



REVIEW ARTICLE

Nanotechnology in wood science: Revolutionizing durability, sustainability and performance

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Received: 15 January 2026; Accepted: 23 April 2026; Available online: Version 1.0: 08 June 2026

Cite this article: Manish M. Nanotechnology in wood science: Revolutionizing durability, sustainability and performance. Plant Science Today. 2026; 13(sp2): 1-7. <https://doi.org/10.14719/pst.13689>

Abstract

Nanotechnology has emerged as a transformative force in material science, particularly in enhancing the properties of wood and wood composites. As wood continues to serve as a renewable and versatile material, inherent challenges such as biological degradation, dimensional instability and mechanical limitations hinder its broader application. This review explores the integration of nanotechnology to overcome these constraints, focusing on advancements in nanocellulose, metal nanoparticles and functional nanocoatings. By exploring their roles in improving durability, fire resistance, mechanical performance and environmental sustainability, the review highlights the industrial relevance and future prospects of these innovations. The findings underscore the potential of nanotechnology not only to enhance wood's utility but also to align with sustainable development goals, making it a pivotal player in modern materials engineering. Furthermore, the study underscores the interdisciplinary approach required to harness these technologies effectively, from lab-scale innovations to scalable industrial applications. As demand for sustainable, high-performance materials grows, nanotechnology stands at the forefront of revolutionizing wood-based industries globally.

Keywords: environmental sustainability; nanocellulose; nanocoatings; versatile material; wood-based industries

Introduction

Wood modification through nanotechnologies has made remarkable progress in recent years, offering significant advancements that hold promise for addressing various challenges in material science. Nanotechnology is a multidisciplinary field that combines science and technology to develop new and improved materials with significant functionality and physical and chemical properties. However, a comprehensive review that systematically organises, compares and summarises existing research remains limited. In the context of modern industrialisation, diminishing resource availability and rising demand underscore the need to explore practical, green and sustainable materials such as wood (1-3).

Wood, a natural, biodegradable and renewable material, has diverse applications ranging from structural components and ornamental objects to aerospace technology. Its unique properties, including low thermal and electrical conductivity, have made it indispensable for specific purposes throughout human history. However, wood is not without its limitations. Issues such as susceptibility to fungi, insects, fire and dimensional instability due to water absorption (WA) pose significant challenges to its broader utility (4).

Over the past few decades, nanotechnology has emerged as a research field, revolutionizing material science by enhancing the properties of various materials, including wood and wood composites (5, 6). When materials are reduced to the nanoscale (1-100 nm), they exhibit unique physical and chemical properties,

enabling innovative applications across disciplines (7). This has positioned nanotechnology as one of the most actively researched areas of the 21st century, offering immense potential to improve the quality and performance of wood-based products (5).

Nanotechnology's multidisciplinary nature integrates science and technology to develop materials with superior functionality and unprecedented properties. In the wood-based industry, these advancements can address traditional shortcomings of wood, such as susceptibility to biological and environmental factors, while unlocking new functionalities. For instance, nanotechnology has enabled the development of stronger, multifunctional and lighter wood-based products (7, 8). Traditional forest products such as pulp and paper, wood composites, coatings and preservatives are being transformed into high-performance materials with enhanced mechanical strength, improved barrier properties, antimicrobial functionality, fire resistance and smart sensing capabilities, thereby expanding their application in sustainable construction, packaging, biomedical materials and advanced engineering sectors (9).

This review critically evaluates specific nanoscale modification strategies including nanocellulose reinforcement, nano-metal impregnation and functional nanocoatings—and analyses their mechanistic role in enhancing dimensional stability, durability, fire resistance and mechanical performance of wood and wood composites. The study further examines how nanoscale interventions contribute to value addition through extended service life, reduced preservative consumption, improved strength-to-

weight ratios and the development of high-performance engineered wood products and sustainability metrics such as reduced carbon footprint, improved resource efficiency and potential economic gains through advanced wood-based materials in construction, packaging and functional applications.

Methodology

This review was conducted in accordance with the PRISMA guidelines to ensure a transparent, systematic and reproducible synthesis of the literature on nanotechnology applications in wood science. A comprehensive literature search was performed across major scholarly databases, including Web of Science, Scopus and Google Scholar, covering studies published over the past two decades. The search strategy employed Boolean operators to systematically combine the keywords “Nanotechnology” OR “Nanocellulose” with “Wood Science,” “Forestry,” and “Durability.” This approach ensured both broad and targeted retrieval of relevant studies on the integration of nanoscale materials into wood-based systems (10–12).

