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Chapter

Utilizing Photocatalysts in Reducing Moisture Absorption in Composites of Natural Fibers

Mohammed Mohammed and Rozyanty Rahman

Abstract

Due to growing environmental consciousness and the depletion of oil supplies, numerous efforts have been made to replace synthetic fibers in fiber-reinforced composites with natural fibers (NFr). The low cost and abundance of NFr and its biodegradability and low density have encouraged researchers worldwide to study their potential applications in several industrial sectors. However, NFr has several disadvantages: excessive moisture absorption and subsequent swelling and degradation, low chemical and fire resistance, and insufficient interfacial interactions with polymers. Consequently, there is great interest in modifying the surface of NFr using a variety of methods. This chapter presents an overview of the NFr, its characterization, the problems associated with adding NFr to polymer composites. This literature survey suggests an in-depth review of photocatalysis by utilizing photocatalysts nanoparticle (PHNPs) aimed at increasing the hydrophobicity and interfacial bonding between the NFr and the matrix Using a photo-induced oxidation mechanism to disassemble water molecules, pollutants, and bacteria in a wet environment. Additionally, we reviewed the effects of these PHNPs on the moisture absorption, mechanical characteristics, and dimensional stability of NFr composites. As a result, this review article may make a valuable contribution to researchers interested in coating and treating NFr to further enhance their surface characteristics.

Keywords: Photocatalysts, natural fiber, surface treatment, moisture absorption

1. Introduction

Environmental concerns and escalating social demand for the adoption of less hazardous composites materials have prompted a paradigm shift toward employing NFr as a replacement for synthetic and non-renewable reinforcements. This has led to the development of what are usually known as “Green Composites,” or composites made from biodegradable or renewable raw materials with lower environmental effect [1]. The application of NFr in polymer composites is expanding in many sectors such as automotive, furniture, packaging and construction. The utilization of NFr is based on its advantages including decreased tool wear, inexpensive, light weight, high toughness, good specific strength characteristics, ease of separation, improved energy recovery, carbon dioxide sequestration, and biodegradability, as well as

their sustainable renewable characteristics, and having competitive mechanical performance are just some of the significant properties that make them suitable for us. NFr are available in a broad multitude of types and are often used as fillers and reinforcement [2].

However, NFr reinforced composites have a number of disadvantages, including limited wettability, poor fiber/polymer matrix performance, and the ability to absorb more water and moisture [3]. For the majority of NFr users, the influence of moisture absorption properties on NFr-reinforced composites became a warning signal. In reality, this absorption destroys the adhesion force between the fiber and matrix in an enormous manner. Subsequently, it diminishes the composite's strength in a manner proportional to the absorption duration or nature. In addition, it results in inadequate stress transfer and ultimately specimen fracture over time. The moisture absorption involves the following mechanisms: at first, the water molecule penetrates the micro gaps that are present within the chains, then the penetrated water diffuses deep within the chain via the capillary transport mechanism, and finally, the fibers swell due to the micro gaps [4]. The hydrophilic nature of NFr and the presence of components such as wax and pectin preclude an efficient reaction with the thermoset or thermoplastic polymer, therefore preventing the reinforcement and matrix from bonding better. Improved bonding between NFr and resin is critical for stress transmission from the matrix to the reinforcement. As a result, a weak interface reduces the physical and mechanical characteristics of composites [5].

To resolve this concern, chemical treatments of NFr are utilized to enhance the physical, mechanical, and thermal characteristics of the composites. According to Edeerozey et al. and Baiardo et al., chemical treatments can increase interfacial interaction between NFr and polymer matrix by diminishing the hydrophilicity of NFr, cleaning the surface of NFr, augmenting fiber roughness, and lowering moisture content of NFr [6, 7]. The numerous chemical processes were conducted for NFr, such as alkaline, silane, and stearic acid. Further studies have shown that the chemically treated NFr composite materials have superior tensile, bending, impact, and interlaminar shear strengths and hardness levels compared to untreated composites.

