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Novel Fire Retardant Treatments for Wood and Cellulosic Materials in Construction and Furniture: A review

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Abstract

Other cellulosic substances like wood are highly appreciated in the construction and furniture manufacturing businesses because of their beauty, durability and being a friendly environment. Nonetheless, they are very flammable and their use raises serious issues of fire safety, both at residential and commercial places. This review takes a critical look on the developments of fire retardant treatment in raising the fire resistance of wood and cellulosic materials. The study investigates extensive variety of treatments by formulation, such as well-established chemical retardants and the newer and greener products, whose mechanisms action and levels of flame reduction, thermal decomposition and smoke generation are discussed. The study integrates the results of experimental studies published in the last two years, traces of industry studies, and studies presented in scientific literature to compare the effect of these treatments on their comparative performance, on environmental impact, and implications on structural integrity. Use of sustainable and low toxic solutions is especially focused on ensuring that they meet the requirements of green buildings. This study summarized the existing knowledge in order to find the most promising method to increase the fire safety of wood-based products that favor the environmental and structural performance. The results can be useful to material scientists, engineers, and policy makers who occupy themselves with developing safer and more sustainable construction materials and fire resistant furniture applications.

1. Introduction

Cellulosic material such as wood forms essential elements of modern building construction and interior design due to their peculiar viability, aesthetic value, strength and impact in the environment. They are renewable, biodegradable, and allow reducing the ecological footprint of the built environment. Their low embodied energy and the capacity to sequester carbon dioxide in the atmosphere during the lifecycle is making possible international climate strategies [1]. The renewability and carbon-sequestering properties of wood mean that it is part of the process of moving towards the more sustainable construction practices and explain why so many green building certifications and their integration into measures like LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method) come into existence.

The traditional wood construction is now supplemented by the use of engineered wood products, which have significantly increased the level of utility that wood can cover in large scale and load bearing operations especially the most popular engineered wood use, which is the cross-laminated timber (CLT) and the laminated veneer lumber (LVL) and the glue-laminated beams (glulam). Such innovations improve dimensional stability, loading capabilities, and warping resistance or cracking and allow replacing steel or concrete in mid-rise structures [2]. Modular construction and prefabricated design also facilitate induction of these materials as the precision of the manufacturing process is higher, the construction process requires less time, and lastly, fewer emissions are emitted during transportation [3].

Despite these benefits, cellulosic materials have high fire risks. Modern building codes are difficult to meet because they have a high combustibility rate, a relatively low ignition temperature, and release harmful gases and smoke. One of the key drawbacks of lignocellulosic materials in extending its usage to the construction sector is its flammability, especially in cases where fire protection ratings are required [4] .Untreated wood parts are often prohibited or required to be fire-treated, particularly in densely populated urban areas and high-rise buildings where fire containment and evacuation safety are critical considerations [5] .

A close analysis of recent incidents relating to fire has shown that untreated wooden structures are correlated with the fast spread of the fire within commercial and residential establishments and that has led to increased safety regulations. In the United States, the International Building Code [6], dictates the use of fire-retardant-treated wood (FRTW) in structural use where the required fire ratings are surpassed [6]. The fire performance of construction products is also classified under the European standard EN 13501-1, which with growing importance regards fire properties on the basis of flame retardant or intumescent coatings on wood-based products [7].

Economic costs incurred by burning wood during construction activities in the world also serve as an incentive to study environmentally friendly flame retardants that do not undermine the concept of sustainability. This paper focuses on the review of bio-based and halogen-free systems, including phosphorus-, nitrogen-, or silica-based systems, which are effective in reducing wood flammability and do not produce toxic compounds in fire. This is relevant to simultaneously comply with fire safety regulations and the integrity of the environment and introduce cellulosic materials to the mainstream [8]. This study provide a critical evaluation of modern trends in treating wood and other cellulosic materials used in building and furniture with fire-retardants. It also examines a range of technology practices- some traditional systems based on chemicals and more environmentally conscious models that would utilise nano-materials- and evaluates the extent to which they are effective in enhancing fire resistance alongside maintaining structural integrity. Another environmental and health effects accompanying the investigation is further examined with focus on strategies that are in line with the green buildings demands. The objective is to specify the most cost effective and sustainable methodologies of fire retardants, and hence enlighten industry practitioners and policy makers.

Although different treatments of wood and cellulosic material to prevent catching fire have been reported and developed, the literature on the same have not been as exhaustive and the few attempts made to integrate the new achievement in terms of sustainable, non-toxic and performance enhancing treatment have been meagre at the least. The bulk of the earlier studies has concerned the chemical behaviour of the retardants, or the retardant application process itself, as opposed to balancing the fire safety and environmental effects with the retardant durability and compatibility with building and furniture manufacturability. It is this kind of gap that will make it possible to think of the general analysis that will be able not only to synthesise the already achieved, but also to fault the old methods and move towards the novelties in order to establish new solutions, which will become environmentally friendly and forestall-oriented.

It will critically examine and summarise the literature on the subject of fire-retardant wood and cellulose materials currently available and finally outline the trends currently being undertaken with regard to sustainable and environmentally-safe practises. As to make sure that it provides a dynamic solution to the problem, the following research process will be followed: exploration of available strategies, issues and opportunities in the building and furnishing industry to shape up the academic and practical work.

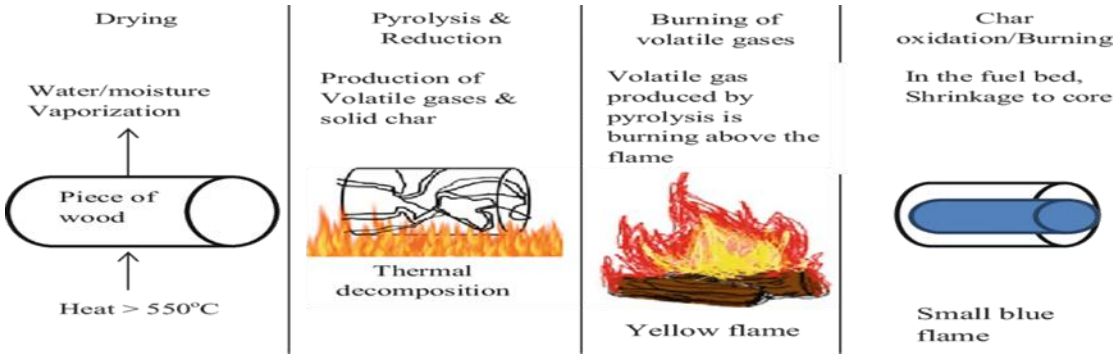

Figure (1): Combustion process of untreated wood and cellulosic materials [9].

