Effect of Nanoparticles in Wood Composite Panels: A Review

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Abstract: Wood is a natural, biodegradable, and renewable material that can be utilised for a variety of purposes, such as structural elements, aesthetic objects, and aeronautical technologies, etc. Nano science and nanotechnology offer abudent propectus for improving the qualities of wood based panels. Wood panel industries relied on polycondensed thermosetting resins that one of the most important is urea formaldehyde. Impact of Nano particles modified thermosetting adhesive on the mechanical performance properties of wood composite panels have been evaluated by several authors. Nanomaterials can be easily used into the production of wood-composite panels to improve their properties. The significance of nanotechnology in the production of wood based panels is critical in reducing formaldehyde emission. This review focuses on current advancement in the use of nanotechnology in wood-based nano composites.

Keywords: Wood composites, Nanoparticle, Emission, Adhesive etc.

1. INTRODUCTION

Wood is a natural, biodegradable, and long-lasting material that can be used for a variety of purposess, including structural parts, ornamental objects, aerospace innovation, etc. In the course of recent many years, nanotechnology was used in numerous sciences [1-4] and it was utilized to improve the quality of different materials, including wood and wood-composites. It is arguably the most effectively and widely developing research areas towardnd the start of the current century [5, 6].

For renewable biomaterials like wood and wood composites, nanoscience and nanotechnology offers several benefits [7-11]. Nanotechnology has been identified as an innovative upheaval by scientists from all over the world [12]. It is required to be a critical driver of worldwide economic growth and development in this century because it is a multi-disciplinary field of research [13].

Nanomaterials often have unique physical and physiochemical properties that set them apart from larger particles of the same substance [14-16]. The use of nanotechnology in the development of various wood panels is critical in addressing the formaldehyde emission problem [17-27].

Nanoparticles seems to create a series of remarkable changes in material properties not produced by micro particles of the same material [28]. Nanoparticles can be utilized as filler or additive in different polymers so that different improvement in material properties can be accomplished. They can likewise be utilized to reinforce thermosetting polymer to inhance final properties of product. Therefore, nanomaterials are getting interest for research and development activities. Three most commonly used adhesives in the wood based panel sector are formaldehyde based adhesives such as urea formaldehyde, melamine urea formaldehyde and phenol formaldehyde [29]. The effect of nanoparticle modified thermosetting adhesives on the mechanical performance of wood composite panels has been evaluated by several authors [30-41].

Nanomaterials contain a lot of mechanical qualities and unique properties that aren't seen in micromaterials, thus they have a lot of future potential [42, 43]. However, more research into nanomaterials is required. To find potential technical applications and industrial productions, we must first establish the mechanical properties of distinct nanomaterials.

This review mainly focuses on the influence of nanomaterials related to mechanical properties, like strength, fracture toughness enhancement and also addresses related factors that affect the effectiveness of nanofillers to obtain the desired mechanical properties of the targeted composite material.

2. REVIEW METHODOLOGY

This review was conducted through a comprehensive narrative analysis of the available scientific literature on the application of nanotechnology in wood composite panels. The objective was to critically examine published studies reporting the influence of different nanomaterials on the performance of wood-based composites, with particular emphasis on mechanical properties, dimensional stability, thermal conductivity, fire resistance, biological durability, bonding performance, and formaldehyde emission. A narrative review approach was adopted because it allows the

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Received on 03-06-2026 Accepted on 11-07-2026 Published on 20-07-2026

E-ISSN: 2311-8741/26

integration and critical interpretation of findings from studies employing diverse experimental designs, materials, manufacturing conditions, and testing methodologies, thereby providing a comprehensive understanding of the current state of knowledge in this field [44-47].

