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Review on Fire Incidents and Coating Methods for Fire Prevention in Timber Structures

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ABSTRACT

Timber is increasingly recognized as a sustainable construction material due to its renewability, carbon sequestration properties, and lower environmental impact compared to conventional concrete building materials. Engineered wood products such as cross-laminated timber, glulam, and laminated veneer lumber offer enhanced structural performance and durability, making them viable for modern construction. However, fire safety remains a critical concern due to timber's combustibility and potential for rapid flame spread. The widespread adoption of timber structures in both urban and rural areas present significant fire safety challenges, highlighting the need for a comprehensive understanding of fire behavior, existing fire prevention measures, and the role of building design in mitigating fire risks. While various fire protection strategies have been reported in the current literature, fire-retardant coatings have gained particular attention for their effectiveness in enhancing timber's fire resistance. This review examines past fire incidents in timber buildings and evaluates the role of fire-retardant coatings as a key fire protection strategy. In conclusion, implementing fire safety measures, especially fire-retardant coatings, is crucial for advancing timber buildings as a safe, eco-friendly, and durable choice for future construction.

Keywords: Timber buildings; fire accidents; safety measurements; fire-retardant coating; sustainable construction

INTRODUCTION

The resurgence of timber as a primary construction material in modern architecture has been driven by its unique combination of sustainability, versatility, and performance (Sannia & Ekundayob 2022). Timber buildings are increasingly popular across the globe, reflecting a shift towards environmentally conscious and aesthetically appealing construction practices. As a renewable resource, timber aligns with the growing emphasis on reducing the environmental footprint of the built environment (Bahrami & Rashid 2024). In addition to its environmental benefits, timber offers remarkable design flexibility and aesthetic appeal. Advances in engineered wood products, such as cross-laminated timber (CLT) and glulam, have enabled timber to be used in larger, more complex structures while maintaining structural integrity and durability. These innovations have led to a new wave of timber construction projects, ranging from residential buildings to multi-story commercial developments (Bahrami 2024).

The choice between timber and concrete as primary construction materials involves weighing sustainability against traditional preferences. Due to its exceptional strength, resilience to fire, and longevity, concrete has long been preferred in concrete constructions. Nevertheless, as the cement sector accounts for almost 8% of worldwide CO_2 emissions, its environmental impact-particularly the significant carbon emissions from cement production has gained increasing attention (Abuzaid et al. 2024; Ruslana et al. 2024; Rashid et al. 2025; Bheel et al. 2021; Ikpa et al. 2021). Conversely, timber buildings have emerged as a more environmentally friendly alternative, as during the development cycle, timber capitalizes on the renewable properties of wood and its ability to both capture and store carbon dioxide. Recent advancements in engineered wood products, such as glulam and CLT, have enhanced the structural performance of timber, making it suitable for high-rise and high-performance buildings. Timber structures reduce material waste, speed up construction through prefabrication, and provide a natural look consistent with ecological design (Ayanleye et al. 2022).

However, the rise of timber buildings has also highlighted the importance of addressing safety concerns, particularly regarding fire performance. Timber is a combustible material, and its behavior in fire incidents is complex, involving factors such as charring rates, heat transfer, and structural integrity under high temperatures. The growing prevalence of timber buildings in urban and rural settings poses significant fire safety challenges (Garcia-Castillo et al. 2023). High-profile fire incidents have not only resulted in property loss and casualties but have also raised questions about the adequacy of current fire safety measures and building codes. These incidents highlight the need to understand how timber structures behave in fires. This includes assessing fire-resistant treatments, design strategies to limit fire spread, and impacts on occupant safety and firefighting. Addressing these challenges is crucial to ensure the safe and sustainable adoption of timber as a primary construction material (Mitchell et al. 2023).

While extensive studies have been conducted on fire properties of timber as a conventional construction material, reviews on fire accidents in modern timber structures remain limited. It is necessary to understand how the fire occurred, fire prevention methods, and fire-fighting options for timber buildings. Analyzing past fire incidents can provide valuable insights into fire ignition sources, spread mechanisms, and structural performance under fire conditions.

Furthermore, there are several methods available such as fire-retardant treatments, fire-resistant design, and active protection systems to prevent fire risks in timber buildings (Lubloy et al. 2021, Korolchenko & Portnov 2024). Methods also include applying fire-retardant coatings, using pressure-treated fire-resistant timber, and incorporating fire barriers like gypsum board for protection. Fire compartmentation, sprinkler systems, and smoke detectors further enhance safety (Salminen et al. 2024; Dârmon & Suciu 2018). Fire-retardant coatings are particularly important as they delay ignition, reduce flame spread, and improve the fire resistance of timber surfaces, allowing more time for evacuation and fire control. By prioritizing fire-retardant coatings, timber buildings can achieve better fire safety while maintaining their sustainability and aesthetic appeal (Wang et al. 2021, Shi et al. 2021; Islam et al. 2022). Additionally, the integration of fire-retardant coatings for fire safety is not comprehensively addressed. This research gap highlights the necessity for a comprehensive analysis of fire occurrences in timber structures to identify vulnerabilities and guide fire safety measures.