The inclusion criteria comprised peer-reviewed research articles on nanocellulose extraction, metal nanoparticle impregnation in wood and functional nanocoatings for wood composites. In contrast, exclusion criteria included non-English publications, patents lacking experimental validation and studies centred on non-lignocellulosic materials. Following the identification and removal of irrelevant records, 124 articles were retained for screening and detailed review. Data extraction was carried out systematically using a predefined framework that captured the type of nanomaterial used, application method (e.g., impregnation versus surface coating) and the resulting improvements in wood performance properties, particularly fire resistance, dimensional stability and mechanical strength. This structured synthesis enabled a critical evaluation of recent advances and emerging trends in nanotechnology-driven wood modification (13) (Fig. 1).

Nanotechnology and the forest industry

Significant advancements have been achieved in understanding the mechanical properties of bulk wood, isolated fibres and cellulosic fibrils. However, there is still much to explore regarding the attributes of intact cell walls, the interactions between different cell wall layers and the nanoscale domains—cellulose, hemicellulose and lignin—that collectively determine the overall properties of wood-based systems (14).

Nanotechnology presents an opportunity for the forest (lignocellulosic) products industry to harness the immense untapped potential of trees. The overarching goal is to apply nanotechnology to ensure the sustainable production of wood-based materials and products, meeting both present and future demands. This can be achieved by leveraging nanotechnology's ability to maximise the value derived from lignocellulosic resources (15).

In papermaking, the scope for nanotechnology applications is vast, including developing novel materials, optimising wet-end chemistry, employing nanofiltration to efficiently recycle water, enhancing coating technologies and creating precision-engineered calendar rolls. Additional applications involve advanced sensors, microscopic imaging techniques and nanoscale assemblers (16). Potential innovations in wood-fibre-based products featuring nanomaterials include moisture-resistant components for electronic devices, cutting-edge filtration membranes, superior loudspeaker cones and high-performance additives for paints, coatings and adhesives (17).

The successful integration of nanotechnology across various sectors requires collaborative efforts among industry, academia and society. Since nanotechnology encompasses multiple disciplines, it is imperative for different sectors to contribute knowledge and methodologies that will drive advancements in this field (18).

Pulp and paper

Paper production relies on lignocellulosic materials that undergo a series of operations, i.e., primary processing, treatment, papermaking, drying and coating. During the papermaking stage, pulp is mixed with additives and these mixtures are tailored to achieve specific properties for various end products. Cellulose and lignocellulose are particularly promising as nanomaterials due to their abundance, renewability, nanofibrillar structure and versatility. These materials can be made multifunctional and self-assemble into precise architectures (9).

To fully exploit their potential, new methods for liberating cellulose-based materials—including nano-dimensional cellulose fibrils, macromolecules and nano minerals—are required. Nanocellulose is actually cellulose at a nanoscale dimension, which can be isolated and prepared from any lignocellulosic materials that include wood pulp, nonwood plants, wood and agricultural residues, bacterial cellulose and tunicates. This new generation of cellulose is produced either via cell wall delamination to obtain nanofibrils or by extracting crystalline cellulose at the nanoscale. Nanocellulose is added to papermaking mainly to increase the paper's strength. Other nanomaterials used in the paper production process include nano-silica (N-SiO₂), nanozeolite, etc (19).

The physical properties of paper are primarily influenced by interactions between fibre-fibre and fibres-additives. Therefore, research efforts often focus on controlling and optimizing these interactions. Notably, nanotechnology-enhanced fibre compounds and related products hold great promise for developing superior paper materials (20).

Cellulose fibres at the nanoscale can be prepared through four primary methods: (1) bacterial cellulose nanofibres, (2) cellulose nano fibres by electrospinning, (3) microfibrillated cellulose plant cell fibres and (4) nanorods or cellulose whiskers. The properties of nanocellulose vary with preparation methods and cellulose source. Table 1 shows the morphology and crystallinity of nanofibrillated cellulose and nanocrystalline cellulose (NCC).

