Review Article

Haoxian Sun, Xuhong Li, Haitao Li*, David Hui, Milan Gaff, and Rodolfo Lorenzo Nanotechnology application on bamboo materials: A review

https://doi.org/10.1515/ntrev-2022-0101 received November 20, 2021; accepted March 18, 2022

Abstract: Bamboo is one of the renewable materials which can be applied in the engineering field widely. Previous research has shown that bamboo's inherent poor durability can limit the application of bamboo materials. And nanotechnology has been receiving more and more attention on improving the properties of natural materials, simultaneously. This article aims to promote the application of nanotechnology on bamboo by presenting some guides. And this article has been organized as follows: first, the characteristics and nanomechanical behavior of bamboo in mesoscopic and nanoscopic scale have been introduced. Then, nanomaterials for modifying bamboo have been presented. Next, some analyses on the improvement of some properties of nano-modified bamboo materials have been made. Finally, future perspectives have been discussed.

Keywords: bamboo, coatings, nanocarriers, nanoindentation, nanoparticles, nanotechnology

Abbreviations

A. niger	Aspergillus niger
AN	acrylonitrile
BFCW	bamboo fiber cell wall
E. coli	Escherichia coli
FAS-17	(heptadecafluoro-1,1,2,2-tetradecyl) tri-
	methoxysilane [CF ₃ (CF ₂) ₇ CH ₂ CH ₂ Si
	(OCH ₃) ₃]
GO	graphene oxide
IV	infection values
MAPE	malleated polyethylene
MMA	methyl methacrylate
MMT	montmorillonite
MOR	modulus of rupture
MT	mesoporous anatase TiO ₂
P. citrinum	Penicillium citrinum
PEA	poly(ethylene-alt-maleic anhydride)
PMHS	poly(methyl hydrogen siloxane)
RH	relative humidity
RT	room temperature
SEM	scanning electron microscope
T. viride	Trichoderma viride
UV	ultra-violet

1 Introduction

Bamboo grows fast and has excellent mechanical properties [1,2]. The structure of bamboo consists of parenchyma cells and sclerenchyma fibers [3]. And the main chemical compositions of bamboo are hemicellulose, cellulose, and lignin [4]. The cell wall is mainly composed of cellulose (40-60%), hemicellulose (about 20%), and lignin (about 25%) [5]. Cellulose is a carbohydrate like starch, but it is a structural polysaccharide, while starch is a storage polysaccharide [6]. And cellulose has been considered as the structural and skeletal part of the bamboo cell wall [7,8]. And the cellulose separates in the secondary wall evenly [9]. Hemicellulose is an amorphous substance that fills in as a binder between fibers and

^{*} Corresponding author: Haitao Li, Department of Building Engineering, College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China; Joint International Research Laboratory for Bio-composite Building Materials and Structures, Nanjing Forestry University, Nanjing 210037, China, e-mail: lhaitao1982@126.com

Haoxian Sun: Department of Transportation and Civil Engineering, College of Civil Engineering, Nanjing Forestry University, Nanjing 210037, China; Joint International Research Laboratory for

Bio-composite Building Materials and Structures, Nanjing Forestry University, Nanjing 210037, China

Xuhong Li: Jiangsu Productivity Promotion Center, Nanjing 210042, China

David Hui: Department of Mechanical Engineering, University of New Orleans, LA 70148, United States of America

Milan Gaff: Department of Furniture, Mendel University in Brno, Design and Habitat Brno, 61300 Brno, Czech Republic

Rodolfo Lorenzo: Department of Civil, Environmental and Geomatic Engineering, University College London, London, WC1E 6BT, United Kingdom

microfibers [10-13]. As the most reactive biomass component, hemicellulose is hydrolyzed into oligomers and monomeric structures. Hemicellulose is similar to cellulose because it is composed of sugar, but it is more diverse [14]. Lignin is a category of hydrocarbon polymers consisting of aliphatic and aromatic structures [15]. Compared with hemicellulose and cellulose, lignin has a lower content of hydroxyl groups, better hydrophobicity, and chemical inertness [18]. Besides, lignin has been considered as a reinforcing agent for cellulose and microfiber/fibril [16]. And more lignin can be found in the narrow lamella of the structure of bamboo fiber than the broad lamella [9] around the cell lumen. In terms of nutrient content, on average, bamboo has starch (2-5%), protein (1.5–6%), glucose (2%), and fat and wax (2–3.5%) [17,18]. Compared to wood, bamboo possesses more polysaccharides and starch [19], causing bamboo to be more vulnerable to damage from mold [17,18].

The inherent disadvantages of bamboo such as the high content of nutrients, hydrophilicity, and dimensional instability shortened the service life [20–22]. Bamboo was characterized by a large number of hydrophilic hydroxyl groups and limited crystallinity making it unsuitable for direct use in the engineering field where good dimensional stability is required [23]. Research on bio-based materials is becoming more and more popular, for instance, wood composites [24,25], test value of wood material constant [26], the energy dissipation of timber [27,28] which can help deal with earthquakes [29], buckling behavior of both wood [30] and bamboo [31], and the connectors of multi-culm bamboo members [32] which can be inspired by studies on bolted connections [33] in some steel structures. The studies on engineered bamboo materials [34], such as laminated bamboo [35-46], bamboo scrimber [47–50], flattened bamboo [51,52], and bamboo composite [53-56] are also increasing more and more.

"Nanotechnology refers to any technology that is implemented at the nanoscale and has applications in the real world" [57]. Nanotechnology has been applied both in wood and bamboo, while the applications in bamboo (both natural and engineered bamboo) are not adequate so far. Some nanomechanical behavior can be revealed *via* the nanoindentation technique to provide some guides to the further modification involving nanomaterials or other nanotechnologies. When it comes to nanomaterials used in modifying bamboo, most of the applications were involving coatings to improve the anti-microorganism capacity, hydrophobicity, wettability, thermal stability, flame-retardant property and ultra-violet (UV) resistance, and so on, and some specific functional properties can also be granted to bamboo such as conductive ability, and so on. However, the application of nanocarriers has not received enough attention which may be due to some financial factors, although nanocarriers in some studies on making drugs have been proved to be effective and the process has been optimized by artificial intelligence.

This article has been organized to introduce the main chemicals and characteristics of bamboo in the mesoscale, and the utilization of nanoindentation technique in revealing the nanomechanical properties of bamboo (especially the bamboo cell walls) has been presented later to better understand the bamboo in the nanoscopic scale so as to offer some guides in modifying bamboo *via* nanotechnology. The milestones of nanomaterials utilized in bamboo materials have been comprehensively presented as the main part of this article and some analyses have been made so that some guides for the further nanotechnology application on bamboo materials can be provided. Review paper on nano-modified bamboo is rare so far, although some papers have reviewed the application of nanotechnology on the wood [58–60].

2 Bamboo in nanoscopic and mesoscopic scale

2.1 Mesoscale characteristics

The morphology of bamboo is different from that of wood. The apparent radial-gradient distribution structure in the cross-section of bamboo, especially from the outside to the inner part, is more non-homogeneous than most wood [61]. The sclerenchyma cells (fibers) are embedded in a matrix of parenchyma cells. On average, parenchyma cells and sclerenchyma fibers take up roughly 50% and 40% of the volume of bamboo culm, respectively [61,62] (while recent research found that the fibers occupy about 25% in volume and the fraction increased from 14.6 to 39.7% when measured from the inner part to the outer [63]). Sclerenchyma fibers dominate the mechanical properties of bamboo culm, including fracture toughness [64], rigidity [65], strength [66], and so on. Parenchyma cells play a key role in resisting buckling failure and improving curve ductility [67]. The heterogeneous structure of bamboo has been shown in Figure 1 [68]. The low microfiber angle (about 10°) and high tensile modulus (about



Figure 1: Schematics of the heterogeneous structure of bamboo [68].

36.7 GPa) of bamboo fibers are more than twice as those of wood fibers [69]. The chemical contents of bamboo are mainly hemicellulose, cellulose, and lignin [70]. The cellulose content increases from the bottom of the culm to the upper part. The outer surface of bamboo culm possesses a higher content of α -cellulose, holocellulose, and lignin but lower ash content and extractive content compared with the inner surface in specific cross-sections [71]. The abundant presence of hydrophilic oxhydryl groups and layered porous structures in bamboo culm can help with absorbing of water.

Although the multicellular structure of both bamboo and wood is well-layered, the layered structure of the cells of bamboo is more variable [61]. There is a large variability in the number of layers, with the minimum number of layers ranging from 2-3 to a maximum of 18 layers depending on the bamboo species and site [61]. The bamboo cell wall is composed of several layers of different thicknesses alternating in sequence [9]. The thickness of these wall layers is usually small, and some are below 100 nm [72]. In addition, a special multi-wall structure of bamboo cells is formed by wall layers with unequal width, which makes it difficult to study the distribution of wall chemicals [9]. It has been recently found that the chemical composition of bamboo cell walls can be better analyzed in situ using nano-infrared techniques, which has exceeded the diffraction limit of conventional infrared spectroscopy techniques to obtain infrared spectra at the nanoscale [9]. This has been considered as an effective method to study the nano-distribution of the chemical composition of bamboo cell walls [9]. The scanning electron microscope (SEM) images of cell walls have been presented in Figure 2. The hierarchical structure of bamboo over different length scales has been proposed by Parameswaran and Liese [72,73], and is shown in Figure 3, which was reprinted by Liu *et al.* [74].

The pore space in bamboo is one of the main factors affecting the mechanical properties and dimensional stability of the bamboo material [4]. The International Union of Pure and Applied Chemistry classification divides pores into three categories: micropores (pore diameter <2 nm), mesopores (pore diameter between 2 and 50 nm), and macropores (pore diameter >50 nm) [75,76]. The distribution of mesopores with different sizes in volume is shown in Figure 4.

2.2 Bamboo's nanomechanical behavior measured *via* nanoindentation

Nanoindentation technique has been used to determine the features of materials and constituents [77,78]. And many papers have introduced this method comprehensively [79,82].



Figure 2: SEM images of bamboo cell wall structures: (a and b) untreated parenchyma cells [4] and (c) untreated sclerenchyma cells [4].



Figure 3: (a) Model of the structure of a bamboo cell wall [74], (b) the middle lamella is the outer-most layer, followed by the primary wall [74], (c) the short tiny fibers [74], (d) nanoscopic scale cellulose grains with orientation and other components [74]. (Reprinted from Parameswaran and Liese [72,73] by Liu *et al.* [74]).

The nano-mechanical behavior of bamboo materials is mainly influenced by the complex arrangement of the solid part of the cell wall, the porosity, and the variation in the chemical composition [4]. Recent related studies were focusing on the determination of nanomechanical properties (such as modulus of elasticity (MOE), hardness, creep behavior, *etc.*) of bamboo materials by using the nanoindentation technique [4,80–83].

The excellent mechanical properties of bamboo are largely derived from the sclerenchyma cell fibers [80].



Figure 4: The mesopore size of Moso bamboo (between 1.5 and 10 nm) [4].

Guo et al. [80] performed nanoindentation tests on three different areas of the cross-section by using the continuous stiffness method. It was found that the outermost fibers had the highest MOE and a decreasing trend from the outside to the inside was observed, with the inner side having 18.1% lower MOE than the outer side, indicating that the functional gradient properties of bamboo material are not only expressed in the macroscopic but also the mesoscopic structure [80]. Fibers of Moso bamboo possess the behaviors in which the constant deformation occurred under constant load and the load kept decreasing while the deformation was constant, i.e., creep and relaxation behaviors of the material [81]. Li et al. [81] investigated the creep and relaxation behaviors of Moso bamboo fiber cell wall (BFCW) using nanoindentation. The results showed that the mechanical properties were unequal in the longitudinal and transverse directions of BFCW, and more pronounced relaxation behavior and stronger creep deformation resistance in the longitudinal direction were observed. The indentation depth and creep displacement of BFCW in the longitudinal direction were smaller than those in the transverse direction, and the differences reached 24.96 and 32.25% at the maximum indentation load of 15 mN. The relaxation capacity of BFCW longitudinal was stronger than that of transverse, and the longitudinal load relaxation was 34.58% higher than that of transverse at a loading rate of 50 nm/s. Qin et al. [82] investigated the static longitudinal nanomechanical properties of Moso bamboo cell walls by using nanoindentation and concluded that the main factors affecting the longitudinal mechanical strength of bamboo fiber cell walls were microfibril angle and lignin content, while correlations with bamboo age and height were kind of minimal (compared in one experiment). The MOE and hardness of these aforementioned research are listed below in Table 1. By comparing the literature in Table, one major factor affecting the properties of bamboo can be found as follows [71,73]. Both MOE and hardness were more sensitive to the variation in the part in cross-section than the change in height and age.