Table (1): Comparison of Global Fire Incidents Linked to Wood and Cellulosic Materials.

Region	Year	Residential Incidents	Commercial Incidents	Primary Material Involved	Common Cause	Estimated Damages (USD)
North America	2022	6,200	2,700	Timber, paper insulation	Electrical faults, cooking	$1.3 billion
Europe	2022	5,400	3,200	Laminated wood, textiles	Heating systems, arson	$1.1 billion
Asia-Pacific	2022	8,100	4,500	Bamboo, wood panels	Open flames, poor wiring	$1.6 billion
Africa	2022	3,500	1,200	Thatch, wooden walls	Cooking fires, candles	$320 million
Latin America	2022	4,300	2,000	Wood frame, fabrics	Smoking, equipment failure	$650 million
Middle East	2022	2,800	1,600	Cellulose panels, furniture	HVAC failure, negligence	$430 million

Sources: Compiled from National Fire Protection Association (NFPA), International Association of Fire and Rescue Services (CTIF), and regional fire safety reports.
Here's the note you can copy directly under your table:

Note: The year 2022 was selected because it represents the most recent year with comprehensive, globally comparable fire incident data available across multiple regions. Additionally, several international fire safety organizations, such as the National Fire Protection Association (NFPA) and the International Association of Fire and Rescue Services (CTIF), reported an unusual concentration of large-scale fire events in 2022, making it a significant benchmark year for analysis in this review.

2. Fundamentals of Fire Behaviour in Cellulosic Materials

2.1. Combustion Mechanisms in Wood and Cellulose

The combustion of wood and cellulose-based materials is a complex, multi-phase process driven by the thermal degradation of their key organic components: cellulose, hemicellulose, and lignin. Upon exposure to elevated temperatures, wood undergoes a sequence of thermal events beginning with dehydration (moisture loss), followed by pyrolysis, ignition, flame propagation, and finally char oxidation. During pyrolysis, cellulose decomposes into combustible volatiles such as levoglucosan, (a cyclic molecule with a six-membered ring (a pyranose ring) and a bridging oxygen between the 1 and 6 positions that is formed during the pyrolysis of cellulose and other carbohydrates) which significantly contribute to flame development. Hemicellulose typically degrades earlier and more rapidly, releasing gases that support ignition, while lignin decomposes over a wider temperature range, forming char that can act as a thermal barrier against further combustion.

The gases formed are very combustible and on exposure to oxygen and heat, they start a bang and carry on the process of combustion. This feedback loop becomes even faster without intervention, which results in extremely swift flame spread and building collapse. According to Ref. [8], cellulose and hemicellulose are used as major sources of fuel in terms of wood combustion, and the char property is valued in terms of fire-resistance measures, which include lignin. Ref. [10] also reported that the emission of flammable volatiles by cellulose was observed to be predominant during the initial phases of ignition sustenance when exposed to thermal stress, and it was suggested that treatments that interfere with gas release and switches to flame should be found. These combustion mechanisms are significant in the determination of the development of fire retardant systems that would interfere with the essential processes like pyrolysis and ignition.

2.2. Parameters Influencing Flammability

The wood and cellulosic products are flammable due to the presence of intrinsic and extrinsic factors. Moisture content is one of the most critical variables; high moisture contents may delay ignition and weaken the flames due to up-take of heat as a source as a thermal sink. This is however in contrast to low moisture that contributes to rapid ignition and allows a good sustained combustion. Another important parameter is density; a dense forest will correspond to slow burning rate due to the compact layer that hampers the air movement and volatilization.

The extraction of the material comprising of the resin as well influences the manner in which they can be burned (e.g. particle board, plywood, etc.). The untreated phenol formaldehyde or the untreated melamine resins that are vulnerable to heat can be used as accelerants. Flame spread and char are also influenced by other factors such as grain orientation, roughness of the surface and porosity. They have also shown how wood species of a higher bulk density and moisture content can ignite at a slower rate and have a lower High Peak Heat Release rate that induces natural fire resistance [11]. A comparative study by Ref. [12] demonstrated that the rates of thermal decomposition can vary tremendously between species and this variability can be explained by resin and hemicellulose content differences and the need to consider species when considering fire-retarding strategies. This means that an efficient fire protection is required to be specific to materials properties and intended environments of use and most especially when used as a load-bearing structure or interior cladding.

2.3. Extraordinary Flame Propagations, Flame Spread, Time of Ignition and Rate of the Heat Release

Fire behavior characterization of wood and other cellulosic materials is done by ensuring the standardized performance metrics are applied so as to understand whether they will be applicable in construction or not. The flame spread, ignition time and heat release rate (HRR) are three of the most extreme parameters. The spread of a fire on any material is known as flame spread. Higher flame-spread ratings raise the possibility of the rapid spread of the flammable product, this enhances the risk of damage on the structure and reduces the safe evacuation times. The difference between the moment one first applies the heat, and moment of sustained combustion is called the ignition time, and the greater the ignition time the better in hazardous locations. The energy that a burning material provides per second is referred to as heat release rate (HRR). High HRR is related to quicker spread of the fire, intensified flames, and increased inability to put out the fire. They tend to be described in the cone calorimetry, limit oxygen index (L.O.I.), ASTM E84 or ISO 5660 surface flame spread. According to the article by Ref. [13], HRR and total heat release coupled with the information on time-to-ignition are most reliably used to predict the overall fire hazard in cellulosic materials. According to Ref. [14], the materials that have low HRR but high smoke generation can also be highly hazardous to health and the smoke performance of materials should be complemented by fire safety integrated testing. These indicators are, thus vital in the classification of material and the code compliance with them and they will be used as a basis of gauging the relative effectiveness of different flame-retardant treatments.

