APPLICATION OF NANOTECHNOLOGY IN WOOD COATING

Abstract

Wood has been integral to human civilization due to its availability, natural regeneration, and diverse applications. Researchers are constantly studying short-rotation plantation species for viability as an alternative to long-rotation trees. However, the plantation species are comparatively weaker, dimensionally unstable, and primarily susceptible to decay and diseases, which results in their infrequent utilization in furniture, handicrafts, and other industries. Nanoscience and nanotechnology are advanced forms of technology which primarily modify the material structure and behaviour at atomic and molecular levels and are used in various industries, including health, information society, energy, transportation, and space exploration. Nanotechnology is rapidly advancing in the building industry, but little emphasis has been given to strengthening wooden buildings. Nanometal oxides are known as UV absorbers, which protect the wood from degradation. Additionally, nanoparticles can be used in film-forming, penetrating surface treatments and as fungicides, biocides, or water repellents.

Keywords: Fire Retardant, Nano-Additive, Nano-Coating, Wood.

Authors

Sumanta Das
Department of Wood Processing and Biomaterials
Faculty of Forestry and Wood Sciences
Czech University of Life Sciences Prague
Kamýcká, Prague, Suchdol
Czech Republic.
dass@fld.czu.cz

Manaswini Mahapatra
Department of Plant Pathology
Agricultre and Allied Sciences
C.V Raman Global University
Bidyanagar, Mahura, Janla
Bhubaneswar, Odisha, India.

I. INTRODUCTION

People have used wood ever since civilization began as it is readily available, naturally regenerates, and has a broad range of applications. Even if steel and concrete have been used in structural applications at a higher frequency over the last 150 years, wood remains an essential component of our infrastructure. It is one of the materials that may be replenished over time. As a result, wood has been transformed into products with a wide variety of uses. The prospect of using different types of wood that are easily accessible and relatively inexpensive as alternatives to traditional timber-producing species is something that researchers are constantly investigating. To satisfy the ever-increasing need for wood, researchers are looking at the viability of short-rotation plantation species as a viable alternative to long-rotation trees. According to Moya & Munoz (2010), the dimensional instability, susceptibility to decay, and lack of strength properties of plantation wood are caused by the wood's lower density, with proportionately higher juvenile wood than heartwood, and larger growth rings. Because of these defects, it is seldom used for applications like furniture, handicrafts, building, and other similar fields. For wood to be useful in technically created applications generated by industry, it must first be treated with additional materials or compounds derived from various sources, referred to as additives.

Nanoscience and nanotechnologies are relatively new branches of science and technology aiming to regulate the structure and behaviour of materials on an atomic and molecular size. Nanomaterials are materials that are between one and one hundred nanometres in size. "Nano" refers to 10^9. Nanotechnology is an interdisciplinary field combining the study of technology to produce new and improved materials that are better in their functional, physical, and chemical properties. According to Jasmani et al. (2020), the properties shown by compounds at this scale are unique from those exhibited by the same substances at their distinct dimensions. As a result, research into the unconventional applications of nanotechnology might benefit various industries. Health, information society, industry, energy, transportation, and space exploration are just some areas that use hundreds of different products that incorporate nanomaterials. Nanotechnology significantly boosts innovation in previously established processes and products, particularly in construction and cultural heritage. Their application contributes to their propagation in specific architectural settings worldwide. The building industry is one of the essential industries in which nanotechnology is now experiencing tremendous development. However, it is crucial to keep in mind that the majority of research has concentrated on materials in concrete and metallurgy. Several nano-products are now available to preserve wood, but relatively little attention has been dedicated to reinforcing wooden buildings (Marzi, 2015).

