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Sustainable and Environmentally Friendly Flame Retardants for Wood Materials Used in Construction

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Abstract. Wood is a material that widely used in construction due to its strength, renewability, and natural appearance. However, its flammability poses significant fire safety challenges in buildings. Traditional flame retardants are effective at reducing fire risks but often introduce new environmental and health hazards, such as toxic smoke and persistent pollution. In response, recent research has focused on developing sustainable and eco-friendly flame retardants for wood. This paper reviews several categories of these newer solutions, including bio-based compounds derived from plants, fully degradable additives, and non-toxic inorganic materials. It examines how these substances work to protect wood by slowing ignition, promoting char formation, and creating physical barriers to flames. The paper also discusses different manufacturing and application methods, highlighting how they affect performance, cost, and real-world use. By comparing traditional and sustainable approaches, the study emphasizes the potential for safer, greener fire protection technologies to play a major role in future construction.

Keywords: sustainable flame retardants, wood fire safety, eco-friendly materials.

1. Introduction

Wood is one of the materials that widely used in building. The primary reason for its popularity is because its high strength, lightweighting, renewability, sustainability, cost-effectiveness, and ease of manufacture. Wood is considered as an environmental-friendly material as it has low carbon footprint. During the manufacturing process, it has a lower embedded energy than steel or concrete, and it is a natural insulator that reduces operational energy needs of buildings. Moreover, trees absorb carbon dioxide during growth, which can sequester carbon for the life of a building [1]. In recent years, timber has been widely utilised as a building material. This is because its property of durability, cost-effectiveness, diverse range of species, and ease of processing. However, there is a major safety concern lying under using of wood and timber in construction. Wood is a flammable material. Fires in residential and public buildings often spread rapidly when wooden parts such as floors and furniture. This has caused significant property damage and loss of life in accidents, which makes fire safety a critical requirement for modern construction standards.

To reduce the flammability of wood, scientists start using flame retardants. Scientists found chemical substance could work by delaying ignition, slowing fire spread, and reducing smoke release [2]. Traditional flame retardants, such as halogenated flame retardants, have a long history of

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use. Although they are highly effective in improving fire resistance, they also bring serious environmental and health concern. This is because these chemicals make the smoke from fire more toxic. Moreover, due to their persistent nature, they cause long-term toxicity. These toxic substances accumulate in living organisms and the food chain. As a result, this pollution poses threats to both ecosystems and human health, leading to stricter regulations in many countries.

Based on the known toxicity of conventional flame retardants, researchers and industries continue exploring flame retardants that are more sustainable and environmentally friendly for wood materials, while keeping their effectiveness. For example, researchers have put spotlights on bio-based compounds, which are derived from natural sources such as plants or marine organisms. Besides, research on degradable flame retardants, which could break down without leaving harmful residues, is also progressing rapidly. Although these sustainable solutions are still in the research stage, these are promising solutions to be used for wood protection in the future.

This paper will first explain the mechanisms of flame retardants and how they protect wood from burning. Then, it will discuss several categories of sustainable flame retardants, including their properties, performance, and limitations. Finally, it will review some manufacturing and application methods, before drawing a conclusion about the outlook of eco-friendly fire protection for wood in construction.

2. Flame retardant

The concept of flame retardancy can be explained by interrupting the self-sustaining combustion cycle [3]. There are three main elements required during combustion: oxygen, heat and fuel. Besides, exothermic redox chemical reaction, kinetics reaction and phase formation of materials are involved in combustion. When wood exposed to heat, it acts as fuel and its temperature continues to rise. Exposure in oxygen, it reached to required level of pyrolysis and oxidation degree, resulting to wood combustion. The combustion rate is determined by both oxygen concentration and combustibility of wood. This process converts volatiles within the wood into char and gases whilst releasing heat. The resulting volatiles and heat continuously supply energy to the flame, sustaining the combustion process [4].