This review examines fire incidents related to timber buildings, to identify strategies to mitigate associated risks while promoting timber as a sustainable and viable construction material. Furthermore, fire-retardant coatings, as a key fire prevention method, have been extensively analyzed, and their effectiveness has been summarized to enhance the understanding of fire behavior in timber structures. This comprehensive review aims to contribute to the development of fire-safe and environmentally sustainable timber buildings.

SIGNIFICANCE OF THE STUDY

The growing use of timber in construction highlights the need to address its fire performance to ensure both sustainability and safety. While timber offers notable environmental and structural benefits, its combustibility presents serious fire hazards. This study is significant as it bridges the gap between sustainable timber use and fire safety by comprehensively analyzing real-world fire incidents in timber buildings.

By reviewing previous fire accidents in timber buildings, this study offers critical insights into failure mechanisms by investigating how fire spreads through different building configurations and materials, particularly partition walls, facades, and timber frames etc.

The importance of implementing safety precautions in timber structures to reduce fire spread and enhance occupant safety. Among fire prevention methods, the primary emphasis of this study is on fire-retardant coatings. These has been evaluated for both effectiveness and a detailed discussion of their mechanisms. Additionally, the study summarizes and analyses various coating types, highlighting their advantages and applicability through experimental results.

Altogether, this study contributes to safer timber construction by aligning sustainability with robust fire protection strategies, guiding engineers, designers, and policymakers toward more resilient building practices.

FIRE ACCIDENTS IN TIMBER BUILDINGS

A massive fire made a great impact on a complex apartment in Tustin, California, USA (Gernay & Ni 2020). The building was a two-story timber-framed building. Based on the North American classification system, the incident was categorized as a five-alarm fire. Arson was the reason for the fire. It began on the first floor and rapidly extended to the upstairs of the complex. A courtyard was in the center of the complex. Figure 1a depicts how the building was completely destroyed by the fire as it spread throughout the structure. Within 24 minutes, the complex's roof collapsed, injuring two people. Figure 1b shows firefighters extinguishing hotspots and searching for occupants over five hours after the 911 call. Around 120 firefighters responded. 38 of 40 units destroyed and approximately 100 residents displaced.

(a) Fire spreading the building

(b) Firefighters working

FIGURE 1. An apartment fire in Tustin, USA. (Gernay & Ni 2020)

A significant fire was experienced in San Francisco, USA (Figure 2) (Keeley & Syphard 2021). Five nearby buildings within a two-block area were rapidly affected by the fire when it started early in the morning. It took 160 firefighters using 60 vehicles to stop the fire, which was burning intensely and spreading rapidly. In a short time, the firefighters were able to put out the fire. Six buildings were completely destroyed. To check for hot areas, firefighters stayed overnight on the incident. One firefighter was reported as having a minor injury.

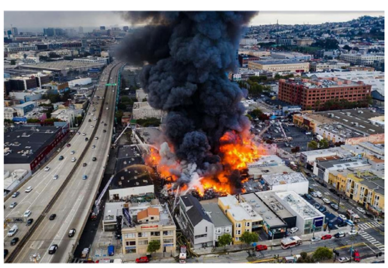

FIGURE 2. Several buildings affected by large fire (Keeley & Syphard 2021).

A fire broke out at Worcester Park in London, UK (Taylor & Appleby 2020). The four-story timber frame structure had 20 apartments. Noncombustible cladding and light-frame construction made up the construction system. No sprinkler was present in place. From a timber balcony, fire was initiated. After entering the cavities of the timber structures, it rapidly spread across the whole structure, as illustrated in Figure 3a. The firefighting operation required around 125 firefighters, 20 pumps, 20 fire engines, and aerial platforms. Five hours was the duration of the fire. As illustrated in Figure 3b, the structure was fully demolished in the end. The fire did not spread to adjoining buildings.

(a) Fire in the building

(b) The building after the fire

FIGURE 3. Fire in an apartment in Worcester Park, UK. (Taylor & Appleby, 2020)

A total of 150 persons had to evacuate during the event. The lack of warning equipment in several units resulted in numerous tenants being clueless to the fire until neighbors notified them by pounding on their doors. Fortunately, there were no recorded injuries or fatalities. The tragedy prompted UK authorities to reconsider requiring sprinklers in residential buildings under 18 meters. Furthermore, it highlights the importance of installing warning systems within individual units.