Nanoscale structured coatings have garnered significant attention and have been a focal point of much study. In addition to meeting the established performance criteria, which include longevity, durability, resistance to environmental factors, higher bonding performance, eco-friendly, these coatings incorporate supplementary features include photocatalytic characteristics, resilience to water and fire, scratching, graffiti, and germs, to name a few. This is in addition to the fact that they meet all of the standard performance criteria (Marzi, 2015). Recent research into using nanoparticles to enhance wood's characteristics has been limited. A number of studies (Mahltig et al., 2008; Wang et al., 2006) have demonstrated that the incorporation of nanoparticles into a wide range of polymers, papers, and textiles may greatly enhance their mechanical, combustion, hydrophobic, and other properties. It was further observed that using nanoparticles to enhance wood characteristics has only favourable outcomes. Various nanoparticles may increase UV protection, mechanical features, and durability and decrease moisture absorption (Mahltig et al., 2008; Moya et al. 2017) also provide opportunities to enhance fire resistance (Ren et al., 2018; Yao et al., 2019). The findings above have shown new opportunities for application in wood science and technology. Full cross-section treatments, in addition to surface treatments, may extend the useful life of wood goods. This chapter will focus on the current advancement of nanotechnology applications in wood-based sectors, particularly wood coatings primarily used to enhance the wooden product's performance and durability.

II. NANOTECHNOLOGIES FOR WOOD IN THE CONSTRUCTION FIELD

Around 100 nanometres thick, a nano-thin layer is deposited onto the substrate during the nano-coating process, which may improve the already present characteristics or introduce new ones. Nano-coating might benefit a more substantial material with a vast surface area. When used in situations where its stability is a limiting factor, wood coated with nanocomposite materials may have improved performance and functionality, which may help it survive longer. On the other hand, it has been brought to people's attention that some standard wood preservation technologies and treatments now available on the market are harmful to human and environmental health. As a result, there is a need for novel non-toxic products. It is possible to apply a variety of nano-impregnations on wood, and nanomaterials are often included in either aqueous, organic, or polymeric coatings. Spreading them evenly over a suitable medium is necessary to prevent nanoparticle aggregation. Due to their higher ratio of surface to mass, even a meagre percentage of accumulation in coatings may have a discernible impact on the physical, chemical, and thermal, properties of the coatings (Jasmani et al., 2020). Recently, the use of nanocoatings increased exponentially due to improved techniques that enable nanoscale control of the structure of coatings (Jasmani et al., 2020; Marzi, 2015). Marzi (2015) researched the present state of nano-based wood coatings available in markets worldwide, shown in Fig. 1. The ability to withstand water and the effects of UV radiation are two of the most important applications for these goods. It is essential to consider that the world is teeming with nanoparticles, each with a unique and valuable characteristic. There is often more than one choice of nanomaterials for a given application; however, silica (SiO_2) and titanium oxide (TiO_2), may be used in various contexts.

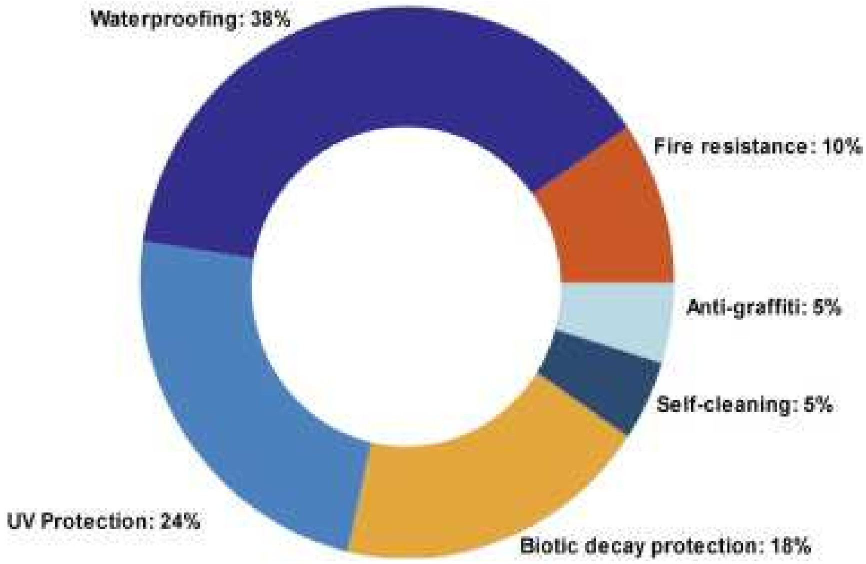

Figure 1: The Primary uses of Commercially available Nano-based Coatings for Wood (Marzi, 2015)