2.1. Structure of wood

To understand how flame retardants work on wood material, it is important to understand the nature of wood. The hierarchical structure of wood is presented in Figure. 1. Single cell walls of wood are mainly composed of three biopolymers, which are cellulose, hemicellulose, and lignin. Common woody structures comprise cellulose (40–50%), hemicellulose (20%), and lignin (25–35%) [5]. Diving deeper into the layered cellular structure, scientists found that the structure provide sufficient stability and strength. Its multi-layered cell walls make it a perfect material for construction. However, its combustibility limits its application. When exposed to heat, these components decompose and release flammable gases such as carbon monoxide and other volatile organic compounds. These gases ignite easily, producing flames that quickly spread across the wooden surface. At the same time, the structure of the wood weakens as it loses mass, leading to rapid fire growth. Therefore, preventing or slowing down this process is the key goal of flame retardants.

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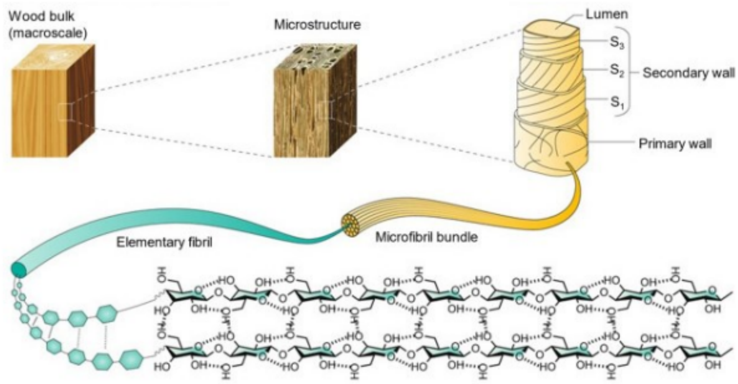

Figure 1. Hierarchical structure of wood [6]

2.2. Flame retardant mechanisms

Flame retardants can act through several different mechanisms. The basic logic under flame retardancy mechanism is to decrease the flammability of the material and slow down the spread of the flame. This section will explain these mechanisms in detail.

2.2.1. Gas phase mechanism

The first is the gas phase mechanism. This mechanism act by disrupting the combustion process, therefore slowing flame propagation and reducing the heat absorbed by the material, shown by figure 2 [7]. However, the inhibition property of flame retardant in the gas phase is influenced by flame and properties of inhibitors as well. Some flame retardants release gases, such as water vapor or inert gases, when heated. The primary mechanisms of vapor-phase flame retardancy include inert gas dilution and chemical quenching of active radicals. The former dilution effect refers to the release of non-combustible vapors during combustion, which dilute the oxygen supply to the flame or reduce fuel concentration below the flammability limit. Most hydroxide and carbonate metal additives operate through this mechanism. Their thermal decomposition is an endothermic reaction, yielding substantial quantities of non-combustible gases such as H_2O and CO_2. These gases dilute the concentration of flammable substances in the air and disrupt the chain reactions that sustain combustion. For example, halogenated flame retardants (now being phased out for environmental reasons) acted in the gas phase by releasing halogen radicals that interfered with the burning process.

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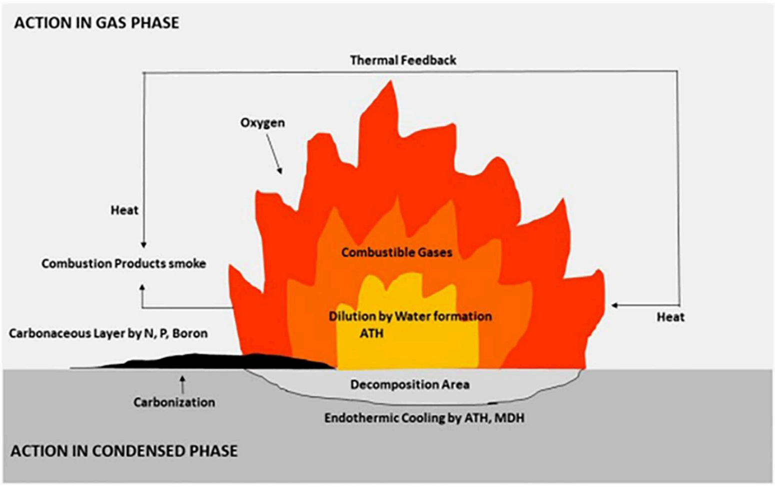