In Crewe, UK, in a three-story timber building, fire broke out (Gernay & Ni 2020). This building had the highest timber content with 1,700 m^3 of timber frame. From the roof space, the fire started accidentally. It expanded quickly, involving the building's walls, allowing the fire to spread and eventually causing those walls to collapse. The fire was extinguished by twelve fire engines and sixteen fire crews. Fire was lasted for 14 hours. The building partially collapsed and was severely damaged. The fire was extinguished before it could reach nearby buildings. Alternative accommodation was necessary for a total of 150 residents who were displaced. Fortunately, there were no recorded injuries or fatalities.

In Wisconsin, USA, a 16-unit apartment complex caught fire (Kramer et al. 2018). An asphalt-shingle roof and vinyl cladding decorated the exterior of the two-story timber-framed structure. A plastic box on an outside porch caught fire when a cigarette was dropped. The fire swiftly went through the siding and into the attic. The fire and smoke spread quickly because there were no firewalls. The thick haze stopped smoke detectors and alarms from working. However, all 20 residents managed to escape safely before more than 70 firefighters arrived. The building suffered $1.02 million in losses and was totally demolished.

In Marseille, France, fire occurred in an 8-story hybrid timber building, which housed 337 apartments and multiple facilities, including a hotel, nursery school, restaurant, meeting room, gym, and store (Bralic, 2021). Timber walls, ceilings, and floor joints made up with the building's basic structural frame, which was made of concrete.

In this incident, the fire started on the first floor but was initially contained along the facade by spears. However, light-frame timber partition walls allowed it to spread internally. Although the fire seemed under control after three hours, it later reached hotel rooms on the seventh and eighth floors and several upper-level duplexes. In total, it destroyed eight duplexes, three hotel rooms, and around 30 flats. Firefighters took over 28 hours to fully extinguish it, and 1,600 people were evacuated. Fortunately, no injuries or fatalities were reported.

In Missouri, USA, a 68-unit wood-frame condominium experienced a major fire while occupied (Pei et al. 2016). The fire began on a balcony-likely on the second or third floor-and rapidly spread to the building's exterior, attic, and upper levels. Although manual pull stations and smoke detectors functioned as intended, the sprinkler system was only partially effective, as it did not cover the balconies or attic where the fire originated and spread. The lack of sprinkler coverage in these areas hindered early containment. Additionally, thunderstorms during firefighting operations reportedly worsened the fire. The incident resulted in an estimated $14 million in damages.

An explosion occurred at a 114-unit hotel in New York, USA, characterized as a one- and two-story building constructed with exposed timber frame (Chapple 2020). The fire was propagated by an electrical line in the attic near to the pool. It spread uncontrollably in the attic, affecting the fitness center, second-story guest rooms, and lobby. The hotel had a comprehensive smoke detection system that effectively notified guests and the fire brigade. Despite the installation of a wet-pipe sprinkler system, it failed to contain the fire at its source. It suffered $10 million in losses when the roof and ceiling collapsed during the fire.

As shown in Figure 4, fire destroyed a five-story building in Washington, D.C., USA (Elsanadedy et al. 2022). The incident was considered to be a four-alarm fire. The fire began at the top level of the building. As the building was under construction, no sprinkler system was installed. The weather was quite windy, which made it challenging to put out the fire. The fire completely destroyed 14 residential units and damaged 28 vehicles. 150 firefighters worked in this incident. Firefighters controlled the blaze for eight hours. A nearby community's residents were evacuated. With minor injuries, one tenant and two firefighters were sent to hospitals.

FIGURE 4. A huge fire in multi-story construction site and firefighters battling (Elsanadedy et al. 2022)

A fire destroyed Japan's 500-year-old Shuri Castle (Benesch & Zwigenberg, 2019). It started in the main hall and spread quickly. Seven wooden buildings, including the Seiden hall, were collapsed. Over 100 firefighters and more than 10 fire engines responded. The Castle, a World Heritage site, served as the capital of a kingdom between the years 1400 and 1800, spanning four centuries. The main methods of fire protection were twice-yearly inspections and yearly fire exercises. Sprinklers were installed beneath the main structure's roof to restrict fire from spreading from the outside, but the castle itself lacked them.

Figure 5 shows the fire at Paris' Notre-Dame Cathedral (Katz & Weber 2020). Although fire detection systems were in place, there were no suppression systems. The cathedral was under renovation at the time, and the fire started in the wooden roof. Steep stairs made firefighting difficult, especially on the upper floors. The wooden frame in the north tower, holding eight large bells, also caught fire. If the bells had fallen, the towers and the whole building might have collapsed. Over 400 firefighters responded, while another 100 formed a human chain with police and social workers to save valuable artifacts. Firefighters worked mainly inside the cathedral to avoid forcing flames inward, as external water posed that risk. Luckily, the stone-vaulted ceiling contained the fire, limiting interior damage. As of September 2020, the exact cause remained unknown, with possible sources including an electrical short circuit or a cigarette.

