Review Article

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Recent advancements in nanotechnology application on wood and bamboo materials: A review

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Abstract: Wood and bamboo are the greenest renewable materials used for construction, furniture, and decor from the ancient ages. However, wood and bamboo have intrinsic faults like durability, ductility, physical and mechanical strength, and stability, limiting their applications in the industry. On the other hand, nanotechnology is a popular technology having numerous applications in different fields, resulting in a significant increase in expectations among academics, investors, the government, and industries. In contrast, nanotechnology can protect wood and bamboo from extreme conditions (bacteria, climate, *etc.*) by improving physicochemical characteristics because of its unique features. Nowadays, the trend of merging nanotechnology and forest industries to overcome the limitations mentioned above and get economically sustainable materials for construction, furniture manufacturing, flexible sensors developments, energy storage, battery manufacturing, and many more is increasing. Presently, several reviews on wood and bamboo modification by nanoparticles and nanomaterials have already been published. But, at this time, this study is essential because it aims to provide a brief guide about the recently developed eco-friendly sustainable materials from wood and bamboo, their uses, and how they can affect people's daily life and helps to point out the gap of the current knowledge. In addition, we briefly describe the conventional and modern modification methods, including the influence of nanomaterials on wood and bamboo structures. This article is outlined as follows: The first phase of the review deals with wood and bamboo modification methods. The second phase explains how the modification method improves the properties of wood and bamboo materials, and the last step will describe the recent innovation of wood and bamboo materials.

Keywords: wood, bamboo, nanotechnology, application, nanoparticles, nanomaterial

1 Introduction

Wood and bamboo have porous and fibrous structures cells [1,2]. The cells are composites of cellulose, hemicellulose, lignin, and other extractives. Bamboo has higher fibre content [3,4]. According to different research results, nanocellulose and nano-lignin particles can be extracted from wood and bamboo materials, as cellulose has been considered a matrix compound because it binds fibre and microfibre [2], and lignin is made up of aliphatic and aromatic structures ("glue-like"), which hold and secure the cell walls together and provide rigidity in wood and bamboo [5,6].

Wood and bamboo are the most promising sustainable and renewable materials from the ages as they are biodegradable and renewable and do not cause any pollution to the environment. Recently, the demand for sustainable renewable products is increasing due to environmental pollution and climate change. According to Oliver *et al.*, wood's carbon footprint is lower than steel and concrete, and increasing the use of wood can reduce CO_2 emissions by 14% [7]. Coherently, wood and bamboo base products have been used in building construction and furniture making for a long time. With time, wood and bamboo became unpopular because of their inherent disadvantages of faster decay, high moisture-holding capacity, changing colour quickly, swelling, and shrinking due to sunlight, rain, temperature, and microbial erosion in the external environment [8]. These swelling and shrinking cycles induce stresses in the wood's cell walls, leading to

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the wood's warping and cracking. It also damages the microstructure of the wood and bamboo surface and structure, affecting dimension stability and service life by limiting the application of wood and bamboo materials and their base composites [9–12]. Therefore, it is necessary to improve the functional quality of wood and bamboo by changing the microstructure of the wood and bamboo surfaces to develop better physical and mechanical properties [13]. In addition, the ancient traditional practice of using wood and bamboo is becoming vogue but in newer ways. Jones and Sandberg demonstrated that the global demand for wood modification is significantly increasing. They claim that the growth of modification of wood will be higher in the next few years due to its eco-friendly approach [14]. Many research studies and reviews claim to modify the properties of wood and bamboo materials through conventional methods but these methods can affect the structure and colour of the materials [15].

But, nowadays, these problems can be solved by using nanomaterials for improving the functional quality of wood and bamboo materials. Nanomaterials can enhance the quality of wood and bamboo, which has widened the usage horizon of such products not only in the construction and furniture industry but also in energy sectors, electronic devices, and many more [16–21]. Using nanotechnology in wood and bamboo preservation and application is one of the new topics with enormous promise for the industry [22]. There are many more processes that are discussed in the article later. Yet, it is still important to evaluate any possible risks associated with the use of nanomaterials in wood and bamboo preservation and application in different fields. For example, Sun *et al.* [23] explained "the mesoscopic characteristics and nanomechanical properties of bamboo" and the benefits of modified bamboo materials and their uses, and Bi *et al.* [24] analysed and well described different modification methods and the effects of the modification methods on the wood properties in their review article. Rao *et al.* [25] reviewed the recent advancements in bamboo protection in the outdoor field through the study of photodegradation and photostability. This review article attempts to give an overview of current innovations and product development by nanomaterials from wood and bamboo materials (cellulose and lignin) in different sectors.

2 Classification of modification methods

Applying chemical, mechanical, physical, or biological techniques to change the qualities of a material is referred to as "wood modification," which is a broad word. The definition of "wood modification" in this sense encompasses practically everything that occurs to wood after it departs the forest. Different ways of modifying and treating wood/bamboo for more sustainable use exist. The wood modification includes applying a chemical, biological, or physical agent to the material, enhancing the desired quality during the wood's service life. The modified wood should not emit harmful compounds while in use or at the end of its useful life after being disposed of or recycled. It should also be harmless by itself under service circumstances. The action method should be non-biocidal if the alteration increases resistance to physical assault. It should be emphasized that the above-mentioned does not exclude the use of potentially dangerous chemicals in the production of wood that has been changed, provided that there are no hazardous residues left over after the modification process is completed [26]. It is significant to note that the number of wood modification processes that have been created or are currently being tested have their entire or partial roots in the ground-breaking studies and ground-breaking effort of "Alfred J. Stamm and his colleagues at the Forest Products Laboratory in Madison, Wisconsin, in the 1940s and 1950s" [17] (Figure 1).

2.1 Chemical modification

According to Hill's book, the reaction of a chemical reagent with the polymeric elements of wood, resulting in the

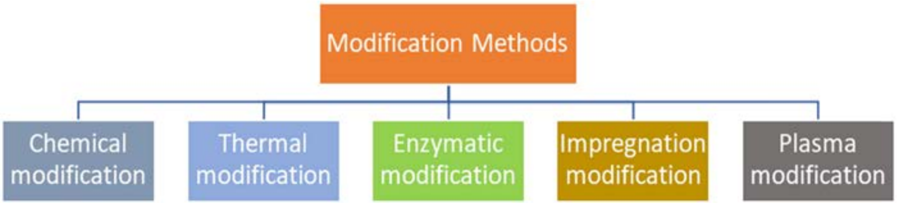

Figure 1: Categorization of modification methods.

development of a covalent link between the reagent and wood substrate, is known as the chemical modification of wood [26]. Wood can be altered by active modifications, which modify the material's chemical composition, or passive alterations, which change the qualities of the material without changing its chemical composition. Most active modification techniques included a chemical interaction between the –OH group and the reagent in the cell wall of polymers. These –OH groups are the most reactive locations and play a significant role in the wood–water interaction. When wood is wet, water molecules settle between the wood polymers and create hydrogen bonds with hydroxyl groups of specific water molecules. The amount of these water molecules fluctuates, causing the wood to shrink and swell. All possible wood treatments have an impact on how wood and water interact. Multiple wood-treatment interaction mechanisms frequently take place at once. One method of altering cell-wall polymers is heat modification, which can result in cross-linking, a decrease in OH-groups, and the unintended breaking of the polymer chains [27]. According to Teacă and Tanasă, the catalysts, reactor types, and the matter composition of the reactant, and the process have undergone significant development and are still widely employed [28]. Homan *et al.* described the chemical modification and Plato processes in their review. They found that the shrinkage and swelling were reduced, and the durability and ultraviolet resistance increased. They noticed that mechanical properties are also affected by the modification treatments [29].

2.2 Thermal modification

Heat treatment is a well-known commercial technique for enhancing wood's dimensional stability and durability. Applying heat to wood to reach the desired improvement in the material performance is referred to as the thermal modification of wood. This discovery was made in the 1920s by Tiemann. There are many great reviews on this subject [30]. The thermally treated timber (TMT) features that change in dry or wet circumstances vary significantly. These variances include variations in weight loss, sorption behaviour, and dimensional stability. A post-treatment water-soaking cycle partially reverses the reduced hygroscopicity of TMT treated under heat treatment-dry circumstances. Still, the dimensional stability of TMT modified under heat treatment-wet settings can be worse than unmodified timber (Figure 2).