Figure 2. Gas phase mechanism [8]

2.2.2. Condensed phase mechanism

The second one is the condensed phase mechanism. This mechanism is used for the purpose of covering the solid surface to avoid or delay the generation of combustible gases and the thermal decomposition of materials. Many flame retardants induce or promote the formation of a char layer. For instance, bio-flame retardants like phytic acid, tannins are very effective in promoting the formation of char [9]. This mechanism is successful in maintaining the structure of the material for a longer time.

2.2.3. Cooling mechanism

Another interesting mechanism is the cooling mechanism. Some inorganic flame retardants like aluminum hydroxide, magnesium hydroxide etc. release water vapor when they are burnt. The water absorbs the heat, and the wood becomes harder to ignition [4]. Although these additives are environment friendly, they require a large amount to reduce the mechanical strength of wood.

2.2.4. Barrier effects

Flame retardants can also act via physical barrier effects. This mechanism is called surface creolization process, and it works by the mechanism of a physical barrier that reduces the transfer of heat to the polymer [10]. For example, when the polymer is ignited, the nanoparticle flake falls off and generates a network structure. The flake structure together with a small amount of carbonaceous coke. The coke layer or ceramic layer is thermally stable and acts as a thermal barrier, which hinders the transfer of heat to the flame [11]. It also acts as an isolating barrier between combustion products and decomposition products.

As discussed above, flame retardants can act with one or several of the ways explained above at one time. An efficient flame-retardant system should be composed of a combination of different mechanisms, for example gas phase interruption and char formation, to provide reliable fire protection for wood in construction.

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3. Sustainable flame-retardant materials

To mitigate the environmental impact of conventional flame retardants, scientists have been developing safer, renewable, and more eco-friendly materials. These sustainable flame retardants are designed to maintain high fire resistance, while avoiding the release of toxic substances or harmful residues. They can be categorized into several groups, including bio-based flame retardants, biodegradable flame retardants, and environmentally friendly inorganic additives.

3.1. Bio-based flame retardants

Bio-based flame retardants are derived from natural materials such as plants, animals, or marine organisms. They represent one of the most promising approaches to sustainable fire protection, because of their renewability and biodegradability.

One example is phytic acid (PA). This is a natural compound found in many seeds and grains. PA contains 28% phosphorus. Notably, PA releases phosphorus or polyphosphate during heating, accelerating carbonization of the polymer matrix to form a protective char layer. In the gas phase, polyamide decomposes into PO• and HPO radicals, capturing H• and OH• species to terminate chain reactions and achieve flame retardancy [12]. Consequently, polyamide has rapidly emerged as a research focus for implementing sustainable development strategies. Studies have shown that when wood is treated with phytic acid, the surface develops a thicker, stronger char layer that slows down flame spread and reduces smoke. PA is especially attractive because it is abundant and non-toxic [13].

Another class of bio-based flame retardants are tannins. This ingredient are polyphenolic compounds extracted from tree bark, fruits, or leaves. Although tannins are widely spread in the plant nature, it has limited application as synthetic polymer additives, might due to its colouration nature or incompatibility with hydrophobic polymers [14]. However, tannins are already used in leather production and as natural dyes. In flame retardancy, tannins exhibit exceptional carbonisation capabilities and antioxidant properties. These characteristics make them ideal materials for bio-based flame retardants [15].

Chitosan is a material obtained from the shells of shrimp and other crustaceans. It rich in nitrogen and hydroxyl groups, is often used as a charring agent in flame-retardant composites. At high temperatures, amino groups within the chitosan structure form NH_3, diluting the oxygen concentration in the system. Simultaneously, combustion promotes ring-opening reactions within the chitosan, forming aromatic ring structures and producing a dense char layer within the condensed phase. When used as a coating on wood, chitosan can reduce heat release and delay ignition. Since chitosan is biodegradable and can be obtained from seafood industry waste, it is both eco-friendly and cost-effective [16].