The literature included in this review comprises original research articles, review papers, book chapters, and technical reports published in internationally recognized journals related to wood science, composite materials, polymer science, nanotechnology, and forest products. The reviewed studies primarily focused on the incorporation of nanoparticles such as nano-silica (SiO_2), nanoclay, nano-wollastonite, nano-zinc oxide (ZnO), nano-alumina (Al_2O_3), titanium dioxide (TiO_2), copper nanoparticles, silver nanoparticles, and nanocellulose into wood, wood adhesives, and engineered wood products including particleboard, plywood, medium-density fibreboard (MDF), oriented strand lumber (OSL), laminated wood products, and wood–plastic composites. Particular attention was given to studies evaluating the interactions between nanoparticles and thermosetting adhesive systems, including urea-formaldehyde (UF), melamine urea-formaldehyde (MUF), phenol-formaldehyde (PF), and bio-based adhesive formulations.

The selected literature was critically analysed and synthesized according to the type of nanomaterial used, composite manufacturing process, adhesive system, nanoparticle loading level, and the resulting improvements in physical, mechanical, thermal, and environmental performance. Comparative evaluation of the reported findings was undertaken to identify consistent trends, limitations, research gaps, and future opportunities for developing high-performance and environmentally sustainable wood composite panels. Emphasis was placed on studies demonstrating improvements in modulus of rupture, modulus of elasticity, internal bond strength, dimensional stability, water resistance, thermal conductivity, fire retardancy, biological durability, and reduction of formaldehyde emission, as these properties are considered critical indicators of composite panel performance. The collected information was then organized into thematic sections to provide a coherent overview of recent advances in nanotechnology applications in wood-based composites and to identify promising directions for future research [1, 25, 35].

3. WOOD COMPOSITE MANUFACTURING PROCESS

Wood composites are often formed from the same hardwoods and softwoods used in lumber, with the exception of sawmill scraps and wood waste, and are made by combining pulverised wood particles with heated thermoplastic or thermosetting resin.

3 mm thick aluminium caul plates of required board dimension with 10 % excess in margin is taken. A square wooden frame with dimension equal to that of the aluminium caul plates. BOPP paper is placed over the aluminium caul plate followed by the wooden frame. Glued particles are taken inside the frame and spread uniformly by hand. The lid is placed over the particles within the frame and pressed hard to compact the particles as much as possible. The frame is progressively removed without damaging the mat, keeping the lid in place. The lid is then taken off. A BOPP paper is placed over the mat and finally covered with a aluminium caul. Aluminium rods of required thickness (thickness of the board to be made) are placed on two sided of the furnish formed mat. The assembly is ready for hot pressing. The pre-pressed mat assembly was then inserted into a hot press, where the platens were kept at the same temperature. Supporting rods to control the thickness were placed on either ends of the assembly. A required pressure for compression cycle both the resin system followed by curing cycle was employed as per thickness.

The pressure is initially increased to get a high surface density on the board. After the time was up, the pressure was reduced to zero for a few seconds to release the steam that had built up on the boards, and the finished output was extracted from the hot press. After removing the boards were stacked on a flat platform to attain equilibrium moisture and then trimmed to required size. The composite manufacturing technique is shown in Figure **1**.

4. NANOMATERIALS' EFFECT ON COMPOSITE MATERIAL MECHANICAL PROPERTIES

Nanoparticles have been used to solve a variety of technological problems in the last decade, including engineering, medicine, water purification, catalysis, and other fields of research, to name a few [48-56]. One such region in which nanoparticles, mostly metal nanoparticles have proved to be instrumental is wood protection.

The mechanical properties fiber reinforced materials rely on the among fiber and matrix and the quality of the fiber. Increase the surface area between the matrix and the fibre to improve fiber-matrix bonding. Factors like type, size distribution, agglomeration state/dispersion, chemical deposition, crystal structure, surface area, surface chemistry, surface charge, shape/morphology, dissolution/solubility, physical/ chemical properties of nanoparticles affect the property