III. NANO-ADDITIVES IMPROVING WATER ABSORPTION

Water and moisture pose a severe hazard to wood as the chemical constituents of wood are prone to wetness. Because of its interaction with water, wood is subject to biodegradation, dimensional instability, and fast weathering. As a result, nanotechnology is being used as an alternative way to modify and functionalize wood. Increasing the amount of water wood absorbs by incorporating nanoparticles into polymeric coverings is possible. Utilizing hydrophobic nano-coatings is and interesting technological developments made in recent years to preserve wood from the weather and boost its performance in facade treatments. The majority of these products are composed of silica nanoparticles. This may be used to produce a barrier that is impermeable to water while yet allowing air to pass through it (Fig. 2). It is important to point out that this nano-structured coating is entirely free of volatile organic compounds (VOCs) and has essential water-repellent characteristics. According to Papadopoulos et al. (2019), the nanoparticles may be integrated into the coatings by either a solution mixing technique or an in-situ addition procedure. In their research, Wu et al. (2020) created a super-hydrophobic coating on the surface of poplar wood by applying a waterborne UV lacquer product (WUV) modified with ZnO nanoparticles and stearic acid. This coating had a contact angle of up to 158.4 degrees. Since the zinc stearate/waterborne UV lacquer super-hydrophobic coating ($ZnSt_2$/WUV) has a greater resistance to water than WUV, it is an excellent choice for the preparation of super-hydrophobic coatings in a way that is both practical and beneficial to the environment. Researchers employed a varnish of water mixed with titanium dioxide nanoparticles (TiO_2) (Moya et al. 2017). This allowed them to compare the finishes of nine different tropical wood species. The varnish that had not been changed with the addition of TiO_2 nanoparticles broke down entirely after one year of exposure to the elements. On the other hand, the modified varnish layer remained intact since adding TiO_2 decreased the water absorption values. Before polymerization can begin, the in-situ addition process, also often called a chemical operation, requires the addition of chemicals directly to monomers. The nanoparticles may be created by various chemical processes on the wood surface, including hydrothermal procedures and sol-gel deposition. Gao et al. (2016) used AgNPs coated with fluoroalkyl silane to create a super-hydrophobic, conductive wood surface with improved oil repellency. The multifunctional coating displays a wide variety of potential uses, from biomedical electronics to the development of self-cleaning surfaces. Based on the research conducted by Li et al. (2015a), it was observed that ZnO nanosheet networks were synthesised by a hydrothermal process on the surface of bamboo. Subsequently, these networks were subjected to modification using fluoroalkyl silane. The bamboo that underwent successful treatment had a range of notable attributes, such as a significant level of super-hydrophobicity, the capacity to withstand UV radiation and freezing temperatures, and a surprising resilience when subjected to an acid rain simulation. Li et al. (2015b) reported that the hydrothermal deposition of anatase TiO_2 nanoparticles, followed by the modification with octadecyl trichlorosilane, led to the enhancement of characteristics in bamboo wood in a similar fashion. Additional techniques for the preparation of super-hydrophobic wood surfaces involve the application of a waterborne perfluoroalkyl methacrylic copolymer (PMC)/TiO_2 nanocomposite through spray coating onto a surface pre-coated with PDMS. Another method entails the layer-by-layer assembly of polyelectrolyte/TiO2 nanoparticles multi-layers, followed by hydrophobic modification using perfuoroalkyltriethoxysilane (POTS) (Lu & Hu, 2016). Wang et al. (2018) also investigated the utilisation of soft lithography in the construction of a SiO2 super-hydrophobic bamboo surface, employing a biomimetic technique that closely mimics the characteristics of a lotus leaf.