In summary, the main factors influencing the nanomechanical properties of bamboo were crystallinity, moisture content, chemical composition, density, and microfibril angle [84–86]. The main factors affecting the longitudinal mechanical strength of bamboo fiber cell walls were microfibril angle and lignin content, while the factors were little correlated with age and height of bamboo [83]. The improvement in creep properties can be improved in some research by increasing crystallinity and forming cross-linkages between cell wall polymers [87].

3 Nanomaterials for modifying bamboo

So far, many studies have been implemented on the nanotechnology application on wood. Related review papers [58–60] have indicated that the chemical properties of the surface and material properties (cell walls show molecular-scale porosity due to the partial filling of spaces between cellulose and microfibers) can be improved. And these were mainly due to the presence of pores in the wood so that nanomaterials can penetrate the material wall [58–60]. But the microscopic properties of bamboo are different from those of wood, which may cause changes in the penetration and distribution of nanomaterials.

Chemical methods (such as using some preservatives) to improve the durability of bamboo materials can bring good results. However, the chemical treatment process may use some chemicals that are toxic to the environment and human beings (such as alkaline copper quaternary compound [88], chromated copper arsenate [89], *etc.*). Therefore, chemical modification has some limits [90].

Intender's type	Part in cross-section	Height along the culm/m	Age/year	MOE/GPa	Hardness/GPa	Ref.
A trigonal diamond indenter (Berkovich-type indenter)	Outside	3-4	3.5	13.8	0.29	Guo <i>et al.</i> [80]
	Middle	3-4	3.5	12.0	0.28	Guo <i>et al</i> . [80]
	Inside	3-4	3.5	11.3	0.28	Guo <i>et al</i> . [80]
The tip radius of indenter is less than 100 nm (Berkovich-type indenter)	Outside	5	6	20.65	0.54	Qin <i>et al.</i> [82]
	Middle	5	6	19.57	0.49	Qin <i>et al.</i> [82]
	Inside	5	6	17.82	0.44	Qin <i>et al.</i> [82]
	Middle	3	6	22.83	0.58	Qin <i>et al.</i> [82]
	Middle	5	6	22.91	0.59	Qin <i>et al.</i> [82]
	Middle	7	6	23.86	0.53	Qin <i>et al.</i> [82]
	Middle	5	2	23.23	0.67	Qin <i>et al.</i> [82]
	Middle	5	4	21.35	0.59	Qin <i>et al.</i> [82]
	Middle	5	9	22.91	0.59	Qin <i>et al.</i> [82]

Table 1: The MOE and hardness of bamboo cell wall

Among the studies involving the nanomaterials applied in modifying the bamboo, most studies mainly focused on the treatment towards the surface (coating treatment). And most of the nanomaterials used in bamboo modification involved metals or metal-oxides, and a lot of efforts have been carried out including impurity doping, metallization, sensitization and coating, and so on [91,92]. Nanomaterials applied in bamboo modification mainly involved: (i) coatings, (ii) nanocarriers, and (iii) nanosized compounds penetration.

Most of the research works were focused on improving the durability of the bamboo. And one solution was via reducing the interaction with moisture/water, which can make the super-repellency towards water, and special liquid sorption properties on the substrate. And this solution has become popular in determining wood conservation. And the other was improving the anti-microorganism ability. Photocatalytic microorganism disinfection depended on the interaction between microorganisms and reactive oxygen species from photocatalysts when the light is cast on them, for instance, OH⁻ and 0^{2-} , which can be released by the sunlight, are harmful to some microorganisms [93]. However, not all the antimicroorganism abilities were derived from the good photocatalytic performance of nanomaterials. Li et al. [94] coated Ag-TiO₂ composite films on the bamboo and excellent antifungal activity with this synergistic antifungal effect was found while it was unrelated to photoactivity.

Some other interesting properties have also been developed on bamboo. Jin *et al.* [95] considered that inorganic-nano-materials/polymer-composite (wood or bamboo) could be seen as a kind of portable bio-based photocatalysts for the degradation of contaminated solutions because of the merits of wood, bamboo, and cellulose materials for the immobilization and growth of nanomaterials and the environmentally friendly, easily biocompatible, easily designed, and feasibly biodegraded characteristics of those cellulose-based materials [96,97]. And the conductive ability of the bamboo surface has been realized using copper nanoparticles by Bao *et al.* [98].

3.1 Nanosized metal, metal, and non-metal compounds

Biomass composite involving inorganic materials possessed some functional properties such as specific electrical, magnetic, optical, and biological properties. And nano-sized metal compounds with tiny sizes, high surface-to-volume ratio, and even tunneling effect (which is related to quantum mechanics) [99], and so on, can render biomass materials some specific values or expand the applications [100].

3.1.1 Nanosized metals and metal compounds

Nanosized metals or metal compounds can be synthesized mainly by using chemical methods, namely: (i) solutionbased synthesis (sol-gel, sonochemical, and solvothermal) and (ii) vapor-based synthesis (combustion and chemical vapor deposition) [58-60]. Nano-sized metal oxide particles, such as zinc oxide (ZnO) [101], titanium dioxide (TiO₂) [102], cerium oxide (CeO) [103], CuO [104], Ag [105], and so on have been reported to have strong antibacterial properties. And these nano metals and their compounds have been reported to be more active than non-nanometals, which were attributed to their higher surface area and ability to exhibit unique physical and chemical properties. Inorganic materials (especially nano-sized materials [such as nanosized metal compounds]), can interact with microorganisms such as fungi, bacteria, and so on, by the electrostatic reaction which negatively affects the active external pump transport system of β-lactamase and thus, the excellent antibacterial outcome can be reached [106].

Nanosized metal particles can show bright color because of the localized surface plasmon resonance characteristics (the surface plasmon excited by light) [107]. The conduction electrons around metal nanoparticles vibrated at a certain frequency when the light interacted with the metal nanoparticles [108]. Localized surface plasmon resonance characteristics of metal nanoparticles have been widely applied in the field of modifying the surface and other fields [109,110]. And notably, plasma combined with a resin-based protective agent has been used in modifying bamboo to improve its anti-organism ability and compression strength, decrease equilibrium moisture content and wet swelling rate of natural bamboo, and besides, cracks, mold, and decay at the end part of bamboo strips and tubes can be mitigated [111].

As to Ag nanoparticles [112], they have been found to be easy to be synthesized and characterized, which possessed good chemical stability when covered by some organic stabilizer, high biocompatibility, and large atomic weight when compared to bamboo matrix [113,114]. Pandoli *et al.* [114] filled the bamboo matrix with silver colloids as nanofiller agents for the first time. The effectiveness of Ag countering microorganism attacks (especially fungi) has been proved due to the broad spectrum of bactericidal properties of Ag nanoparticles [113,115].

As to Cu, it is a metal with excellent electrical conductivity, and nano copper particles [116] have been proved to be a low-cost and effective reagent, which possesses good antibacterial activity [117] and excellent UV protection performance [118]. Notably, the transportation efficiency of Cu can be increased by electric field [119]. Ju et al. [110] fabricated a functional bamboo with nanosized Cu in it and the functional bamboo was realized by combining Cu nanoparticles with hemicellulose and lignin under a high voltage electric field. After the leaching test, in situ impregnation of Cu under a high voltage electric field possessed an excellent fixation performance. The functional bamboo also possessed significant antibacterial properties and excellent UV protection performance. The concentration of Cu ions reached the highest while the treatment condition was 60 kV/24 h.

As to γ -Fe₂O₃, it is a kind of popular metal compound in many fields due to the excellent non-toxicity, thermal stability, chemical stability, especially the superparamagnetic performance [120], and thus, it has been widely applied in environmental protection [121], biomedicine [122], microwave absorption [123], drug delivery [124], and magnetic resonance imaging [125]. Notably, the self-healing property of γ -Fe₂O₃ particles in the oscillating magnetic field was also interesting [126].

ZnO is gaining more and more attention [127] due to its good chemical stability, non-toxic (is selectively toxic to bacteria, while it is almost harmless to human cells [128]), cost-efficient, and has good anti-microorganism ability [129]. And meanwhile, ZnO has been classified as "Generally Recognized as Safe" by the US Food and Drug Administration [130]. Compared to nanomaterials with large sizes, ZnO is smaller and possesses a higher surface-to-volume ratio, and thus, ZnO can better interact with microorganisms [131]. After further studies, it was found that ZnO-treated bamboo materials performed better when interacting with *Aspergillus niger* (*A. niger*) and *Penicillium citri* (*P. citri*)), while they were less resistant to *Penicillium glabra*, according to Li *et al.* [131].

Anatase TiO_2 , has often been used to provide roughness of surfaces due to its chemical stability and non-toxicity [132]. When used in the modification for low-surface-energy coatings, it provided superior water resistance which can separate the wetting properties from the natural properties of the substrate [133]. However, bare TiO_2 has been found to be inefficient and with a narrow photoreaction range, and besides, the agglomeration of TiO_2 nanoparticles on the surface can significantly reduce photocatalytic activity as well. Therefore, the

application of bare TiO_2 in photocatalysis under sunlight [115] has been limited to some extent. While its drawbacks can be minimized by collaborating with other nanoparticles such as Ag [115] or Fe [134], and so on.

As to the modification with nanosized particles during the fabrication process of engineered bamboo, the anticorrosion and anti-mildew properties, physical and mechanical properties, excellent weather resistance, and special functions of the recombinant bamboo can be developed and improved via the presence of nano-materials. Therefore, the purpose to simultaneously improve the quality and added value of recombinant bamboo can be met [100]. Lou et al. [100] fabricated the recombinant bamboo (also known as bamboo scrimber, and parallel bamboo strand lumber) with good compressive properties, dimensional stability, mildew resistance, and last but not least, efficient electromagnetic dissipation capacity. The fabricating process is shown in Figure 5. After the experiment, they found that the bamboo bundles prepared by impregnation with 0.4 mol/L iron salts resulted in the recombinant bamboo boards possessing the best compression property, dimensional stability, and antimildew capacity. These brief fabrication methods and effects of nanomaterials have been presented in Table 2. By comparing the literature in Table 2 [100,110,114], the discussion can be made as follows. Bamboo samples with Ag particles possessed better anti-organism ability than those with Cu and Fe_3O_4 , and thus Ag can be purposely used to resist microorganism while Cu and Fe_3O_4 can be applied to the mixed particles planted in/on bamboo to improve the ability of fixation of particles and some physical properties of bamboo.

3.1.2 Non-metal compounds

Graphene oxide (GO) has received more and more attention in the areas of interdisciplinarity such as chemistry and biology due to its excellent physical and chemical properties such as anti-microorganism activity, biocompatibility, non-toxicity, and so on [135]. As to the GO nanosheets, they possess a large surface area with a two-dimensional structure and contain different groups with oxygen. And these abundant oxygen-containing groups render GO good hydrophilic and excellent biocompatibility properties [135-137], and the adhesion between GO and bamboo fibers can be enhanced due to the abundance of oxygenated functional groups (such as OH and COOH groups) [138]. Recently, Wang et al. [138] incorporated the GO nanosheets with densified bamboo after heat-pressing treatment. The mechanical properties were well improved especially when compared to natural bamboo. Densified bamboo fibers, collapsed cells, and GO nanosheets (tightly attached to the surface of fibers), and the change in hydrogen bonds in bamboo can be seen in Figure 6.



Figure 5: Schematic diagrams for (a) iron ions-impregnating bamboo bundle [100], (b) nano-Fe₃O₄ modified bamboo bundle [100], (c) phenolic resin-impregnating bamboo bundle [100], (d) recombination and hot-pressing treatment [100], (e) hydrophobic behavior [100], and (f) electromagnetic dissipation performance of nano-Fe₃O₄/bamboo bundles/phenolic resin oriented recombination ternary composite penal [100].