FIGURE 5 Notre Dame Cathedral fire in Paris (Katz & Weber 2020)

In Allentown, Pennsylvania, USA, a fire broke (Kraus 2018). The four-story building experienced fire. it was made of strong brick walls and a wood frame, and was empty. As the factory was being renovated into apartments, there was a lot of lumber inside. It contributed to large fire. To put out the fire, 35 firefighters and additional help from other towns were called in. With the help of a drone that warned them of hot areas, fire firefighters utilized aerial trucks to extinguish the fire from above the building. In addition to the impact from the flame, the water used to put out the fire also caused further damage to the structure. While the fire was put out after 13 hours, hot spots remained the next day. Many stories of the structure collapsed, and the entire building was damaged. There were only a few minor injuries and no deaths, however one firefighter had hand burns.

A significant fire broke out in Waltham, Massachusetts, USA, (Delp & Singer 2020), consisting a 260-unit luxury apartment building that was under construction. The site had 5 buildings at different stages of completion, with one finished and potentially having gas and electricity activated. Although sprinklers and smoke detectors were installed, they were not yet functional. The fire started around 4 a.m., and strong winds helped it spread quickly to nearby vehicles and buildings. It soon burned down three more buildings, completely destroying two of them. A total of 20 vehicles were destroyed. Ultimately, all five structures failed, resulting in total damages estimated at $110 million.

An explosion occurred in Portsmouth, UK (Mian et al. 2019). The building was a large storehouse made of timber. The company' sprinkler system was turned on when the fire broke out at the end of the 2-block long structure. As soon as firefighter arrived, the fire was limited to one end. In addition to some heat and moderate structural damage, there was smoke inside. Nobody was injured.

More similar fire accidents in timber buildings are summarized in Table 1. Table 1 presents the building description, how the fire propagated, safety measurements for the building, building collapse, firefighting methods etc.

TABLE 1. Other fire accidents in timber buildings

Ref	Location	Building description	Spreading method in the building?	Measurements for fire safety	Did the building fail?	Firefighting Operations	Spread to nearby structures?
Gernay & Ni (2020)	Barking, UK	A complex of apartments with 6 stories and balconies made of wood	Fire spread through wooden balconies	Sprinkler and fire alarm, did not work	No, but 20 flats were damaged by the flames and 10 more were damaged by smoke and heat	15 fire engines, about 100 firefighters	N.F.
Gernay & Ni (2020)	South Dakota, USA	Timber construction of 17 apartments in a 3-story building	Start and spread in the attic	Heat detectors, smoke alarms, a wet-pipe automatic sprinkler system	No	N.A.	No
Baofo et al. (2016)	Wolverhampton, UK	A 3-story building of timber construction	N.A.	N.A.	No, but the structure was unstable after fire.	11 hours, 40 firefighters	N.A.
D'Errico (2016)	Maine, USA	10 apartments in a 4-story, unprotected wood frame structure	3rd-story balcony grill burned timber construction components. Fire developed to soffit, unnoticed, into the attic, and into living rooms.	A complete wet-pipe sprinkler and a smoke detector system, but nothing in the attic	N.A.	N.A.	No