Figure 2: The Lotus Effect and Waterproofing Provided by Silica Nanoparticle-based Nano-Coatings on Wood Surfaces (Marzi, 2015)

IV. NANOADDITIVE FOR IMPROVEMENT OF ULTRA-VIOLET RAY (UV) ABSORPTION

The initiation of a chain reaction occurs upon the wood's exposure to sunlight, wherein the wood undergoes light absorption, resulting in a change in coloration and subsequent erosion. Teaca et al. (2013) have reported that the structural constituents of wood, namely lignin, cellulose, and hemicellulose, exhibit susceptibility to photochemical degradation. The photodegradation process commonly results in the diminished water resistance of wood and other materials, hence accelerating their biodegradation in the ambient environment. The implementation of light-stabilization technologies, surface coatings, or substitution of materials with greater resistance to UV radiation has the potential to mitigate the extensive harm inflicted by the UV component of solar radiation (Jasmani et al., 2020). Nanoparticles with functional coatings that provide UV-blocking capabilities provide good UV radiation protection without reducing the surface's transparency. Nanoparticles are far more effective in blocking UV radiation than natural materials (Jasmani et al., 2020). This is due to nanoparticles' large surface area to volume ratio and their microscopic size. Lignin may be protected from the damaging effects of sunlight by coatings that absorb UV radiation. Nanoparticles of TiO_2 and ZnO are frequently used as UV absorbers, significantly reducing the photo discolouration of the wood surface, and the system remains chemically stable (Wallenhorst et al., 2018). Coatings for the outside of bamboo that are made of acrylic and include nanoparticles of benzotriazole (BTZ) and zinc oxide (ZnO) have been studied by Rao et al. (2019). They reported that the formulation with a ratio of 2:1 had the most synergistic effects among the BTZ-ZnO coatings. Covering the bamboo surfaces minimized discolouration when the surfaces were exposed to light. One of the best UV and VIS treatments for wood colour stability is benzotriazoles hindered amine light stabilisers (HALS) with TiO2 and ZnO nanoparticles (Panek et al., 2018). In their study, Zheng et al. (2016) conducted an experiment in which they treated wood samples with rutile TiO2, as well as different combinations of methyltrimethoxysilane and hexadecyltrimethoxysilane. The researchers then proceeded to evaluate the resulting effects on weathering resistance, surface colour alteration, and weight reduction. When wood is exposed to ultraviolet (UV) radiation in the absence of water spray, it appears that the TiO2 coating enhances its ability to retain its colour. Nevertheless, it has been observed that the presence of TiO2 leads to a deterioration of the wood surface in the nearby vicinity, owing to its photocatalytic activity (Zheng et al., 2016).

V. NANOADDITIVE FOR IMPROVEMENT OF WOOD DURABILITY

Nano-coating using nanoparticles may increase the molecular durability of wood and non-wood goods. Coatings have the potential to impede the proliferation of microorganisms such as bacteria and fungus. Previous studies have shown the potent antibacterial capabilities of metal oxide nanoparticles, including zinc oxide (ZnO) and titanium oxide (TiO) (Chakra et al., 2017), and cerium oxide (CeO_2) (Tomak et al., 2018). The remarkable capacity of graphene to impede the propagation of diseases is likewise deserving of attention. In order to enhance the resistance of mould and the antibacterial properties, it has been suggested by Wang et al. (2018) that a two-step dip-dry and hydrothermal technique may be used to coat bamboo-based outdoor goods with reduced graphene oxide and nano-ZnO. Weththimuni et al. (2019) observed that the hydrothermally produced nano-structured ZnO exhibited efficacy in mitigating the process of biodeterioration on wood surfaces. According to Cheng et al. (2020), the incorporation of nanocrystalline cellulose (NCC) and silver nanoparticles (AgNPs) into waterborne polyurethane coatings (WPU) resulted in enhanced antibacterial properties in wood boards. Silver nanoparticles (AgNPs) are well recognised for their strong antibacterial properties; however, they often exhibit a tendency to agglomerate throughout the manufacturing process. Therefore, the incorporation of NCC resulted in improved compatibility between AgNPs and WPU as well as other coatings. Furthermore, the use of NCC as a reinforcing agent has shown commendable performance in enhancing the mechanical characteristics of nanocomposites. In order to inhibit the proliferation of black-stain fungus on wooden surfaces, Boivin et al. (2019) conducted the synthesis of acrylic latex coatings containing AgNPs using micro-emulsion polymerization. The antibacterial capabilities of silver and zinc oxide nanoparticles in acrylic coatings for particleboard and medium-density fibreboard were examined by Izdinsky et al. (2018). Further, the antibacterial activity of Ag and ZnO nanoparticles was found to be less effective against