Overall, bio-based flame retardants show strong potential because they use renewable resources and combine multiple protective mechanisms. However, many of them are still at the laboratory stage and need to be improved for long-term durability in real construction environments.

3.2. Degradable flame retardants

Another strategy is the development of flame retardants that are fully degradable after use, so that there will be no harmful residues in the environment. These materials protect the wood during their lifetime and will decompose safely when thrown away.

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One of the biodegradable flame retardants is Biodegradable phosphate esters. This material contains phosphorus groups. When the material burns, the metal hydroxide will go through dehydration, and the water vapor generated can work effectively through condense phase mechanism or gas phase mechanism to dilute the concentration of combustible gas [17].

Polylactic acid (PLA)-based systems is also another example. It is also a biodegradable and bioactive thermoplastic polyester. It is synthesized from renewable resources like corn starch or sugarcane. Biopolymers like PLA and starch, reinforced with natural fibers like wood fibers are becoming more and more popular due to their sustainability and mechanical properties. For its usage as flame retardants, not much research is reported. Now, researchers try to blend flame retardant additives into PLA-based coatings and then coated on wood [18]. The effectiveness of this coatings is still under investigation.

However, the main challenge for all degradable flame retardants is to remain stable in use for the lifetime of the wood product before they decompose rapidly after disposal. This balancing act is still under investigation.

3.3. Inorganic eco-friendly additives

Inorganic flame retardants are not a new phenomenon. However, some of them are classified as sustainable due to their safe use, availability, and lack of toxicity. Unlike halogenated species, the additives will not release toxic gases when combusted.

Typical inorganic materials are aluminum hydroxide (ATH) and magnesium hydroxide (MH). Both are nanostructured and when heated, the hydroxides release water vapor that can cool the material and dilute the flammable gases, thereby decreasing the likelihood of ignition and delaying flame spread [19]. Large amounts are typically needed, which can decrease the mechanical strength of wood if not properly used.

Another class of nanostructured materials that shows much promise is layered double hydroxides (LDHs). These can act as protective barrier layers and retardants by reducing the transfer of heat and oxygen to the combustion front, thereby enhancing fire resistance. LDHs can also be combined with bio-based compounds to improve their performance [20]. Graphene oxide and clay nanoparticles are also investigated as flame-retardant additives [21]. When used as protective coatings, they can slow down the transfer of heat to the wood and act as a barrier to the ingress of oxygen. Such nanomaterials are effective in small amounts, which makes them attractive for preventing the mechanical and aesthetic quality of wood from being compromised.

4. Synthesis and manufacturing methods

The fire-retardant efficacy of sustainable flame retardants does not only depend on the chemical itself, but also on how well it infiltrates into the wood. Engineers have tested a wide variety of preparation techniques over the past decade. The goal is to find a balance between cost, durability, and ease of large-scale production. In many cases, the choice of technique will determine whether a technology will succeed in transferring from the laboratory to real-life application on the factory production line.

Solution impregnation remains as the most popular technique today. In this technique, the flame-retardant chemical is a water-soluble salt or phytic acid, a plant acid [22]. The wood is placed inside a sealed chamber. Vacuum and pressure cycles push the solution deep into the cell walls of the wood. As the chemicals make their way to the core of each individual plank, the protection survives after sanding, planning, and surface abrasion. One major shortcoming of this technique is that it

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requires expensive pressure vessels and pump systems. This makes it less attractive for small wood workshops and for construction in remote areas.

Yet another technique that is being intensely studied is the LbL, or layer-by-layer, assembly method. Here, wood is alternately dipped in positively and negatively charged solution baths, or treated with each via spraying. Each dip deposits an ultra-thin layer of a few nanometers, so dozens of layers can be built up, each one a nearly invisible composite coating. Common combinations include biopolymers such as chitosan (cationic) and phytate (anionic) [23]. Because so much control exists over thickness and composition at the atomic level, researchers can fine-tune fire resistance without adding mass. Yet the repetitive steps required to build up the layer by layer stacks limit production efficiency, so a true large-scale manufacturing process has remained elusive.