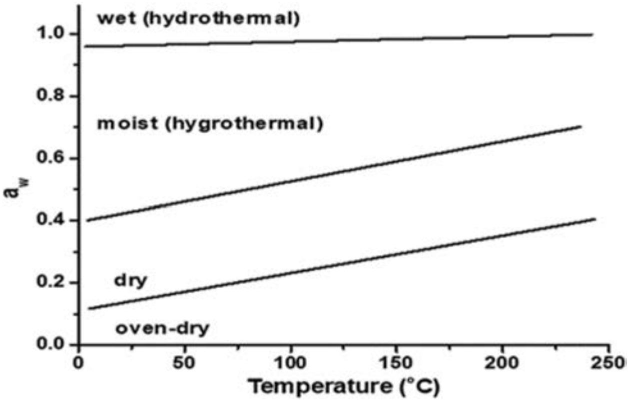

Figure 2: Various moisture conditions of wood after thermal modification [31].

The method has been much improved since then but the basic idea has not changed: wood is subjected to high temperatures (150–250°C) without oxygen and goes through a chemical transformation. Outside this range, undesirable changes occur below 150°C, water loss typically occurs, and over 250°C, carbonisation begins. Hemicellulose starts to break down and undergoes dehydration as the temperature increases, which causes the hydrophilic OH groups to vanish [32]. Cellulose eventually breaks down, but initially, its amorphous portion. Due to the crystalline nature of cellulose, which makes it more heat-resistant, the sample will become more crystalline and the hydroxyl groups will become less accessible to water and other chemicals [33]. During the degradation of lignin, polycondensation occurs, which creates more cross-links. The removal of the OH groups and the resulting lower attraction for water raises the wood's lignin content and structural stability. Overall, heat treatment enhances the durability of wood by reducing the amount and availability of hydroxyl groups. However, it also dramatically affects the mechanical characteristics of wood by degrading hemicellulose and amorphous cellulose. Thermal treatments are occasionally coupled with water or outside forces to get better outcomes in terms of characteristics. These techniques are either thermomechanical or thermo-hydromechanical [34–36].

2.3 Enzymatic modification

The use of biotechnology in the pulp and paper industry has been extensively studied; over the last few decades, some enzymatic techniques such as bio-pulping and bio-bleaching have already been used as industrial processes. However, the wood or wood-based business still shows little interest in biotechnological treatments [37]. In addition, Kudanga *et al.* reported a stepwise method to bind functional molecules to an enzymatically modified wood surface with anchor groups. Using the 62 kDa "Trametes hirsute laccase" as an anchor group, phenolic amines were linked to lignin moieties of wood. The coupling reaction to lignin was simulated using the lignin model compounds 4-*O*-methyl guaiacylglycerol-guaiacyl ether A, guaiacylglycerol-guaiacyl ether E, dehydrodivanillyl alcohol type dibenzodioxins D, and syringylglycerol-guaiacylether. Another use of laccases is the wood veneer treatment process [38]. During a coupling event driven by laccase, a hydrophobic surface was produced. In this study, several hydrophobic molecules were grafted onto the surface of wood, and stable covalent connections between the functional groups on the surface and the compounds were formed, creating a persistent hydrophobic layer on the wood surface.

2.4 Plasma modification

Depending on the thermodynamics involved, plasma, a partly or completely ionised gas, might be considered the fourth state of matter. The presence of neutral and electrically charged particles, including atoms, radicals, free electrons, ions, and photons, especially UV photons, distinguishes it [39].

The Present study demostrates the treatment of wood samples using cold, remote plasma method. Cold plasma therapy is a solvent-free, ecologically friendly alternative to chemical surface treatment procedures that uses relatively little energy and resources. It can also be used to treat materials that are susceptible to heat. Due to these benefits, cold plasma surface modification is becoming more and more common across various sectors, and surface property customisation is a hot research topic. The following two applications were investigated: The first method uses an (N_2 + O_2) mixture as a plasma gas to treat various wood types (fir, pine, oak, and beech) to prevent them from rotting. It also improves their impregnability as measured by dynamic water contact angles and absorption. The effects of three experimental parameters were evaluated and optimised: O_2/N_2 ratio, transmitted microwave power, and treatment duration. The second application involves the cold remote (N_2 + O_2) plasma (CRNOP) polymerising 1,1,3,3 tetramethyldisiloxane to deposit a superhydrophobic layer over hardwood samples to improve their durability. Under optimal conditions, depositions were carried out on beech wood pre-treated with CRNOP to promote coating penetration inside the wood [40].

There are several uses for atmospheric plasmas. Plasmas are often used in medical procedures involving dangerous or undesired waste or gases. When discharged into the atmosphere, volatile organic compounds (VOCs) or inorganic gases like nitrogen oxides (NO_x) or sulphur dioxide contaminate the ecosystem. These harmful compounds may interact with the plasma's reactive particles to create free radicals, which may merge into non-toxic molecules. In the industry, plasma can create several gases, including acetylene or the conversion of methane to higher hydrocarbons [41,42].

Consequently, X-ray microtomography was used to examine the coating distribution on the radial surfaces of untreated and plasma-treated spruce and beech wood samples. It was demonstrated that beech samples had a more comprehensive range of coating penetration than spruce samples. Before the coating was applied, the beech specimen's plasma treatment had no discernible effect on how deeply the coating penetrated. However, the spruce surface undergoing plasma treatment showed a deeper coating penetration. Nevertheless, more thorough research with more samples will be needed for a universal description [20].

Earlier developed low-pressure plasmas are frequently employed in surface preparation and material processing. They differ from atmospheric plasmas in various ways, such as having a higher concentration of ions and radicals and a more uniform glow over a larger gas volume. Still, the need for a vacuum constrains their usage during operation. The entire process is time- and energy-consuming and expensive equipment is needed. As a result, according to some authors, atmospheric equipment is suited for mass production, whereas low-pressure plasma systems are only suitable for the preparation of value-added products [43]. The findings of an exploratory investigation by Blanchard *et al.* [44] employing various gases and mixes (N_2, H_2, O_2, and Ar) at multiple pressures to apply plasma treatments to sugar maple wood board surfaces are described in that study's findings (13.3–665 Pa). The wood's water wettability and adherence to aqueous polyurethane coatings on wood were investigated. The findings reveal a substantial enhancement in coating/wood adhesion, ranging from 30% to 50%, under specific conditions. This improvement can be attributed to the increased wood surface energy resulting from the treatment. Although the methods employed (treatment duration, vacuum process) were not immediately transferrable to the industry, they might be easily modified for an affordable rate [45].

2.5 Impregnation modification

Impregnation is one of the earliest techniques for preserving wood composition, dimensions, or colour [46].

The basic idea behind the methodology is to inject various organic, inorganic, or a combination of such substances into the lumen and cell walls [47]. Intermolecular interactions may emerge between the impregnant and the cell-wall components, such as dipole–dipole or hydrogen bonds. Throughout the process, they produce a dimensionally stable wood with improved resistance to diverse types of degradation. Resins, polymers, oils, and inorganic salts – which may penetrate deeply into the wood structure – are frequently used as impregnation agents. Pressure or vacuum are often utilised to produce an effect close to ideal [48]. There are two different forms of impregnation, each with a different mechanism: either a monomer is injected into the cell wall and is then fixed by the subsequent polymerisation stage or a soluble chemical scatters into the cell walls and is then rendered insoluble [49].

The purpose of impregnation is to permanently swell the cell wall, making the hydroxyl groups physically or chemically inaccessible to water or other substances. Resins (such as phenol, urea, or melamine-formaldehyde resin), polymers, silicon-containing chemicals, or inorganic salts are the most common impregnates. However, it is only used to form a shielding coating on the surface of the wood. The coating agent may be powder, solvent-, or water-based. Traditional painting techniques can apply a volatile substance or a pigment to the surface after being dissolved or dispersed in the solvent. There is also powder coating, which creates a continuous layer of material after the surface has been coated with powder and treated with heat or radiation [50].

To prevent degradation, wood items are treated with wood preservatives. Depending on the end-product usage, pressure or non-pressure preservative treatments can integrate biocide into the wood. In contrast, ZnO/Zn was coated with cold plasma; spraying into a wooden block can improve the UV-blocking properties [23]. Alternative treatments for improving the dimensional qualities of wood and providing natural resistance include thermal and chemical changes. However, there is a contemporary movement in using nanotechnology to preserve wood. Nanotechnology can achieve this goal by impregnating wood with a suspension of metallic nanoparticles or encapsulating biocide in nanocarriers. Various nanomaterials can also be utilised in wood modification, particularly coating treatments, to improve serviceability. Nonetheless, further research is needed to provide standards for the safe deployment of nanomaterials (Table 1).