Staphylococcus aureus while effective against the *Escherichia coli* (Jasmani et al., 2020). Since from a longer time, colloidal nanosilver has been available commercially and is well recognised for its biocidal abilities. Upon contact with water, silver ions are liberated from compounds that contain silver. Catalytically useful nanosilver particles are protected by a polymeric matrix and coating. The process of leaching from paints typically results in the conversion of nanosilver into less hazardous substances, such as silver sulphide, as shown by Kaegi et al. (2010). This transformation serves to mitigate any health hazards associated with nanosilver. The use of nanosilver to wood has been shown to effectively mitigate biodegradation (Fig. 3) and enhance resistance against termites (Marzi, 2015).

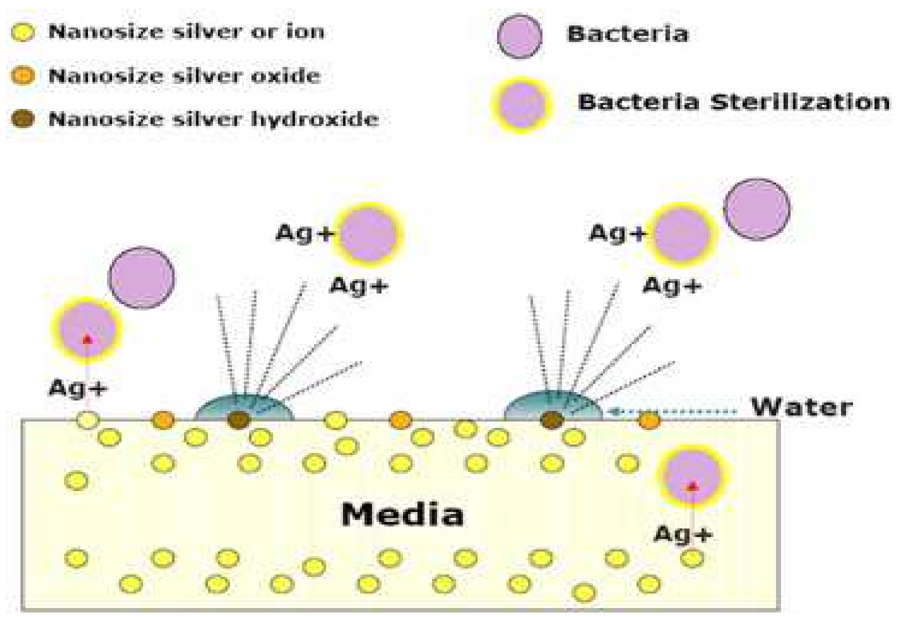

Figure 3: Silver Nanoparticles Against the Microbial Activity of Wood (Marzi, 2015)

Nanotechnology-based treatments may be used to make wood more durable against biodegradation agents and the elements (Papadopoulos et al., 2019). Incorporating nano-products into wood increases its longevity in use and in contrast, complete system penetration allows for the homogenous dispersion of nano-products (Papadopoulos et al., 2019). There are several nano-products (nano preservatives) on the market for protecting wood, and many more are in different phases of research. The two most frequent types of wood protection nanotechnology are nanocapsules and nanomaterials.

