Antibacterial capsules, with UF resin containing Ag solution, were added to water-based coating formulations for aundoung wood. The treatment was very effective against *E. coli* and *S. aureus.*	Zou *et al.* 2023
AgCu alloy nanoparticles were coated onto wood and showed 100% antibacterial effect, suggesting a synergistic action.	Qi *et al.* 2024
An antibacterial agent used in a waterborne stain did not prevent fungal infection during a rainy season.	Yang & Kang 2024

Fungicides

Protection against fungal attack, by means of wood coatings, has received considerable research attention, which is summarized in Table 24. According to the review article by Stirling and Temiz (2014), treatments of uncoated wood to protect it against fungi generally can be placed into the categories of oil-based treatments, inorganic treatments, and a category that here will be called "petrochemical". Some of the most important agents are listed under these categories in Fig. 19.

Oil-based

Heavy oils with…
Creosote
Pentachlorophenol

Inorganic

Chromated copper borate
Copper boron azole
Zinc naphthenate
Previously: chromated copper arsenate

Petrochemical

Triazoles
Thiabendazole
Propiconazole
Tebuconazole
Carbamates
Chlorothalonil

Fig. 19. Three categories of agents or formulations for the protection of wood (mostly by impregnation) against fungal colonization and degradation

Based on Table 24, it is apparent that a wide range of additives have been found to be effective in suppressing fungal growth on coated wood surfaces. These include known fungicides, such as copper naphthalate and bis(tri-N-butyl tine) oxide (Williams *et al* 1996), melamine (Rapp and Peek 1999), copper-containing compounds (Upreti and Pandey 2005), silver nanoparticles (Sorensen *et al.* 2010; Boivin *et al.* 2019), cooper nanoparticles (Yang and Kang 2024, natural oils such as olive oil, jatropha seed oil, and thyme oil (van Nieuwenhuijzen *et al.* 2015; Bessike *et al.* 2022; Tari *et al.* 2022), alkyd-type coatings (Bjurman 1992; Bobadilha *et al.* 2020), mono(hydroxyethoxy-ethyl)phthalate (Lu and Chang 2020), and pyridine-related compounds (Awad *et al.* 2023). In a couple of cases, the antifungal effects appeared to be enhanced by systems of microencapsulation of the fungicide (Kazemi *et al.* 2022; Tari *et al.* 2022). In addition, UV-absorbing oxide particles have been found to be effective in combination with incident light (Weththimuni *et al.* 2021; Hernandez *et al.* 2023).

Table 24. Key Findings from Studies Considering Wood Coatings that Protect Against Fungal Degradation

Themes of Publications	**Citation**
Spruce wood was painted with 23 different formulations. Those with an alkyd resin generally showed good antifungal ability. Coatings that included unidentified fungicide were very effective against fungal colonization.	Bjurman 1992
Effective fungicides include copper naphthalate and bis(tri-N-butyl tin) oxide. It is recommended that all outdoor paints should include an anti-mildew agent to prevent the greying of a paint layer.	Williams *et al.* 1996
Different paint formulations, some with fungicides, were applied to spruce wood, which was placed in a humid environment.	Bardage 1998
Melamine pretreatment of pine and spruce suppressed fungal colonization, even at low concentrations.	Rapp & Peek 1999
A pyridine biocide was evaluated in an alkyd varnish applied to pine panels, followed by incubation for 30 days in a chamber. The addition of 0.3% biocide was sufficient to suppress filamentous fungi and bacteria.	de Sousa & G. 2002
More effective fungicidal coatings were needed in New Zealand in comparison to Germany.	Dawson *et al.* 2005
After treatment with aqueous solutions of ammoniacal copper ferricyanide, acid copper chromate, acid copper chrome arsenate, ammoniacal copper chromate, and ammoniacal copper chrome ferricyanide, wood surfaces were then coated with three different	Upreti & Pandey 2005