Nano- particle	Bamboo type	Method	Optimal formulation	Effect	Ref.
Ag	<i>Dendrocalamus giganteus</i> (4 years old)	Colloidal solution (Ag $^{\rm +}$ and NaBH_4)	Particle diameter: 14.3 \pm 3.6 nm. Particle concentration: 1.25 $\times 10^{11}$ particle mL ⁻¹	No fungal colony for 5 months (A. niger)	Pandoli <i>et al.</i> [114]
Сц	Phyllostachys pubescens (4 years old)	High voltage electric field <i>in situ</i> copper impregnation	Voltage: 60 kV. Duration: 24 h	Copper content > 1.5% Excellent UV protection performance: color difference < 4.0 Excellent fixation performance:	Ju et al. [110] Ju et al. [110] Ju et al. [110]
				leaching rate < 7% Antibacterial ring's diameter (<i>E.</i> <i>coli</i>): 54.22 mm	Ju <i>et al.</i> [110]
r 1	bamboo bundles (moisture content was around 10%)	(molar ratio of $Fe^{3+/}Fe^{2+'} = 2.1$) with a concentration of 0.2, 0.4 and 0.6 mol/L FeCl ₃ -6H ₂ O and in ammonia solution (w/w, 10%)	0.4 mol/L iron salts	water contact angle = 116.8° Mildew resistance (A. <i>niger</i>): infection percentage = 78% after 22 days Transverse compressive strength: 47.17 ± 3.52 MPa Compressive strength along the	[100] Lou <i>et al.</i> [100] Lou <i>et al.</i> Lou <i>et al.</i>
				gram: 00.09 ± 2.42 mra Good dimensional stability	[100] Lou <i>et al.</i> [100]
:	:				

Table 2: Brief processes and effects of utilizing nanosized metal and metal oxide particles

E. coli = Escherichia coli.



Figure 6: (a) Cross section of GO/bamboo [138], (b) fracture surface of GO/bamboo [138], (c) the hydrogen bonding in densified delignifiedbamboo [138], and (d) GO/bamboo composite [138].

As to nano-clay, montmorillonite (MMT) is the basic raw material used in producing nano-clay. Clay nanofiller possesses a multi-layered morphology [139], and notably, MMT as one of the abundant types of clay has been widely used [140]. Rahman et al. [141] reinforced bamboo strips by taking MMT as nanosized filler and poly(ethylene-alt-maleic anhydride) (PEA) as a compatibilizer. The nano-clay layers can limit the movements of polymer chains as well as the movement of molecules in the amorphous region, while no covalent bond can be formed between this nano-clay and bamboo. And the anhydride of PEA can react with hydroxyl groups of the bamboo cell walls (a covalent bond can be formed to enhance the interfacial adhesion) [141]. Both PEA and nano-clay can enter the para-crystalline region to turn it into a crystalline region. Therefore, the MOE and MOR were improved [141]. The adhesion between polymer and bamboo can be improved due to the presence of nano-clay in the lumen, void spaces, and cell walls of bamboo so that the hydrophobicity and thermal stability can be improved [141]. Furthermore, Rahman et al. [142] found that the combination of MMT nano-clay and acrylonitrile (AN) is better than that of MMT and methyl methacrylate (MMA) as to the improvement of mechanical properties of the bamboo strip, which was mainly due to the better capability.

And as to the optimization of bamboo modified by nanomaterials, Rahman *et al.* [143] evaluated the optimization of AN/malleated polyethylene (MAPE)/nano-clay bamboo nanocomposites *via* response surface methodology, and simultaneously, properties and characteristics were also investigated. And the authors predicted that this bamboo nanocomposite can have an edge over conventional nanocomposites used for indoor or outdoor construction applications [143].

To briefly sum up, compared with some expensive nanosized metals or metal compounds, GO and nanoclay might be more suitable for wide application in the engineering field. And the brief methods and effects of using particles without metal or metal compounds can be seen in Table 3. Mechanical properties of bamboo can be more largely improved *via* GO nanosheets than MMT nano-clay fillers which may be due to the hydrogen bonds and the robustness of nanosheets. And the combination of GO nanosheets and MMT nano-clay fillers may be a better choice to improve the mechanical performance of bamboo considering both the cost and effects.

3.1.3 Some combinations of nanomaterials

The cost of some nanoparticles can be high, but the combination of different nanomaterials can reduce the cost. Li *et al.* [94] found that compared with TiO_2 /bamboo, the Fe-doped TiO_2 /bamboo exhibited much higher photocatalytic disinfection activity to fungi in the natural environment. The electron-hole pair separation efficiency

Nanomaterial	Bamboo type	Method	Optimal formulation	Effect	Ref.
GO (nanosheets)	<i>Phyllostachys heterocycle</i> (delignified and hot-pressed)	Immersed in GO suspension and degassed under vacuum	The GO concentration: 0.2 mg/mL	Tensile strength: increased by about 468% (compared to natural bamboo); increased by about 74% (compared to the densified delignified-bamboo)	Wang et al. [138]
				Young's modulus: Increased by about	Wang
				961% (Compared to natural bamboo); increased by about 57% (Compared to the	<i>et al.</i> [138]
				densified delignified-bamboo)	
				Flexural strength: Increased by about 74%	Wang
				(Compared to natural bamboo); increased	et al. [138]
				by about 125% (Compared to the densified	
				deulgiiiited-bamboo) Elavural modulus: increased by about 50%	Mang.
				(compared to pating hamboo). increased	ot al [138]
				by about 49% (compared to the densified	CCT (1)
				delignified-bamboo)	
				Density: increased by about 6% to	Wang
				1.25 g/cm ³ (compared to the densified	<i>et al.</i> [138]
				delignified-bamboo)	
MMT (nano-clay	<i>Gigantochloa scortechinii</i> (oven	Immersed in a solution	15 g nano-clay and 10 mg poly(ethylene-alt-	MOE: increased by about 142%	Rahman
filler)	dried strips)		maleic anhydride) at $pH = 9$ (500 mL		<i>et al.</i> [141]
			ethanol) (The PEA3 sample)	MOR: increased by about 77%	Rahman
					et al. [141]
MMT (nano-clay	<i>Gigantochloa scortechinii</i> (oven	Immersed in a solution	Treated with 1 wt% MMA and 5 wt% MMT	Tensile strength: increased by	Rahman
filler)	dried strips) <i>Gigantochloa</i>	Immersed in a solution	(the MMA1 sample)	about 288%	<i>et al.</i> [142]
	<i>scortechinii</i> (oven dried strips)			Tensile modulus: decreased by about 5%	Rahman
					<i>et al.</i> [142]
			Treated with 1 wt% AN and 5 wt% MMT (the	Tensile strength: increased by	Rahman
			AN4 sample)	about 349%	et al. [142]
			Treated with 10 wt% AN and 5 wt% MMT	Tensile modulus: increased by about 14%	Rahman
			(the AN1 sample)		<i>et al.</i> [142]
MMT (nano-clay	<i>Gigantochloa scortechinii</i> (oven	Immersed in a solution	Impregnation solution included 8 w/v% of	MOE: increased by about 165%	Rahman
filler)	dried strips)		AN/MAPE and 12g of nano-clay; 10 min for		<i>et al.</i> [143]
			impregnation (the 8/12/10 BNC sample)		
			Impregnation solution included 8 w/v% of	MOR: increased by about 270%	Rahman
			AN/MAPE and 12 g nano-clay; 60 min for impregnation (the 8/12/60 BNC sample)		<i>et al.</i> [143]

Table 3: Brief processes and effects of utilizing non-metal materials

can be increased by Fe dopants, and their recombination was inhibited leading to a lifetime increase in the generated electrons, and thus the antifungal activity, even under natural light, was improved. Zhang et al. [135] employed ZnO nanoparticles and GO nanosheets via a facile method to modify bamboo material. The combination of the ZnO nanoparticles and GO nanosheets gave the bamboo better antimicrobial properties compared to modify bamboo with ZnO nanoparticles or GO nanosheets alone. The antibacterial behavior of bamboo was investigated by the bacteriostatic circle method, and the results showed that ZnO/GO/bamboo materials possessed excellent antibacterial activity against E. coli (Gram-negative) and Bacillus subtilis (B. subtilis, Gram-positive) bacteria and high thermal stability. Besides, the Zn/GO bamboo composites also exhibited higher thermal stability. Liu et al. [115] incorporated Ag nanoparticles into TiO₂ nanoparticles, and thus, the photocatalytic activity in visible light was enhanced, and meanwhile, the surface plasmon absorption of silver can help extend the absorption range of bare TiO_2 to the visible region [144].

3.1.4 Applications in some other fields

In the electric field, the bamboo product was functionalized because metal ions can be triggered and released. Besides, ionic metals can penetrate the cell structures to combine with hemicellulose and lignin effectively and thus ionic metals can remain in the matrix of bio-materials such as wood [145] and bamboo. The direct current electric field had better antibacterial performance than alternating current and high-frequency current [146].

In the field of solar steam generation, natural bamboo has become a novel type of substrate for photothermal materials due to the merits of oriented microchannels, thermal insulation, hydrophilicity, and so on. Sheng et al. [147] applied bamboo in solar steam generation via modifying bamboo with plasmonic metal materials (as photothermal conversion materials) which can help improve the optical absorptivity of bamboo. The structure of photothermal conversion was formed by the uniform deposition of plasmonic metal nanoparticles in the oriented microchannels where water can be transported by the capillary effect. The plasmonic bamboo material displayed a high conversion efficiency of 87% under a tensun illumination (the solar flux is $10,000 \text{ W m}^{-2}$) and excellent cycling stability with no degradation after 140 h of cycling under 5 suns (the solar flux is $5,000 \text{ W m}^{-2}$).

Some more nanometal structures involving plasmon can be found in the paper presented by Yang *et al.* [148], while the durability of bamboo has not been considered enough in this study. It is worth noting that this modified bamboo with optical absorptivity [147] can be a kind of potential material utilized for photovoltaic building integration [149].

As to the development of renewable catalysis system, a novel continuous-flow method was used to disperse Ag nanoparticles around the microchannels in bamboo vascular bundle evenly and tightly, aimed to reduce nitroaromatics [150]. The catalytic capillary microreactor displayed high catalytic activity and good long-term stability.

3.2 Coatings

The surface of bamboo possesses very similar properties as wood: (i) porous structure and (ii) abundant hydroxyl groups. This can facilitate the attachment and growth of nanomaterials to the bamboo surface [95]. However, some researchers believed that the immobilization of inorganic nanomaterials on organic bamboo surfaces may not be easy, which was mainly due to the lack of highly reactive functional groups on the bamboo surface that can provide strong binding forces [115,151]. But notably, as mentioned before, GO nanosheets [138] can provide more opportunities for the formation of hydrogen bonds which can be a solution for the lack of functional groups on the bamboo surface. There is more research related to the use of nanotechnology treatments on wood, and there are two main ways of adding metals or metal oxides to the coating, which is adaptable to bamboo [58]: (i) solution mixing and (ii) in situ deposition/growing. The first way is mixing nanoparticles into coatings and having the surface coated by brushing or spraying or dipping. And the second method can be seen as a chemical method that can be more beneficial compared to the first one, due to the little molecules that can diffuse among nanoparticles [58]. From a review of recent research on bamboo, it was found that the main method of coating is the in situ growth method. The main ways used to seed nanomaterials on the surface of bamboo by in situ growth method are (i) hydrothermal deposition [92,115,132,152–154] and (ii) sol-gel method [131,155-158]. One of the merits of deposition in solutions is that cavities and affinity can be provided by the microstructures and hydroxyl groups on

the surface of bamboo for the creation and immobilization of nanoparticles through electrostatic and hydrogenbonding interactions at the microscale [157].

Research papers related to the application of nanomaterials on bamboo materials were mostly focusing on the coating treatment. Therefore, some coating processes and effects of nanomaterials on the bamboo surface have been sorted and shown in Table 4. Different aggregate forms of the immobilized nanoparticles caused different effects. Functional properties involving anti-microorganism ability, UV-resistant properties, hydrophobicity, photocatalytic ability, etc., can be well generated or improved via metal nanomaterials in most literature, while mechanical properties of bamboo were mentioned in literature involving nano-clay [143], and SiO₂ [138] which are nonmetal nanomaterials. Notably, the good fixation ability of nanomaterials can be seen in literature [98,115,162] which can be arranged to the outmost part of a layered structure to protect the whole structural material.