Figure (2): Thermal decomposition stages of cellulose Created by authors.

Table (2): The fire behaviour parameters of the untreated and chemically treated cellulosic samples.

Fire Behavior Parameter	Untreated Cellulosic Material	Treated Cellulosic Material	Reference
Ignition Time (seconds)	15–30 seconds; ignites quickly under moderate heat	60–120 seconds; delayed ignition due to fire-retardant barriers	[8] ; [10]
Flame Spread Rate	High; flames spread rapidly on surface	Significantly reduced; some treatments create intumescent barriers	[12] ; [13]
Heat Release Rate (HRR)	> 250 kW/m²; rapid energy release	Reduced to 50–150 kW/m² depending on formulation	[11] ; [14]
Total Heat Release (THR)	High (> 100 MJ/m²); sustains fire	Moderate to low (< 80 MJ/m²); reduced fuel availability	[5] ; [8]
Smoke Production	Dense, toxic smoke; harmful to occupants	Significantly reduced; halogen-free systems produce fewer toxic volatiles	[14]
Char Formation	Weak or uneven char; limited thermal barrier	Strong, insulating char layer; slows down heat and gas transfer	[4] ; [13]
Structural Integrity During Fire	Weakens rapidly; collapses under thermal stress	Enhanced stability; maintains form longer due to slower degradation	[10] ; [12]
Environmental Impact	High emissions and pollutant release during combustion	Reduced toxicity; bio-based systems lower ecological footprint	[11] ; [8]

3. Conventional Fire Retardant Treatments

3.1. Traditional Fire Retardant Chemicals

The history of traditional FR applications has remained a major ingredient in the flammability reduction of wood and other celluloses, particularly in building, furnishings and transportation in which fire-safety regulations have been quite inhibiting. The main chemicals used to retard fires are ammonium phosphates, ammonium sulfates, boric acid and borax. The mode of action of these compounds involves different mechanisms which restructure the breakdown of cellulose by either promoting the production of char, which is a diluting flame gasses or inhibition of the combustion reactions.

3.2. Ammonium Phosphates and Sulfates

Ammonium phosphate (e.g., monoammonium phosphate and diammonium phosphate) and ammonium sulfate are widely used for their dual-mode action. Upon exposure to heat, these salts decompose to release phosphoric acid and ammonia gas, which together promote the formation of a protective char layer on the surface of cellulose while simultaneously diluting combustible volatiles in the gas phase. The char acts as a barrier to heat and oxygen, thus retarding flame propagation. This process is illustrated in Figure (3).

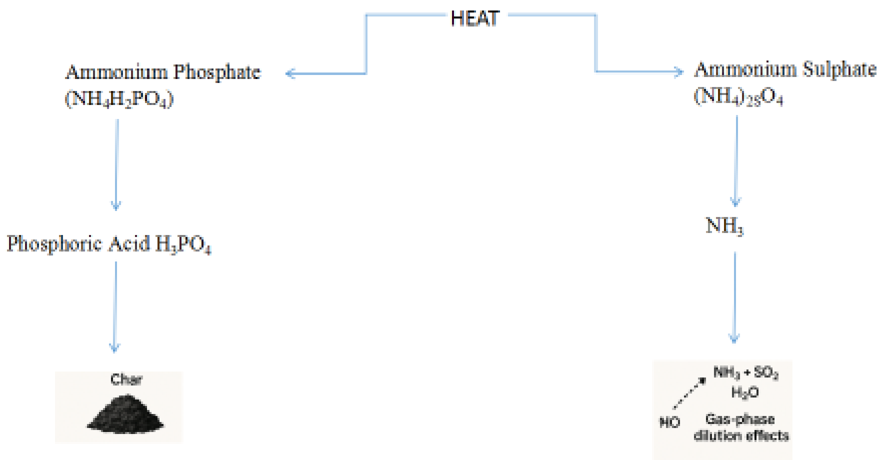

Figure (3): Thermal decomposition mechanism of ammonium phosphate and sulfate salts Created by Authors.

3.3. Boric Acid and Borax (Sodium Tetraborate):

Borates operate differently by inhibiting the depolymerization of cellulose, which delays the release of volatile gases during pyrolysis. They also suppress smoldering combustion by forming a glassy coating on the fiber surface and increasing the thermal stability of cellulose. This mechanism is especially effective in low-oxygen or slow-burning conditions, making borates ideal for interior applications where low-smoke emission is critical. According to Ref. [4], boron-based treatments increase char yield and reduce toxic smoke generation, offering a safer profile in confined or occupied spaces.

4. Application Techniques

The three major methods of application of the fire retardant chemicals are:

1. Pressure Impregnation: This would also guarantee that there is harsh penetration into the wood structures and would last quite a long duration.

2. Vacuum Treatment: The composite panel and the veneer will go through the process of vacuum treatment thereby providing even delivery of the chemicals without compromising the aesthetics of the surface.

3. Sprays or Surface Coatings: The method makes available, to accessible surfaces, which all are of lower wear/leach resistance, fire retardant.

Of these techniques, a given solution will be a matter of the nature of the substrate, fire-resistance level required and anticipated deployment environment. Ref. [1] has ascertained that ammonium polyphosphate formulations are some of the most economical and commercially feasible treatment agents in medium density fiberboard (MDF) and oriented strand board (OSB) that are used in construction. At the same time, boron based compounds are gaining in popularity due to their green building certification friendliness and non-hazardous profiles.

Despite the widespread acceptance of these fire-retardant systems due to their low cost, ease of application and proven safety records there are challenges that are continuously proving that these traditional systems need to be modified because of their leachability, hygroscopic nature and smoke suppression output.