VI. ENHANCEMENT OF FIRE RETARDANCY BY THE APPLICATION OF NANOADDITIVES

Fire safety concerns have led to the imposition of restrictions on both wooden and concrete constructions. The comprehensive assessment of the flame-retardant properties of the materials is crucial for addressing their inherent limits and ensuring their safe use. In recent times, the use of nanoparticles has been seen in the development of fire-resistant nanocomposites. The use of nanoparticles, either by itself or in combination with conventional fire retardants, is one possible strategy for reducing the combustibility of wood. Nanomaterials possess notable commercial and economic benefits in comparison to conventional chemicals, owing to their diminutive dimensions and expansive surface area.

According to a study conducted by Deraman & Chandren (2019), the application of TiO_2 coating on wood demonstrated a reduced flammability and a decreased rate of flame propagation in comparison to wood that had not been treated. Ren et al. (2018) accomplished the synthesis of double-nanostructures consisting of ZnO and TiO_2 on a bamboo substrate. The material's flame-retardant properties were significantly enhanced by the use of a ZnO-TiO_2 coating, as shown by a notable increase in the oxygen index from 25.6% to 30.2%. Layered double hydroxides (LDHs) exhibit significant efficacy as flame retardants due to their ability to effectively absorb substantial quantities of heat during the process of thermal degradation, hence mitigating the concentration of flammable gases and effectively sequestering hazardous acid gases (Yao et al., 2019). Nano magnesium aluminium layered double hydroxide (Mg-Al LDH) applied to bamboo in a single step reduced total heat by 33.3% and smoke production by 88.9%, according to Yao et al. (2019). By incorporating Zn-Al LDH nanostructures into wood, Wang et al. (2018) found that peak heat release rate (PHRR) and total smoke production could be reduced by 55% and 47%, respectively, compared to untreated wood. Esmailpour et al. (2020) demonstrates that nano-structured carbon compounds like graphene may be used to provide wood and wood composites fire resistance. The potential enhancement of fire safety might be achieved by the use of thin film fire retardant coatings including titanium and silicon dioxide nanoparticles. Regular airless sprayers may be used to disperse these chemicals, which are designed to suppress flames and reduce the emission of smoke. When subjected to heat, they effectively suppress the fire by depriving the flames of oxygen. According to Bertolini et al. (2010), it is necessary to develop a substantial layer of char in order to effectively mitigate the risk of surface ignition. The possible enhancement of fire resistance and heat transmission in wood has been the subject of investigation regarding nanosilver coatings, owing to their notable thermal conductivity (Taghiyari, 2012). Based on the existing data, it has been observed that the use of Nanosilver treatment on solid wood products has the potential to enhance their fire-resistant properties. The use of such a coating has the potential to mitigate thermal degradation and carbonization processes by minimising heat buildup. Fire-retardant properties of solid woods and wood composite products were found to be significantly enhanced by the inclusion of wollastonite nano-fibres (Poshtiri et al., 2014). According to Taghiyari (2012), the use of nano-sized wollastonite as a fire retardant is attributed to its ability to provide a physical barrier between the flames and the wood.

VII. CONCLUSION

Nanotechnology in wooden industry is promising have can potentially change sector globally and domestically. Wooden products possessed lower resistance to the UV light; hence, many studies have focused on colour preservation techniques. Nanometal oxides provide UV absorbers that match or surpass organic ones. However, we believe inorganic absorbers' long-term stability has to be confirmed. In the present and the future, in particular, safety and health laws will impact how well people are protected against microbes. There are several methods for keeping wood from weathering its natural colour when used outdoors, but few are sustainable or effective in the long run. UV protection systems based on nanoparticles might be the answer to this issue. They're versatile enough to be utilized as a filler in film-forming, penetrating surface treatments, or even on their own. Further they often have additional benefits like a fungicide or biocidal or as water-repellent.