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Smith (2009)	Croydon, UK	Five-story complex with timber-frame structures	Fire spread via hidden wall voids to adjacent floors and the apartments' roofs.	N.A.	The top floor failed including two floors downside.	N.A.	N.A.
Hancock (2003)	Virginia, USA	100-unit apartment building with 4 stories and covered wood frames	The fire originated on a third-story balcony, ascended the façade, and git in the attic via roof soffits; it subsequently developed horizontally and descended to the apartments on the 3rd and 4th floors.	Smoke detection equipment and wet-pipe sprinkler heat are fully covered, but balconies are not.	N.A.	N.A.	No
Nelson (1996)	Worcester, MA, USA	Heavy timber structure on the upper levels of a 6-story cold storage warehouse	Fire propagated to the 2nd floor. Spread by interior wooden elements	No fire detection and sprinkler systems	4 upper floors failed to the 2nd floor	6 firefighters passed away in this accident	N.A.
Meacham & McNamee (2020)	New Jersey, USA	Heavy timber multi-story warehouse with a saw-toothed roof structure	N.A.	Wet-pipe sprinkler system	N.A.	N.A.	N.A.
Scouse (2018)	North Carolina, USA	Strong wooden 2-story house structure with cedar shingles and walls made of rock and wood.	A significant fire was raging over the grill and spreading inside the home.	There was no sprinkler system, although there were battery-operated electric smoke alarms.	$1.25 million in damages to the residence and $175,000 in loss to its furnishings	N.A.	N.A.
Gernay & Ni (2020)	Seattle, Washington, USA	L-shaped commercial structure made of massive wood components with two 2-story sections along the north-south axis and a single-story wing to the west.	The fire originated in the basement of the central part; the floor above the basement subsequently fell; thereafter, the fire propagated to the northern wing.	Fire barriers made of brick with gaps and openings	Floor failed due to the failure of a timber-framed pony wall supporting the floor joints ends.	100 firefighters; five-alarm as per US classification	No
Manrique & Haglund (2019)	Iowa, USA	The four-story dormitory had a substantial timber frame, brick facade, wood floor, a wood roof deck, and roof framing.	An incident of lightning striking the building's four-story roof	A central station alarm was linked to a wet-pipe sprinkler system and hard-wired smoke detector; even so, the fire started at an area above the apparatus.	500,000$ in loss to the structure; 300,000$ in loss to contents	N.A.	No
Paultre et al. (2013)	St. Louis	A strong timber-built 3-story brick structure	N.A.	N.A.	The warehouse was damaged	80 firefighters; 4-alarm fire	N.A.
Panel (2019)	Wilsonville, USA	Wood-framed 3-story complex	N.A.	N.A.	Major destroys to at least 20 occupied condominiums	Last for 3 hours	Yes
Clark (2017)	Dorchester, MA, USA	Six-story wood-framed structure	The fire infiltrated the vacant area, first at the ceiling and subsequently extending to the roof.	Sprinklers added but inactive	N.A.	125 firefighters	N.A.
Adams & Macdonell (2016)	Kingston, ON, Canada	Four-story wooden framed structure for student housing	N.A.	N.A.	Yes	Lasted for almost 6 hours; a helicopter team; 12 firefighters;	Yes, spread to a hotel and a nearby housing project.

N.A. = Not available
N.F. Not found

SAFETY PRECAUTIONS IN TIMBER STRUCTURES

It is important to take fire safety measures in timber structures because wood is a combustible material. It can ignite and spread fire quickly if not properly treated (Yuen et al. 2021). Fire can weaken the structural integrity of timber, increasing the risk of collapse and endangering lives. Implementing fire-resistant designs and preventive strategies helps slow down fire spread, giving occupants more time to evacuate and reducing property damage. Compliance with fire safety regulations ensures that buildings meet safety standards, preventing legal issues and improving overall fire resilience. By taking appropriate fire safety measures, both human lives and assets can be better protected in the event of a fire. The following are some of the precautions to prevent fire in timber structures:

1. Opt for timber treated with fire-retardant chemicals that delay ignition and slow the spread of fire. Use engineered wood products like CLT, which char predictably and maintain structural integrity longer during a fire. Apply fire-resistant paints or coatings that expand to form an insulating layer when exposed to heat (Zang et al. 2023).
2. Divide the building into fire-resistant compartments using firewalls and fire doors to prevent fire spread. Seal gaps between structural elements with fire-resistant materials to block fire and smoke. Ensure structural elements maintain their load-bearing capacity during a fire through adequate sizing and treatment (Palma & Steiger 2020).
3. Install sprinklers to detect and suppress fires in their early stages. Use interconnected smoke alarms for early warning in all critical areas. Provide portable extinguishers suitable for wood fires throughout the building. Use advanced sensors to monitor heat and smoke levels.
4. Adhere to local building codes and fire safety standards, such as the International Building Code (IBC) or equivalent. Design components to meet required fire resistance ratings (e.g., 30, 60, or 120 minutes of resistance). Develop and display clear emergency evacuation plans (Östman et al. 2010).
5. Incorporate design elements that allow for controlled charring of timber, which creates a protective layer and slows down fire penetration. Use non-combustible materials like gypsum board as a protective layer on timber surfaces. Use fire-resistant insulation materials within walls and ceilings (Dietsch & Kreuzinger 2011).
6. Conduct regular fire drills and train occupants in fire safety protocols. Regularly inspect and maintain fire safety systems, such as alarms, sprinklers, and extinguishers. Install adequate lighting to guide occupants during an evacuation. Consult fire safety experts during the design phase to optimize safety measures. Work with local fire departments to ensure access for firefighting and compliance with safety codes.

By integrating these measures, timber structures can achieve a high level of fire safety while maintaining their sustainability and architectural appeal.