5. Mechanisms of Action

The effectiveness of the traditional fire-retardant (FR) systems is not dependent upon the other processes like char promotion, gas-phase dilution, and the creation of the endothermic reaction. The phosphate based compounds physically separate the cellulosic substrates resulting in dehydration reaction which forms the thick carbonaceous char. This coating discourages the flow of heat and oxygen supply, and this slows down the process of combustion. At the same time, ammonium salts thermolysis yields non-flaming gases, that is, ammonia and water vapor that dilutes the oxidizer-fuel mixture and cools the combustion region. Borates inhibit volatile hydrocarbon production in a liquid phase, and therefore the exposure to pyrolysis is at a minimum. The high smoke concentrations can be linked to the low peak heat release rates because the agents containing ammonium make the production of inert gases and solids inorganic. According to Ref. [13], the boron compounds may be applied along with phosphates to enhance heat resistance and minimize the level of smoke evolution. These mechanisms combine to give our FR systems the ability to increase ignition resistance, reduce velocity of flame-spread and scale down the rate of heat release, thus making our high-hazard places and their surroundings safer than before.

6. Limitations and Environmental Concerns

Though traditional fire retardants have previously proven to be very effective they are being challenged in the extent of their persistence in the environment, the toxicity that is related to them, and stability over the time. A vast percentage of the phosphate and sulfate based compounds are soluble in water, which makes them prone to leaching in wet or humid environments; leaching gravitationally reduces the protective value of such compounds over time, and poses an environmental hazard in terms of ground and water contamination. Although borates are usually classified as being of low toxicity to humans, they tend to concentrate in the overall ecological environment and may disturb biodiversity (microbe or aquatic life) in a poorly regulated state. In addition, high salt levels may also cause the wood to deteriorate, resulting to the higher hygroscopicity, dimensional changes, and corrosion of the metal fasteners. Ref. [14] has proved that fire retardants like ammonium phosphate undergo heavy leaching in the conditions of cyclic weathering, which also damages fire resistance and generates hazards of runoff. Ref. [12] warn against certain types of wood treated with borates because of their low-to-moderate mechanical stability after a year, especially when exposed to changes in the level of humidity. Subsequently, Ref. [2] also point out that traditional FRs may release toxic gases upon ignition due to the residue that can increase the risk of health in confined areas. With increased worldwide interest in more sustainable construction methods, inadequacies of the old-school retardants have raised the demand of environmentally friendly, long-lasting, and emission-free retardants that fit all the new criteria of performance without causing environmental compromises.

Table (3): Commonly Used Chemical Fire Retardants with Mode of Action, Toxicity Level, and Limitations.

Fire Retardant	Mode of Action	Toxicity Level	Limitations	References
Ammonium Polyphosphate (APP)	Promotes char formation via phosphoric acid; releases NH_3 for gas-phase dilution	Low to Moderate	Water-soluble; leaches in humid conditions; reduces long-term durability	[1]; [11]
Ammonium Sulfate	Decomposes into ammonia and sulfur dioxide; dilutes combustible gases	Moderate	Corrosive; can degrade fasteners and reduce mechanical performance	[2]; [13]
Boric Acid / Borax	Alters pyrolysis; suppresses smoldering and enhances carbonaceous char	Low (Human)	Leachable; poor outdoor durability; potential aquatic toxicity	[4]; [12]
Zinc Borate	Acts as a synergist; delays ignition and suppresses afterglow	Low	Ineffective as stand-alone agent; typically used in combination with other FRs	[14]
Monoammonium Phosphate	Releases phosphoric acid; forms a protective char layer on the wood surface	Low	Hygroscopic; may cause swelling or distortion in wood materials	[1]

Diammonium Phosphate	Catalyzes char formation and releases inert gases to suppress ignition	Low to Moderate	Susceptible to moisture; not UV-stable; requires re-treatment in outdoor conditions	[11]
Magnesium Hydroxide	Endothermic reaction; releases water vapor at high temperature to cool surface	Low	Requires high loading; may weaken mechanical properties of substrate	[13]
Aluminum Hydroxide	Thermal decomposition releases water, reducing surface heat and flammability	Low	Requires large volume loading; affects finish and mechanical integrity	[2]
Halogenated Compounds (e.g., PBDEs)	Scavenges free radicals in flame zone; disrupts combustion chemistry	High	Persistent, bioaccumulative, environmentally restricted; many types banned in EU/US	[12]; [14]

7. Advances in Novel and Sustainable Fire Retardants

7.1. Bio-Based and Eco-Friendly Fire Retardants

In an era where sustainability is reshaping every sector, the demand for environmentally responsible flame-retardant solutions has never been more pressing. The conventional retardants operate at the expense of contributing to major environmental and health problems. Due to this, bio-based fire retardants have become an attractive alternative, whose cost, safety and environmental compatibilities were impacted. The environmentally-friendly materials are being used to revolutionize wood and other cellulosic material fire safety using renewable material including agricultural by-products, plant extracts, and biopolymers as natural compounds.

Their dualities are remarkable to a high degree: bio-based retardants also do what they are originally made to do: suppress flames and simultaneously favorable material lifecycle characteristics. Phosphorous compounds present in seeds and grains also have been known to promote the char in combustion which results in giving these some sort of insulating effect on the substrate. The effectiveness of phytic-acid-based formulations in suppression of fires can also be demonstrated in accordance with the Ref. [15] that states the wood treated with the phytic-acid-based formulations did not ignite without huge amounts of heat and did not physically burnt.

Traditionally considered to be a forestry and agricultural waste, natural tannins and lignin have once again aroused an interest as fire-retardant additives historically. When they are in the solid phase, these polyphenolic compounds also enhance thermal stability as well as the decrease of the toxic smoke emission. The authors show that a blend of lignin and phytic acid bio-spray results in the postponement of the spreading of flame and high-temperature maintenance of char yield [16]. When synergistic reaction occur, it cannot be ignored They confer the ability to provide formulations that achieve code requirements of fire safety coupled with the overall more encompassing environmental requirements in terms of LEED and BREEAM when combined with mild mineral salts or plant-based acid sources. In spite of durability and resistance to weathering being an area still under research, research is progressively narrowing the path between the concept of green chemistry and one that can be practically applied. Therefore, biogenic-derived fire retardants should be considered as a replacement not only in terms of being green but also a new direction in fire protection in modern building. They allow such materials as wood to maintain a visual appeal and sustainability combined with offering safety that never compromises.