REFERENCES

[1] Bertolini, C., Crivellaro, A., Marciniak, M., Marzi, T., & Socha, M. (2010). Nanostructured materials for durability and restoration of wooden surfaces in architecture and civil engineering. *Proceedings of World Conference on Timber Engineering,* 20.-24., *Riva Del Garda, Trento, Italy.*

[2] Boivin, G., Ritcey, A. M., & Landry, V. (2019). The effect of silver nanoparticles on the black-stain resistance of acrylic resin for translucent wood coating application. *BioResources*, *14*(3), 6353-6369.

[3] Chakra, C., Raob, K., & Rajendar, V. (2017). Nanocomposites of ZnO and TiO_2 have enhanced antimicrobial and antibacterial properties than their disjoint counterparts. *Dig J Nanomater Biostruct*, *12*, 185-193.

[4] Cheng, L., Ren, S., & Lu, X. (2020). Application of eco-friendly waterborne polyurethane composite coating incorporated with nano cellulose crystalline and silver nano particles on wood antibacterial board. *Polymers*, *12*(2), 407.

[5] Deraman, A. F., & Chandren, S. (2019). Fire-retardancy of wood coated by titania nanoparticles. In *AIP Conference Proceedings, 2155*, AIP Publishing.

[6] Esmailpour, A., Majidi, R., Taghiyari, H. R., Ganjkhani, M., Mohseni Armaki, S. M., & Papadopoulos, A. N. (2020). Improving fire retardancy of beech wood by graphene. *Polymers*, *12*(2), 303.

[7] Gao, L., Lu, Y., Li, J., & Sun, Q. (2016). Superhydrophobic conductive wood with oil repellency obtained by coating with silver nanoparticles modified by fluoroalkyl silane. *Holzforschung*, *70*(1), 63-68.

[8] Iždinský, J., Reinprecht, L., & Nosál, E. (2018). Antibacterial efficiency of silver and zinc-oxide nanoparticles in acrylate coating for surface treatment of wooden composites. *Wood Res*, *63*(3), 365-372.

[9] Jasmani, L., Rusli, R., Khadiran, T., Jalil, R., & Adnan, S. (2020). Application of nanotechnology in wood-based products industry: A review. *Nanoscale research letters*, *15*, 1-31.

[10] Kaegi, R., Sinnet, B., Zuleeg, S., Hagendorfer, H., Mueller, E., Vonbank, R., et al. (2010). Release of silver nanoparticles from outdoor facades. *Environmental pollution*, *158*(9), 2900-2905.

[11] Li, J., Sun, Q., Yao, Q., Wang, J., Han, S., & Jin, C. (2015a). Fabrication of robust superhydrophobic bamboo based on ZnO nanosheet networks with improved water-, UV-, and fire-resistant properties. *Journal of nanomaterials*, *2015*, 1-1.

[12] Li, J., Zheng, H., Sun, Q., Han, S., Fan, B., Yao, Q., et al. (2015). Fabrication of superhydrophobic bamboo timber based on an anatase TiO_2 film for acid rain protection and flame retardancy. *Rsc Advances*, *5*(76), 62265-62272.

[13] Lu, X., & Hu, Y. (2016). Layer-by-layer deposition of TiO2 nanoparticles in the wood surface and its superhydrophobic performance. *BioResources*, *11*(2), 4605-4620.

[14] Mahltig, B., Swaboda, C., Roessler, A., & Böttcher, H. (2008). Functionalising wood by nanosol application. *Journal of Materials Chemistry*, *18*(27), 3180-3192.

[15] Marzi, T. (2015). Nano-structured materials for protection and reinforcement of timber structures: A review and future challenges. *Construction and Building Materials*, *97*, 119-130.

[16] Moya, R., & Munoz, F. (2010). Physical and mechanical properties of eight fast-growing plantation species in Costa Rica. *Journal of Tropical Forest science*, 317-328.

[17] Moya, R., Rodríguez-Zúñiga, A., Vega-Baudrit, J., & Puente-Urbina, A. (2017). Effects of adding TiO_2 nanoparticles to a water-based varnish for wood applied to nine tropical woods of Costa Rica exposed to natural and accelerated weathering. *Journal of Coatings Technology and Research*, *14*, 141-152.