As to SiO₂, Zhou *et al.* [165] compared bamboo strips treated with ammonium dihydrogen phosphate + disodium octaborate tetrahydrate, ammonium dihydrogen phosphate + disodium octaborate tetrahydrate + nano-SiO₂ sol, and ammonium dihydrogen phosphate + boric acid + nano-SiO₂ sol (ABS), and found that bamboo treated with ABS possessed lower hygroscopicity, the best leaching resistance behavior, and good thermal stability. And therefore, ABS can be an optimal compound for the bamboo's retardant [165]. And besides, SiO₂ has also been coated on the GO/bamboo nanocomposites to improve the hydrophobicity and thermal stability of GO/bamboo nanocomposite which rendered excellent mechanical properties as reported by Wang *et al.* [138]

As to ZnO, Yu et al. [156] coated the bamboo surface with a series of different ZnO films, and the results indicated that the photostability and antifungal properties of bamboo were greatly improved and highly dependent on the crystallinity and morphology of the ZnO films. ZnO with nanostructured networks with the best photostability (mainly due to higher separation efficiency of electron and hole pairs because of nanosized effects) and antibacterial ability (mainly due to the high crystallinity of this form) can be seen as the optimized one. However, longer immersing duration in colloids tended to promote the production of irregular aggregates. Yu et al. [156] found that the growth of ZnO nanonetworks was promoted within a duration of 4 h when the bamboo was immersed in the ZnO nano-sol. An aqueous solution method for growing ZnO nano-metallic films onto bamboo substrates at low temperatures has been presented by Yu et al. [158]. The formed ZnO nanosheet films consisted of

randomly oriented irregular nanosheets and occasionally by nanowires/nanorods. The modified bamboo possessed photostability and antifungal and antibacterial properties at the same time. However, Li et al. [157] thought that the results were not representative. Besides, ZnO possessed the excited energy of 60 mV and a bandgap of ~3.4 eV, and thus it can be used to improve the UV resistance [166], antibacterial activity [167], and thermal stability [168]. While a kind of recycled green ZnO/bamboo composite can also be fabricated by growing cross-linked ZnO nano-walls on the bamboo [95]. And the excellent photocatalytic ability enabled the functionalized bamboo to become a potential recyclable bio-based catalyst for the purification of pollutant solutions. The photocatalytic efficiency has been measured to be 70%, and it can be recycled 3 times at least. And notably, hydrogen bonding can be formed between bamboo and nanosized ZnO complex layer via coordination reaction between ZnCl₂ and urea [169].

The distribution of TiO₂ with different sizes is shown in Figure 7 [154]. Most sizes of TiO₂ decorated on the surface of bamboo were from 1.8 to 2.0 nm. Li et al. [134] found that when Fe was doped in the TiO_2 lattice, the optical absorption edge can be shifted to the visible region, the photocatalytic activity was improved, and the crystallinity and crystallite size of the TiO₂ products can also be significantly influenced. The variation in the morphology of the surface of bamboo can be seen in Figure 7(d) after the deposition of TiO_2 in different forms. Rao et al. [170] compared benzotriazole, benzophenone, nano-TiO₂, and nano-ZnO which were intentionally used for absorbing UV light. And the coatings containing both organic and these inorganic UV light absorbers were investigated. They found that coatings containing benzotriazole showed the best surface photostability, and with the existence of inorganic absorbers, the degradation rate of organic absorbers decreased. And nano TiO₂ also showed good photo-degradation resistance when coated on thermally treated bamboo [171]. Both nanosized TiO2 and ZnO are considered as potential components of coating for absorbing UV [172]. Synergistic effects on UV light resistance were achieved by incorporating organic absorbers with these two inorganic ones, and Rao et al. [172] found that benzotriazole can be a better option as the organic part when compared with benzophenone.

As to the nanosized Cu, in some cases, the fungus might not recognize nano-copper. And thus, the nano-particles can enter the cell wall of fungi, and then, the reactive oxygen species with the fungal cell can be created which can affect the erosion of wood [60]. Bao *et al.* [98] coated the bamboo's surface with copper which

Nanomaterials and forms	Process	Effect	Ref.
ZnO (nanoparticles)	 Colloid solution deposition of ZnO Wet chemical treatment 	Resistance against <i>A. niger</i> and <i>P. citrinum,</i> but weaker resistance against <i>T. viride</i> Pers. ex Fr (<i>T. viride</i>)	Li et al. [157]
ZnO (irregular nanosheets and nanowires/nanorods)	 Seed coating in ZnO nano-sol Crystal growth in a zinc salt aqueous solution 	UV-resistant property; antifungal and antibacterial activities	Yu <i>et al</i> . [158]
ZnO (nanosheet networks (nano-walls))/FAS-17	1) Bamboo being treated with ZnO sol and then the ZnO nanosheet networks grew onto the bamboo surface hydrothermally	Robust super-hydrophobicity (especially after being treated by FAS-17)	Li <i>et al</i> . [131]
	2) Being subsequently modified with fluoroalkyl silane FAS-17	Stable repellency towards simulated acid rain (pH = 3) (especially after being treated by FAS-17) UV-resistant property Fire-resistant property	
7nQ (cross linked name	1) Dinning in 7n0 col colution and then being	Superior water-resistant property	lin at al [OF]
walls)	dried	pollutant solution)	Jili <i>et ut</i> . [95]
	2) Cross-linked ZnO nano-walls were grown via an aqueous solution route with a mixture of solutions	Recyclability	
ZnO/PMHS	1) Bamboo being dipped in ZnO sol solution	Super-hydrophobicity (especially after	Chen <i>et al</i> .
	and then being dried	being modified with PMHS)	[159]
		caused by ZnO and PMHS)	
Crystalline anatase TiO.	3) Subsequently modified with PMHS	Antifungal canability	lietal [154]
ZnO-TiO ₂ -Layered Double- Nanostructures	1)TiO ₂ being deposited on the bamboo surface <i>via</i> the liquid-phase deposition method	Antifungal ability	Ren <i>et al.</i> [160]
	 2) ZnO-TiO₂-layered double-nanostructures being synthesized in solution 	Thermal stability	
Flower like 7n0	1) TiO being deposited on the homboo	Flame-retardant property	Don at al
microstructures supported on TiO_2 thin films	surface <i>via</i> the liquid-phase deposition method	Excellent anthungal ability	[161]
	TiO_2 thin films being synthesized in solution		
Ag/TiO ₂	 Modified by mussel-inspired polydopamine 	Anti-mildew property	Liu <i>et al</i> . [115]
	2) Ag and TiO ₂ nanoparticles being immobilized on the surface of polydonamine bamboo composite <i>via</i>	Photocatalytic performance	
	impregnation-adsorption and <i>in situ</i> growth		
A - /T:O		Resistance leachability	1:
Ag/ 110 ₂	 1) 102 thin being immobilized on bamboo by the hydrothermal method 2) Ag nanoparticles embedded into the TiO2 films 	viride and P. citrinum was inhibited	Li <i>et at</i> . [94]
Cu film	Magnetron sputtering and nanoimprint stamps	Mechanical stability of the film	Bao <i>et al</i> . [98]
		Super-hydrophobicity Conductive ability	
MgAl-layered double hydroxide	Bamboo being immersed in the mixture (an <i>in situ</i> one-step method)	Flame-retardant properties	Yao <i>et al</i> . [162]
		Smoke suppression performance Wear resistance	

Table 4: Some coating processes and effects of nanomaterials

(Continued)

Table 4: Continued

Nanomaterials and forms	Process	Effect	Ref.
AN/MAPE/nano-clay	1) Components being mixed	Mechanical properties	Rahman <i>et al</i> . [143]
	2) Bamboo being immersed in the mixture	Thermal stability	
γ-Fe ₂ O ₃	1) Particles being deposited on the bamboo surface by a co-precipitation method	Superhydrophobic performances to water and some common liquids (like coffee, milk, ink, tea, and coke)	Jin <i>et al</i> . [163]
	2) Treated by FAS-17	Robust magnetism microwave absorbance performance	
Fe-doped TiO_2 thin films	Deposited on the bamboo surface by a co- precipitation method and the doping being carried out simultaneously	Further improved the antifungal activity of ${\rm TiO}_2$	Li et al. [134]
SiO ₂	Bamboo immersed in a solution	Super-hydrophobicity (inboard bamboo was best, followed by the outboard bamboo surface)	Qin <i>et al</i> . [164]
SiO ₂	SiO_2 being sprayed on the GO/bamboo	Super-hydrophobicity	Wang <i>et al</i> . [138]
		Dimensional stability	
		Good mechanical properties	
		Good environmental stability	

PMHS = Poly(methyl hydrogen siloxane).

 $\mathsf{FAS-17} = (\mathsf{Heptadecafluoro-1,1,2,2-tetradecyl}) \ trimethoxysilane \ [\mathsf{CF}_3(\mathsf{CF}_2)_7\mathsf{CH}_2\mathsf{CH}_2\mathsf{Si} \ (\mathsf{OCH}_3)_3].$

RT = Room temperature.

T. viride = Trichoderma viride.



Figure 7: (a) SEM images of original bamboo [154] and bamboo timber coated by TiO_2 (RT, 7 days): (b) at low magnification [154] and (c) high magnification [154]. (d) The size distribution of TiO_2 (RT, 7 days) [154].

promoted the applications of superhydrophobic and conductive bamboo products.

Some of these studies have investigated the antiorganism ability (mainly resists mold and fungi) according to the Chinese standard: GB/T18261-2013 [173] which is a test method for anti-mildew agents in controlling wood mold and stain fungi. Five grades (0-4) have been classified and defined in this standard depending on the areas infected, as shown in Table 5. And different antiinfection abilities by different nanomaterials are shown in Table 6. From the reviewed papers, it is understood that the infection of *T. viride* can be tough to resist. Bamboo coated by ZnO-TiO₂ [161], nano-zinc complex (U2-t2) (an ionic liquid (ZnCl₂/urea molar ratios $[n(ZnCl_2)/n(urea) =$ 1:2]) for 2h) [169], PMHS-ZnO [159], and Ag nanoparticle-decorated MT (Mesoporous anatase TiO₂) film [94] were well optimized. The infection values (IV) of the 3 kinds of fungi kept at 0% after 28 days or even after 90 days. The bamboo modification was provided by effective approaches to extend the service life of bamboo.

In summary, nanomaterials have been mainly utilized as coatings on bamboo, and good outcomes have been achieved with no doubt in improving the weatherability, thermal stability, anti-microorganism ability, and so on. While more attention should be paid to shrinking the cost and the recyclability of the whole bamboo materials coated by nanomaterials to facilitate their application in construction, photovoltaic building integration, or something else.

3.3 Nanocarriers

The polymeric carriers are considered as a delivery system at nanoscale or microscale which can provide a container for some nanoparticles by physical encapsulation or chemical bonding connection [60]. So far, few studies were focusing on carriers. Nanocarriers have been used in wood modification for some interesting properties in improving the permeability of wood preservatives [59].

Table 5: The description of infection value [173]

Grades	Area of infection
0	No hypha or mold
1	Surface infection area less than 1/4
2	Surface infection area between 1/4 and 1/2
3	Surface infection area between 1/2 and 3/4
4	Surface infection area over 3/4

The nanocarriers can provide a way for organic biocides or nanoparticles so as to be immobilized in or on bamboo. And it has been proved to be beneficial for those biocides or nanoparticles being hard to adhere to bamboo material. Some synthetic polymers employed in the preparation of nanoparticles for the delivery of antimicrobial contents have been presented by Spizzirri *et al.* [174]. And some functionalization of photosensitive nanocarriers has been sorted and presented by Fernández *et al.* [175]. It is worth noting that Abd-algaleel *et al.* [176] presented a process of drug loading optimization that may be a guide to the application of nanocarriers in the modification of bamboo which involved artificial intelligence and machine learning, as shown in Figure 8.

The hydrogel can be seen as a carrier for some nanoparticles. Huang *et al.* [177] prepared loaded nano/ZnO composite hydrogels, as shown in Figure 9. The hydrogels which were sensitive to the temperature helped control the release of the drugs or nanoparticles. Nano-ZnO/poly(*N*isopropylacrylamide) hydrogel was synthesized by the addition of nano-ZnO dispersion to realize the smaller particle, the more even dispersion, and the higher stability by Zhang *et al.* [178], when compared to the hydrogel with the addition of nano-ZnO particles with dispersant sodium dodecylbenzene sulfonate, nano-ZnO particles with dispersant polyvinylpyrrolidone, and nano-ZnO particles with dispersant hexadecyltrimethylammonium bromide.

And the nano-Ag was also embedded in hydrogels which helped the anti-fungal properties by Wei *et al.* [179]. Yu *et al.* [180] designed Ag-loaded thermal-sensitive nanogels to resist microorganisms at ambient temperature, and the optimal impregnation process was revealed. While research on the nanocarriers applied in the bamboo modification is rare by far which may be due to the higher cost, MMT nano-clay as a nanomaterial costing less has been used in a drug carrier system [181]. And the MMT composite can be produced *via* utilizing anionic, cationic, and nonionic surfactants to have the basal spacing enhanced so that organoclay can be used in drug loading and drug release [182].