3 Wood/bamboo modification by nanoparticles/nanomaterials

Nano means exceedingly tiny, a state at the microscopic level; it comes from the Greek word “Nanos,” which means “dwarf.” Combined with technology, it became nanotechnology, first introduced by The American Noble Prize-winning physicist Richard Feynman.

Nanotechnology is considered an interdisciplinary field in sharing knowledge tools and techniques of physics, chemistry, medicine, biology, engineering, and many sub-subjects of science that belong to the nanoscale level. Nanotechnology is not entirely new because chemists have synthesised polymers, large molecules structured by microscopic subunits, in earlier days. In computer chips, nanotechnology has been more than 20 years. On the other hand, Engler and Schweizer proposed some “top-down” and “bottom-up” techniques for synthesising, producing, adjusting, or even manipulating nanoparticles/nanomaterials. The “top-down” approach is based on the cutting and etching of constructing a device, and the” bottom-up” approach is based on the fundamental component of matter (atom) for creating an instrument [26,53]. Nowadays, these two methods combine and pick new hybrid modes of manufacture.

It is essential to describe why nanotechnology is necessary for wood science. Now an attractive science, nanotechnology produces new materials with enhanced properties. The materials that have a dimension of 100 nm are called nanomaterials. Nanomaterials have a high surface/volume ratio that shows more significant attraction in surface-related phenomena than bulky systems with an identical

Table 1: Summary of different wood/bamboo modification methods

Methods	Wood structure affected by the modification process	Ref.
Chemical modification	Cell walls	[24]
Enzymatic modification	Surface	[38]
Thermal modification	Cell walls	[5,51]
Plasma modification	Surface	[19,40]
Impregnation modification	Modified substances are filled in lumens. Cell walls are impregnated	[52]

mass [54]. Nanomaterials' change in the material properties is mainly due to the large interface area that enhances the properties of the original materials, shows excellent compatibility with the conventional materials. and causes a limited modification of their original features [55]. The main advantage of applying nanotechnology in wood science is the unique ability of the nanoparticles to penetrate deeply into wood and bamboo substrates, which mainly focuses on dimensional stability and resistance to attack by microorganisms. Wood and bamboo have well-established cell walls, which show the molecular scale's porosity. In addition, small-size nanoparticles can easily penetrate and be uniformly distributed into the wood and bamboo. As a result, it alters the surface chemistry of wood and bamboo and improves their properties; therefore, a product's hyper-performance can be manufactured [56,57].

In the recent trend, three methods have been used to improve the performance of wood and bamboo materials.

(i) Nanosized metals impregnate directly in the substrate.
(ii) Polymeric nanocarriers control the release of nanoparticles.
(iii) Surface coating treatment by nanoparticles.

3.1 Impregnation of nanosized metals

There are two chemical methods to synthesise nanosized metals: solution-based and vapour-based. Sol–gel, solvothermal, and chemical are solution-based syntheses [57]. Chemical vapour deposition and combustion are vapour-based syntheses. Nanosized materials like metal nanoparticles (silver, gold, and copper) and metal oxides have unique characteristics of a high surface, particles' equal size distribution, and stability against bacterial growth [58]. These nanomaterials are more active than non-metals because of their physical and chemical properties. The metal oxides used for wood and bamboo treatment are inorganic materials with a higher surface-to-volume ratio. They show a tunnelling effect (related to quantum mechanics) [59].

Nanosized metal nanoparticles have plasmon resonance properties because they show the bright colour of the surface [60]. When the microscopic light interacts with the metal nanoparticles, the conduction of the electrons around metal nanoparticles vibrates at a specific frequency and shows a bright colour [61]. So, the plasmon resonance characteristics are used widely to determine the metal nanoparticles for surface modification [62].

Copper (Cu) is a ductile metal with excellent thermal and electrical conductivity [63]. It is a low cost-effective reagent with good antibacterial and UV resistance properties [64]. According to Ju *et al.*, Cu nanoparticles impregnated with bamboo give a high-voltage electric field and significant antibacterial resistance with ultraviolet resist properties. Wood treated with nano-copper oxide (CuO) in polystyrene improves the wood's dimensional stability [65]. Akhtari and Nicholas reported that when wood was exposed to a termite attack, the nano-copper formulation could reduce the weight loss from 6.8 to 0.2% [66].

Zinc-based nano-compounds are applied to wood and bamboo to increase their durability. Zinc oxide (ZnO) has good chemical stability, is cost-efficient with antibacterial and fungal ability, and is less harmful to human cells [67]. Because of this reason, it is gaining more attraction in the surface treatment and coating field. US Food and Drug Administration classified ZnO as "generally recognised as safe" [68]. Li *et al.* also found that ZnO-treated bamboo materials performed better when interacting with *Aspergillus niger* and penicillium cites [69].

Studies of zinc and copper nano-compounds show that zinc is more active than copper in terms of termite mortality, the inhibition of termite feeding, and white root fungi decay, as shown in Figure 3. Bak and Németh [70] reported the effectiveness of nanoparticles like zinc borate, zinc oxide, copper borate, copper oxide, copper, and silver against the white root fungus. Among the five other nanoparticles, zinc borate was more effective. However, they concluded that the zinc oxide provided complete protection to the wood after leaching [71]. Figure 3 also shows the difference between different nanoparticles.

Titanium dioxide (TiO_2) nanomaterials are photocatalysts activated by UV. Due to the photoreaction range, TiO_2 nanoparticles are used for wood and bamboo surface treatment, allowing a thin water film to be formed on the treated substrates that significantly reduce the photocatalytic activity. Its chemical stability and non-toxicity reduce water availability and prevent fungal and bacteria growth [72].

Silicon dioxide (SiO_2) is a commonly used nanoparticle. SiO_2 has a high surface/weight ratio, and its small size allows it to quickly penetrate the wood and bamboo surface and distribute evenly. It helps to increase the thickness of the cell wall, reduce the moisture absorption of the wood, and improve dimensional stability [73]. The impregnation of SiO_2 depends on the deposition time which increases the quality of the composite material, and the thermal and mechanical properties are significantly improved. According to Han *et al.*, impregnation of modified wood with itaconic acid (IA) increases the cell wall thickness significantly, reduces moisture absorption, and improves dramatically the dimensional stability of the wood [74]. Figure 4 shows the process of the reaction.

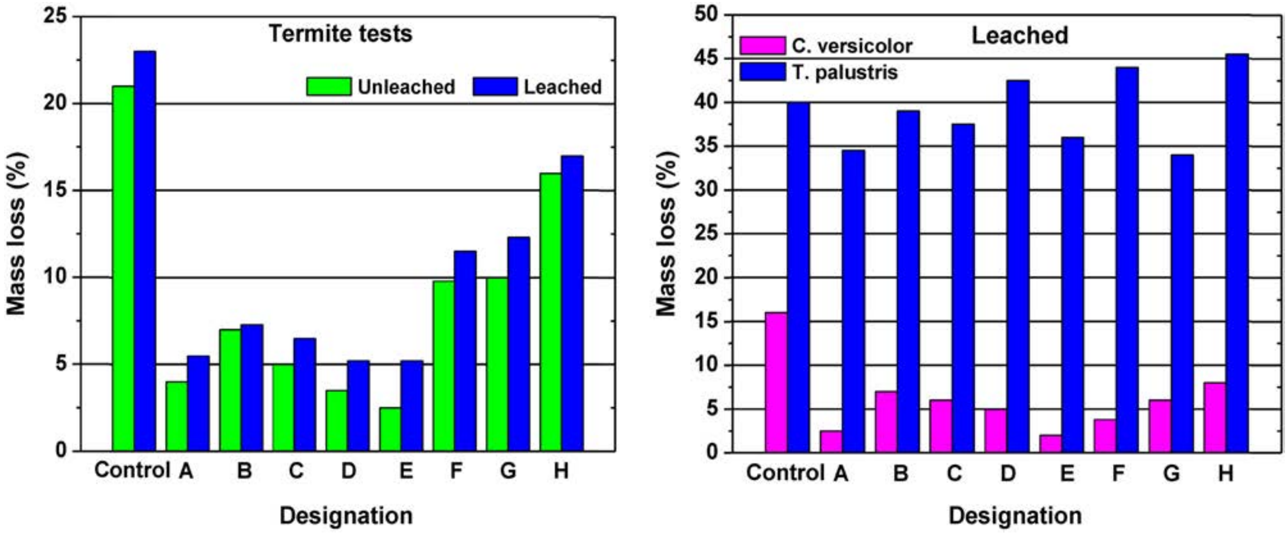

Figure 3: The mass loss (%) following termite resistance for leached and unleached pine wood: (i) nano-ZnO; (ii) nano-ZnO plus binder A; (iii) nano-ZnO plus binder B; (iv) nano-zinc borate; (v) nano-zinc borate plus binder A; (vi) nano-CuO; (vii) nano-CuO plus binder A; and (viii) nano-CuO plus binder B [71].