formulations. Acid copper chromate was the most effective treatment against fungal growth during outdoor exposure.	
This review article considered the usage of fungicides in wood products and coating formulations for wood.	Hansen 2008
Silica nanoparticles were employed to achieve slow release of 3-iodoprop-2-ynyl N-butylcarbamate biocide within a wood coating. The fungicide had a prolonged effect, as shown by accelerated weathering tests.	Sorensen *et al.* 2010
Addition of various organic biocides to various coating formulations was found to be effective against various tested fungi in lab and field tests.	Stirling *et al.* 2011
A bluish shade of painted spruce specimens exposed to natural weathering suggests that the surfaces had been colonized by blue-stain fungus. Color change was less in pigmented coatings.	Reinprecht & P. 2015
Shellac-based varnishes were applied to wood. One of the formulations showed moderate resistance against decay fungi.	Remadeva *et al.* 2015
An intentional fungal mold staining of wood was achieved as a decorative effect on linseed oil treated pine sapwood exposed to outdoor weather. Olive oil promoted the growth of the mold.	van Neiuwenhuijzen *et al.* 2015
The best performance on larch wood was found with a semi-transparent oil-based film containing TiO_2 and a propiconazole fungicide. However, after artificial weathering, all coatings were susceptible to fungal mold.	Simunková *et al.* 2019
Silver nanoparticles were added to acrylic latex formulations. A level of 0.03% was able to suppress *S. pityophila* and *E. nigrum* growth. Higher treatment was needed to suppress *A. pullulans*.	Boivin *et al.* 2019
Solvent-based and waterborne coatings were applied to wood and exposed outdoors for a year. Fungal growth was lower on pigmented coatings. Higher moisture content yielded more growth.	Podgorski *et al.* 2019
Cross-laminated timber was coated with various commercial water- and solvent-based stains. Alkyd-type coatings completely prevented fungal decay.	Bobadilha *et al.* 2020
Various antimicrobial agents based on mono(hydroxyethoxy-ethyl)phthalate (M(HEEP)(2)) with different metals ("M") were added to waterborne urethane formulations. The treatment was effective against *E. coli* and *S. aureus.*	Lu & Chang 2020
Fungicide addition to transparent acrylic or alkyd coatings for spruce wood did not influence adhesion strength of the coating, based on outdoor weathering tests.	Reinprecht *et al.* 2020
ZnO and ZrO_2 nanoparticles were silane-treated and then added to shellac-based varnish. Both nanoparticles showed hydrophobicity and conferred fungal resistance.	Weththimuni *et al.* 2021
Jatropha curcas seed oil and vegetable resins were added to a varnish formulation for the coating of ayous wood *Triplochiton scleroxylon*. The treated varnish was effective against multiple types of fungi, as shown by reduced loss of mass.	Bessike *et al.* 2022
A slow-release microbial paint was developed and found to be effective, based on zones of inhibition and weathering tests.	Kazemi *et al.* 2022
Thyme oil was used in both free and encapsulated form in waterborne polyurethane cations. The encapsulated system was much more effective, even after accelerated aging.	Tari *et al.* 2022
Dihydropyridine derivative was added to polyurethane formulation as an anti-fungal agent. Antifungal effects were observed.	Awad *et al.* 2023
Inorganic photoactive nanoparticles (TiO_2 and ZnO) and coatings were used to protect weathered pine surfaces from fungal colonization. None of the particle treatments were effective.	Hernandez *et al.* 2023

Cellulose nanocrystals were added to a waterborne acrylic coating formulation. Improved fungal resistance was shown in terms of reduced weight loss and FTIR tests.	Tamantini *et al.* 2023
Copper nanoparticles in a waterborne stain provided resistance to fungi.	Yang & Kang 2024

Insecticidal additives

Termites are a major concern to homeowners. Wood degradation by termites not only can degrade the value of a wood-constructed building, but it also can interfere with the approval of mortgages for the purchase and sale of properties. However, relatively little research has been devoted to anti-insect or anti-termite additives for wood coatings. It is possible that researchers have assumed that wood impregnation treatments, rather than formulation of wood coatings, may be a more appropriate way to address such problems.