Sol-gel processing provides a third alternative. Liquid precursors containing silicon, aluminum, or other metals are brushed, sprayed, or dipped onto the wood. As the liquid solvent evaporates, the precursors polymerize into a hard, glass-like network embedded in—or bonded to—the wood. These films are transparent, mechanically tough, and resistant to moisture—and they offer attractive properties for architectural finishes that must display natural grain [24]. But sol-gel chemistry requires close control of pH and temperature and curing time. Operational errors can result in cracking and powdery residues on the surface, increasing manufacturing complexity.

The sol-gel process provides a third route. Liquid precursors containing metals such as silicon and aluminum are applied to the wood surface by brushing, spraying or dipping. As the liquid solvent evaporates, the precursors polymerize into a glass-like network embedded in – or bonded to – the wood. Such layer exhibit transparency, mechanical strength, and moisture resistance, making them suitable for architectures that requires natural wood grain display. However, sol-gel processes require strict control of pH, temperature and curing time. Operational errors may result in cracking and powdery residues, increasing manufacturing complexity.

In summary, these three routes highlight one familiar trade-off in materials science: the faster or cheaper a process, the harder it is to achieve perfect coverage and long-term stability. We'll see if hybrid routes, quick impregnations followed by a thin sol-gel seal, can capture the best features of each process while driving cost down.

5. Application of sustainable flame-retardant in woods

Any good flame retardant needs to move from the lab bench to a practical application – in this case, timber boards, beams and columns. They also need a practical application – in this case, homes, schools and offices. Now, three main application routes are being tested on an industrial scale or commercialized in coatings, impregnations and composite systems. Each approach is designed to increase fire resistance while maintaining the natural appearance and strength of the timber.

The most common ones are surface coating technologies such as paints, stains or clear varnishes with environmentally friendly additives. Tannic acid, lignin or nanocellulose may be bio-based additives that slow down ignition and smoke emission together with mineral fillers such as nano clay [25]. Since these coatings can be applied using existing finishing production lines, it is also possible to put them into practice on a large scale by furniture and flooring manufacturers. The weakness of coatings is their abrasion resistance. Heavy foot traffic, UV exposure or abrasive cleaning will eventually wear away the surface, so periodic recoating or spraying with a reinforcement must be performed.

A more penetrating treatment is pressure impregnation. A liquid formulation such as phytate salts, phosphates or nitrogen-phosphorus compounds is injected directly into the core of a column, flooring or structural beam through alternating vacuum and pressure cycles. The obtained fire

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resistance fulfils the strictest building codes and survived even after deep cutting or sanding [26]. On the other hand, pressure impregnation requires the use of autoclaves and rigorous chemical management, making the impregnation plants capital-intensive and highly regulated.

The next technological frontier should be hybrid treatment: the addition of sol-gel films or layered nanocoating to the surface of impregnated timber. For example, boards drenched in magnesium hydroxide and then coated with a thin clay layer, showed 3 times increase in ignition delay and greatly reduced smoke density. By spreading protective functions over the wood's interior and surface, this integrated approach reduces the amount of chemicals and has potential for maintaining wood stiffness and color. Pilot production lines in Europe and Asia are investigating the production cycles, waste streams and life cycle costs.

The current research still faces challenges in terms of cost, long-term weather resistance and potential interactions with coatings or adhesives. The steady flow from laboratory samples to factory trials suggests that sustainable flame retardants are gradually entering mainstream applications in timber construction.

6. Conclusion

Timber provides architects with an exceptional combination of high strength, low weight and renewability, but its flammability has limited its use, especially in high-rise and public buildings. Traditional halogenated flame retardants ensured fire safety, but with side-effects. They cause concern because they are persistent and can bio-accumulate. These questions lead regulators in North America, Europe and some Asian countries.