7.2. Nanotechnology in Fire Retardancy (e.g., Nanoclays, Carbon Nanotubes)

The advent of nanotechnology in the context of fire protection has completely changed the sphere, providing the idea of using ultra-fine additives that work on the molecular level and disrupt the process of combustion. Nanoclays and carbon nanotubes (CNTs) are among the most effective as they enhance the thermal conductivity and barrier of the polymeric and cellulosics materials. These additives of nanomaterials are well dispersed in the host matrices, forming thick char materials that impedes thermodiffusion and blockage of oxygen in case of combustion. They are applicable to very low levels of loading as opposed to the traditional fire retardants and do not lead to severe degradations of the strength or flexibility of the underlying material. This constellation of properties means that they are very well suited to use in furniture, textiles, wood composites, and insulation of buildings, where structural support and fire safety are required. The synergetic flame resistance is also offered by offering carbon nanomaterials in the fire-retardant systems in the context of their synergistic barrier properties and catalytic ones [8].

8. Intumescent Coatings and Layered Double Hydroxides (LDHs)

Intumescent coatings offer a visually passive yet chemically powerful defence against fire. When exposed to high temperatures, these coatings undergo a controlled expansion, forming a heat-insulating char layer that protects the underlying substrate. Their composition typically includes a carbon source, an acid donor, and a gas source all reacting in sync to swell into a thermal barrier. To further enhance performance, Layered Double Hydroxides (LDHs) have been incorporated as multifunctional nanofillers. LDHs contribute not only flame retardancy but also smoke suppression, improved adhesion, and stability in humid environments. Their ability to release water and inert gases upon decomposition also helps dilute combustible volatiles, delaying ignition. Layered double hydroxides enhance the thermal shielding and char integrity of intumescent systems, making them promising additives for high-performance fire coatings [4].

Table (4): Performance Comparison of Novel Fire Retardant Treatments.

Treatment Type	Flame Retardancy (Rating)	Environmental Score (1–10)	Structural Impact and Reference
Nanoclays	High	8	Minimal (with dispersion), [17]
Carbon Nanotubes (CNTs)	Very High	6	Strength-enhancing, [8]
Layered Double Hydroxides (LDHs)	High	9	None to Minimal, [8]
Intumescent Coatings	Moderate to High	7	Surface coating only, [19]
Bio-based Retardants	Moderate	10	Low to moderate depending on source, [19]

Note: The environmental scores presented in this table were not directly extracted from the cited literature in their exact numerical format. Instead, they were derived through a comparative evaluation of the life-cycle impact, toxicity, and sustainability indicators reported in the referenced studies. Scores were standardized on a scale of 1–10, where 1 represents high environmental burden (e.g., persistence, toxicity) and 10 represents highly sustainable, low-impact materials. This approach ensures consistency across different treatment types while maintaining traceability to the original references.

9. Experimental Protocols Used

In the contemporary laboratory investigation of the wood and non-wood cellulosic material fire protectant, one delivers a fusion of such sorts of tests as thermogravimetric analysis (TGA), cone calorimetry (ISO 5660), limiting oxygen index test ASTM D2863, and vertical burning test UL-94, ASTM E84. Collectively, the given methods offered detailed characterisations that dealt with flame retardancy, thermodynamic degradation paths, the formation of smoke, and char formation.

It is traditionally equilibrated at room temperature (23°C) and 50% relative humidity to 48 hours before carrying out fire retardant exposure. The vacuum-pressure, dipping, or brushing impregnation procedures are undertaken using the formulations that contain phytic acid, lignin-based retardants, and nano-clays, or bio-polymer. Weights gains (WGP) in post treatment are taken as a percentage and are used as a pointer to the level of absorption efficiency.

Ref. [18], have highlighted the geometric similarity between spectra of TGA and cone calorimetry experiments, having stated that, the reproducibility of their thermal decomposition profiles was clearly seen with a significant correlation between the thermal decomposition pattern measured under TGA and the peak heat release rate measured in cone calorimetry trials, based on which the methodological synergy can be established. At the same time, Ref. [20] utilized TGA coupled with microscale combustion calorimetry (MCC) to study flammability of membrane with and without phosphorus in the bio-retardant-treated cellulose fibre.

10. Fire Retardant Performance Evaluation

The estimation of ignition time, peak heat release rate (PHRR), total heat release (THR) and smoke production rate (SPR), and char residue tend to be determined by systematic performance testing of fire retardants. The current researches demonstrate that bio-based formulations (modified tannin, phytic acid, and protein-based agents) can provide flame suppressions and, at the same time, reduce the smoke toxicity.

Indicatively, Ref. [8] have reported that the use of ammonium polyphosphate and lignin-based fire retardant formulations produced 60 percent reduction in PHRR and 30 percent increase in char residue. Ref. [4] also showed that the wood samples treated with LDH would take up to an extra 90 seconds to ignite.

11. Effect on Mechanical and Aesthetic Properties

Going beyond the fire resistance demands, the existing research studies how fire retardants affect the mechanical properties and the cosmetic qualities of the wood treated. Some compounds used in treatments with a high level of acidity or salt often take place in fiber degradation or discoloration. On the other hand bio and nano layered up retardants are more compatible with structural property and aesthetic. According to Liu and Kwak 2023, nano-silica coatings retained around 95% of the original gloss on the surface and at the same time increased flexural strength. Ref. [21] collected parallel results and recorded a modulus of rupture (MOR) decrease of 5% in the protein-rich wood compared with over 20% in the traditional forms that were treated with borates.

Table (5): Recent experimental findings.