Table 25. Key Findings from Studies Considering Wood Coatings that Protect Against Insects, Including Termites

Themes of Publications	Citation
Extracts from *Thuja plicata* and *Chamaecyparis nootkatensis* were found to be effective in protecting against termite attack.	Taylor *et al.* 2006
Organophosphate- and pyrethroid-containing coatings for wood achieved long-term effectiveness against *Triatoma infestans*, which is a major vector of a serios disease in South America.	Amelotti *et al.* 2009
Three wood stains were found effective against termite attack.	Taşcıoğlu *et al.* 2014
Certain wood extracts were shown to protect pine wood against termite infestation.	Syofuna *et al.* 2016
Pressure-impregnation of shellac-based varnish was especially effective against termite colonization.	Remadevi *et al.* 2015
Addition of herbal oils to varnish formulation almost completely eliminated the mass loss due to termite action.	Bessike *et al.* 2022
Dihydropyridine derivatives were added to the formulation of polyurethane wood coatings. Insecticidal effects were observed.	Awad *et al.* 2023
Waterborne stain was prepared with an antibacterial agent, an insect repellent, and copper nanoparticles.	Yang & Kang 2024

Repainting of Coated Wood

It appears that relatively little attention has been paid to the science of repainting wood that previously had been coated, followed by weathering of the coated wood. Bottcher (1984) found that almost any coating that they considered was successful in the repainting of wood, with the stipulation that there first needed to be inspection and appropriate conditioning of the previously painted surfaces. In some cases this can include removal of loose paint, washing using conventional solutions, hot water rinsing, fungicidal treatments if needed, and replacement of wood that is no longer in good condition. Feist and Ross (1995) considered the refinishing of previously coated wood that had initially been coated with several different formulations after impregnation with chromated copper arsenate (CCA). Refinishing efforts were judged to be successful, with a noticeable benefit due to the CCA pretreatment before the original coatings.

SUMMARY OF MEASURES TO ACHIEVE LONG SERVICE LIFE OF COATINGS ON EXTERIOR WOOD

The purpose of this section is to provide a stepwise summary of recommended options, based on the literature reviewed in this article, when the goal is to achieve wood protection that lasts for a long time in outdoor applications. The order of presentation does not correspond to the relative importance of the steps. Rather, it reflects a logical ordering of steps, noting that in many cases the order may be flexible.

1. Select a ***type and grade level of wood*** that is suitable for the project (*e.g.* providing siding for a house in Alabama *vs.* Minnesota) that is being envisioned. For example, lower-graded wood is likely to have a higher proportion of knots, which can cause trouble with bleeding of wood resins, which can adversely affect coating performance (Pánek *et al.* 2017).
2. Apply any desired ***heat treatment*** of the wood (for purposes of developing a more attractive color and enhancing the dimensional stability) before any other chemical treatments.
3. Apply ***pressure impregnation*** in cases where the wood needs to be highly resistant to termites and microbiological attach, such as wood pieces that will be in contact with the ground.
4. Carry out suitable ***planing of the wood surfaces***, not only to achieve the target dimensions of the lumber pieces, but also to favor the performance of coatings. For instance, peripheral planing has been shown to lead to favorable adhesion of coatings (Cool and Hernández 2016).
5. In cases where ***chemical derivatization of the wood surface*** is planned (although this is not a commonly used step), it would make sense to wait until after planing of the wood before carrying out such treatment. Acetylation of wood by exposing it to acetic anhydride has been shown to render the wood more resistant to decay and allowing for longer service life of wood coatings due to resistance to peeling (Beckers *et al.* 1998; Rowell and Bongers 2015, 2017; Fodor *et al.* 2022).
6. ***Sanding of the wood surface***, with avoidance of unnecessary delay before the first coating application (such as a primer), should begin with a coarseness suitable for removing any relatively large defects (such as groove patterns) left by sawing or planing (Singh and Dawson 2006; Singh *et al.* 2007). The final grit fineness, for routine outdoor applications, is suggested as 150 or 180 grit (Allen 1984), aiming for a level that is course enough to offer strong adhesion of the coating but not contribute to a large increase in the final roughness of the coated surface. Especially for the final sanding, the sandpaper should be replaced with suitable frequency before it becomes dull or overly filled with debris too stubbornly attached to come off with routine tapping of the surface (Flexner 1994).
7. Apply any ***specialized pretreatments***, such as bleaching, extraction of wood resins, stains, antibacterial impregnants, or specialized sealants. For example, wood impregnation is commonly used to protect it against rot and termites if it will be exposed to damp conditions during usage (Williams *et al.* 1996). If plasma treatment is planned, this would be a suitable place in the order of treatments to include such a treatment (Reinprecht and Somsák 2015; Reinprecht *et al.* 2020; Gholamiyan *et al.* 2022).