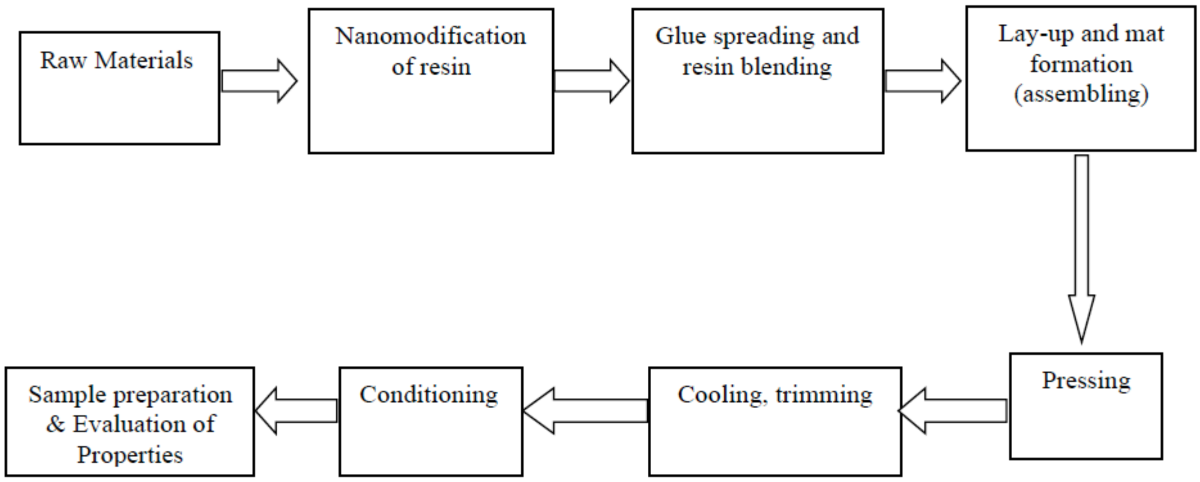

Figure 1: Process Flow chart of nano wood composites.

of composite material characteristics [57]. Mechanical properties such as tensile strength, flexural strength, modulus of elasticity and the physical properties like thermal stability and barrier properties can all be increased significantly by adding the right amount of nanomaterials to fiber reinforced plastic composite materials [58, 59]. Consequently, the impacts of different kiinds of nanomaterials (in great extent nanoclay) on the mechanical properties of composite materials are checked on.

Five types of modifiers have been developed to improve the wood characteristics of popilus tomentosa triplod clones [60]. To make UF-SiO_2- wood composites, the wood samples were impregnated with the modifiers and heated. The antiswelling efficiency, water absorption resistance, flame resistance, and hardness were all assessed.

Eight adhesive formulations were prepard by urea formaldehyde and melamine urea formaldehyde resins and as a supplementary filler for interior beech plywood adhesives, four levels of soium montmorillonite nanoclay were used at 0, 2.5, 5, and 7.5 percent. The results of physical and mechanical properties of MUF resin bonded plywood showed optimum at 5% nanoclay [61].

Soy protein adhesive was modified with SiO_2 nanoparticles at a loading level of 0; 0,5; 1; and 2% and developed the plywood panels. It was found that dry bonding strength of the panels significantly increased by addition of SiO_2 nanoparticles up to 1%. It was also reported that further increase in SiO_2 nanoparticle loading level decreased the bonding strength of the panels [53].

Urea formaldehyde resin chas been developed with different amounts of SiO_2 nanoparticles and studied the effect of nano SiO_2. TGA study demonstrated that SiO_2 had no effect on the resin's thermal stability. From the result they found that the mechanical properties of the panels are enhanced with increasing nano SiO_2 concentration [62].

At various loading levels, the effects of nano SiO_2, nano Al_2O_3, and nano ZnO materials were investigated and determined the formaldehyde emission properties of the particle board and plywood. They found that using nanotechnology, it is possible to produce environmentally friendly wood composite panels with low formaldehyde emission [63].

Nano-wollastonite, a silicate compound ($CaSiO_3$), has been shown to improve fire retardant characteristics in MDF and wood [64, 65] as well as increasing biological resistance to fungi that degrade wood [66]. The use of nano wollastonite as a fire retardant in MDF has yielded promising results [67]. However, no research has been done on how it affects the physical and mechanical qualities of composite panels.

The impact of wollastonite nano fibres on particle board physical and mechanical properties has been investigated [68]. Nano wollastonite with a size range of 30 to 110 nm, was applied at 5, 10, 15 and 20 % of the dry weight of wood chips; and the results were compared to control specimens. Tests were carried out in accordance with ASTM D 1037 specification and concluded that surface application of nano wollastonite at the 15 % consumption level can be recommended for use in particle board.