Cellulose micro/nanofibrils as reinforcing materials for composites

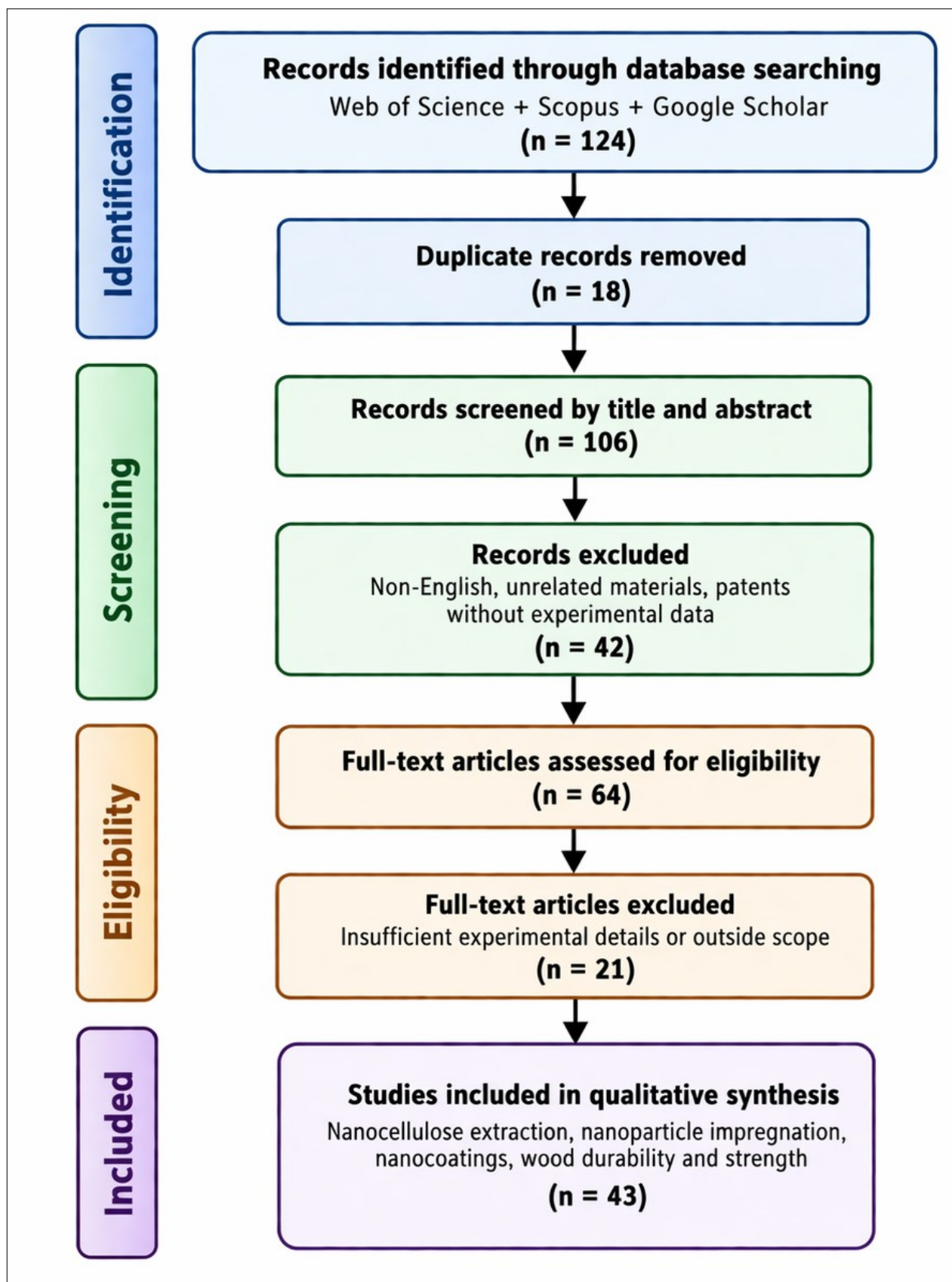
The use of cellulose micro/nanofibrils (CMNF) as reinforcing agents in composites is gaining significant attention in composite science due to their lightweight nature and impressive strength properties (26). A completely new kind of high-strength composite was manufactured using microfibrillated cellulose (MFC) derived from kraft pulp. Because of the unique structure of nano-order-scale interconnected fibrils and microfibrils greatly expanded in the surface area that characterizes MFC, it was possible to produce composites that exploit the extremely high strength of microfibrils (27). The nanofibres demonstrate promising characteristics as reinforcement material for optically transparent composites (28).

While investigating the theoretical and practical advantages of incorporating nanofibres into composite filter media. It was concluded that nanofibres can enhance filter efficiency without causing a significant increase in filter pressure drop. These materials have been shown to extend the lifespan of filters in pulse-clean cartridge systems used for dust collection and to improve air filtration efficiency in the personnel cabins of mining vehicles (29).