In the modification process, IA is used to functionalise the –OH groups in the wood cell wall, followed by *in situ* polymerisation of nano-SiO_2.

Ferric oxide (Fe_2O_3) is one of the primary oxides of iron. It has excellent thermal and chemical stability, non-toxicity, and superparamagnetic performance [75]. It provides superior dimensional strength and mildew resistance to wood and bamboo. Fe_2O_3 is widely used in the biomedical field of microwave absorption, drug delivery, MRI, and environmental protection [76,77]. In the experiment with bamboo bundles, they impregnate into nano-Fe_3O_4 at 0.4 mol/L [78].

Based on the above, copper, ZnO, TiO_2, and SiO_2 offer a broad range of protection features in the wood modification process. For the bamboo, a sample combination of Ag, Cu, and Fe_3O_4 is used to resist the microorganism and improve its physical properties.

3.2 Polymeric nanocarriers

Polymeric nanoparticles range from 1 to 1,000 nm that can absorb the polymeric core's surface [79]. It is used for drug delivery. Inwood preservation industry is not popular as nanoparticle impregnation and coating treatment. In the future, technology might rise in the wood preservation industry. Polymeric nanoparticles are made up of poly (lactide) (PLA), epsilon-caprolactone (PCL), poly (lactide-*co*-glycolide) (PLGA) copolymers and poly (amino acids), and some natural polymers like alginate, gelatine, and albumin [80]. Polymeric nanoparticles facilitate rapid and spontaneous diffusion of polymer solutions into the liquid phase, actively avoiding water molecules. Impregnating wood with these nanoparticles enables the incorporation of organic biocides, followed by water-borne treatments for enhanced performance and protection [81]. In this way, polymeric wood substrates can control the release rate of biocide while acting as a storage reserve and protecting it from exposure to the environment. This process will help shield the material for a long time. Several techniques can be conducted by encapsulating the active ingredient into polymeric nanocarriers [70]. Figure 5 shows different types of nanocarriers for operational ingredient delivery.

The polymer capsules were synthesised using amphiphilic gelatine copolymers grafted with methyl methacrylate. The diameters of the polymer capsules ranged from 200 to 400 nm or 10 to 100 nm, depending on the core/polymer shell mass ratio [82].

The polystyrene-soybean copolymer was effectively used by Can *et al.* to encapsulate nano-silver. They investigated the Scots pine's resistance to the white-rot fungus by impregnating it with capsules (Trametes Versicolor). The study results show that polystyrene, soybean oil, and nano-silver contributed significantly to the synergistic impact that increased Scots pine's resistance to decay [83].

3.3 Nano-coating treatment on surfaces

Nanotechnology offers a better surface coating than the traditional coating of wood and bamboo. Standard coating

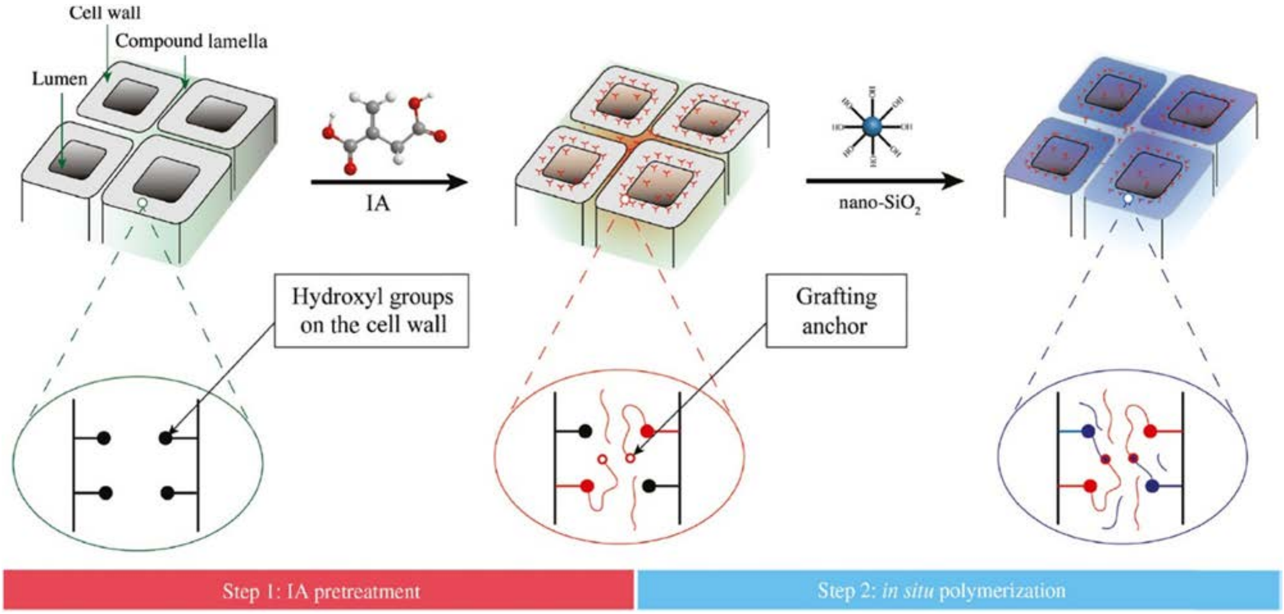

Figure 4: The addition of functional groups of –OH with IA is impregnated by *in situ* polymerisation of nano-SiO$_2$ in the wood cell wall [74].

only improves the mechanical properties of materials, while decreasing the flexibility of the hand nano-coating can solve the problems with advanced protection [57]. Due to their high surface volume ratio, coating with nanomaterials can improve physical, mechanical, fire resistance, UV absorption, *etc.* Also, it maintains the transparency of the coating. Metal inorganic nanoparticles are widely used for nano-coating: (a) solution blend and (b) *in situ* chemical processes. The surface properties of wood and bamboo are almost similar. The first method is to dissolve the polymer in a suitable solvent before applying pressure to create dispersion. The nano-based coating is sprayed, brushed, or dipped onto a wood surface [84]. The second method entails mixing the nano-compound with monomers, distributing it, and polymerising the resulting mixture. *In situ* chemical processes such as sol–gel deposition and hydrothermal techniques are used to create nanomaterials on a wood surface [82]. So, the coating process with the nanooxides is also identical. Table 2 gives a summary of coating materials and their advantages.

However, it has not been demonstrated to be an efficient agent for increasing water absorption and surface hardness in woods over the fibre saturation limit or in air-dried wood. Inorganic particles mixed into organic polymers are often utilised to improve the mechanical properties of wood treatments. Inorganic materials' stiffness and hardness are coupled successfully with the polymer's processability as fillers. When applied in micron size, inorganic particles have drawbacks such as reducing the material's flexibility and decreasing the coating system's transparency [85]. Nanocomposite coatings produce a rough hydrophobic surface without compromising the wood's suppleness

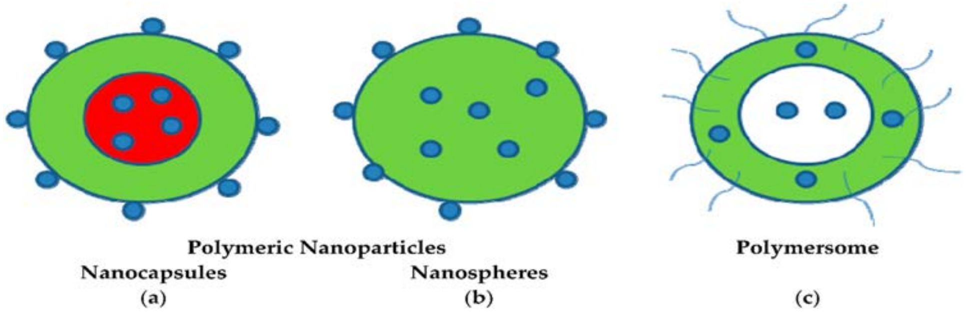

Figure 5: Polymeric nanocarriers. (a and b) The active ingredients in the polymeric nanoparticles are encapsulated in polymers. (c) Polymers and copolymers are arranged in a lipophilic bilayer vesicular system with a hydrophilic inner core [56].

or abrasion resistance. Nanomaterial impregnation lowers the pore size and space accessible within the cell wall for water molecule absorption. When wood comes in touch with an ignition source, it is made up of cellulose, hemicelluloses, and lignin, which can cause it to degrade thermally. Wu *et al.* [86] reported using a water-borne UV (WUV) lacquer product modified with ZnO nanoparticles and stearic acid to create a super-hydrophobic coating with a contact angle of up to 158.4° on the surface of poplar wood. The water resistance of zinc stearate/water-borne UV lacquer super-hydrophobic coating was higher than that of WUV, making it easier and more ecologically friendly to create super-hydrophobic layers. Although numerous fire retardants increase the fire performance of wood, there has been limited efficiency, leaching, and significant environmental and health risk associated with many of these compounds.