Some nanotubes have been applied in modifying bamboo. Zhang *et al.* [183] utilized halloysite, which is a natural mineral with a nanotube structure, and iodopropynyl butycarbamate was loaded on it to achieve good anti-mildew activity (resist mold and blue-stain fungi). And the effects of utilizing nanocarriers on bamboo, which were mainly relevant to the anti-microorganism ability, are presented in Table 7.

In summary, the purpose of lengthening the service life of bamboo has been met *via* nanotechnology and some specific functions have also been granted to bamboo.

Bamboo with nanomaterials or untreated bamboo	Resist T. viride	Resist A. niger	Resist P. citrinum	Ref.
ZnO-TiO ₂ /bamboo	To resist a hybrid fungi group just inclu	ding these three: IV almost remained 0% for 90 day	s (recorded for 90 days)	Ren
TiO ₂ /bamboo	To resist a hybrid fungi group just includ	ing these three: IV almost remained 0% for 21 days (r	ecorded for 90 days), and stepped up until the 75th	<i>er al.</i> [161] Ren
Introstad bamboo	day, reaching 100% To resist a hubrid funci aroun inst inclus	boby one 2 days of the second of the second	for OO dave) and then increased chardle varching	<i>et al.</i> [161] Don
	100% in the following 6 days	וופ נובסב נוובבי וי ובוומוובת לאומו ל ממלז (ובכסותבם	ווטו אם ממשאל מוות נווכו וווכו במשבת שומו אנץ, ובמכוווווש	et al. [161]
ZnO/bamboo	IV sharply increased after 3 days,	IV steadily increased for 7 days and kept the IV	IV steadily increased for 16 days and kept around	
	reaching 100% after 8 days	around 18% for 4 days, and then increased steadily reaching and keeping around 38% till the 30th day	32% till the 30th day	et al. [157]
Untreated bamboo timber	IV reached 100% in 4 days	IV reached 100% in 7 days	IV reached 100% in 9 days	Li
				et al. [157]
Nano-zinc complex layer	IV barely increased even after 28 days	recorded for 28 days)		Gao
Original hamboo	aveh 7 ni 2000 bodzeoz VI	aveh 7 ni 2000 bodzez VI	11 Noarhad 100% in 7 dave	et al. [169] Gao
	IN LEACHER TOO 10 III / RAYS	A LCACHER TOO 10 HILL ARAD	IN ICACHER TOO VOINT CARDS	<i>et al</i> [169]
PMHS-ZnO/bamboo	IV barely increased even after 28 days	recorded for 28 days)		Chen
		~		<i>et al.</i> [159]
ZnO/bamboo	IV barely increased even after 19 days	IV barely increased even after 19 days (recorded	IV barely increased even after 15 days (recorded	Chen
	(recorded for 28 days), and kept below	for 28 days), and kept below 25% till the 28th day	for 28 days), and kept below 25% till the 22nd day,	<i>et al.</i> [159]
	25% till the 28th day		and increased, reaching 25% and kept below 50% till the 28th dav	
Original bamboo	IV reached 100% in 8 days	IV reached 100% in 10 days	IV reached 100% in 7 days	Chen
				<i>et al.</i> [159]
Ag NP-decorated MT film- coated hamboo	IV barely increased even after 28 days	recorded for 28 days)		Li et al [94]
MT film-coated bamboo	IV barelv increased after 16 davs and	1	IV barelv increased after 16 davs. and increased to	u u: [/4] Li
	increased to 100% in the following		100% in the following 12 days	et al. [94]
	8 days			
Ag/bamboo	IV barely increased after 8 days, and	1	IV barely increased after 12 days, and increased to	::
	increased to 100% in the following		around 33% in the following 16 days	<i>et al.</i> [94]
	12 days			
Original bamboo	IV reached 100% in 8 days	1	IV reached 100% in 8 days	Li <i>et al.</i> [94]

Table 6: The ability to resist fungus (T. viride, A. niger, and P. citrinum)

IV = Infection values (%). U2-t2 = Bamboo coated with nano-zinc complex which was treated in an ionic liquid (ZnCl₂/urea molar ratios [n(ZnCl₂)/n(urea) = 1:2]) for 2 h. Bamboo timber refers to the bamboo material without inner and outer parts [153].



Figure 8: Contribution of different analytical and in silico tools to the drug loading optimization in different classes of nanocarrier [176].



Figure 9: Preparation of the ZnO/poly(*N*-isopropylacrylamide-*co*-acrylic acid) hydrogel [177].

The majority of the studies were focusing on the coatings using nanosized metals or metal compounds, while insufficient attention has been paid to using nanocarriers which was mainly focusing on hydrogels that are sensitive to temperature by far, and the nanocarriers in modifying bamboo need more exploration in the future.

4 Future scopes

Nanoindentation technique has been widely applied in determining some nanomechanical behaviors of bamboo such as MOE, hardness, creep behavior, and so on, and many investigations have been implemented. Further

Vano-particle or chemical agent	Carrier	Optimal formulation	Effect	Ref.
ŝ	Hydrogel	Impregnation treatment duration: 90 min; concentration of Ag-loaded nanogel: 0.9 wt% and air pressure: 0.5 MPa	The gel penetrates bamboo and fills the cell cavities and covers the cell walls; protective and long-term anti-fungi effect (resisted <i>P. citrinum, T. viride</i> , and <i>A</i> .	Yu <i>et al.</i> [180]
łg	Poly(N-isopropyl acrylamide) (NIPAM) and acrylic acid (AAc)	AAc concentration was 0.64 µL/mL	<i>niger)</i> The smallest particle size (59.4 nm)	Peng <i>et al.</i> [184]
odopropynyl butycarbamate chemical anti-mildew agent)	Halloysite nanotubes	1	The best dispersion Excellent anti-mold properties against common bamboo molds (<i>P. citrinum, T. viride</i> , and <i>A. niger</i>) Excellent anti-mildew activity against <i>A. niger, P.</i> <i>citrintim, T. viride</i> , and <i>Botryodiplodia theobromae</i> Sustained-release property (increased with the higher	Zhang <i>et al.</i> [183]
			amount of iodopropynyl butycarbamate)	

research involving both nanoindentation technique and nanomaterials may focus on the determination of the improvements in nanomechanical behavior of some nanomodified bamboo materials.

As to nanoparticles, (1) bamboo materials' properties can be well improved *via* merging nanomaterials with bamboo. More attention may be paid to the cost of the modification process, via combining the nanotechnology with chemical treatments or heat treatment, or the concentration of nanomaterials used so that a compromise can be made between the cost and practical use. And this aim may be well-realized *via* artificial intelligence. (2) More research may be needed on the selective distribution of different nanoparticles in the pores or vascular bundles of bamboo considering some impacts on the deposition and distribution of the nanomaterials by the variation in the number of circles. (3) Nanoparticles in different forms were subject to agglomeration, and perhaps electromagnetic fields can help solve this problem in addition to adding other nanoparticles. And more experiments for comparisons are needed, considering the variations in bamboo as a natural biomass material. (4) Combining plasma and nanomaterials may help develop some more efficient plasma-synthesized nanomaterials which can be granted with some specific functions for modifying bamboo. (5) Some studies on giving bamboo with some properties related to the field of electron-wave or solar power system were refreshing while insufficient attention has been paid to the durability at the same time.

As to coatings, anti-organism ability has been well improved *via* coatings. While more attention may be paid to the cost and the recyclability of the whole bamboo materials coated by nanomaterials to facilitate their application in construction, photovoltaic building integration, or some other aspects.

As to nanocarriers, Attention granted to the utilization of nanocarriers in modifying bamboo has not been enough so far. Some carriers that can be made from non-polymeric materials may collaborate with some other polymeric materials to obtain better outcomes. MMT nano-clay has been used as carriers for drugs and thus, it may be applied in modifying bamboo in future work.

Bamboo materials mentioned in this article were mainly some isolated small bamboo strips, while bamboo cylinders and other engineered bamboo materials have not received enough attention. And some other parameters may be considered more such as residual stress during or after the modification processes, and so on.

5 Conclusion

This article has reviewed the application of nanotechnology in modifying bamboo materials. The mesoscopic characteristics and nanomechanical properties (via nanoindentation technique) of bamboo has been presented. The utilization of nanomaterials in modifying bamboo materials (mainly involving the main part of bamboo materials instead of cellulose fibers, etc.) has been reviewed to promote the application of bamboo nanocomposites in the engineering field. And the effects of different nanomaterials have been summarized in Sections 3.1. 3.2, and 3.3. The mentioned experimental studies have contributed to a better understanding of the mechanisms of the effects brought by nanomaterials in/on bamboo. Nanomechanical properties, like MOE and hardness, were more sensitive to the variation in the part in cross-section than the change in height and age. Bamboo samples with Ag particles possessed better anti-organism ability than those with Cu and Fe₃O₄. Functional properties involving anti-microorganism ability, UV-resistant properties, hydrophobicity, photocatalytic ability, etc., can be well generated or improved via metal nanomaterials in most literature. And some non-metal nanomaterials can help improve the mechanical properties of bamboo well. Mechanical properties can be more largely improved via GO nanosheets than MMT nano-clay fillers which may be due to the hydrogen bonds and the robustness of nanosheets. And the combination of GO nanosheets and MMT nano-clay fillers may be a better choice to improve the mechanical performance of bamboo considering both the cost and effects. So far, research involving carriers in modifying bamboo materials mainly aimed at improving the anti-microorganism ability. And the carriers for carrying nanoparticles were mainly hydrogels that are sensitive to temperature. Research work on nanotube carriers was rare in modifying bamboo and it was mainly used to carry chemical anti-mildew agents.

Funding information: The research work presented in this article is supported by the National Natural Science Foundation of China (Nos. 51878354 & 51308301), the Natural Science Foundation of Jiangsu Province (Nos. BK20181402 & BK20130978), University student practice innovation program (2020NFUSPITP0378, 201810298047Z, and 202010298039Z), six talent peak high-level projects of Jiangsu Province (No. JZ029), and Qinglan Project of Jiangsu Higher Education Institutions. Any research results expressed in this article are those of the writers and do not necessarily reflect the views of the foundations.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: David Hui, who is the co-author of this article, is a current Editorial Board member of *Nano-technology Reviews*. This fact did not affect the peer-review process. The authors declare no other conflict of interest.

References

- Hu K, Huang Y, Fei B, Yao C, Zhao C. Investigation of the multilayered structure and microfibril angle of different types of bamboo cell walls at the micro/nano level using a LC-PolScope imaging system. Cellulose. 2017;24:4611–25.
- [2] Liu K, Jayaraman D, Shi Y, Harries KA, Yang J, Jin W, et al. Very sustainable construction material – 2021 International Online Seminar summary report. Sustain Struct. 2022;2(1):000015.
- [3] Dixon PG, Gibson LJ. The structure and mechanics of moso bamboo material. J R Soc Interface. 2014;11(9):20140321.
- [4] Ye C, Huang Y, Feng Q, Fei B. Effect of hygrothermal treatment on the porous structure and nanomechanics of moso bamboo. Sci Rep. 2020;10:6553.
- [5] Cao Y. Study on the performance effect of high temperature oil heat treatment of moso bamboo [dissertation].
 Hangzhou: Zhejiang A&F University; 2019 (In Chinese).
- [6] Deschamps P, Haferkamp I, D'Hulst C, Neuhaus HE, Ball SG. The relocation of starch metabolism to chloroplasts: when, why and how. Trends Plant Sci. 2008;13(11):574–82.
- [7] Lin Q, Huang Y, Yu W. An in-depth study of molecular and supramolecular structures of bamboo cellulose upon heat treatment. Carbohydr Polym. 2020;241:116412.
- [8] Salim R, Wahab R. Effect of oil heat treatment on chemical constituents of Semantan bamboo (Gigantochloa scortechinii Gamble). J Sustain Dev. 2008;1(2):91–8.
- [9] Wei P, Huang Y, Liu R, An X, Fei B. Research on chemical constituents of bamboo fibers' cell wall based nano-IR technology. Spectrosc Spectr Anal. 2017;37(1):103–8 (In Chinese).
- [10] Song L, Wang X, Ma J, Li Y, Li Y, Xu B. Effect of high temperature saturated steam treatment on bamboo properties. J Eng. 2018;3(2):23–8 (In Chinese).
- [11] Bobleter O, Binder H. Dynamischer hydrothermaler Abbau von Holz. Holzforschung. 1980;34(2):48–51.
- [12] Carrasco F, Roy C. Kinetic study of dilute-acid prehydrolysis of xylan-containing biomass. Wood Sci Technol. 1992;26:189–208.
- Klauditz W, Stegmann G. Beiträge zur Kenntnis des Ablaufes, und der Wirkung thermischer reaktionen bei der bildung von holzwerkstoffen. Holz Roh-Werkst. 1955;13(11):434-40.
- Pecha MB, Garcia-Perez M. Pyrolysis of lignocellulosic biomass: oil, char, and gas. In: Dahiya A, editor. Bioenergy.
 2nd ed. Cambridge(MA): Academic Press; 2020. p. 581–619.