The impact of a 200 ppm nanocopper suspension with particle sizes ranging from 10 to 80 nm on the physical and mechanical charcteristices of synthesized industrial scale particles board was investigated. At two levels, nanocopper suspension was applied to the mat. Hot pressing time was reduced by 5.7 and 3.4 % at 100 and 150 ml of nanocopper respectively. Also physical and mechanical properties evaluated [69].

The effect of an addition of nano SiO_2 to urea resin on the properties of rape straw board has been determined [70]. It has been found that the optimum amount of nano SiO_2 1.5%/100 gm of UF resin was showed the improved properties of the boards.

Fourier's law for heat conduction was used to investigates the impact of wollastonite nanofibers on the improvement of thermal conductivity coefficient of medium density fiber board. In compared to control boards, thermal conductivity rose by 11.5 percent in nano wollastonite treated MDF boards. This improved thermal conductivity resulted in a better resin cure in the MDF mat's core part, resulting in imported physical and mechanical properties in prior studies [71].

Poplar species particle board was made with Nanomer PGV and Nanomer 1.44p nanoclays. By mechanical mixing, nano clays were used as reinforcing filler for urea formaldehyde resin. The dispersion and exfoliation of nanoclays in the adhesive were validated by scanning electron microscope (SEM) pictures and X-ray diffraction (XRD). For Nanomer PGV reinforced resin, a long gelation time was found. Particle board with a thickness of 12mm and a density of 700 kg/m^3 was created using nanoclay reinforced resin. The water absorption and thickness swelling of the laboratory produced particle board were assessed using Indian standards. By adding Nanomer1.44 p to the resin, water absorption and thickness swelling of wood composites were dramatically reduced. The particle board's water absorption stability and thickness swelling were unaffected by Nanomer PGV [72].

Particle board made using (0.25% wt and 0.5% wt) PGV nanoclay were compared with (0% and 0.5%) boric acid. The nanoclay was dispersed in UF and MUF resin by Mechanical mixing, which was then analysed by X-ray diffraction. The Effectiveness of nanoclay against white rot fungus (polyporousversicolour) was investigated using the S:4873 agar block method. The board's physical and mechanical properties were assessed in accordance with IS:3087-2005. The physical and mechanical qualities of the boards were unaffected by nanoclay reinforcement in the resin. Nano clay has proved to be effective in reducing average weight loss in particle board caused by the white rot fungus. Nanomer PGV (0.25% and 0.5%) has outperformed boric acid (0% and 0.5%). The board's resistance to white rot fungus shows that the addition of nanoclay boosted the boards, endurance without compromising its physical and mechanical qualities [73].

Wollastonite nanofibers in suitable wood (*populous nigra*) were investigated for their fire-retardant properties [74] as well as various physical properties as water absorption, volumetric and anti swelling efficiency. The results indicated that fire-retarding properties were significantly improved in nano wollastonite treated specimen water absorption increased.

The effect of nano wollastonite (NW) on physical and mechanical properties of MDF has been studied [2]. Nano wollastonite was applied at 5,10,15 and 20 g/ kg dry weight basis of wood fibres and results were compared with control specimen. Addition of nano wollastonite contributed in improving physical and mechanical properties of the panels; both were applied internally or as surface treatment. It was concluded that nano wollastonite contents of 10 % and 15 % were the optimal levels for industrial purpose.

The impact of nano clay on weight loss of wood plastic composites (WPC) by five fungi were studied. Nano clay particles of 20 to 50 nm size were applied at 2.4 and 6 % WPC of 0.90 g/cm^3 density. T. Versicolon and P. Vitreas generated the biggest and lowest mass losses in the control and 6 percent nano clay treatments, respectively.

Particle board composites with superior physical and mechanical performance have been created using nano SiO_2, nano Al_2O_3, and nano ZnO at 0%, 1%, and 3% urea formaldehyde resin. As a result of the findings, it was discovered that all nanomaterials enhanced MOR, MOE and screw withdrawal. The greatest results were obtained with 1 % nano SiO_2 or 1% nano Al_2O_3 [75].