Nanoparticles, alone or in combination with other fire-retardant chemicals, can lower the ignitability of wood while also limiting fire-retardant chemical leaching [87]. Graphene also has a high ability to prevent microorganisms from growing. Merging reduced graphene oxide and nano-ZnO to coat bamboo-based outdoor materials *via* a two-step dip-dry and hydrothermal method has improved mould resistance and antibacterial activity features [88]. To increase the antibacterial properties of wood, water-borne polyurethane (WPU) coatings containing nanocrystalline cellulose and silver nanoparticles were utilised, which is reported by Cheng *et al.* [89]. In their extraordinary work, a straightforward, one-step solvothermal technique was used by Yao *et al.* to create a strong, superamphiphobic ZnO nanorod array (ZNA)-treated wood effectively. The superamphiphobic properties were intact in the presence of corrosive substances, mechanical impact, varying temperatures, and water spray. The wood sample in its prepared state also demonstrated higher resilience to UV rays. This research may offer a workable method for creating ZnO/wood hybrid composites that perform well. While constructed, superamphiphobic solid wood treated with ZNA has excellent potential for anti-corrosion, self-cleaning, high-temperature, and humidity functions. The durability of the generated ZnO nanostructures and the dimensional stability of the wood, however, is likely to be the method's constraints. Due to high temperatures and pressures, using autoclaves with expanded dimensions presents additional issues regarding cost, safety, and the environment [90] (Figure 6).

4 Application of nanotechnology

Nanotechnology integrates technology and science with its multidisciplinary approach, intending to develop new and innovative materials with functional, chemical, and physical qualities [91]. Nowadays, it plays a significant role in the forest and agriculture industries. This part of the literature review will briefly describe the role of nanotechnology in the energy sector, flexible electronics, and green nanotechnology by wood and bamboo materials.

The world is on the verge of a global energy crisis as energy is a valuable resource closely linked to economic growth and development. Though the requirement of

Table 2: Nano-coating materials and their advantages

Coating materials	Advantage of coating	Ref.
ZnO and its different forms (nanoparticles, nanorods, nanosheets, nano-walls)	Super-hydrophobic, UV protecting, fire resistance, antimicrobial properties, durability, and mechanical properties	[92–94]
TiO_2 (anatase and rutile form) nanoparticles	The photocatalytic effect, water absorption, fire resistance, durability, and antifungal capacity	[95–97]
TiO_2 + ZnO	UV resistance, antifungal capacity, thermal stability, fire resistance capacity	[18,98,99]
Ag	Antifungal, durability, and mechanical properties	[100,101]
Ag/TiO_2	Antifungal activity, good photocatalytic performance, leaching resistivity, and durability	[102]
SiO_2	Water and fire resistance capacity and increased mechanical properties	[73,103,104]
GO with nanoparticles	Dimensional stability and mechanical properties	[88]
γ-Fe_2O_3	Thermal stability, hydrophobicity, and magnetic microwave absorption	[105]
Fe_2O_3 and TiO_2	Antimicrobial resistance	
Nano-clay/ceramic nanoparticles	Improved mechanical properties	[106]
CuO/Cu	Water absorption properties, durability, flexibility, and mechanical properties	[98]
Al_2O_3	Thermal and mechanical properties, decay resistance, and electrical conduction	[52]

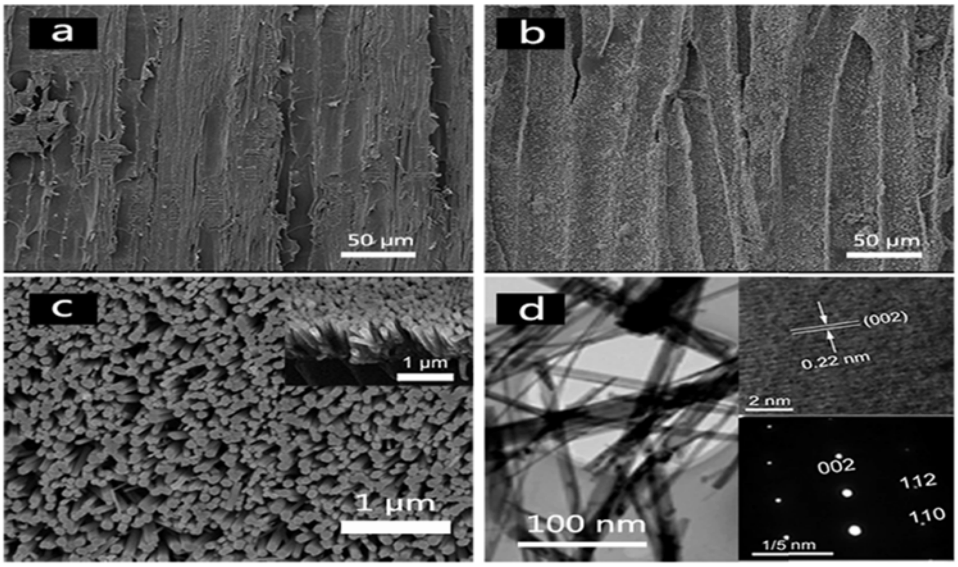

Figure 6: SEM image of the surface of (a) wood untreated, (b) wood with ZNAs in low magnification, (c) wood with ZNAs in high magnification, and (d) wood with ZNAs peeled off by the TEM image, HRTEM, and SAED pattern [90].

altering the source of energy and the usage of technology can secure a reliable quality and safe ecological life, "low carbon life" incorporates all the requirements that should be implemented on a man scale and not just by the individual scale and technical performance. Around 80% of the world's carbon dioxide (CO_2) emissions come from the energy sector. According to IEA "global Energy review: CO_2 emissions in 2021," in 2020, global CO_2 emissions increased by almost 2.1 Gt levels. It places 2021 above 2010 as the largest ever "year-on-year" increase in energy related to CO_2 emission. In 2021, coal accounted for more than 40% of the overall increase in global CO_2 emissions [107]. So, to reduce CO_2 emissions, scientists and engineers are working hard to give an effective solution. The literature described some extraordinary research work made in past years. For example, Sun *et al.* [108] demonstrated a next-generation self-power green building materials by enhancing the elastic compressibility of balsa wood through the sustainable fungal decay pre-treatment. Therefore, the piezoelectric output was increased and a single cube of wood can produce a maximum voltage of 0.87 V and a current of 13.3 nA under 45 kPa stress. Klochko *et al.* [109] developed the nanocellulose (NC) thin film at near room temperature. They are biodegradable and can be an alternative to petroleum-based polymer substrates for use in flexible electronics due to their renewability, biodegradability, biocompatibility, and extensive capacity for modification. With flexibility and variable shape, nano-cellulose exhibits a strong potential for solar energy. Lithium sulphur batteries are now using NC because of its biodegradability, renewability, flexible chemical tunability, and excellent mechanical and thermal properties. Yiju Li *et al.* [110] briefly described the structure, properties, and synthesis of NC-based materials, the advantages and disadvantages, and the application of NC into lithium sulphur batteries. Baloch and Labidi [111] reviewed the usage of lignin in different lithium-based conventional and next-generation batteries. According to them, this next-generation sustainable, ecological, and cost-effective material is the new pathway to a sustainable future as lignin has an electroactive redox property with abundant activity. Therefore, it has a high charge-holding capacity, making it a suitable candidate for energy storage. Espinoza-Acosta *et al.* [112] explained how lignin can be used in batteries, advanced supercapacitors, and solar and fuel cells and described the toxicity and cost effectiveness. Chen *et al.* [113] fabricated a scalable, high-elastic cellulosic material to improve the natural wood's tuneable conductivity by the top-down freeze-drying and chemical treatment approach. The experiment was designed to achieve the direction-dependent structure because it provided mechanical robustness and tenable conductivity. It developed into a flexible wood suitable for sensors, nanofluidic systems, oriented tissue engineering, human–machine interface, water filtration, and many more. Figure 7 demonstrates the morphological structure and characterisation of the natural and elastic wood by SEM image and bounce of the end product.