References	Material Studied	Treatment Method	Fire Retardant Performance
[4]	Pine wood	Intumescent coating with nano-silica	Reduced peak heat release rate (HRR) by 42%, delayed ignition
[22]	Bamboo fiber board	Phosphorus-nitrogen flame retardant via dip coating	Enhanced LOI to 32.5%, improved char residue by 20%
[23]	Cellulose fabric	Layer-by-layer deposition of bio-based polyelectrolytes	Achieved V-0 UL-94 rating, maintained tensile strength
[24]	MDF panels	Boric acid & zinc oxide nano-composite spray	Increased thermal stability, minimized smoke production
[25]	Wood-polymer composite	Incorporation of melamine phosphate via extrusion	Reduced total smoke release by 30%, retained mechanical integrity
Musa et al. (2025)	Particle board	Green synthesis of flame-retardant nanocoating (from neem extract & $Mg(OH)_2$)	35% increase in time-to-ignition, no significant color change

12. Environmental Impact and Health Implications

12.1. Toxicity and Off-Gassing of Chemical Retardants

Chemical fire retardants, while effective in reducing flame spread, often introduce significant health concerns due to their toxic composition. Many conventional formulations particularly those containing brominated or chlorinated compounds can emit harmful volatile organic compounds (VOCs) and persistent pollutants during application or in the event of a fire. These emissions, known as off-gassing, may linger indoors, compromising air quality and posing risks to human health over time. Ref. [26] demonstrated that halogenated flame retardants used in plywood can release formaldehyde and dioxin-like substances upon thermal degradation, which are linked to respiratory issues and endocrine disruption in occupants. The recent literature presents the need to have safer substitutes, especially in confined places like homes, learning institutions, and workstations that expose people to long durations.

12.2. Leaching Behavior and Waste Disposal Issues

Environmental consequences of chemical fire retardants do not just end at the danger they bring about during combustion. These chemicals can even pollute the surrounding ecologies with slow extraction of residues of treated substrates. In situ (that is, decks, cladding or infrastructure in moist or wet climates), since wet-dry cycles are facilitated; the prolonged cycles can increase the spread. Rainwater acts as the most important medium of conveyance of fire-retardant along with flushing out of residues, thereby contaminating grounds and water and retarding various microbial and other aquatic living beings. New evidence has demonstrated that the borate-based and phosphate-based treatments prove to have considerable leaching during a wet-dry cycle test run over an extended period, which reduces future performance of a specific treatment additionally to the environment-related concerns. Also, the disadvantages of the treated wood improper disposal increase the problems: when burned, problematic residues are released and when buried, the treatment produces acidic soils or toxic ash remains.

12.3. Standards for Green Building Certifications (LEED, BREEAM)

As construction industry slowly turns green with the sustainable building approach, the measure of complying with the green certification systems, that is, LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) has become the process of selecting materials. These frameworks promote the use of low emission and recyclable and non-toxic materials in the whole lifecycle of a structure including the consideration of fire safety. Fire retardants must therefore meet two goals that of maximizing fire resistance, and that of achieving conformance with human and environmental performance. Although bio-derived retardants have only recently been published by Ref. [27], they can now be utilized in exterior cladding when phosphorus is used as a retardant, in this instance, the wood materiel does not compromise LEED indoor environmental quality (EQ) design as well as not risking loss of fire safety.

In consideration of this dynamic environment it is agreeable that products that can afford the balance between fire protection and adherence to green principles are not optional, but necessary. Stakeholders are therefore urged to embrace the use of fire retardants that protect the lives of occupants and at the same time help in protecting the planet so that future generations of people can live to see the world.

Table (6): Environmental and health risk rating of different fire retardants.

Fire Retardant	Chemical Group	Environmental Risk	Health Risk	Remarks
Ammonium Polyphosphate (APP)	Inorganic Phosphates	Low to Moderate	Low	Leaches in humid environments
Tetrabromobisphenol A (TBBPA)	Brominated	High	Moderate to High	Persistent and bioaccumulative
Aluminum Hydroxide	Inorganic	Low	Low	Releases water vapor, non-toxic
Decabromodiphenyl Ether (DecaBDE)	PBDE	Very High	High	Banned in many regions due to toxicity
Magnesium Hydroxide	Inorganic	Low	Low	Thermal decomposition releases water
Melamine	Nitrogen-based	Moderate	Moderate	Can release toxic gases when burned
Zinc Borate	Boron Compounds	Low	Low	Acts as smoke suppressant, low leaching potential
Chlorinated Paraffins	Chlorinated	High	High	Suspected carcinogens and persistent pollutants
Red Phosphorus	Elemental Phosphorus	Moderate	High	Highly reactive and potentially explosive
Expandable Graphite	Carbon-based	Low	Low	Eco-friendly, expands to form intumescent layer

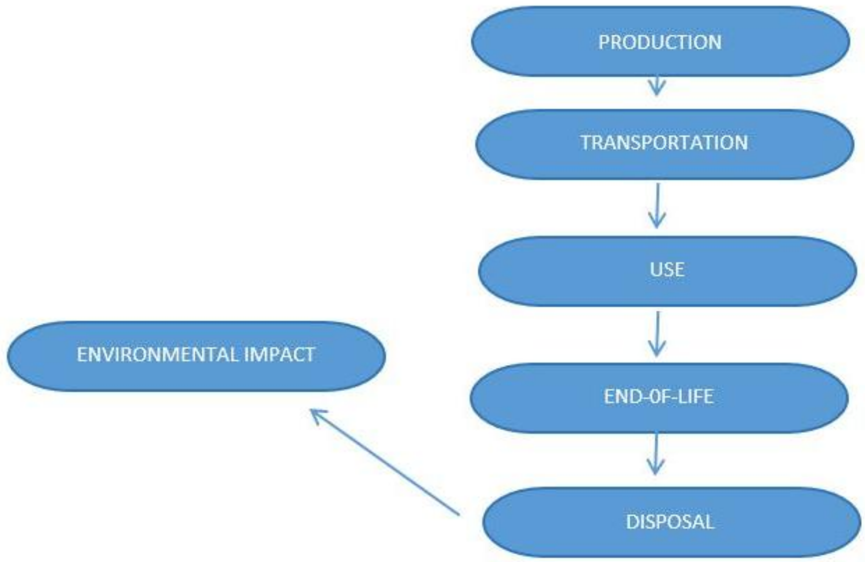

Figure (4): Environmental impact pathway from production to disposal.