- [15] Ghalia M, Dahman Y. Synthesis and utilization of natural fiber-reinforced poly(lactic acid) bionanocomposites. In: Jawaid M, Tahir PM, Saba N, editors. Lignocellulosic fibre and biomass-based composite materials. 1st ed. Cambridge: Woodhead Publishing; 2017. p. 313–45.
- [16] Hao X, Wang Q, Wang Y, Han X, Yuan C, Cao Y, et al. The effect of oil heat treatment on biological, mechanical and physical properties of bamboo. J Wood Sci. 2021;67(1):1–14.
- [17] Sun F, Bao B, Ma L. Mould-resistance of bamboo treated with the compound of chitosan-copper complex and organic fungicides. 2012;58(1):51–6.
- [18] Wang Q, Wu X, Yuan C, Lou Z, Li Y. Effect of saturated steam heat treatment on physical and chemical properties of bamboo. Molecules. 2020;25:1999.
- [19] Sjöström E. Wood chemistry-fundamentals and applications.2nd ed, New York: Academic Press; 1993.
- [20] Depuydt DEC, Sweygers N, Appels L, Ivens J, van Vuure AW. Bamboo fibres sourced from three global locations: A microstructural, mechanical and chemical composition study. J Reinf Plast Compos. 2019;38(9):397–412.
- [21] Yu Y, Huang X, Yu W. A novel process to improve yield and mechanical performance of bamboo fiber reinforced composite *via* mechanical treatments. Compos Part B Eng. 2014;56:48–53.
- [22] Lei W, Zhang Y, Yu W, Yu Y. The adsorption and desorption characteristics of moso bamboo induced by heat treatment. J For Eng. 2021;6(3):41–6.
- [23] Zhang X, Zhou Z, Zhu Y, Dai J, Yu Y, Song P. High-pressure steam: A facile strategy for the scalable fabrication of flattened bamboo biomass. Ind Crop Prod. 2019;129:97–104.
- [24] Liang R, Gangarao, Hota G. Development and evaluation of load-bearing fiber reinforced polymer composite panel systems with tongue and groove joints. Sustain Struct. 2021;1(2):000008.
- [25] Shen Z, He Y, Sayed U, Wang J, Zhou Y, Wang Z. Measurement of the elastic constants of carbon fiber board based on modal analysis. BioResources. 2022;17(1):255–68.
- [26] Zhang Y, Zhu H, Wang Z, Dauletbek A. Analysis of the influence of accelerometer quality and installation position on the test value of wood material constant. Exp Tech. 2021; 23:1–15.
- [27] Zhou Y, Huang Y, Sayed U, Wang Z. Research on dynamic characteristics test of wooden floor structure for gymnasium. Sustain Struct. 2021;1(1):000005.
- [28] Ponzo FC, Antonio DC, Nicla L, Nigro D. Experimental estimation of energy dissipated by multistorey post-tensioned timber framed buildings with anti-seismic dissipative devices. Sustain Struct. 2021;1(2):000007.
- [29] Corbi O, Baratta A, Corbi I, Tropeano F, Liccardo E. Design issues for smart seismic isolation of structures: past and recent research. Sustain Struct. 2021;1(1):000001.
- [30] Wang X, Zhou A, Zhao L, Chui Y. Mechanical properties of wood columns with rectangular hollow cross section. Constr Build Mater. 2019;214:133–42.
- [31] Harries KA, Bumstead J, Richard M, Trujillo D. Geometric and material effects on bamboo buckling behaviour. Proc Inst Civ Eng Struct Build. 2017;170:236–49.
- [32] Pradhan NPN, Paraskeva TS, Dimitrakopoulos EG. Quasistatic reversed cyclic testing of multi-culm bamboo members with steel connectors. J Build Eng. 2020;27:100983.

- [33] Ashraf M, Hasan MJ, Al-Deen S. Semi-rigid behaviour of stainless steel beam-to-column bolted connections. Sustain Struct. 2021;1(1):000002.
- [34] Sharma B, van der Vegte A. Engineered bamboo for structural applications. In: Harries KA, Sharma B, editors. Nonconventional and vernacular construction materials characterisation, properties and applications. Cambridge: Woodhead Publishing; 2019. p. 597–623.
- [35] Dauletbek A, Li H, Xiong Z, Lorenzo R. A review of mechanical behavior of structural laminated bamboo lumber. Sustain Struct. 2021;1(1):000004.
- [36] Su J, Li H, Xiong Z, Lorenzo R. Structural design and construction of an office building with laminated bamboo lumber. Sustain Struct. 2021;1(2):000010.
- [37] Shan B, Chen CQ, Deng JY, Li TY, Xiao Y. Assessing adhesion and glue-line defects in cold-pressing lamination of glubam. Constr Build Mater. 2021;274:122106.
- [38] Xiao Y, Yang RZ, Shan B. Production, environmental impact and mechanical properties of glubam. Constr Build Mater. 2013;44:765–73.
- [39] Lv Q, Wang W, Liu Y. Study on thermal insulation performance of cross-laminated bamboo wall. J Renew Mater. 2019;7:1231–50.
- [40] Reynolds T, Sharma B, Harries K, Ramage M. Dowelled structural connections in laminated bamboo and timber. Compos Part B Eng. 2016;90:232–40.
- [41] Verma CS, Chariar VM. Stiffness and strength analysis of four layered laminate bamboo composite at macroscopic scale. Compos Part B Eng. 2013;45(1):369–76.
- [42] Sinha A, Way D, Mlasko S. Structural performance of glued laminated bamboo beams. J Struct Eng. 2014;140(1):04013021.
- [43] Correal JF, Echeverry JS, Ramírez F, Yamín LE. Experimental evaluation of physical and mechanical properties of glued laminated Guadua angustifolia Kunth. Constr Build Mater. 2014;73:105–12.
- [44] Mahdavi M, Clouston PL, Arwade SR. A low-technology approach toward fabrication of laminated bamboo lumber. Constr Build Mater. 2012;29:257–62.
- [45] Chen G, Jiang H, Yu Y, Zhou T, Wu J, Li X. Experimental analysis of nailed LBL-to-LBL connections loaded parallel to grain. Mater Struct Constr. 2020;53:81.
- [46] Huang Y, Zhang Y, Wang Z, Dauletbe A, Lu Y, Shen Z. Analysis of crack expansion and morphology of cross-laminated timber planar shear test. J Renew Mater. 2022;10(3):849–70.
- [47] Wei Y, Zhao K, Hang C, Chen S, Ding M. Experimental study on the creep behavior of recombinant bamboo. J Renew Mater. 2020;8:251–73.
- [48] Yu Y, Liu R, Huang Y, Meng F, Yu W. Preparation, physical, mechanical, and interfacial morphological properties of engineered bamboo scrimber. Constr Build Mater. 2017;157:1032–9.
- [49] Zhong Y, Ren HQ, Jiang ZH. Effects of temperature on the compressive strength parallel to the grain of bamboo scrimber. Materials. 2016;9(6):436.
- [50] Liu J, Zhou AP, Sheng BL, Liu YY, Sun LW. Effect of temperature on short-term compression creep property of bamboo scrimber. J For Eng. 2021;6(2):64–9.

- [51] Li YJ, Lou ZC. Progress of bamboo flattening technology research. J For Eng. 2021;6(4):14–23.
- [52] Liu HR, Yang XM, Zhang XB, Su Q, Zhang FD, Fei B. The tensile shear bonding property of flattened bamboo sheet. J For Eng. 2021;6(1):68–72.
- [53] Sun X, He M, Li Z. Novel engineered wood and bamboo composites for structural applications: State-of-art of manufacturing technology and mechanical performance evaluation. Constr Build Mater. 2020;249:118751.
- [54] Tian L, Kou Y, Hao J. Axial compressive behaviour of sprayed composite mortar-original bamboo composite columns. Constr Build Mater. 2019;215:726–36.
- [55] Lv Q, Ding Y, Liu Y. Study of the bond behaviour between basalt fibre-reinforced polymer bar/sheet and bamboo engineering materials. Adv Struct Eng. 2019;22:3121–33.
- [56] Kou Y, Tian L, Jin B. Axial compressive behavior of bamboo slices twining tube-confined concrete. Eur J Wood Wood Prod. 2021;80:115–29.
- [57] Bhushan B. Nanotechnology definitions and examples. In: Bhushan B, editor. Springer handbook of nanotechnology. Berlin, Heidelberg: Springer; 2017.
- [58] Papadopoulos AN, Bikiaris DN, Mitropoulos AC, Kyzas GZ. Nanomaterials and chemical modifications for enhanced key wood properties: A review. Nanomater. 2019;9(4):607.
- [59] Teng TJ, Mat Arip MN, Sudesh K, Nemoikina A, Jalaludin Z, Ng EP, et al. Conventional technology and nanotechnology in wood preservation: A review. BioResources. 2018;13(4):9220–52.
- [60] Bi W, Li H, Hui D, Gaff M, Lorenzo R, Corbi I, et al. Effects of chemical modification and nanotechnology on wood properties. Nanotechnol Rev. 2021;10(1):978–1008.
- [61] Liese W. Anatomy and properties of bamboo. In: Rao AN, Dhanarajan G, Sastry CB, editors. Proceedings of the International Bamboo Workshop. The Chinese Academy of Forestry; 1985. p. 196–208. Oct 6–14 Beijing, China. Beijing.
- [62] Liese W. The anatomy of bamboo culms. 1st ed. Beijing: International Network for Bamboo and Rattan Press; 1998.
- [63] Wang Z, Zhang X, Yao L, Zhang Q. Experimental study and numerical simulation on the macro and micro mechanical properties of bamboo. J For Eng. 2022;7(01):31–7.
- [64] Chen G, Luo H, Yang H, Zhang T, Li S. Water effects on the deformation and fracture behaviors of the multi-scaled cellular fibrous bamboo. Acta Biomater. 2018;65:203–15.
- [65] Mannan S, Knox JP, Basu S. Correlations between axial stiffness and microstructure of a species of bamboo. R Soc Open Sci. 2017;4:160412.
- [66] Youssefian S, Rahbar N. Molecular origin of strength and stiffness in bamboo fibrils. Sci Rep. 2015;5:11116.
- [67] Zhang X, Li J, Yu Z, Yu Y, Wang H. Compressive failure mechanism and buckling analysis of the graded hierarchical bamboo structure. J Mater Sci. 2017;52(12):6999–7007.
- [68] Tang T, Zhao B, Liu X, Wang W, Chen X, Fei B. Synergistic effects of tung oil and heat treatment on physicochemical properties of bamboo materials. Sci Rep. 2019;9:12824.
- Yu Y, Wang H, Lu F, Tian G, Lin J. Bamboo fibers for composite applications: a mechanical and morphological investigation.
 J Mater Sci. 2014;49:2559–66.
- [70] Khalil HPSA, Bhat IUH, Jawaid M, Zaidon A, Hermawan D, Hadi YS. Bamboo fibre reinforced biocomposites: A review. Mater Des. 2012;42:353–68.