FIRE PREVENTION METHODS

Fire prevention in timber buildings involves a combination of fire-resistant treatments, design strategies, and active protection systems (Gan et al. 2020, Kielė et al. 2020). Applying fire-retardant coatings or chemically treated timber helps reduce flammability, while encapsulating timber elements with materials like gypsum board enhances fire resistance (Chorlton & Gales 2020; Chu et al. 2025). Structural design considerations, such as allowing for charring resistance and using thicker timber sections, help maintain integrity during a fire. Fire compartmentation with fire-rated walls, doors, and barriers prevents fire spread, while active systems like sprinklers, smoke detectors, and fire alarms ensure early detection and suppression (Ko & Elsagan 2023; Zang et al. 2023; Östman et al. 2010). Compliance with fire safety regulations, proper building spacing, and regular inspections further enhance fire prevention and occupant safety.

FIRE-RETARDANT COATINGS

Fire-retardant coatings are a suitable fire prevention method for timber buildings due to their ability to delay ignition and slow flame spread without compromising the wood’s structural integrity (Wang et al. 2021, Horrocks 2020, Jamadar et al. 2022). Unlike fire-resistant cladding or encapsulation, these coatings are cost-effective, easy to apply, and do not alter the natural aesthetic of timber. Intumescent coatings, in particular, expand under heat to form an insulating char layer, providing enhanced fire resistance. Additionally, they offer a lightweight solution compared to gypsum boards or other protective materials.

Their effectiveness in improving fire performance while maintaining sustainability makes them a practical choice for modern timber construction.

Fire-retardant coatings for timber are specially formulated protective coatings designed to reduce the material's flammability and slow the spread of fire (Wang et al. 2020; Ji et al. 2022). These coatings work by forming a protective barrier or undergoing a chemical reaction when exposed to heat, which helps insulate the timber and delay ignition. Intumescent coatings are a common type that expands when heated, creating a thick, insulating char layer that protects the wood from high temperatures. Fire-retardant coatings are widely used in construction to enhance the fire resistance of timber structures, helping to meet safety regulations and reduce fire hazards.

MECHANISMS OF FIRE-RETARDANT COATINGS

Fire-retardant coatings operate through a variety of mechanisms, often acting synergistically to enhance their overall effectiveness. These mechanisms can be broadly categorized as follows:

1. Intumescence: This process involves the formation of a thick, expanded char layer upon exposure to heat (Popescu & Pfriem, 2020). This char layer acts as an insulating barrier, slowing the rate of heat transfer to the underlying wood and reducing the release of flammable gases. The intumescent char layer is typically composed of a carbonaceous matrix that is often expanded by the release of gaseous products during the pyrolysis of the coating. The effectiveness of intumescence depends on factors such as the chemical composition of the coating, its application thickness, and the heating rate.
2. Heat Absorption: Certain additives incorporated into fire-retardant coatings can absorb significant amounts of heat energy (Gan et al. 2020). This reduces the temperature of the underlying wood, delaying ignition and slowing the rate of combustion. Endothermic chemical reactions within the coating can further enhance this heat absorption capacity. Materials like hydrated salts are commonly used for this purpose.
3. Free Radical Scavenging: Combustion is a chain reaction involving the formation and propagation of free radicals. Some fire-retardant coatings contain additives that act as free radical scavengers (Ma et al. 2024). These scavengers interrupt the chain reaction, inhibiting the propagation of flames and reducing the overall rate of combustion. Phosphorus-containing compounds are frequently employed as free radical scavengers.
4. Formation of a Protective Barrier: The coating itself can act as a physical barrier, restricting the access of oxygen to the wood surface (Liu et al. 2023). This oxygen limitation slows down the combustion process and can also reduce the release of flammable gases. The effectiveness of this barrier mechanism depends on the coating's integrity and its ability to withstand the high temperatures associated with fire.

Understanding the interplay of these mechanisms is crucial for designing effective fire-retardant coatings. The optimal combination of mechanisms will vary depending on the specific application and the desired properties of the coating.

TYPES OF FIRE-RETARDANT COATINGS FOR TIMBER

A diverse range of fire-retardant coatings are currently available or under development, each with its own unique characteristics and applications:

1. Waterborne Polymeric Coatings: These coatings, based on water as the primary solvent, offer several advantages, including ease of application, reduced VOC emissions, and lower environmental impact compared to solvent-based coatings (Ma et al. 2024). Recent research has focused on developing highly effective, self-healing waterborne polymeric coatings (Ma et al. 2024). These coatings utilize multiple synergies between functional groups, such as catechol, phosphonic, and hydroxyethyl groups, inspired by the adhesive and self-healing properties of mussels, to achieve strong adhesion, rapid self-healing, and high fire-retardant efficiency. The dynamic non-covalent interactions enabled by these groups contribute to the formation of a robust char layer, significantly enhancing fire protection.
2. Intumescent Coatings: These coatings undergo a significant volume expansion upon exposure to heat, forming a thick, insulating char layer (Popescu & Pfriem, 2020). They typically consist of an acid source, a charring agent, and a blowing agent. Upon heating, the acid source catalyzes the dehydration of the charring agent, generating a

carbon-rich char layer while the blowing agent produces gases that expand the char, creating a thick insulating barrier. The formulation and application thickness of intumescent coatings are crucial factors determining their effectiveness.