13. Structural and Aesthetic Implications of Treatments

13.1. Impact on Mechanical Strength and Moisture Resistance

Fire retardant treatments (FRTs) are able to alter the mechanical behaviour of wood and other cellulosics where the result is dependent upon the type of treatment and route of application of the treatment. The encapsulating/sealing-contact properties of nanoparticle-based formulation are better because they penetrate the host matrix and form strong interfacial bonds, and the formulation of soaking or covalent surface coating might introduce a porous/moisture-affinity issue due to the absence of proper sealing. Water-resistance can be very crucial in a rainy environment where natural wood could easily expand, become distorted and other unwanted effects. The contemporary FRTs are more aimed at providing or supporting the dimensional stability and flexural strength. This integration will allow intact use of nano-creatures that can imply both enhancement in stiffness and high-moisture tolerance, altogether on treated wood that does not diminish the structural activities [28].

13.2. Color, Texture, and Surface Integrity Post-Treatment

Aesthetic preservation is a key challenge in fire retardant formulation, as many treatments tend to darken, yellow, or dull the natural appearance of wood. This visual alteration may be subtle or pronounced depending on chemical composition, curing temperature, and UV sensitivity. Intumescent coatings, for instance, form foamy residues that can compromise visual quality unless concealed. Modern treatments strive to maintain color clarity and smoothness, with the integration of optical stabilizers or transparent flame-retardant formulations. Surface discoloration remains a common side effect in conventional fire retardant systems, prompting the need for color-stable additives [20].

13.3. Compatibility with Furniture Finishes and Coatings

The final appearance and usability of treated wood often depend on how well it integrates with stains, sealants, and finishes. Some fire retardants form residues or surface layers that inhibit adhesion or cause blotching, requiring post-treatment sanding or priming. However, well-formulated treatments enhance compatibility by being chemically inert or synergistic with commercial coatings. This ensures that fire safety does not come at the cost of surface quality, especially in high-end architectural or furniture applications. Surface-modified flame retardants offer improved finish adhesion, making them suitable for wood-based furniture and decorative uses [29].

Table (7): Mechanical property changes (modulus of rupture, elasticity) post-treatment.

Material	Treatment Type	Modulus of Rupture (MPa)	Modulus of Elasticity (GPa)	Observation
Wood (Spruce)	Thermal treatment	65 → 55	12.5 → 11.0	Reduced strength due to degradation of hemicellulose
Wood (Pine)	Chemical treatment (Borate)	72 → 68	13.2 → 12.9	Minor decrease; slight impact on flexibility
Bamboo	Heat treatment	110 → 95	18.0 → 16.5	Improved dimensional stability, moderate strength loss
Steel	Fire exposure	450 → 300	210 → 180	Significant loss in strength and stiffness
Concrete	High-temperature curing	45 → 50	30 → 32	Increased strength due to enhanced hydration
Composite (FRP)	UV exposure	850 → 770	45 → 41	Degradation of resin matrix over time
Plastic (PVC)	Heat aging	55 → 40	2.9 → 2.0	Loss in flexibility and brittleness increased

14. Regulatory Standards and Compliance

14.1. Fire Safety Codes in Construction

Regulatory fire codes set the baseline for how building materials perform under fire exposure, shaping their use in residential, commercial, and industrial environments. These codes vary by country and building type, but they universally emphasize flame spread limitation, smoke suppression, and structural integrity retention. Fire retardant-treated wood must meet specific ignition resistance and flame propagation thresholds to be permitted in high-occupancy zones or structural applications. As building design trends shift toward sustainability and material diversity, these codes are increasingly integrating performance-based criteria. Modern fire safety regulations require materials to meet performance thresholds tailored to specific building environments and uses [30].

14.2. Testing Standards (ASTM E84, ISO 5660, EN 13501)

The quantitative results obtained after routine standard exposed combustion regimes on material treated under standardized protocols of experimental fires will yield good results on the behavior of those treated materials that can be repeatedly subjected to the standardized protocols of the experimental fires. The most frequently adopted procedure in the US is the ASTM E84 (Steiner Tunnel Test) that is based on the measurement of the speed of flame and production of smoke. The ISO 5660 (Cone Calorimeter Test), which is mainly used in the other locations is associated with the measurements of heat release rate and ignition time. In the European rating per EN 13501-1, groups (A1 to F) of reaction-to-fire are employed and the ratings are dependent on various performance criteria. The protocols offer competent and similar results between products and geographic locations and consequently, they are the backbone of product development and also the regulatory authority approval process. The tests ASTM E84 and ISO 5660 consequently offer a uniform structure of vitality, in deciding on the quality of flame-retardants in various countries [31].

14.3. Certification and Labelling Requirements

Compliance with fire standards must be demonstrated through official certification, which often includes rigorous third-party testing and production audits. Labels such as Class A (ASTM E84) or Euroclass B (EN 13501) are not just regulatory tools but also marketing assets, signalling product safety and quality to buyers and builders. In some regions, green building programs (e.g., LEED, BREEAM) also require documentation of flame-retardant content and environmental impact. Manufacturers must balance performance with transparency to meet both code and consumer expectations. Certification labels act as both compliance proof and quality assurance, particularly in regulated construction markets [32].

Table (8): List of international fire safety standards and what they test.