The effect of wollastonite fibres on the physical and mechanical properties of MDF made up of wood fibres and upto 10 % camel thorn chips was investigated. The inclusion of camel thorn caused more variable impacts on the panel properties, but wollastonite greatly improved most of the physical and mechanical properties. The addition of upto 10 % camel thorn to the panel would have no harmful consequences. The use of a mixture of 10 % camel thorn and 5 % wollastonite fibres resulted in panels with improved properties [76].

Effects of nano wollastonite (NW) adsorption on the cellulose surface and physical and mechanical properties of medium density fibre board panels were studied [77]. Physical and mechanical tests were carried out in accordance with the Iranian national standard iSIRI 9044 PB Type 2 (compatible with ASTM D 1037-99) specification. The substantial absorption of nano wollastonite on cellulose surface increased mechanical qualities as well as improved biological and thermal conductivity, according to the findings.

The elastic modulus and yield stress for polypropylene-based wood-plastic composites has been studied as a function of wood flour type, nanofillers type and technique of incorporation. Nanofillers' impact on the WPC structure is also examined. It is demonstrated that optical and scanning electron microscopy allows one to make a morphological analysis of the WPC structure [78].

To build a system with a lower level of toxicity, a nano form of Copper oxide, Zinc oxide and Copper sulphate was developed for wood based panel products. Wood preservatives are products which has been used for the safeguard of wood from deterioration by fungi, moulds or pests etc. Nano form of Copper oxide, Zinc oxide and Copper sulphate were synthesizd by mechanical milling in the high energy planetary ball mill. According to the findings, the nano form of the preservatives was better matched with the glues than their soluble forms among the three validated preservatives. The result also shows the bonding quality of the plywood with satisfactory limit of acceptance [79].

The effect of calcined nanoclay (CNC) on the microstructure and mechanical properties of treated hemp fabric-reinforced cement nanocomposites has been investigated. The optimum hemp fabric content for these nanocomposites was 6.9 wt% (6 fabric layers). Mechanical properties were improved by the calcined nanoclay (CNC) inclusions. The tests were carried out with inclusions of 1, 2 and 3 wt% and 1 wt% CNC replacement of regular Portland cement was shown to be the most effective. The microstructure of composite materials usually showed porosity [80].

Titanium dioxide nanoparticles have been synthesized by microwave-assisted hydrothermal method to incorporate them to the structure of Pinus elliottii wood [81]. The color changes and the decay resistance of impregnated wood was studied. In comparison to the untreated wood, titanium dioxide nanoparticles did not modify the natural colour of the wood while also reducing the degree of white rot fungus (Ganoderma applanatum) colonisation in the wood structure and wood degradation. In compared to wood treated with chromated copper borate, titanium dioxide treated wood samples exhibited equivalent protection against deterioration. Impregnation with titanium dioxide nanoparticles can be an useful way to reduce/avoid.–

The physical and mechanical properties of MDF were investigated after adding nano wollastonite and date palm prunings [82]. They used UF and isocynate (IC) resins were used to produce panels at contents of 10 % and 5 %, respectively based on dry weight of the composite material. Nano wollastonite was employed at concentration of 5 % and 10 % based on the dry weight of the resins and the results were compared to the non added nano wollastonite panels. Palm leaf wastes were shown to be a viable raw material for the production of MDF panels utilising both UF and isocynate resins. Nano wollastonite is also recommended as an addition in composite panels containing 10% palm residues to help compensate for some of the property losses. The effect of addition of nano wollastonite and camel thorn chops on fire resistance of medium density fibre boards were assured [83]. In the panels, adding 5 or 10% nano wollastonite to urea formaldehyde resin resulted in significant improvements in the timings to ignition and glowing, as well as the burning length. The better resin curing was aided by the higher heat conductivity. The findings show that nano wollastonite has the ability to improve fire characteristics in MDF qualities.