Similarly, Song *et al.* [114] developed flexible, breathable wood materials that claim that they can be used as "structure material, flexible electronic, biosensor and flexible 3D conductors." Moreover, tissue engineering also plays a promising role in bioscaffold material. Figure 8 demonstrates

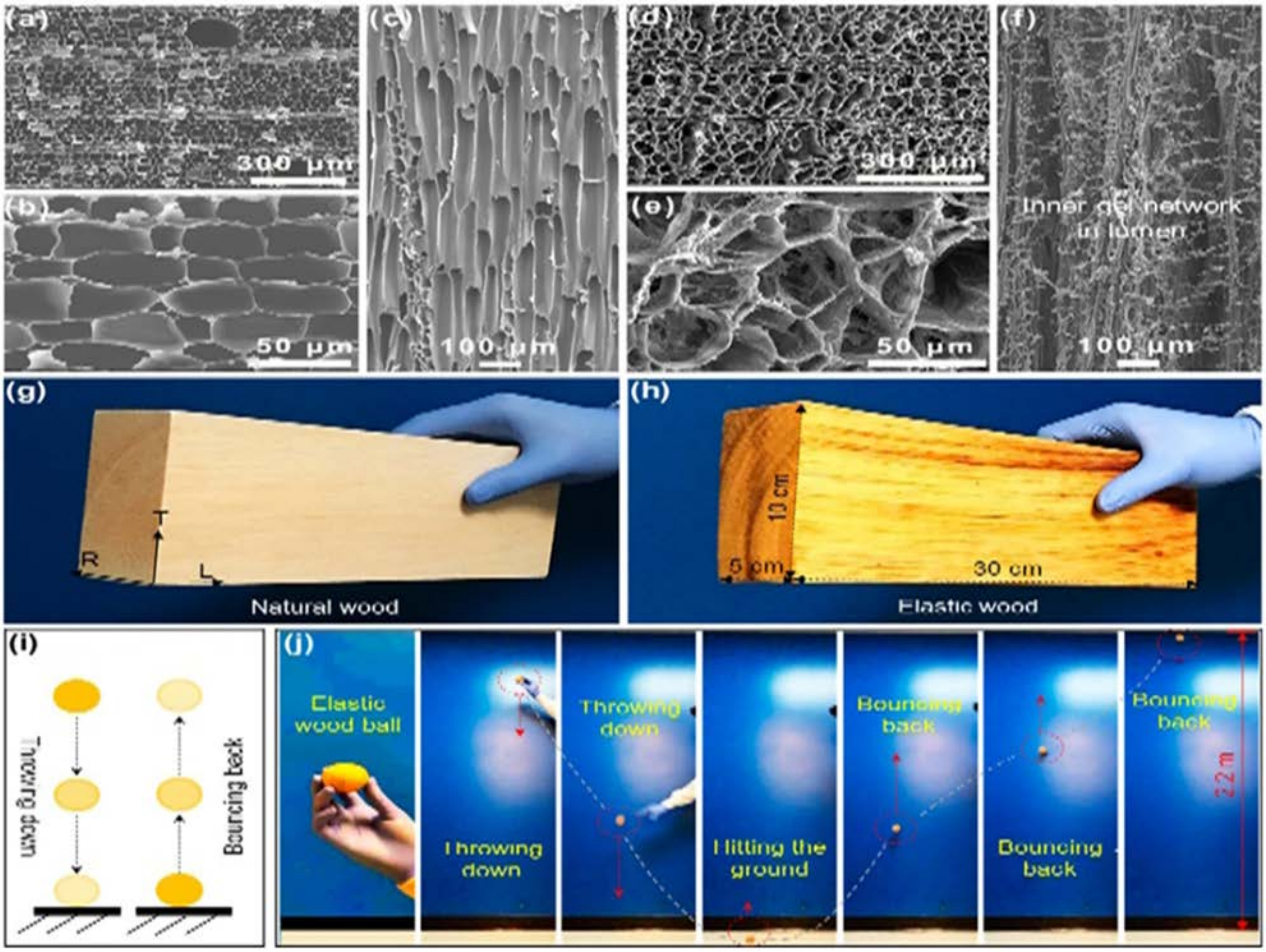

Figure 7: (a) The growth path of natural wood, (b) the magnification of image (a), (c) the longitudinal section of multiple lattice-like channels of natural wood, (d) the growth path of elastic wood, (e) the magnification of image (d), (f) longitudinal-section view of the channels with an interconnected fibril network of elastic wood, (g and h) large-sized image of natural wood and elastic wood, and (i and j) the image of an excellent bounce of elastic wood balls [113].

the process of creating 'supper flexible wood' by changing the pH.

Through surface machining and chemical treatment, Guan *et al.* showed a simple method for fabricating a wood-based flexible pressure sensor (FW/rGO) with high performance. The wood-based flexible pressure sensor had a fundamental level of sensitivity of 1.85 kPa^{-1} over a wide range (0–60 kPa), improved strength over 10,000 cycles, a quick response time (150 ms), and a low detection limit (60 Pa). This innovative and customisable concept for flexible pressure sensors derived from wood will likely bring many new possibilities for improving wearable e-skins, biomedical devices, and electronics [115] (Figure 9).

Li *et al.* [116] created electrically conductive nano-bamboo charcoal /ultra-high molecular weight polyethene composites by the high-speed mechanical mixing and hot-pressing method. The method used in this study to create the electrically conductive nano-bamboo charcoal was simple, cost-effective, sustainable, and suitable for industrial production.

Gan *et al.* developed conductive wood, which has a load-bearing capacity and structure of electromagnetic interface of the shielding material. The electrically conductive wood is suitable for flexible electronics, electromagnetic shielding, and energy storage. As per the author's report, the conductive wood has an EMI shielding effectiveness of 58 dB and a better tensile strain than the traditional carbonised wood, which is approximately 3 and 28.7 times higher. Conductive wood can be used as new generational material as it has advantages like uniform electrical capacity and exceptional compressive strength and is a lightweight, sustainable, renewable, low-cost scalable material [117].

Fu *et al.* [118] developed a light scattering, polymer matrix-free, and uniformly luminescent 2D flexible wood film with solid mechanical properties using a top-down