Standard	Organization	Test Focus	Scope/Application
ISO 11925-2	International Organization for Standardization (ISO)	Ignitability of building materials	Tests material resistance to direct flame exposure
ISO 9705	ISO	Full-scale room fire test	Evaluates fire growth, smoke production, and heat release in a room scenario
ASTM E84 (UL 723)	ASTM International / Underwriters Laboratories	Surface burning characteristics	Measures flame spread and smoke development in interior finishes
NFPA 701	National Fire Protection Association (USA)	Flame propagation of textiles	Used for curtains, drapes, and other hanging fabrics
BS 476 Part 6 & 7	British Standards Institution (UK)	Fire propagation and surface spread	Part 6 evaluates fire propagation; Part 7 assesses surface flame spread
EN 13501-1	European Committee for Standardization (CEN)	Fire classification of construction products	Combines results from multiple tests to assign fire performance ratings
UL 94	Underwriters Laboratories (USA)	Flammability of plastic materials	Rates plastics from HB (horizontal burn) to V-0 (best vertical burn resistance)
AS 1530.3	Standards Australia	Combustibility of building materials	Tests for ignitability, flame spread, heat release, and smoke development
CAN/ULC-S102	Underwriters Laboratories of Canada	Flame spread and smoke development	Canadian equivalent of ASTM E84 for building materials
DIN 4102	German Institute for Standardization (DIN)	Building material classification	B1 class indicates low flammability; B2 for normal flammability

15. Challenges and Future Perspectives

15.1. Bridging Performance and Sustainability

One of the major obstacles in the flame-retardancy research area is finding a compatibility between high flame resistance and environmentally balance and human health. The other systems, although generally effective, are either based on halogenated compounds or heavy metals, which are long term liabilities as far as the ecology is concerned. Compared to them, green alternatives to them are using bio-based molecules, nontoxic nanoparticles, or phosphorus based chemistries, with a lower risk profile but usually, are less thermally stable or resist humidity poorly. The next level of innovation will therefore have to combine the aspect of green-chemistry with ensuring that formulations that could be considered clean do not compromise the key performance indicators. Continued innovation of flame retardants with high efficiency and low environmental impact - therefore this is one of the key scientific and regulatory goals [33].

15.2. Scalability and Cost of Green Fire Retardants

The scaling-up of production of laboratory-produced green flame retardants into an industrial scaled-up production remains a huge challenge. In many cases, the low cost and accessible nature of the new technologies rely on the new technology with nanomaterials, enzymatic catalysis, or renewable precursors, which must use special equipment or rare and expensive raw materials. This challenge can only be tackled through long-term cooperation between scientists and producers to optimize synthetic routes, maximize the efficiency of the yield, and take advantage of the oversupply that waste-derived feed stocks present. Adoption in the construction and furniture industries also center on economic feasibility and to a large degree, this sentiment is influenced by the cost sensitivity. Finally, commercialisation of sustainable flame retardants depends on the occurrence of developments that are both scalable and competitive in terms of cost structures [34].

15.3. Research Gaps and Industry Needs

Some areas in the discipline of fire protection engineering have been least explored in spite of the growing interest and investment. Applications of these fields are the long term aging behavior of treated materials, any interaction between the treated surfaces and an overlay, such as a coating, or adhesive, and the formulation of multi-functional systems possessing both fire resistance and antimicrobial or ultraviolet shielding properties. The industry stakeholders also emphasize shorter testing procedures, uniformed labelling guidelines and enhanced compatible mode of operations with commonly accepted construction guidelines. These loopholes will require intensive cooperation across the lines and establishment of the full field-testing environments. Sustainable fire retardant treatments should therefore be multidimensional, effective irrespective of where they are used and simple to integrate with the building systems [35].

16. Recommendations for Researchers, Engineers, and Policymakers

Develop Multifunctional, Eco-Friendly Fire Retardants

Researchers should focus on designing advanced formulations that combine fire resistance with added functionalities such as mechanical reinforcement, UV protection, and antimicrobial properties while ensuring environmental safety. Emphasis should be placed on long-term performance evaluation through accelerated aging and life cycle assessments. This integrated approach will ensure that future materials are both safe and sustainable in diverse application environments.

17. Integrate Fire Retardants Early in Design and Construction

Engineers and architects must incorporate fire-retardant-treated wood and cellulosic materials at the earliest design stages to ensure compatibility with other building systems (e.g., HVAC, insulation, coatings) and to maximize functional performance. Specialized training in application and maintenance should be standardized to enhance field effectiveness. Proactive integration ensures better structural coherence, cost-efficiency, and regulatory compliance.

18. Promote Unified Standards and Green Policy Incentives

Policymakers should work towards harmonizing international fire safety codes and testing standards (ASTM, ISO, and EN) while creating incentives such as subsidies and green certification benefits for manufacturers adopting sustainable flame retardant technologies. Regulatory alignment and supportive policy frameworks are key to accelerating innovation and global market adoption.

19. Vision for Safer and Greener Wood-Based Products

Looking ahead, the future of fire retardant technology lies in safety without compromise materials that are both eco-responsible and functionally superior. Advances in nanobiotechnology, bioinspired surface treatments, and adaptive coatings point toward a new generation of smart, self-extinguishing wood composites. As climate resilience and green building standards become global imperatives, fire-safe wood products will play a pivotal role in reshaping architectural norms. The vision is clear, wood products that do not just resist fire but also reflect a commitment to human health, environmental responsibility, and design excellence.

20. Conclusions

In addition to the interest in fire resistant building material and furniture designs, the interest in sustainable building material and furniture designs has led to further developments in exploring newer operations on wood and other cellulosic material to introduce fire resistance (F-R). Other intriguing advances in halogen-free and green systems also described in this review are the use of intumescent coats, intumescent nanoparticle and bio-based retardant formulations. These emerging technologies have demonstrated beneficial improvements in fire resistance, thermal stability, smoke suppression, and have lost no notable mechanical or aesthetic properties. But there are certain questions and contradictions. Speaking only of one example, the borate treatment has been called as environmentally non-hazardous, but, the mechanical stability and chances of washing away the same are questionable. Similarly, FRs based on nanoparticles may be useful to facilitate thermal behaviour, though their longer term environmental impact is not well understood. Other major impediments to large-scale industrial adoption are cost and performance and scalability trade-offs and that many new formulations are prohibitively expensive to run at scale, or have complex deployment requirements. That means the way must be low-toxicity formulations with low ecological footprint and issues of both economic viability and compatibility with large scale production. In addition to the above, to improve the level of performance and life of the materials, obtaining the materials to be treated with the FR treatments during the production of the engineered wood products, rather than treating the materials after the production, would also result to an improved performance. The fuel-devouring FRs are still being consumed, but the less-toxic and more-sustainable versions are finding safer applications. To keep up this process of changing over, more interdisciplinary approaches to materials science, environmental chemistry, industry stakeholders and regulators will have to be put in place to bridge the gap between lab work and application.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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