The effect of the fortification level of nano wollastonite on UF resin and its effect on mechanical and physical properties of oriented strand lumber has been investiagated. Two amounts of nano wollastonite are combined with the resin (10 and 20 percent). It is found that the fortification of urea formaldehyde resin with 10 % nano wollastonite can be considered as an ideal. Results cleared the improvement of thickness swelling values, physical and mechanical properties of the panel [84].

In a concept of sustainable material management, the effect of mixed inorganic elements on wood hardness and flame-retardancy qualities was investigated. The vacuum-pressure approach is used to fortify Scots pine (Pinus Sylvestris L.) sapwood with sodium silicate and TiO_2 nanoparticles [85]. The treated wood's hardness rose, with the 10 percent Na_2SiO_3–nTiO_2 modified wood achieving the highest value (a 44 percent increase in hardness). The results demonstrated a strong link between the TG and the flammability test; the limiting oxygen index (LOI) values for the wood–inorganic composites rose by 9–14% when compared to untreated wood.

The impact of nanomaterials and particles on the behaviour of composite material structures has been studied, with consideration given to material structural features, method of production, compatibility with other phases, size, dispersion process, adhesion, and other aspects. It also revealed how much filler to use to improve mechanical qualities (such as stiffness and strength) and fracture toughness from both an interlaminar and intralaminar standpoint. Aside from that, the effects of soft, hard and hybrid fillers were organised to show how some filler have spectacular benefits for specific property enhancements. Finally, the review paper discusses how the addition of nanofillers and particles to fiber reinforced plastic composites influences damage onset and behaviour [86].

A new technology for using metal nanoparticle for wood protection that is both environmentally bengin and financially effective has been investigated. Plant extracts that are known to have wood preservation characteristics were used to make metal nanoparticles. The synergistic effects of plant extracts' intrinsic properties and the biocidal properties of metal nanoparticles were used. Copper oxide nanoparticles were made using leaf extracts from Neem (Azadirachta indica), Pongamia (Pongamia pinnata), Lantana (Lantana camara), and orange peel extract (Citrus reticulata). The efficacy of a synthesised plant extract and copper oxide nanoparticle combination against wood deterioration is investigated. The impact of the copper oxide nanoparticle formulation against termites is evaluated using a graveyard test. Initial results are promising, and work is underway to develop a stable and environmentally friendly wood preservative compound containing metal nanoparticles and plant extracts) [87].

The effect of adding nano wollastonite to medium density fibre board (MDF) on fire characteristics was investigated. Nano-wollastonite was added at four different levels (2%, 4%, 6%, and 8%). The results indicated the significant enhancement on ignition, which attributed to an increase in thermal conductivity of nano wollastonite modified baord. It was inferred that for applications where fire properties are of prime significance, nano-wollastonite content of 8% can be suggested [88].

Recent studies have demonstrated that the application of nanotechnology in wood composite panels has shifted towards the utilization of sustainable bio-based nanomaterials such as cellulose nanocrystals (CNC), cellulose nanofibrils (CNF), and lignin nanoparticles. These nanomaterials exhibit excellent compatibility with thermosetting adhesives and significantly improve bonding quality, tensile shear strength, modulus of rupture (MOR), modulus of elasticity (MOE), and dimensional stability while simultaneously reducing formaldehyde emissions. Furthermore, nanocellulose acts as an effective reinforcing agent by increasing the viscosity and cohesive strength of adhesive systems, thereby enhancing the overall performance and durability of engineered wood products. Likewise, lignin nanoparticles have emerged as environmentally friendly alternatives capable of improving mechanical strength, moisture resistance, and sustainability of wood composite panels, making them promising materials for next-generation green wood products [89, 90]. Table **1** showed the comparative summary of nanoparticles used in wood composite panels and their effects.

4. FUTURE PROSPECTS OF NANOTECHNOLOGY

Nanomaterials have received a lot of attention in recent years due to their unique properties and importance in specific applications. Many researchers have begun to investigate nanomaterials. These studies are primarily concerned with three aspects: theoretical research, simulation analysis and experimental investigation.