Table 1. Characteristics of nanocellulose from different sources

Source	Type of Nanocellulose	Length (nm)	Width (nm)	References
Hardwood pulp	Nanofibrillated cellulose	Not determined	5-35	22
	Nanocrystalline cellulose	100-150	4-5	23
Softwood pulp	Nanofibrillated cellulose	Not determined	16-28	21
	Nanocrystalline cellulose	100-200	4-5	23
Agricultural crop	Nanofibrillated cellulose	Not determined	10-90	24
	Nanocrystalline cellulose	100-500	3-5	25

nm: nanometer

**Fig. 1.** PRISMA-based workflow for systematic literature selection in nanotechnology-driven wood science research.

Polymer matrix reinforced with 10 % nanofibres in 90 % polyvinyl alcohol (PVA), revealed that even at a 10 % concentration, nanofibres exhibited exceptional reinforcing capabilities. Utilization of the electrospinning technique to produce smooth, nonwoven mats containing cellulose nanocrystals reinforced with PVA. These fibre nanocomposites exhibited enhanced thermomechanical properties, demonstrating their potential for advanced applications (30, 31).

Composites reinforced with nanofibres could achieve strengths comparable to those of mild steel or magnesium alloys. Furthermore, the lightweight nature of MFC offers the potential to significantly reduce automobile weight when used as a replacement for heavier alloys (32). However, the broader use of biopolymers in such applications has been constrained by their typically poor mechanical and barrier properties. These limitations can be addressed by incorporating reinforcing fillers to improve composite properties (33).

Nanoparticles, due to their high surface area relative to their microscale counterparts, enhance filler-matrix interactions and improve the performance of the resulting composite. Beyond serving as nano reinforcements, nanoparticles can also impart additional functionalities to polymers, such as antimicrobial properties, enzyme immobilisation and biosensing capabilities. For instance, nanocomposite edible films have been developed by incorporating cellulose nanofibres (CNF) at varying concentrations as reinforcements into mango puree-based and chitosan films. These films exhibited enhanced mechanical and functional properties, demonstrating the versatility of nanofibre applications (34).

Metal nanoparticles for enhancing thermal conductivity

A significant issue with wood and wood-composite materials is their vulnerability to biological deterioration caused by agents such as fungi, insects, termites and marine borers. Various processes and wood preservatives have been developed to address this challenge. Among these, heat treatment stands out as the most commercially advanced process (35). This method alters the molecular structure of wood components, making them resistant to fungal enzymes and significantly enhancing the durability of both wood and wood-composite materials.

In addition to improving durability, heat treatment affects the molecular structure of wood by altering hydrogen bonding and inducing cross-linking of free hydroxyl (-OH) groups. These changes help reduce WA and thickness swelling (TS), which are typically caused by the presence of these free hydroxyl groups. Consequently, heat treatment results in a significant decrease in both WA and TS. However, one limitation of the heat treatment process is the low thermal conductivity of wood (36), which hinders the uniform heat distribution during treatment, especially in larger wood members.

To address this issue, impregnating wood with metal nanoparticles has been found to enhance the uniformity of heat treatment (37). Metals such as silver and copper, with their high thermal conductivity, help improve heat treatment by facilitating rapid heat transfer from the surface to deeper layers of the wood. Furthermore, the addition of nanosilver (N-Ag) and nanocopper (N-Cu) helps prevent heat accumulation in the surface layer, protecting it from overheating and mitigating the risk of significant degradation of mechanical properties from thermal damage. Impregnating wood with nano-metal suspensions also aids in the even distribution of nanoparticles across the wood structure and its cell walls (37, 38).

Wood composites

Wood is a valuable natural resource due to its biodegradability and renewability, making it suitable for a variety of applications. However, wood has several limitations, including fragility, limited flexibility and vulnerability to termite damage and other forms of decay. When used in wood composites, these challenges persist, including low bulk density, poor thermal stability, high moisture absorption and increased susceptibility to biological degradation. The application of nanotechnology, widely used in numerous scientific fields, offers a promising approach to improving the properties of wood and wood-based composites, enhancing their overall performance. Nanoparticles of zinc oxide (ZnO) exhibit good antimicrobial activity. These nanoparticles are added to melamine-urea formaldehyde (MUF) glue before being used for particleboard production (39). Silver nanoparticles, which are well-known biocide additives, also exhibited similar antibacterial and antimold efficacy when applied to the melamine-laminated surfaces of particleboards (40). The combination of nanocopper oxide and an alkane surfactant was also confirmed to improve the water and termite resistance of treated plywood specimens (41).

Nanotechnology for enhanced water-resistance in wood-composites

Another limitation of wood-composite materials is their susceptibility to water and vapour. Wood exhibits thermo-hygro-mechanical behaviour, meaning its properties are influenced by the combined effects of temperature, relative humidity and mechanical load variations (42). The water-repellent properties of nanozycosil (NZ) have been shown to significantly reduce gas and liquid permeability in medium-density fibreboards (MDF) (43). Nanozycosil contributes to this improvement by enhancing the bonding of wood fibres and providing its own water-repellent effect to water and vapour. Additionally, nanowax (NW), N-Ag and NC have also been reported to reduce WA in wood and wood-composite panels (44, 45).