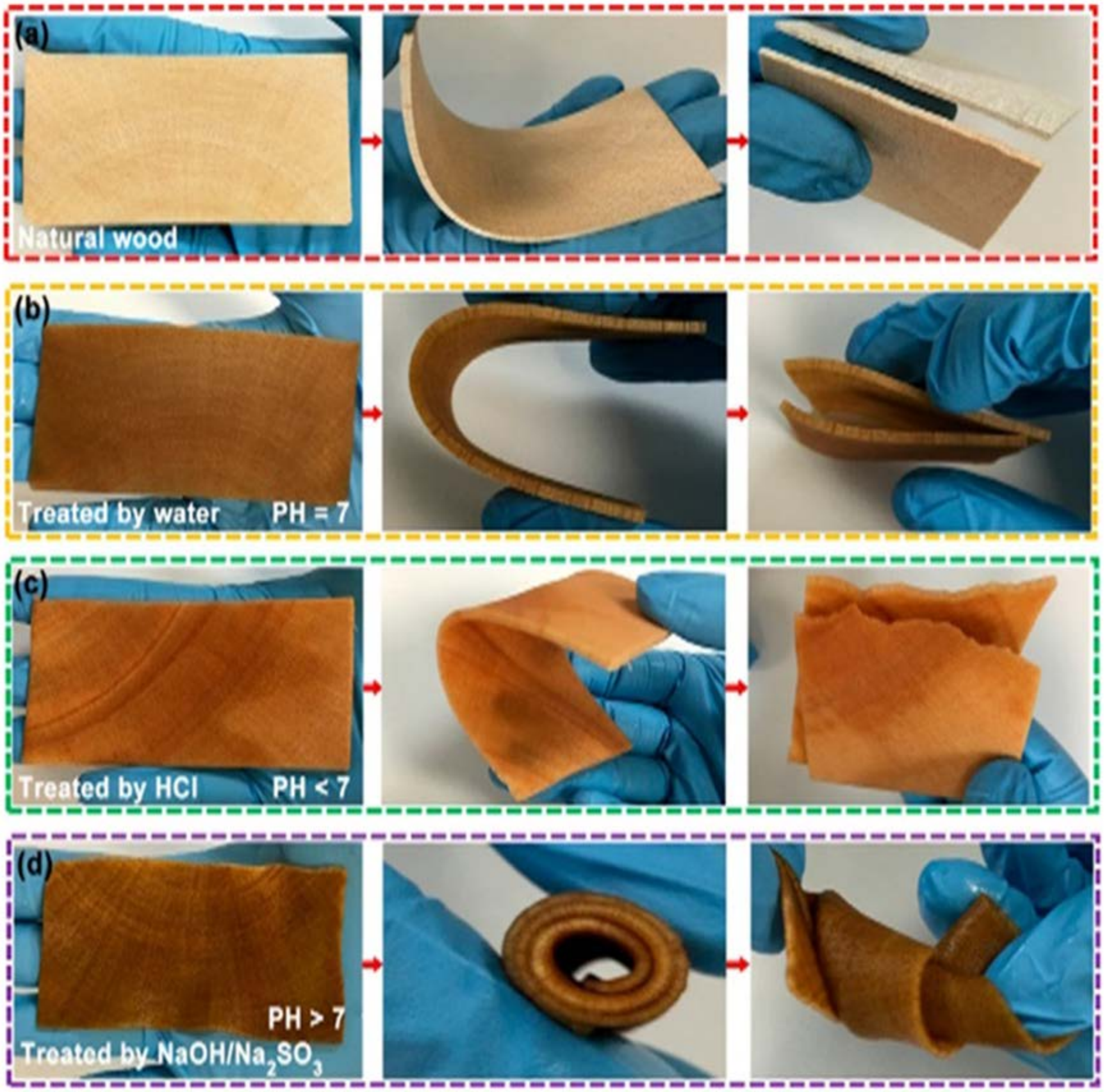

Figure 8: Some simple tests showing the final product flexibility after the treatment [114]. (a) Unmodified natural wood tissue, (b) water treatment done on natural wood tissue, (c) wood tissues are modified by HCl treatment, and (d) after NaOH/Na$_2$SO$_3$ treatment, wood tissues become highly flexible.

approach. The authors use organic CdSe/Zn solution for the delignified template, which was modified and designed using a mild chemical treatment process. As a result of being nanostructured and coated with hexadecyltrimethoxysilane (HDTMS), the luminescent wood film became flexible, hydrophobic, and luminous, which scatter light uniformly. To take the experiment one step further, the author's insert of various QDs is potential, allowing for producing a wide range of colours. They visualise expanding on this concept by creating a crystal transparent wood film with different quantum dots or inorganic nanoparticles. Figure 10 demonstrates the process and uses of the material.

4.1 Green nanotechnology

Nanomaterials have attracted much attention due to advancements in the material world because of their better chemical, physical, and biological capabilities [119]. The size, surface morphology, form, and composition determine nanomaterial qualities. They have been synthesised and modified for defence, pharmaceuticals, communications, agriculture, and environmental clean-up [120]. However, the increased production of nanomaterials on an industrial scale raises serious concerns about human health and the environment. As a result, developing green pathways for synthesising nanomaterials

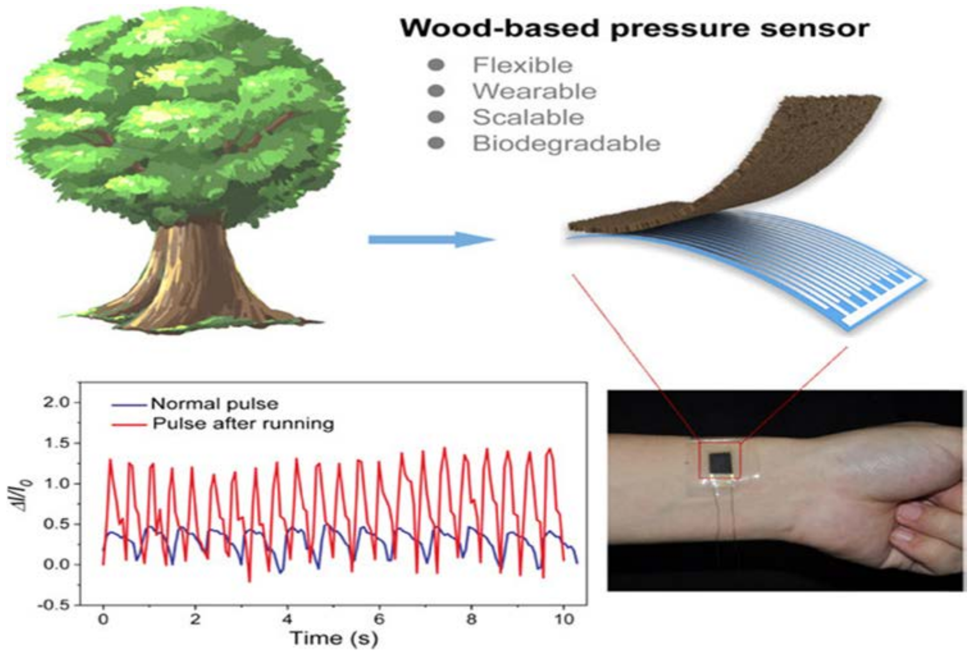

Figure 9: A wearable pressure sensor made of natural wood [115].

from bio-based sources employing green nanotechnology with the most negligible waste output has become a significant problem for researchers [121]. Green nanotechnology creates nanomaterials using biological processes such as plants, bacteria, viruses, proteins, and lipids [122]. Green nanotechnology is far more advanced than other physical and chemical processes for synthesising nanoparticles. Green nanotechnology satisfies current demands without risking future generations' potential. It also minimises waste output by altering garbage generating and disposal procedures. Green routes contain less expensive chemicals, use less energy, and create ecologically acceptable products and decomposition products. Researchers and scientists looking into less hazardous waste creation have used green chemistry concepts as a reference guide [123].

Zahara *et al.* reported identifying the formulations that performed the best and offered the highest resistance to

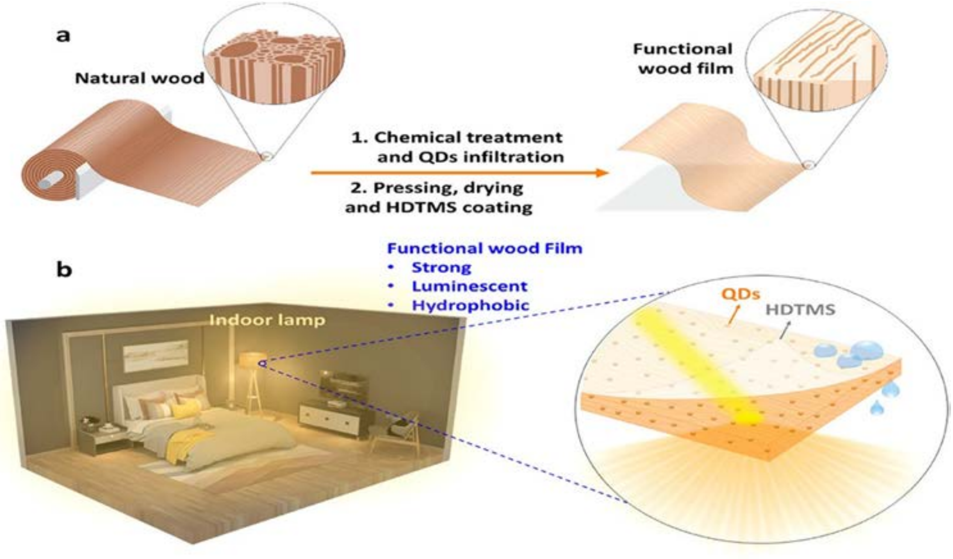

Figure 10: The schematic diagram for (a) using a top-down approach, luminescent and hydrophobic wood-based functional materials created by chemical vapour deposition with HDTMS. (b) Optical lighting material for interior illumination [118].

weathering. The effects of olive leaf extract were combined with the addition of TiO_2, ZnO, benzotriazole as UV absorbers and the hindered amine light stabilisers. The same outcomes for complete colour changes were also displayed. Overall, it can be said that polyacrylate with olive leaf extract is an efficient way to shield thermally treated wood from UV radiation and moisture. Further research is needed to produce the finest models [124].

In research, commercial lignin-coated cellulose nanocrystal (L-CNC) particles were used to varied sizes, and irregular surfaces were used to provide a strong base for a superhydrophobic coating. The L-CNC particles are environmentally friendly, biodegradable, and formed by spray-drying the CNC solution containing a small amount of lignin. Spraying an L-CNC/polyvinyl alcohol composite paint and altering it *via* chemical vapour deposition creates a superhydrophobic covering. As a result, the coating offers excellent abrasion resistance, good superhydrophobicity and self-cleaning qualities. Additionally, neither inorganic nor organic solvents were employed in the production. Consequently, this coating may be used in applications that call for harmless materials [125].