Apparently nanotechnology will proclaim the next generation of wood-based products with hyper-performance and advanced service abilities when utilized for exterior purpose. Nanotechnology appears to introduce a tool to broaden structural performance and the scientists and researchers can manage the serviceability of wood, allowing them to manipulate and maybe eliminate the occurrence of random flaws. Modern or low-hazard nanomaterials like nano-dimensional zinc oxide, silver, titanium dioxide, and even possibly clays might be utilized as either preservative treatments or moisture barriers. The use of nano-dimensional materials such as titanium dioxide and clays can also improve fire resistance. It has been discovered that a lack of knowledge regarding nanoparticles has hampered their widespread use. They should be assessed for their possible impact on both health and the environment using tools like a life-cycle assessment. As a result, laws and several testing must be completed prior to the commercialization and manufacturing of such items, particularly those designed for indoor usage. As concluded by Bauer the issues and elements of a common framework for LCA and nanotechnology can be summarized as: ‘(i) the structuring of typical functions as the basis for common system boundary definitions to enable comparisons, (ii) the establishment of modular LCI models to describe the variety of materials and manufactured properties, and (iii) the agreement on provisional procedures to document nanoparticle release even in the absence of applicable impact assessment models' [91].

The impact of Nanotechnology on the building sector has lately been investigated. Because wood is regarded as a crucial engineering material, the authors choose to allude to the study's key findings, namely, (i) the construction sector has high hopes of nanotechnology to tackle some of the industry's most

Table 1: Comparative Summary of Nanoparticles used in Wood Composite Panels and their Effects

S.N.	Nanoparticle Type	Typical Loading Level	Composite Material	Key Findings	Major Advantages	Limitations	References
1	Nano-SiO_2	0.5–2.0 wt%	Particleboard, Plywood, UF resin	Improved MOR, MOE, internal bond strength and reduced water absorption	Better mechanical properties and dimensional stability	Agglomeration at higher loading levels	Xu *et al*. (2011) [54]; Roumeli *et al.* (2012) [62]; Dorota (2013) [70]
2	Nanoclay (MMT, PGV)	0.25–7.5 wt%	Particleboard, Plywood	Enhanced bonding strength, reduced thickness swelling, improved fungal resistance	Better moisture resistance and durability	Excess loading may reduce adhesive flow	Lei *et al*. (2008) [7]; Doosthoseini and Hosseinabadi (2010) [61]; Mamatha *et al.* (2015) [73]
3	Nano-Wollastonite	5–20 wt%	MDF, Particleboard, OSL	Improved MOR, MOE, thermal conductivity, fire resistance and biological durability	Enhanced curing efficiency and fire retardancy	High dosage may increase production cost	Taghiyari *et al*. (2013) [67]; Taghiyari and Nouri (2015) [2]; Hassani *et al*. (2019) [84]
4	Nano-ZnO	1–3 wt%	Particleboard, Plywood	Reduced formaldehyde emission and improved antimicrobial performance	Eco-friendly wood protection and durability	Uniform dispersion is essential	Candan and Akbulut (2013) [59]; Nosal and Reinprecht (2017) [63]
5	Nano-Al_2O_3	1–3 wt%	Particleboard	Improved MOR, MOE and screw withdrawal strength	Enhanced mechanical performance	Limited studies on long-term durability	Kumar *et al*. (2013) [6]; Candan and Akbulut (2015) [75]
6	Nano-TiO_2	1–5 wt%	Wood, Plywood	Improved UV resistance, decay resistance and surface hardness	Better weathering resistance and self-cleaning potential	Higher cost compared to conventional fillers	Dukarska and Lecka (2009) [41]; Zanatta *et al.* (2017) [81]
7	Nano-Cu/CuO	100–200 ppm	Particleboard, Plywood	Improved biological durability and reduced pressing time	Effective wood preservative	Possible environmental concerns at high concentrations	Taghiyari and Bibalan (2013) [43]; Gao and Du (2015) [37]
8	Nano-Ag	0.5–2 wt%	Particleboard surfaces	Excellent antibacterial and antifungal activity	Improved hygienic properties	High material cost	Taghiyari (2011) [42]; Nosal and Reinprecht (2019) [36]
9	Nanocellulose (CNF/CNC)	0.5–3 wt%	Plywood, Engineered wood products	Improved adhesive bonding, MOR, MOE and reduced formaldehyde emission	Renewable, biodegradable and sustainable reinforcement	Industrial-scale processing requires optimization	Naghizadeh *et al*. (2024) [97]; Silva *et al.* (2025) [90]
10	Lignin Nanoparticles	1–5 wt%	Wood composites, Bio-based adhesives	Improved mechanical properties, water resistance and sustainability	Renewable alternative to petroleum-based additives	Commercial application is still limited	Bansal *et al*. (2024) [89]