8. Apply a ***primer coat*** to the sanded wood surface (Cassens and Feist 1986; Knaebe *et al.* 1996; Williams *et al.* 1996). Again, this should be done with a minimum of delay (usually within a day or less, when possible) of the last mechanical treatment, such as planing or sanding. Select a primer that has suitably low viscosity to be able to penetrate well into the pores at the wood surface and which has a resin type that offers good wettability and adhesion for the next planned coating formulation. When any coating is applied outdoors, it is recommended to wait until after the surfaces have been warmed by the sun (USDA Forest Product Laboratory 1972; Williams *et al.* 1996; Cox 2003).
9. ***Select a coating type*** that makes sense for your application. For example, water-borne acrylic formulations are often preferred due to the low amounts of volatile organic compounds, the ease of washing the brushes with soap and water, and the flexibility and toughness of the films (Feist 1994). However, one needs to check whether the surface has been previously coated with a suitable primer, such as to achieve satisfactory adhesion of such a waterborne coating to the wood.
10. Apply ***at least two layers*** and ideally three layers of the finish coating (or "topcoat") formulation. A higher number of coatings has been shown to greatly extend the expected service life of the coating system (USDA Forest Products Laboratory 1972; Grüll *et al.* 2014; Hysek *et al.* 2018). Successive layers (including the first finish coat applied over a primer layer) should be applied without delay (no more than a few days) of the previous coating (Cox 2003).
11. The inclusion of ***UV-absorbing or UV-scattering additives*** in finish coating layer formulations is highly recommended. In the case of opaque paints, especially white paints, it is recommended to use TiO_2 particles that have been prepared with a surface layer of silica. The purpose of such treatment is to minimize unwanted effects of the photoactivity of the TiO_2, while still taking advantage of its very strong absorbance of UV light and (when the particles diameters are greater than about 100 nm) to strongly scatter light, leading to high opacity and further protection against UV light. Other options include ZnO particles (Weichelt *et al.* 2010) and organic compounds such as benzotriazole, hydroxyphenyl-s-triozine, and hindered amine light stabilizers (HALS) (Özgenç *et al.* 2012; Reinprecht and Somsák 2015; Oberhofnerová *et al.* 2018; Queant *et al*. 2019; Reinprecht *et al.* 2020).
12. The inclusion of ***highly platy mineral particles*** is recommended, after suitable development and testing, for coating layers that are intended to provide a strong barrier against diffusion of water vapor or oxygen (Nkeuwa *et al.* 2014a). However, for routine applications, there is a need to avoid excessive blocking of water vapor, which needs to be able to diffuse back out of the wood material after rain events or plumbing failures.
13. A more promising goal, to maximize coating performance in exterior applications, is to consider adding an agent to ***increase the hydrophobic nature*** of the coating. For instance, silicone and silane agents have been found to be effective (Husić *et al.* 2023).
14. Further developmental work is needed before strong recommendations can be made regarding ***the inclusion of reinforcing particles, such as nanocellulose***, within wood coatings. Research findings have shown promise (Wang *et al.* 2023).
15. Inclusion of ***biocidal agents*** in wood coating formulations appears to be a good idea, especially in such applications where mildew or rot have been encountered (de Souza and Gaylarde 2002).

CONCLUDING STATEMENTS

One of the lessons that appears to emerge from this review of ways to achieve more effective wood coatings for external use is that there is not just one key measure that should be recommended. Rather, there are a large number of best practices. Some of them can be optionally selected, whereas some others, such as fresh sanding of surfaces to be coated with a primer, can be regarded as mandatory. In addition, as represented by the list of best practices presented in the previous section, many of these recommended best practices are amenable to being combined in different ways, depending on the desired outcomes.

The Hypotheses Revisited

Near to the beginning of this article there was a set of hypotheses presented. These statements will be repeated again here, each followed by some perspective based on the reviewed findings from the literature:

1. Durability of the coating layer itself, including its resistance to clacking, flaking, and peeling, is of paramount importance, since without such strength and adhesion to the wood surface, it will not remain present to provide its other functions.

   This hypothesis appears to be generally supported by the fact that many studies have reported better weathering resistance of coated wood products in comparison to uncoated wood (de Meijer and Militz 2001; Miklecic and Jirous-Rajkovic 2011; Fufa *et al.* 2013b; Sjökvist *et al.* 2019; Kabasakal *et al.* 2023; Kelkar *et al.* 2023).