Nair *et al.* [126] successfully demonstrated for the first time a quasi-solid separating electrolyte for high-energy lithium sulphur batteries designed for ambient temperature use. Thermal polymerisation (curing) was used to create a green polymer electrolyte composed of a methacrylate-based polymer matrix and naturally abundant, natural nanoscale micro-fibrillated cellulose. The overall electrolyte preparation process is water-based and scalable.

4.2 Patents of the wood/bamboo industry

Combining wood science and nanotechnology is a promising research area where sustainable products are manufactured for the betterment of human life. The advancement of these is shown in Table 3.

5 Environmental impact and future prospective

Although many features of wood modification treatments are understood, it is still unclear how the procedure affects the product's functionality, environment, and end-of-life circumstances. It is crucial to incorporate interactive analyses of process parameters, developed product attributes, and environmental implications to support the low-carbon economy and sustainable development. The life cycle assessments (LCAs) should be used to conduct unbiased environmental impact analyses of commercial modification processes and incorporate environmental impact analyses into wood modification processing and product development, containing recycling and advancement at the end of service life. In addition to the environmental cost of producing wood that has not been treated, there is an additional environmental cost connected with the modification of wood. When there is a long period of time between coats, the potential environmental advantage that may be attained through the usage of modified wood is undeniable. If stored carbon is not considered, the benefits of timber items' longer lifespans become less noticeable [127]. The standards of ISO 14040 [101] and ISO 14044 [102] outline the same LCA approach. Numerous approaches have been developed since the 1980s, when LCA analysis was first introduced, to categorise, characterise, and normalise environmental consequences. The most prevalent are those that concentrate on the following environmental effect indicators: resource consumption, greenhouse gas emissions, eutrophication, ozone layer depletion, several forms of ecotoxicity, air pollutants, and acidification. In the wood industry, few LCA studies are geographically dispersed, employ a range of databases, and follow effect assessment methodologies. Jones and Hill presented the carbon footprint of 14 main wood products using a cradle-to-gate study. For all items made from sawn wood, removing the wood from the forest is the primary source of emissions; for products made from kiln-dried sawn wood, the drying process comes in second. They addressed the advantages of utilising wood as a building material in connection to the benefits of using wood goods in terms of the environment and compared the carbon footprints, including stored carbon of wood products with various "end-of-life" scenarios and degrading susceptibility. They concluded that there is a crucial need for research into the interactive assessment of the process, product properties, and environmental impact, including recycling and disposal options at the end of the service life, towards upcycling after their service life based on the cradle-to-cradle concept [128].

Werner and Richter studied the environmental effects of the life cycle of wood-based products used in the building industry to functionally similar goods made of other materials, focusing on Central and Northern Europe, North America, and Australia. The study concluded that, compared to competing products, wood products typically consume less fossil fuel, have less potential to contribute to the greenhouse impact and generate less solid waste. Additionally, depending on the preservative, impregnated wood goods are more problematic than comparable items regarding the toxicological effects and photo-generated smog [129].

Despite being one of the most popular building materials, wood has inherent flaws such as dimensional instability and degradation through weathering, fire, and decay that prevent it from being competitive with non-renewable resources in the building and construction sector. By combining intelligent materials with conventional wood modification processes, nanotechnology is one of the most modern and successful wood protection technologies that can open new economic opportunities for using wood in challenging situations. Even if the environmental and physiological risks posed by nanoscale materials are not precisely determined in most research, the potential effect of the technology takes centre stage and calls into question the long-term viability of nano-based treatment [130].

Bi *et al.* reviewed various wood modification systems' principles, production processes, benefits and drawbacks, and directions for improvement were compiled and summarised. They thus studied the unique properties of the

Table 3: Patents on wood and bamboo protection and uses

Patent number	Year	Name of patents	Ref.
US20140363664A1 EP2615126B1 US10843375B2	2016 2013	Use of modified nanoparticles in wood materials for reducing the emission of VOCs	[131]
US9056987B2	2015	Super-hydrophobic coating	[132]
US8828485B2	2014	Carbon-encased metal nanoparticles and sponges as wood/plant preservatives or strengthening fillers	[133]
CN103978532B	2015	Timber, bamboo wood modification processing method and improved wood, bamboo wood, and floor	[134]
CN108638263A	2018	It is to improve the anti-mildew processing method of bamboo wood	[135]
US11161271B2	2019	Method for preparing room-temperature cured multifunctional wood modifier and method for wood modification	[136]
US6753035B2		Compositions and methods for wood preservation	[137]
US20190165402A1, US10818952B2	2020	Lignin-based electrolytes and flow battery cells and systems	[138]
CN101880508B	2013	Preparation method of high abrasion water-borne wood coating	[139]
CN1010164314A	2009	Nano-antibacterial water woodenware paint and the preparation method thereof	[140]
CN102002315B	2012	Oily UV white light surface wood lacquer abstract	[141]
CN102250537A	2011	Water-borne wood paint	[142]
CN101974285A	2011	Long-acting antibacterial polyurethane water-based wood paint composition	[143]
CN105647362A	2016	High-durability high-efficiency nano-antimicrobial water-based wood paint and the preparation method thereof	[144]
US6675994B2	2017	Superhydrophobic coatings and methods for their preparation	[145]
WO2014190515A1 EP3004190B1	2014 2020	Composition of wood coating	[146]
CA2635875C US7754801B2	2014 2010	Translucent coating compositions providing improved UV degradation resistance	[147]
CN102952337B	2015	Modified bamboo fibre-reinforced polypropylene composite material and the preparation method thereof	[148]
CN105675597B	2018	The preparation of a kind of three-dimensional colorimetric and optical electro-chemistry paper substrate equipment and its application in hydrogen peroxide detection	[149]
CN103535376B	2015	Preparation method of nanometre zinc oxide-bamboo charcoal composite particle with antibacterial and adsorption functions	[150]
JP6190356B2	2017	Coating composition and coating film obtained from the composition	[151]
US20190185638A1	2019	Oleophilic and hydrophobic NC materials	[152]
US10919985B2	2021	NC compositions and processes to produce the same	[153]
US10906994B2	2021	Processes and apparatus for producing NC and compositions and products produced therefrom	[154]
WO2015153536A1	2015	NC production using lignosulphonic acid	[155]
WO2015200584A1	2015	Processes for producing NC-lignin composite materials, and compositions obtained therefrom	[156]
EP3872172A1	2021	Conductive cellulose composite materials and uses thereof	[157]
US11046858B2	2021	Nano-cellulose compositions, coatings, and uses thereof	[158]

various wood chemical alteration procedures. They offered suggestions and resources for investigating and creating more affordable and efficient modification methods. Due to their high cost or significant effect on wood strength, thermosetting resin modification, polymer monomer modification, nanotechnology, and paraffin wax modification are still in the research stage [24].

Some companies have achieved Environmental Products Declarations, and manufacturers of modified wood goods have considered the environmental effects of their products. However, the worldwide environmental impact of wood and bamboo modification processing and additional applications of the changed wood products are not yet considered in developing processes and goods, according to a more thorough analysis [159]. Furthermore, the future prospective will be to a large degree, their environmental effects are still unknown, which must alter to satisfy the needs of increasingly environmentally conscious corporate and consumer markets who want to choose the products and services they want to use in an ecologically responsible manner.

6 Conclusion

Wood-based and bamboo-based biomaterials are emerging as desirable answers to various technical problems. These substances – cellulose, hemicellulose, and lignin – are plentiful on Earth and biocompatible and contain intrinsic natural structures that might significantly improve the performance of materials. Although many modern technologies and applications have been established, significant obstacles in fundamental research and understanding must be overcome to accelerate the commercialisation of wood and bamboo materials. There is another big problem with extracting cellulose and lignin. There are gaps to overcome, particularly for innovative technologies like flexible electronics devices, energy storage applications, and green nanotechnology. These include the apparatus's efficiency with suitable lifetime, durability, and cost-effectiveness, the extraction of biomaterials from wood, system-level integrations with numerous device components, and human health risks. But now, efforts are being made globally to advance novel wood-derived material technologies for a sustainable environment for the next generation. The primary wood modification techniques that use nanomaterials for improving the structure and coatings are reviewed in this article, along with any potential environmental effects of the integrated nanomaterials. An emphasis is placed on the application of lignin, cellulose, and hybrid wood and bamboo applications. The literature review's in-depth discussion will provide emerging innovations that impact our daily lives.

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