difficult challenges; (ii) Although expectations are high, a major impediment is a lack of literacy on nanoscale topics and a detachment from active R&D initiatives. (iii) To overcome these constraints, systematic industry- or company-wide initiatives, such as roadmaps and strategic plans, must be implemented in order to reap the benefits of nanotechnology and establish a competitive advantage in specific application areas and product categories.' There are also significant worries about the impact of nanoparticles on human health and the environment. Nanomaterials may have an unfavourable effect on the respiratory and digestive tracts, as well as the eyes and skin surface, due to their small size [92-94].

Despite this, only a few research have been conducted to provide answers to the environmental and social challenges associated with the use of nanomaterials [95]. Last but not least, being an emerging technology, nanotechnologies' economic prospects, are based on the opportunity to improved material properties in a more refined manner. In this way, the seriousness of an organization, and subsequently its development, may depend, sooner rather than later, on its capacity to apply nanotechnologies and to utilize nanomaterials.

Recent developments indicate that nanotechnology is rapidly advancing from conventional nanoparticle reinforcement towards multifunctional and sustainable wood protection systems. Current research emphasizes nano-enabled coatings with self-cleaning, superhydrophobic, UV-resistant, antimicrobial, and fire-retardant characteristics, together with the development of bio-based nanomaterials such as nanocellulose and lignin nanoparticles for environmentally friendly wood modification. In addition, nano-reinforced adhesive systems are receiving increasing attention due to their ability to enhance bonding performance, improve durability, and reduce dependence on petroleum-derived chemicals. These innovations are expected to facilitate the commercialization of high-performance, low-emission, and sustainable wood composite panels for structural and non-structural applications [96, 97, 89].

Nanotechnology-based coatings were shown to be 20 times more effective in terms of water repellency. The global market for nanomaterials is expected to reach $340 billion in the next twenty years, according to estimates.

5. CONCLUSIONS

Nanotechnology ofers the possibilities to change the scene of wood-based products industry locally and universally. The fundamental reason for using nanotechnology in wood science and technology is the unique ability of nano-based materials to penetrate deeply into wood substrates in an efficient manner, altering the surface chemistry of the wood. As a result, the characteristics of the wood improve. Nanomaterials improved the attributes of wood as a raw material while just slightly altering its inherent characteristics.

Bonding performance, modulus of rupture, modulus of elasticity, and screw withdrawal resistance have been determined to be more important performance for composites made using sustainable biomaterials.

Recent investigations suggest that future research should focus on improving nanoparticle dispersion, optimizing bio-based adhesive formulations reinforced with nanocellulose, developing multifunctional hybrid nanocomposites, and evaluating the long-term durability and life-cycle sustainability of nano-engineered wood products. The integration of renewable nanomaterials with advanced adhesive technologies is expected to promote environmentally sustainable wood composites possessing superior mechanical performance, enhanced durability, and substantially reduced formaldehyde emissions, thereby supporting the transition toward greener wood-based industries.

Based on the survey of utilization of nano-materials in wood and wood-composite panels, it can be concluded that nanotechnology and nanomaterials have an extraordinary probability to be utilized in solid woods as well as wood-composite materials in order to enhance their properties as well as overcome some of their shortcomings.

The review is to summarize the effect of various types of nanomaterials on the mechanical characteristics of the composite materials with polymeric matrix.

AUTHOR CONTRIBUTION

NA.

FUNDING DECLARATION

The authors received no financial support for the publication of this article.

CONFLICT OF INTEREST

The review work has been done in the point of Indian wood industry. I have not submitted same work anywhere else. So, there is no conflict of interest.

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