[18] Panek, M., Oberhofnerová, E., Hýsek, Š., Šedivka, P., & Zeidler, A. (2018). Colour stabilization of oak, spruce, larch and douglas fir heartwood treated with mixtures of nanoparticle dispersions and UV-stabilizers after exposure to UV and VIS-radiation. *Materials*, *11*(9), 1653.

[19] Papadopoulos, A. N., Bikiaris, D. N., Mitropoulos, A. C., & Kyzas, G. Z. (2019). Nanomaterials and chemical modifications for enhanced key wood properties: A review. *Nanomaterials*, *9*(4), 607.

[20] Poshtiri, A. H., Taghiyari, H. R., & Karimi, A. N. (2014). Fire-retarding properties of nano-wollastonite in solid wood. *Philippine agricultural scientist*, *97*(1), 52-59.

[21] Rao, F., Zhang, Y., Bao, M., Zhang, Z., Bao, Y., Li, N., et al. (2019). Photostabilizing efficiency of acrylic-based bamboo exterior coatings combining benzotriazole and zinc oxide nanoparticles. *Coatings*, *9*(9), 533.

[22] Ren, D., Li, J., Xu, J., Wu, Z., Bao, Y., Li, N., & Chen, Y. (2018). Efficient antifungal and flame-retardant properties of ZnO-TiO2-layered double-nanostructures coated on bamboo substrate. *Coatings*, *8*(10), 341.

[23] Taghiyari, H. R. (2012). Fire-retarding properties of nanosilver in solid woods. *Wood Science and Technology*, *46*, 939-952.

[24] Teaca, C. A., Roşu, D., Bodîrlău, R., & Roşu, L. (2013). Structural changes in wood under artificial UV light irradiation determined by FTIR spectroscopy and color measurements-A brief review. *BioResources*, *8*(1).
[25] Tomak, E. D., Yazici, O. A., Parmak, E. D. S., & Gonultas, O. (2018). Influence of tannin containing coatings on weathering resistance of wood: Combination with zinc and cerium oxide nanoparticles. *Polymer Degradation and Stability*, *152*, 289-296.
[26] Wallenhorst, L., Gurău, L., Gellerich, A., Militz, H., Ohms, G., & Viöl, W. (2018). UV-blocking properties of Zn/ZnO coatings on wood deposited by cold plasma spraying at atmospheric pressure. *Applied Surface Science*, *434*, 1183-1192.
[27] Wang, J., Li, J., Zhuang, X., Pan, X., Yu, H., Sun, F., et al. (2018). Improved mould resistance and antibacterial activity of bamboo coated with ZnO/graphene. *Royal Society Open Science*, *5*(8), 180173.
[28] Wang, Z., Han, E., & Ke, W. (2006). An investigation into fire protection and water resistance of intumescent nano-coatings. *Surface and Coatings Technology*, *201*(3-4), 1528-1535.
[29] Weththimuni, M. L., Capsoni, D., Malagodi, M., & Licchelli, M. (2019). Improving wood resistance to decay by nanostructured ZnO-based treatments. *Journal of Nanomaterials*, *2019*.
[30] Wu, Y., Wu, X., Yang, F., & Ye, J. (2020). Preparation and characterization of waterborne UV lacquer product modified by zinc oxide with flower shape. *Polymers*, *12*(3), 668.
[31] Yao, X., Du, C., Hua, Y., Zhang, J., Peng, R., Huang, Q., & Liu, H. (2019). Flame-retardant and smoke suppression properties of nano MgAl-LDH coating on bamboo prepared by an in-situ reaction. *Journal of Nanomaterials*, *2019*.
[32] Zheng, R., Tshabalala, M. A., Li, Q., & Wang, H. (2016). Photocatalytic degradation of wood coated with a combination of rutile TiO_2 nanostructures and low-surface free-energy materials. *BioResources*, *11*(1), 2393-2402.