Nanocoatings for enhanced durability

Nanocoatings enhance the durability of wood and non-wood products by using nanoparticles and nano delivery systems that operate at the molecular level to improve material properties. One of the primary functions of these coatings is to prevent the growth of microorganisms, such as fungi and bacteria. Nanoparticles of metal oxides, including ZnO (46, 47), titanium dioxide (TiO₂) (47, 48) and cerium oxide (CeO₂) (49), have been reported to exhibit strong antimicrobial properties.

Research has focused on the direct deposition of nanoparticles onto wood surfaces or the functionalization of wood surfaces with these nanoparticles. For example, ZnO nanoparticles were successfully applied to bamboo timber using a simple, low-temperature wet-chemical method involving sol-gel-prepared ZnO seed layers. The treated bamboo showed improved resistance against *Aspergillus niger* and *Penicillium citrinum*, though it demonstrated less resistance to *Trichoderma viride* (50). Graphene has also been shown to effectively inhibit bacterial growth. A two-step dip-dry and hydrothermal process, combining reduced graphene oxide and nano-ZnO, was used to coat bamboo-based outdoor materials, thereby enhancing mold resistance and antibacterial properties (51). Similarly, the use of nanostructured ZnO via a hydrothermal process has proven effective in protecting wood surfaces from biodeterioration (52).

Nanoadditives for the enhancement of mechanical properties

Inorganic particles integrated into organic polymers are commonly used in wood coatings to enhance mechanical properties. When used as fillers, these inorganic materials effectively combine the rigidity and hardness of inorganic materials with the processability of polymers. However, when applied in micron sizes, these particles can reduce the material's flexibility and decrease the transparency of the coating system (53). Using inorganic particles at the nanoscale significantly increases the surface and interfacial areas, thereby influencing the overall properties of the composite material (54).

Recent studies have focused on using nanocellulose as a renewable reinforcement for developing bio-based nanocomposite coatings with improved performance. Due to its incompatibility with polymer matrices, nanocellulose has been surface-modified. For instance, the addition of (2,2,6,6-Tetramethylpiperidin-1-yl)oxyl (TEMPO)-oxidised cellulose nanofibres has been shown to enhance the mechanical properties of waterborne polyurethane (WPU) coatings (55). In the case of non-polar polymer matrices (56), NCC was modified through two methods: acryloyl chloride or a cationic surfactant. Increasing the NCC loading to 2 % led to improvements in hardness, elastic modulus and tensile strength.

Nano-silica is another commonly used nanoparticle that improves the mechanical properties of coatings. Nano silica offers high hardness and can be easily chemically modified to enhance compatibility with the polymer matrix. A study reported the preparation of castor-oil-based waterborne acrylate (CWA)/silica (SiO₂) hybrid coatings with an organic-inorganic covalently cross-linked network structure via sol-gel and thiol-ene reactions (57). The findings indicated that at 10 wt % SiO₂, the emulsions exhibited good stability and the coating's thermal and mechanical properties significantly improved. The enhancement of mechanical properties through N-SiO₂ addition has also been observed in other coating systems, such as waterborne nitrocellulose (58) and acrylate coatings (59).

Conclusion

Nanotechnology has redefined wood science, particularly in addressing the inherent challenges of wood and wood composites, such as biological degradation, WA and mechanical limitations. This study emphasises the transformative role of nanotechnology in advancing the durability, fire resistance, mechanical strength and sustainability of wood-based products. By integrating nanocellulose, metal nanoparticles, nanocoatings and functional additives, wood can be engineered to meet the demands of modern industries, from aerospace to sustainable construction. Nanocellulose can also be made into nanopaper or thin films for use in paper packaging or other sectors, such as electronics, offering an alternative to non-renewable plastics. Nanocellulose used in wood composites can enable the development of advanced composites tailored to specific applications. Together with their strength properties and affordability, they make them a viable solution to reduce the need for solid wood.

The findings underscore nanotechnology's potential to revolutionise wood-based industries by enhancing product performance while aligning with global sustainability goals. By bridging the gap between laboratory research and industrial application, these advancements pave the way for the development

of high-performance, environmentally friendly materials. Collaborative efforts across disciplines are essential to fully realise this potential, ensuring scalable solutions that meet current and future demands. As the global focus shifts towards green technologies, nanotechnology will remain a cornerstone in elevating wood-based materials to new horizons of innovation and utility.

Compliance with ethical standards

Conflict of interest: The authors do not have any conflict of interest to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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