2. Finish formulations for outdoor application need to contain a component capable of absorbing ultraviolet light, so as to protect the lignin in the outermost wood layer (about 1 mm) from photochemical degradation.

   This statement is supported not only by the review article of Williams *et al.* (1996) but also by numerous studies that have shown the effectiveness of UV-absorbing compounds and mineral oxide particles and nanoparticles in protecting the wood against discoloration and the breakdown of the underlying lignin (see Tables 16 through 18).

3. Finish formulations for outdoor application need to contain sufficient hydrophobic resin component to prevent liquid water (from rain) from contacting the wood directly.

   Although this hypothesis is regarded as generally true, it is somewhat difficult to demonstrate based on the published literature, since the resin composition of typical coating formulations intended for outdoor use in wood coatings are already hydrophobic. Perhaps the best demonstration in favor of this hypothesis are studies showing the additional protection of wood that can be achieved by supplemental addition of hydrophobic additives (Williams and Feist 1999; Panek and Reinprecht 2014; Samyn *et al.* 2014; Saei *et al.* 2015; Gholamiyan and Tarmian 2018; Bessike *et al.* 2022; Husić *et al.* 2023).

4. Biocidal, including antifungal, antibacterial, and insect-resistant treatments can play significant roles in extending the useful lifetime of wood finish in outdoor applications.

Multiple studies have shown the effectiveness of antibacterial (Table 23), antifungal (Table 24), and anti-termite (Table 25) treatments.

5. The formulation of a wood finish for outdoor applications can significantly affect its outward appearance both initially and during its period of use.

   The effect of weathering on the color of unprotected wood is well known (Kropat *et al.* 2020). Coatings of different types are able to either hide, modify (such as conferring a glossy appearance), or minimize changes over time of the initial color of the wood (Schaller *et al.* 2012; Forsthuber *et al.* 2013a,b; Veronovski *et al.* 2013; Grüneberger *et al.* 2015; Wallenhorst *et al.* 2018; Akbarnezhad *et al.* 2020; Janesh *et al.* 2020; Hernandez *et al.* 2023; Song *et al.* 2024).

6. By investing more in the quality of wood preparation and in the composition of the coating layer formulations, there is potential to greatly increase the length of time during which a wood coating can effectively protect wood that is exposed outdoors.

This final hypothesis is quite hard to demonstrate, since no one set of studies that was considered in this review article attempted to investigate the effects of more than a handful of different strategies being carried out all at the same time. The coating developer's dream would be to come up with a system that is durable, yet also so affordable, that it would take back a much larger part of the market currently shared with vinyl siding, aluminum siding, fiber-cement cladding, and other competitors to coated wood. Based on what has been learned from the research cited in this article, it can be expected that such a system will tend to raise the cost, since there will be more time spent in such steps as wood preparation (*e.g.* sanding), pretreatments, better primer technology, insisting on high-quality resins, insisting on suitable levels of UV-blocking additives (including TiO_2 levels in pigmented coatings), and also antimicrobial additives. It is likely that the recommended system to achieve a long lifetime also would entail more coating layers compared to current typical practice.

Since many of these extra measures are aimed at achieving results that won't be obvious until several years in the future, there will be a strong motivation for steps to be skipped. It follows that some form of certification could be helpful. When the consumer buys a set of vinyl siding, they can directly see what they are buying. To raise a comparable level of confidence in a system based on wood preparation and wood coatings, the consumer needs some assurance that the steps to be used in preparing that system have been certified for an expected number of years, depending on such factors as climate and recommended maintenance.

Some Areas Requiring Research Input

In addition to showing the effectiveness of many individual treatment steps and individual chemical components, the present review also revealed some areas in which more research seems to be needed. These can be listed as follows:

- More research to improve the effectiveness of primer coats, with an emphasis on more reliable long-term adhesion of wood coatings, especially in external applications.
- More research aimed at replacing petroleum-based components of wood coatings with plant-based ingredients, including high-performing resin systems.

- Development of bio-based cladding products, including any specialized coating systems suitable for such products, with a goal to increase the amounts of wood and other plant-based materials in long-lasting products.
- More consideration of end-of-life issues, making sure that coated wood, when taken from deconstructed buildings, still can be used in such projects as recovered solid wood, strand board, particleboard, and wood pellets for fuel, *etc*.

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