3. Inorganic Coatings: Coatings based on inorganic materials, such as hexagonal boron nitride (hBN) nanosheets, offer unique properties (Gan et al. 2020). The anisotropic thermal conductivity of hBN allows for rapid in-plane heat diffusion, slowing the rate of heat transfer through the wood and improving the material's ignition properties. This leads to a significant enhancement in ignition temperature and delay time, along with a reduction in the maximum heat release rate. The scalability of hBN-based coatings is also a significant advantage.
4. Organic Coatings: Organic coatings, derived from polymers such as acrylics, epoxies, or polyurethanes, can provide a decorative finish while offering some degree of fire protection. However, many organic coatings are flammable themselves and can generate smoke and toxic fumes during combustion (Popescu & Pfriem, 2020). Their application is therefore generally limited to situations where the fire risk is relatively low or where the coating's primary function is decorative. The incorporation of fire-retardant additives into organic coatings can improve their fire resistance.
5. Bio-based Coatings: Growing environmental concerns are driving research into the development of sustainable, bio-based fire-retardant coatings (Yang et al. 2017, Khademibami & Bobadilha, 2022). These coatings utilize renewable resources such as lignin (Alinejad et al. 2019) or cellulose nanofibers (Yang et al. 2017), offering a more environmentally friendly alternative to conventional coatings. For example, cellulose nanofibers can be nano-wrapped with molybdenum disulfide (MoS_2) nanosheets to create ultralight, highly thermally insulating, and fire-resistant aerogels.

The selection of the most appropriate coating type depends on various factors, including the specific application, the required level of fire protection, cost considerations, and environmental impact.

APPLICABILITY OF COATINGS

Uddin Ahmed Shaikh et al. (2018) investigated sodium (Na) and potassium (K) based fly ash geopolymer as fire-resistant coating of timber. Carbon fiber (CF) and basalt fiber (BF) were added as extra reinforcement in the geopolymer coating. The investigation was conducted in pine timber. The results are presented in Table 2.

Kwang Yin et al. (2019) utilized five intumescent flame-retardant coating systems to prepare timber door prototypes for fire resistance. This study used calcium silicate, magnesium hydroxide, aluminum hydroxide, calcium carbonate, titanium dioxide, and chicken eggshell powder, as flame-retardant fillers, while vinyl acetate copolymer emulsion served as a water-based polymer binder.

Xu et al. (2016) examined the impacts of three distinct fire prevention techniques on improving the fire resistance of timber assemblies. The approaches involved the application of a fire-retardant intumescent coating, the utilization of gypsum plasterboard, and the filling of cavities within the timber assembly using mineral wool. Four timber floor assemblies were manufactured and submitted to fire testing following the ISO standard fire exposure to assess their performance.

Aqlibous et al. (2020) studied the combustion and flammability of softwood incorporated with intumescent coatings. In addition to bio-based fillers like eggshell and rice husk ash, the coatings applied to wood surfaces consisting different ratios of commercial fillers such as titanium dioxide (TiO_2) and aluminum trihydroxide ($Al(OH)_3$). The results of this study are presented in Table 2.

After treating CLT made of sesenduk (Endospermum malaccense) with a fire retardant, Jabar et al. (2024) analyzed its fire performance. Teknoksafe 2407 (Tk-Exterior) and Teknoksafe 2457 (Tk-Interior), two fire-retardant coatings, were created and applied on the sesenduk CLT. The analysis and comparison of several fire attributes, including charring rate, surface flame spread, chemical alterations, and fire resistance, pre- and post-fire exposure, were conducted and compared with untreated CLT as a control.

A combination consisting of sand filler and an alkali-activated slag binder combined with polypropylene fiber as alkali-activated materials (AAMs) was examined for its mechanical characteristics by Kielė et al. (2020). This composite plaster was utilized as a fire-retardant layer by applying it to the surface of a 100×250×25 mm timber board. To simulate fire conditions, the constructed sample was subjected to heat exposure on one side using a directional oven.