New research shows promising alternatives. Bio-derived molecules such as phytic acid, tannic acid, lignin, chitosan induce rapid charring, seal surfaces and slow down heat transfer. Environmentally friendly minerals such as aluminum hydroxide or magnesium hydroxide, zinc borate, layered double hydroxides. These materials work by releasing moisture or forming a ceramic-like barrier that cools wood and excludes oxygen. When combined and synergistically formulated, these components reduce chemical usage and side-effects.

But just as vital is the processing technology which must efficiently deliver these green additives to the best zones of target components. Solution impregnation, layer-by-layer self-assembly, sol-gel films and novel hybrid systems offer advantages such as penetration depth, coating precision, transparency or even multi-layer protection. These allow industry to optimize treatment of beams, floors or decorative panels while maintaining the natural grain of wood.

Full commercialization will depend on a combination of three success criteria: a reduction in the cost per cubic metre, proof of long-term durability in the natural humid and sunny environment, and adaptation of the factory process to combine it with the current supply chain. Based on the experience gained over the last decade, and especially with the first pilot-scale hybrid production lines, these three targets appear to be achievable. Sustainable flame retardants are thus not only a brilliant series of laboratory inventions, but a practical model for the future of fire-safe, environmentally friendly timber construction over many decades.

References

[1] Dukarska, D., & Mirski, R. (2023) Wood-Based Materials in Building. Materials (Basel, Switzerland), 16, 8, 2987.
[2] Shen, J., Liang, J., Lin, X., Lin, H., Yu, J., & Wang, S. (2021) The Flame-Retardant Mechanisms and Preparation of Polymer Composites and Their Potential Application in Construction Engineering. Polymers, 14, 1, 82.
[3] Soares, I., Ferreira, J.L, Silva, H., Rodrigues, M.P (2024) Fire-retardant and fire-resistant coatings: From industry to the potential use on cultural heritage. Journal of Cultural Heritage, 68, 316-327.