- [71] Lee C, Yang T, Cheng Y, Lee C. Effects of thermal modification on the surface and chemical properties of moso bamboo. Constr Build Mater. 2018;178:59–71.
- [72] Parameswaran N, Liese W. On the fine structure of bamboo fibres. Wood Sci Technol. 1976;10(4):231–46.
- [73] Parameswaran N, Liese W. Ultrastructural aspects of bamboo cells. Cellulose Chem Technol. 1980;14:587–609.
- [74] Liu D, Song J, Anderson DP, Chang PR, Hua Y. Bamboo fiber and its reinforced composites: Structure and properties. Cellulose. 2012;19:1449–80.
- [75] Yin Y, Berglund L, Salmén L. Effect of steam treatment on the properties of wood cell walls. Biomacromolecules. 2011;12:194–202.
- [76] Yin J, Song K, Lu Y, Zhao G, Yin Y. Comparison of changes in micropores and mesopores in the wood cell walls of sapwood and heartwood. Wood Sci Technol. 2015;49:987–1001.
- [77] Gibson RF. A review of recent research on nanoindentation of polymer composites and their constituents. Compos Sci Technol. 2014;105:51–65.
- [78] Oliver WC, Pharr GM. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. J Mater Res. 1992;7(6):1564–83.
- [79] He LH, Swain MV. 3.9-Microindentation. In: Paul D, editor. Comprehensive biomaterials II. Oxford: Elsevier; 2017.
 p. 144–68.
- [80] Guo Z, Yang Q, Liu Z. Study on the mechanical properties of moso fiber in the direction of thickness. Proceedings of the 7th Chinese Congress of Theoretical and Applied Mechanics (A); 2017 Aug 13–16; Beijing, China. Beijing: Cnki; 2017. p. 697–702 (In Chinese).
- [81] Li SW, Guo ZM, Shang JJ, Liu X, Li X, Yang QS. Study on viscoelastic properties of bamboo fiber cell walls. Chin J Appl Mech. 2020;37(04):1398–405 (In Chinese).
- [82] Qin SS, Yin LP, Li YJ. Longitudinal mechanical properties of bamboo cell wall determined by nanoindentation technique. Trop Agric Eng. 2017;41(Z1):57–61 (In Chinese).
- [83] Li Y, Huang C, Wang L, Wang S, Wang X. The effects of thermal treatment on the nanomechanical behavior of bamboo (phyllostachys pubescens mazel ex h. de lehaie) cell walls observed by nanoindentation, XRD, and wet chemistry. Holzforschung. 2017;71(2):129–35.
- [84] Sawabe O. The fine structure of wood cell walls postulated in view of the pore structure II. Morphological features of the microfibrils within the cell walls of akamatsu (Pinus densiflora) wood. J Jpn Wood Res Soc. 1990;36(9):696–703.
- [85] Wang H, An X, Li W, Wang H, Yu Y. Variation of mechanical properties of single bamboo fibers (Dendrocalamus latiflorus Munro) with respect to age and location in culms. Holzforschung. 2014;68(3):291–7.
- [86] Salmén L. Micromechanical understanding of the cell-wall structure. Comptes Rendus Biologies. 2004;327(9–10):873–80.
- [87] Dwianto W, Morooka T, Norimoto M. Compressive creep of wood under high temperature steam. Holzforschung. 2004;54(1):104–8.
- [88] Bolin CA, Smith S. Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. J Clean Prod. 2011;19(6-7):620-9.

- [89] Janin A, Coudert L, Blais JF, Mercier G, Cooper P, Gastonguay L, et al. Design and performance of a pilot-scale equipment for CCA-treated wood remediation. Sep Purif Technol. 2012;85:90–5.
- [90] Zheng RZ, Zhang QH, He YX, Zhang Q, Yang LS, Zhang ZH, et al. Historical long-term exposure to pentachlorophenol causing risk of cancer-a community study. Asian Pac J Cancer Prev. 2013;14(2):811–6.
- [91] Birben NC, Uyguner-Demirel CS, Kavurmaci SS, Gürkan YY, Turkten N, Cinar Z, et al. Application of Fe-doped TiO₂ specimens for the solar photocatalytic degradation of humic acid. Catal Today. 2017;281:78–84.
- [92] Bae E, Choi W, Park J, Shin HS, Kim SB, Lee JS. Effects of surface anchoring groups (carboxylate vs phosphonate) in ruthenium-complex-sensitized TiO₂ on visible light reactivity in aqueous suspensions. J Phys Chem B. 2004;108(37):14093–101.
- [93] Zhang J, Liu Y, Li Q, Zhang X, Shang J. Antifungal activity and mechanism of palladium-modified nitrogen-doped titanium oxide photocatalyst on agricultural pathogenic fungi Fusarium graminearum. ACS Appl Mater Interfaces. 2013;5(21):10953–9.
- [94] Li J, Su M, Wang A, Wang A, Wu Z, Chen Y, et al. *In situ* formation of Ag nanoparticles in mesoporous TiO₂ films decorated on bamboo *via* self-sacrificing reduction to synthesize nanocomposites with efficient antifungal activity. Int J Mol Sci. 2019;20(21):5497.
- [95] Jin C, Li J, Wang J, Han S, Wang Z, Sun Q. Cross-linked ZnO nanowalls immobilized onto bamboo surface and their use as recyclable photocatalysts. J Nanomater. 2014;2014:687350.
- [96] Imam SH, Gordon SH, Mao L, Chen L. Environmentally friendly wood adhesive from a renewable plant polymer: characteristics and optimization. Polym Degrad Stab. 2001;73(3):529–33.
- [97] Singh M, Martınez-Fernández J, de Arellano-López AR. Environmentally conscious ceramics (ecoceramics) from natural wood precursors. Curr Opin Solid State Mater Sci. 2003;7(3):247–54.
- [98] Bao W, Liang D, Zhang M, Jiao Y, Wang L, Cai L, et al. Durable, high conductivity, superhydrophobicity bamboo timber surface for nanoimprint stamps. Prog Nat Sci Mater Int. 2017;27(6):669–73.
- [99] Singh AS, Halder S, Wang J, Imam MA, Chen P. Tannic acid intermediated surface functionalization of bamboo micron fibers to enhance mechanical performance of hybrid GFRP. Compos Part B Eng. 2019;177:107322.
- [100] Lou Z, Han X, Liu J, Ma Q, Yan H, Yuan C, et al. Nano-Fe₃O₄/ bamboo bundles/phenolic resin oriented recombination ternary composite with enhanced multiple functions. Compos Part B Eng. 2021;226:109335.
- [101] Chang J, Strunk J, Chong M, Poh PE, Ocon J. Multi-dimensional zinc oxide (ZnO) nanoarchitectures as efficient photocatalysts: What is the fundamental factor that determines photoactivity in ZnO? J Hazard Mater. 2020;381:120958.
- [102] Chen X, Selloni A. Introduction: titanium dioxide (TiO₂) nanomaterials. Chem Rev. 2014;114(19):9281–2.
- [103] Liu Y, Zuo J, Ren X, Yong L. Synthesis and character of cerium oxide (CeO₂) nanoparticles by the precipitation method. Metalurgija. 2014;53(4):463–5.

- [104] Yi T, Guo C, Zhao S, Zhan K, Gao W, Yang L, et al. The simultaneous preparation of nano cupric oxide (CuO) and phenol formaldehyde (PF) resin in one system: aimed to apply as wood adhesives. Eur J Wood Wood Prod. 2020;78(3):471–82.
- [105] Laohhasurayotin K, Pookboonmee S. Multifunctional properties of Ag/TiO₂/bamboo charcoal composites: Preparation and examination through several characterization methods. Appl Surf Sci. 2013;282:236–44.
- [106] Tuli HS, Kashyap D, Bedi SK, Kumar P, Kumar G, Sandhu SS. Molecular aspects of metal oxide nanoparticle (MO-NPs) mediated pharmacological effects. Life Sci. 2015;143(15):71–9.
- [107] Huang X, El-Sayed MA. Gold nanoparticles: Optical properties and implementations in cancer diagnosis and photothermal therapy. J Adv Res. 2010;1(1):13–28.
- [108] Kelly KL, Coronado E, Zhao LL, Schatz GC. The optical properties of metal nanoparticles: the influence of size, shape, and dielectric environment. J Phys Chem B. 2003;107(3):668–77.
- [109] Peng L, Guo R, Lan J, Jiang S, Lin S. Microwave-assisted deposition of silver nanoparticles on bamboo pulp fabric through dopamine functionalization. Appl Surf Sci. 2016;386:151–9.
- [110] Ju Z, Zhan T, Zhang H, He Q, Yuan M, Lu X. Preparation of functional bamboo by combining nano-copper with hemicellulose and lignin under high voltage electric field (HVEF). Carbohydr Polym. 2020;250:116936.
- [111] Li B, Zhang J, Zhou X, Du G. Effects on the protection of bamboo by cold plasma and 2D resin-based protective agent. J For Eng. 2021;6(2):57–63 (In Chinese).
- [112] Tseng K, Chou C, Liu T, Tien D, Chang C, Stobinski L. Relationship between Ag nanoparticles and Ag ions prepared by arc discharge method. Nanotechnol Rev. 2018;7(1):1–9.
- [113] Nam G, Rangasamy S, Purushothaman B, Song J. The application of bactericidal silver nanoparticles in wound treatment. Nanomater Nanotechnol. 2015;5:5–23.
- [114] Pandoli O, Martins RDS, Romani EC, Paciornik S., Maurício MHDP, Alves HDL, et al. Colloidal silver nanoparticles: An effective nano-filler material to prevent fungal proliferation in bamboo. RSC Adv. 2016;6(100):98325–36.
- [115] Liu G, Lu Z, Zhu X, Du X, Hu J, Chang S, et al. Facile *in-situ* growth of Ag/TiO₂ nanoparticles on polydopamine modified bamboo with excellent mildew-proofing. Sci Rep. 2019;9:16496.
- [116] Madani M, Hosny S, Alshangiti D, Nady N, Alkhursani S, Alkhaldi H, et al. Green synthesis of nanoparticles for varied applications: Green renewable resources and energy-efficient synthetic routes. Nanotechnol Rev. 2022;11(1):731–59.
- [117] Rtimi S, Kiwi J. Recent advances on sputtered films with Cu in ppm concentrations leading to an acceleration of the bacterial inactivation. Catal Today. 2020;340:347–62.
- [118] Golmohammadzadeh S, Mokhtari M, Jaafari MR. Preparation, characterization and evaluation of moisturizing and UV protecting effects of topical solid lipid nanoparticles. Braz. J Pharm Sci. 2012;48:683–90.
- [119] Christensen IV, Ottosen LM, Jensen SR, Jacobsen MB. Electrochemical re-impregnation of wood with copper. In: 6th Symposium on Electrokinetic Remediation EREM2007; 2007 Jun 12–15; Vigo, Spain; 2007. p. 159–60.

- [121] Galbreath KC, Zygarlicke CJ, Tibbetts JE, Schulz RL, Dunham GE. Effects of NOx, α-Fe₂O₃, γ-Fe₂O₃, and HCl on mercury transformations in a 7-kW coal combustion system. Fuel Process Technol. 2005;86(4):429–48.
- [122] Kılınç E. γ-Fe₂O₃ magnetic nanoparticle functionalized with carboxylated multi walled carbon nanotube: synthesis, characterization, analytical and biomedical application.
 J Magn Magn Mater. 2016;401:949–55.
- [123] Sun G, Dong B, Cao M, Wei B, Hu C. Hierarchical dendrite-like magnetic materials of Fe₃O₄, γ-Fe₂O₃, and Fe with high performance of microwave absorption. Chem Mater. 2011;23(6):1587–93.
- [124] Cao S, Zhu Y, Ma M, Li L, Zhang L. Hierarchically nanostructured magnetic hollow spheres of Fe₃O₄ and γ -Fe₂O₃: preparation and potential application in drug delivery. J Phys Chem C. 2008;112(6):1851–6.
- [125] Taboada E, Solanas R, Rodriguez E, Weissleder R, Roig A. Supercritical-fluid-assisted one-pot synthesis of biocompatible core (γ-Fe₂O₃)/shell (SiO₂) nanoparticles as high relaxivity T2-contrast agents for magnetic resonance imaging. Adv Funct Mater. 2009;19(14):2319–24.
- [126] Kötteritzsch J, Schubert U, Hager M. Triggered and selfhealing systems using nanostructured materials. Nanotechnol Rev. 2013;2(6):699–723.
- [127] Ayoub I, Kumar V, Abolhassani R, Sehgal R, Sharma V, Sehgal R, et al. Advances in ZnO: Manipulation of defects for enhancing their technological potentials. Nanotechnol Rev. 2022;11(1):575–619.
- [128] Raghupathi KR, Koodali RT, Manna AC. Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. Langmuir. 2011;27(7):4020-8.
- [129] Khan MF, Hameedullah M, Ansari AH, Ahmad E, Lohani MB, Khan RH, et al. Flower-shaped ZnO nanoparticles synthesized by a novel approach at near-room temperatures with antibacterial and antifungal properties. Inter J Nanomed. 2014;9:853–64.
- [130] Xie Y, He Y, Irwin PL, Jin T, Shi X. Antibacterial activity and mechanism of action of zinc oxide nanoparticles against Campylobacter jejuni. Appl Env Microbiol. 2011;77(7):2325–31.
- [131] Li J, Sun Q, Yao Q, Wang J, Han S, Jin C. Fabrication of robust superhydrophobic bamboo based on ZnO nanosheet networks with improved water-, UV-, and fire-resistant properties. J Nanomater. 2015;2015:431426.
- [132] Li J, Lu Y, Wu Z, Bao Y, Xiao R, Yu H, et al. Durable, selfcleaning and superhydrophobic bamboo timber surfaces based on TiO₂ films combined with fluoroalkylsilane. Ceram Int. 2016;42(8):9621–9.
- [133] Gao L, Lu Y, Zhan X, Li J, Sun Q. A robust, anti-acid, and hightemperature-humidity-resistant superhydrophobic surface of wood based on a modified TiO₂ film by fluoroalkyl silane. Surf Coat Technol. 2015;262:33–9.
- [134] Li J, Ren D, Wu Z, Huang C, Yang H, Chen Y, et al. Visible-lightmediated antifungal bamboo based on Fe-doped TiO₂ thin films. RSC Adv. 2017;7(87):55131–40.