TABLE 2. Summary of experimental results on timber coatings

Ref.	Type	Results
Aqlibous et al. (2020)	Waterborne intumescent coatings	The fire resistance of wood substrates was significantly increased by adding bio-based fillers to water-based intumescent formulations. At 30 kW/m², the effective heat of combustion decreased by over 40%, and the peak heat release rate dropped from 193.2 to 150.3 kW/m² for wood treated with a formulation containing two industrial and two bio-fillers compared with unprotected wood.
Kwang Yin et al. (2019)	Intumescent flame-retardant coating	With a low timber density of 636.45 kg/m^3 and reduction of temperature up to 54.9 as compared to the commercial prototype, an innovative fire-rated door prototype (P2) demonstrated exceptional fire-resistance rating performance.
Xu et al. (2016)	Fire-retardant intumescent coating, filling the timber assembly void with mineral wool, and gypsum plasterboard	In contrast to the untreated reference timber assembly, which exhibited a fire resistance duration of 37 minutes, the use of fire prevention measures greatly enhanced fire endurance. The most successful approach involved infusing the timber assembly with mineral wool, resulting in a fire resistance duration increase of 142 minutes (384%).
Uddin Ahmed Shaikh et al. (2018)	Geopolymer based coating	By doubling the thickness of the geopolymer layer, the char depth was decreased by 35-45%. The K-based geopolymer coating exhibited better results compared with Na-based geopolymer coating. The BF and CF incorporation in K-based geopolymer coating showed better fire resistance.
Jabar et al. (2024)	Teknoksafe 2407 (Tk-Exterior) Teknoksafe 2457 (Tk-Interior)	Increasing the number of layers and thickness to at least five layers may be necessary for the Control CLT to align with the coated CLT's performance. The average thickness loss for the control panel, Tk-Exterior and Tk-Interior were approximately 43.2 mm (61.45%), 29.2 mm (40.67%) and 31.2 mm (45.10%), respectively.
Kielė et al. (2020)	AAM-based plaster	The passive fire safety of wooden structures is improved by applying a barrier layer of fire-resistant plaster based on AAM to combustible materials. The reduction in length of the alkali-activated slag plaster specimen containing polypropylene fiber was 1.36%.
Ji et al. (2022)	Biobased waterborne epoxy resin (WPDE)	The addition of the Schiff base structure resulted in exceptional flame retardancy in the cured WPDE epoxy thermoset (WPDE/BC919), reducing the peak heat release rate by 57.3% and the overall heat release value decreased by 25.6%.

GAPS AND RECOMMENDATIONS

Further research is needed to refine the strategies and address emerging challenges posed by the increasing use of timber in taller and more complex structures. Based on this study, the following gaps and recommendations are suggested to incorporate in future research:

1. The development of self-healing coatings, bio-based coatings, and coatings with enhanced durability and thermal management properties holds significant promise (Ma et al. 2024). Advanced characterization techniques and modeling approaches, such as computational fluid dynamics and molecular dynamics simulations, can provide valuable insights into the fire behavior of coated timber and aid in the design of more effective coatings (Yuen et al. 2021).
2. The combination of titanium dioxide, aluminum trihydroxide, eggshell, and rice husk ash in coating F showed better fire protection for wood overall when compared to the other examined formulations. Nonetheless, these findings are preliminary, and more development is required, including the exclusive use of bio-based fillers in the composition. Furthermore, executing extensive fire tests is strongly advised to verify and demonstrate these results (Aqlibous et al. 2020).
3. Minimizing the environmental impact of both the coatings and their manufacturing processes is increasingly important. The use of sustainable materials and environmentally friendly manufacturing techniques is essential for promoting sustainable construction practices. Life cycle assessments can help evaluate the overall environmental impact of different coating options.
4. Effective manufacturing processes capable of producing fire-retardant coatings on a large scale are crucial for widespread application. The development of scalable and cost-effective manufacturing processes is essential to meet the demands of the construction industry.
5. Fire-retardant coatings should be considered as part of a holistic fire safety strategy that includes other measures such as early warning systems,

fire suppression systems, and compartmentalization. The integration of fire-retardant coatings with other fire safety measures can create a more robust and effective fire protection system.

CONCLUSION

The increasing use of timber in construction, driven by sustainability goals, demands ongoing research and development to ensure fire safety is not compromised. This requires a collaborative effort among researchers, building code officials, designers, constructors, and other stakeholders to develop and implement effective fire safety strategies for timber buildings. Collaboration between researchers, building codes officials, designers, and constructors is crucial for ensuring the safe and sustainable use of timber in the built environment.

Fire-retardant coatings represent a significant advancement in enhancing the fire safety of timber structures. Their ability to significantly reduce the flammability of wood while preserving its structural integrity and aesthetic qualities offers a valuable solution to the challenges posed by timber's inherent flammability. A holistic approach, integrating fire-retardant coatings with other fire safety measures, is necessary for creating truly effective and comprehensive fire protection systems for timber structures. The continued exploration of innovative materials and technologies, coupled with rigorous testing and standardization, will pave the way for enhanced fire safety in timber buildings.

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DECLARATION OF COMPETING INTEREST

None.

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