DOI: 10.54254/2755-2721/2026.MH30528

[4] Lee, Y.X, Wang, W., Lei, Y., Xu, L., Agarwal, V., Wang, C., Yeoh G.H. (2025) Flame-retardant coatings for wooden structure. Progress in Organic Coatings, 198, 108903.
[5] Ali, S., Hussain, S.A., M.Z.M, Tohir (2019) Fire test and effects of fire retardant on the natural ability of timber: a review. Pertanika J. Sci. Technol., 27, 2.
[6] Chen, C. & Hu, L.B. (2020). Nanoscale Ion Regulation in Wood-Based Structures and Their Device Applications. Advanced Materials. 33.
[7] Salmeia, K.A.; Fage, J.; Liang, S.; Gaan, S. (2015) An Overview of Mode of Action and Analytical Methods for Evaluation of Gas Phase Activities of Flame Retardants. Polymers, 7, 504-526.
[8] Mali, P., Sonawane, N.S., Patil, V., Lokhande, G., Mawale, R., Pawar N. (2022) Morphology of wood degradation and flame retardants wood coating technology: An overview. International Wood Products Journal, 13, 1, 21-40.
[9] Shen, J., Liang, J., Lin, X., Lin, H., Yu, J., & Wang, S. (2021) The Flame-Retardant Mechanisms and Preparation of Polymer Composites and Their Potential Application in Construction Engineering. Polymers, 14(1), 82.
[10] Harhoosh, A.A., Yurtov, E.V. & Bakhareva, N.I. (2022) Flame Retardant Strategies and the Physical Barrier Effect of Nanoparticles to Improve the Thermal Performance of a Polymer. Theor Found Chem Eng 56, 545–553.
[11] Castrovinci, A. and Camino, G. (2007) Fire-retardant mechanisms in polymer nano-composite materials, in Multifunctional Barriers for Flexible Structure: Textile, Leather and Paper. Duquesne, S., Magniez, C., and Camino, G., Eds., Berlin: Springer, 97, 87–108.
[12] Liu, Y., Zhang, A., Cheng, Y., Li, M., Cui, Y., Li, Z. (2023) Recent advances in biomass phytic acid flame retardants. Polymer Testing, Volume 124, 108100.
[13] Liang, Y., Jian, H., Deng, C., Xu, J., Liu, Y., Park, H., Wen, M., & Sun, Y. (2023) Research and Application of Biomass-Based Wood Flame Retardants: A Review. Polymers, 15, 4, 950.
[14] Grigsby, W.J., Bridson, J.H., Schrade, C. (2015) Modifuing Biodegradable Plastics with Additives Based on Condesnsed Tannin Esters. J. Appl. Polym. Sci., 132, 41626–41635.
[15] Tributsch, H., Fiechter, S. (2008) The Material Strategy of Fire-Resistant Tree Barks. In: de Wilde W.P., Brebbia C.A., editors. High Performance Structures and Materials IV. 1st ed. WIT Press; Southampton, UK, 43–52.
[16] Wang, M., Yin, G., Yang, Y., Fu, W., Palencia, J.L.D., Zhao, J., Wang, N., Jiang, Y., Wang, D. (2023) Bio-based flame retardants to polymers: A review, Advanced Industrial and Engineering Polymer Research, 6, 2, 132-155.
[17] Maqsood, M., & Seide, G. (2020) Biodegradable Flame Retardants for Biodegradable Polymer. Biomolecules, 10, 7, 1038.
[18] Guo, B., Liu, B., Zhang, Q., Wang, F., Wang, Q., Liu, Y., Li, J., and Yu, H. (2017) ACS Applied Materials & Interfaces, 9, 27, 23039-23047.
[19] Ou, Y.X., Fang, X.M. (2017) Status quo and development trends of metal hydroxides based flame retardants. Fine Specif. Chem., 15, 1–5.
[20] Zhang, T., Wang, C., Wang, Y., Wang, Y., & Han, Z. (2022) Effects of Modified Layered Double Hydroxides on the Thermal Degradation and Combustion Behaviors of Intumescent Flame Retardant Polyethylene Nanocomposites. Polymers, 14, 8, 1616.
[21] Necolau, M. I., Damian, C. M., Fierăscu, R. C., Chiriac, A. L., Vlăsceanu, G. M., Vasile, E., & Iovu, H. (2021) Layered Clay-Graphene Oxide Nanohybrids for the Reinforcement and Fire-Retardant Properties of Polyurea Matrix. Polymers, 14, 1, 66.
[22] Li, L., Chen, Z., Lu, J., Wei, M., Huang, Y., & Jiang, P. (2021) Combustion Behavior and Thermal Degradation Properties of Wood Impregnated with Intumescent Biomass Flame Retardants: Phytic Acid, Hydrolyzed Collagen, and Glycerol. ACS omega, 6, 5, 3921–3930.
[23] Yan, Y., Dong, S., Jiang, H., Hou, B., Wang, Z., and Jin, C. (2022) Efficient and Durable Flame-Retardant Coatings on Wood Fabricated by Chitosan, Graphene Oxide, and Ammonium Polyphosphate Ternary Complexes via a Layer-by-Layer Self-Assembly Approach. ACS Omega, 7 , 33, 29369-29379.
[24] Bellayer, S., Gossiaux, A., Duquesne, S., Dewailly, B., Bachelet, P., Jimenez, M. (2022) Transparent fire protective sol-gel coating for wood panels. Polymer Testing, 110, 107579.
[25] Gigante, V., Panariello, L., Coltelli, M. B., Danti, S., Obisesan, K. A., Hadrich, A., Staebler, A., Chierici, S., Canesi, I., Lazzeri, A., & Cinelli, P. (2021) Liquid and Solid Functional Bio-Based Coatings. Polymers, 13, 21, 3640.
[26] Holeček, T.& Sedivka, P. & Sahula, L. & Bercak, R. & Zeidler, A. & Hájková, K. (2025) Investigation of Pressure Vacuum Impregnation Using Inorganic, Organic, and Natural Fire Retardants on Beech Wood (Fagus sylvatica) and Its Impact on Fire Resistance. Fire, 8, 8.