- [135] Zhang J, Zhang B, Chen X, Mi B, Wei P, Fei B, et al. Antimicrobial bamboo materials functionalized with ZnO and graphene oxide nanocomposites. Materials. 2017;10(3):239.
- [136] Katsnelson MI, Novoselov KS. Graphene: New bridge between condensed matter physics and quantum electrodynamics. Solid State Commun. 2007;143(1–2):3–13.
- [137] Li Y, Umer R, Samad YA, Zheng L, Liao K. The effect of the ultrasonication pre-treatment of graphene oxide (GO) on the mechanical properties of GO/polyvinyl alcohol composites. Carbon. 2013;55:321–7.
- [138] Wang Y, Li Y, Xue S, Zhu W, Wang X, Huang P, et al. Superstrong, lightweight, and exceptional environmentally stable SiO₂@ GO/bamboo composites. ACS Appl Mater Interfaces. 2022;14:7311–20.
- [139] Silva CR, Lago RM, Veloso HS, Patricio PSO. Use of amphiphilic composites based on clay/carbon nanofibers as fillers in UHMWPE. J Braz Chem Soc. 2018;29(2):278-84.
- [140] Kaur N, Kishore D. Montmorillonite: an efficient, heterogeneous and green catalyst for organic synthesis.
 J Chem Pharm Res. 2012;4(2):991–1015.
- [141] Rahman MR, Adamu M, Bakri MKB. Impact of Poly(Ethylene-Alt-Maleic Anhydride) and nanoclay on the physicochemical, mechanical, and thermal properties of bamboo nanocomposite. In: Rahman MR, editors. Bamboo polymer nanocomposites. Cham: Springer; 2021. p. 21–37.
- [142] Rahman MR, Hamdan S, Bakri MKB. Acrylation and acrylonitrile grafting with MMT bamboo nanocomposite. In: Rahman MR, editors. Bamboo polymer nanocomposites. Cham: Springer; 2021. p. 39–61.
- [143] Rahman MR, Adamu M, Hamdan S, Bakri MKB, Khan A. Optimization and characterization of acrylonitrile/MAPE/ nano-clay bamboo nanocomposites by response surface methodology. Polym Bull. 2021.
- [144] Qi HP, Wang HL, Zhao DY, Jiang WF. Preparation and photocatalytic activity of Ag-modified GO-TiO₂ mesocrystals under visible light irradiation. Appl Surf Sci. 2019;480:105–14.
- [145] Treu A, Larnøy E. Impact of a low pulsed electric field on the fungal degradation of wood in laboratory trials. Inter Biodeterior Biodegrad. 2016;114:244–51.
- [146] Hattori T, Tamura T. On the effect of electricity upon the growth of wood-destroying fungi. Jpn J Phytopathol. 1939;9:211–22 (In Japanese).
- [147] Sheng C, Yang N, Yan Y, Shen X, Jin C, Wang Z, et al. Bamboo decorated with plasmonic nanoparticles for efficient solar steam generation. Appl Therm Eng. 2020;167:114712.
- [148] Yang JK, Hwang IK, Seo MK, Kim SH, Lee YH. Plasmon-suppressed vertically-standing nanometal structures. Opt Express. 2008;16(3):1951–7.
- [149] Meng X, Zhang D, Feng P, Hu N. Review on mechanical behavior of solar cells for building integrated photovoltaics. Sustain Struct. 2021;1(2):000009.
- [150] Li J, Ma R, Lu Y, Wu Z, Liu R, Su M, et al. Bamboo-inspired design of a stable and high-efficiency catalytic capillary microreactor for nitroaromatics reduction. Appl Catal B. 2022;310:121297.
- [151] Ryu J, Ku SH, Lee H, Park CB. Mussel-inspired polydopamine coating as a universal route to hydroxyapatite crystallization. Adv Funct Mater. 2010;20(13):2132–9.

- [152] Jin C, Li J, Han S, Wang J, Sun Q. A durable, superhydrophobic, superoleophobic and corrosion-resistant coating with rose-like ZnO nanoflowers on a bamboo surface. Appl Surf Sci. 2014;320:322–7.
- [153] Li J, Zheng H, Sun Q, Han S, Fan B, Yao Q, et al. Fabrication of superhydrophobic bamboo timber based on an anatase TiO₂ film for acid rain protection and flame retardancy. RSC Adv. 2015;5(76):62265–72.
- [154] Li J, Yu H, Wu Z, Wang J, He S, Ji J, et al. Room temperature synthesis of crystalline anatase TiO₂ on bamboo timber surface and their short-term antifungal capability under natural weather conditions. Colloids Surf A Physicochem Eng Asp. 2016;508:117–23.
- [155] Zhu X, Pei L, Zhu R, Jiao Y, Tang R, Feng W. Preparation and characterization of Sn/La co-doped TiO₂ nanomaterials and their phase transformation and photocatalytic activity. Sci Rep. 2018;8:12387.
- [156] Yu Y, Jiang Z, Tian G, Wang H, Song Y. Improving photostability and antifungal performance of bamboo with nanostructured zinc oxide. Wood Fiber Sci. 2011;43(3):293–304.
- [157] Li J, Wu Z, Bao Y, Chen Y, Huang C, Li N, et al. Wet chemical synthesis of ZnO nanocoating on the surface of bamboo timber with improved mould-resistance. J Saudi Chem Soc. 2017;21(8):920–8.
- [158] Yu Y, Jiang Z, Wang G, Tian G, Wang H, Song Y. Surface functionalization of bamboo with nanostructured ZnO. Wood Sci Technol. 2012;46:781–90.
- [159] Chen J, Ma Y, Lin H, Zheng Q, Zhang X, Yang W, et al. Fabrication of hydrophobic ZnO/PMHS coatings on bamboo surfaces: the synergistic effect of ZnO and PMHS on antimildew properties. Coatings. 2019;9(1):15.
- [160] Ren D, Li J, Xu J, Wu Z, Bao Y, Li N, et al. Efficient antifungal and flame-retardant properties of ZnO-TiO₂-layered doublenanostructures coated on bamboo substrate. Coatings. 2018;8(10):341.
- [161] Ren D, Li J, Bao Y, Wu Z, He S, Wang A, et al. Low-temperature synthesis of flower-like ZnO microstructures supported on TiO₂ thin films as efficient antifungal coatings for bamboo protection under dark conditions. Colloids Surf A Physicochem Eng Asp. 2018;555:381–8.
- Yao X, Du C, Hua Y, Zhang J, Peng R, Huang Q, et al. Flameretardant and smoke suppression properties of nano MgAl-LDH coating on bamboo prepared by an *in situ* reaction.
 J Nanomater. 2019;2019:9067510–12.
- [163] Jin C, Yao Q, Li J, Fan B, Sun Q. Fabrication, superhydrophobicity, and microwave absorbing properties of the magnetic γ-Fe₂O₃/bamboo composites. Mater Des. 2015;85:205–10.
- [164] Qin Z, Zhang J, Gao W. Study on the super hydrophobic property of bamboo by gas phase nano SiO₂ modification. In: 2015 2nd International Conference on Material Engineering and Application (ICMEA); 2015.
- [165] Zhou Z, Du C, Yu H, Yao X, Huang Q. Promotion effect of nano-SiO₂ on hygroscopicity, leaching resistance and thermal stability of bamboo strips treated by nitrogen-phosphorus-boron fire retardants. Wood Res. 2020;65(5):693–704.

- [166] Dong Y, Yan Y, Ma H, Zhang S, Li J, Xia C, et al. *In-situ* chemosynthesis of ZnO nanoparticles to endow wood with antibacterial and UV-resistance properties. J Mater Sci Technol. 2017;33(3):266–70.
- [167] Sirelkhatim A, Mahmud S, Seeni A, Kaus NHM, Ann LC, Bakhori SKM, et al. Review on zinc oxide nanoparticles: antibacterial activity and toxicity mechanism. Nano-Micro Lett. 2015;7(3):219–42.
- [168] Cho K, Hong J, Chung C. Effects of ZnO nano particles on thermal stabilization of polymers. Polym Eng Sci. 2004;44(9):1702-6
- [169] Gao J, Lin H, Wen A, Chen J, Yang W, Li R. Zinc complex derived from ZnCl₂-Urea ionic liquid for improving mildew property of bamboo. Coatings. 2020;10(12):1233–732.
- [170] Rao F, Chen Y, Zhao X, Cai H, Li N, Bao Y. Enhancement of bamboo surface photostability by application of clear coatings containing a combination of organic/inorganic UV absorbers. Prog Org Coat. 2018;124:314–20.
- [171] Tang A, Huang Y, Zhang W, Yu Y, Yang Y, Yuan Z, et al. Effect of the nano-titanium dioxide (nano-TiO₂) coating on the photoaging properties of thermally treated bamboo. Wood Mater Sci Eng. 2021;1–10.
- [172] Rao F, Chen Y, Zhao X, Cai H, Li N, Bao Y. Enhancement of bamboo surface photostability by application of clear coatings containing a combination of organic/inorganic UV absorbers. Prog Org. Coatings. 2018;124:314–20.
- [173] GB/T 18261-2013. Test Method for Anti-Mildew Agents in Controlling Wood Mould and Stain Fungi; Standardization Administration of China: Beijing, China; 2013 (In Chinese).
- [174] Spizzirri UG, Aiello F, Carullo G, Facente A, Restuccia D. Nanotechnologies: An innovative tool to release natural extracts with antimicrobial properties. Pharmaceutics. 2021;13(2):230.
- [175] Fernández M, Orozco J. Advances in functionalized photosensitive polymeric nanocarriers. Polym (Basel). 2021;13(15):2464.
- [176] Abd-Algaleel SA, Abdel-Bar HM, Metwally AA, Hathout RM. Evolution of the computational pharmaceutics approaches in the modeling and prediction of drug payload in lipid and polymeric nanocarriers. Pharmaceuticals. 2021;14(7):645.
- [177] Huang Q, Du C, Hua Y, Zhang J, Peng R, Yao X. Synthesis and characterization of loaded Nano/zinc oxide composite hydrogels intended for anti-mold coatings on bamboo. Bioresources. 2019;14(3):7134–47.
- [178] Zhang J, Huang Q, Du C, Peng R, Hua Y, Li Q, et al. Preparation and anti-mold properties of Nano-ZnO/poly(*N*-isopropylacrylamide) composite hydrogels. Molecules. 2020;25(18):4135.
- [179] Wei J, Chen Y, Liu H, Du C, Yu H, Ru J, et al. Effect of surface charge content in the TEMPO-oxidized cellulose nanofibers on morphologies and properties of poly(*N*-isopropylacrylamide)-based composite hydrogels. Ind Crop Prod. 2016;92:227–35.
- [180] Yu H, Du C, Liu H, Wei J, Zhou Z, Huang Q, et al. Preparation and characterization of bamboo strips impregnation treated by silver-loaded thermo-sensitive nanogels. BioResources. 2017;12(4):8390-401.

- [181] Jayrajsinh S, Shankar G, Agrawal YK, Bakre L. Montmorillonite nanoclay as a multifaceted drug-delivery carrier: A review. J Drug Delivery Sci Technol. 2017;39:200–9.
- [182] Uddin F. Montmorillonite: An introduction to properties and utilization. In: Mansoor Zoveidavianpoor. Current topics in the utilization of clay in industrial and medical applications. London: IntechOpen; 2018. p. 3–23.
- [183] Zhang R, Li Y, He Y, Qin D. Preparation of iodopropynyl butycarbamate loaded halloysite and its anti-mildew activity.
 J Mater Res Technol. 2020;9(5):10148–56.
- [184] Peng R, Yu H, Du C, Zhang J, Hu A, Li Q, et al. Preparation of uniformly dispersed *N*-isopropylacryl-amide/Acrylic acid/ nanosilver composite hydrogel and its anti-mold properties. BioResources. 2021;16(1):441–54.