According to Njuguna et al., PHNPs are a promising filler material for improving the mechanical and physical characteristics of NFr polymer composites while lowering moisture absorption [8]. Since nanoscale fillers are often defect-free, their applications in polymer composite area setup can overcome the limitations of the traditional/conventional micrometer scale. Owing to the uniform and homogenous dispersion of PHNPs, a large matrix-PHNPs interfacial area is formed, which influences relaxation behavior and ensues the mechanical, molecular mobility, and thermal characteristics [9, 10]. PHNPs are often found in the minor zone., whereas just a few microparticles contribute to the deformation of the plastic area. This enables PHNPs to enhance the fracture and mechanical characteristics of fragile matrixes. PHNPs with a higher surface area are of particular interest because they provide superior reinforcement for the production of nanocomposites [9]. PHNPs are typically included as a percentage of the total weight of the composite for nanocomposite advancement [11]. The particular surface area of PHNPs has a significant effect on the composite characteristics, which is continuous. The basic principle behind nanocomposites is to make a high interface between the PHNPs and the matrix. The homogenous dispersion of PHNPs is frequently problematic [12]. Nanocomposites are a type of high-performance material that has exceptional characteristics, combinations, and design options [13].

Polymer/ NFr-nanocomposites	Result of integration of Nano particles into NFr	Reference
Epoxy/banana fiber/ nano clay	(a) The nanoclay-infused banana fiber composites enhanced compressive yield stress, modulus, and strength by 17%, 2 times, and 43%, respectively (b) Microscopy Examination demonstrated that nanoclay infusion in fiber enhanced fiber-matrix interfacial and load transfer characteristics, resulting in a higher level of property enhancement.	[15]
unsaturated polyester resin/ sisal fiber/ Multi-walled carbon nanotubes	The produced composite displayed appreciable mechanical and acoustical characteristics	[16]
Epoxy/Flax fiber/ nano titanium dioxide	composite material projected best flexural strength, impact strength and the hardness value with an increase of 25.05%, 24.29% and 16.01% respectively.	[17]
Polypropylene/wheat straw fiber/nano titanium dioxide	(a) Composite exhibited excellent UV-shielding properties in the range of 100–200 nm (b) exhibited the highest flexural (29.27 MPa), tensile (14.38 MPa), and impact (4.55 kJ/m ²) strengths.	[18]
Epoxy/Coccinia Indica fiber/nano clay	(a) The experimental evidence shows that the increase in weight percentage of nanoclay enhances the tensile, flexural, impact, compression properties of the treated <i>Coccinia Indica</i> fiber reinforced epoxy composites (b) the presence of 3 wt.% nanoclay provides better interfacial adhesion between fibers and matrix	[19]

Table 1.

The implications of integration of PHNPs into NFr.

Despite the fact that review papers and even books have been published on the totality impact of surface treatment on NFr in terms of moisture absorption, mechanical performance, and morphology [2, 14], the researchers believe that a precise book or review papers on the overall surface treatment with PHNPs is an essential first step in providing immunity to NFr polymer composites against quick and unnecessary degradation, resulting in the production of NFr polymer composites with high water repellency and strength properties, has not yet been published; nevertheless, it is anticipated that such a book will be of considerable importance to the composite scientific community. In the published literature, we found no review or book has been written to evaluate the impact of surface treatment with inorganic PHNPs on the hydrophobicity of NFr and relate that with improving the mechanical, physical, and chemical attributes of its composite. In order to achieve this goal, we tabulated in **Table 1**, the effects of the incorporation of PHNPs into NFr on moisture absorption and mechanical properties. The findings will serve as a scientific benchmark for developing high-performance polymer composites incorporating NFr as reinforcement, particularly for use in building applications such as floor decking, door and window frames.

2. Compositions and natural Fibers properties

To acquire a thorough grasp of the degrading issues, it is vital to first fathom the nature and compositions of NFr. NFr are categorized according to whether they

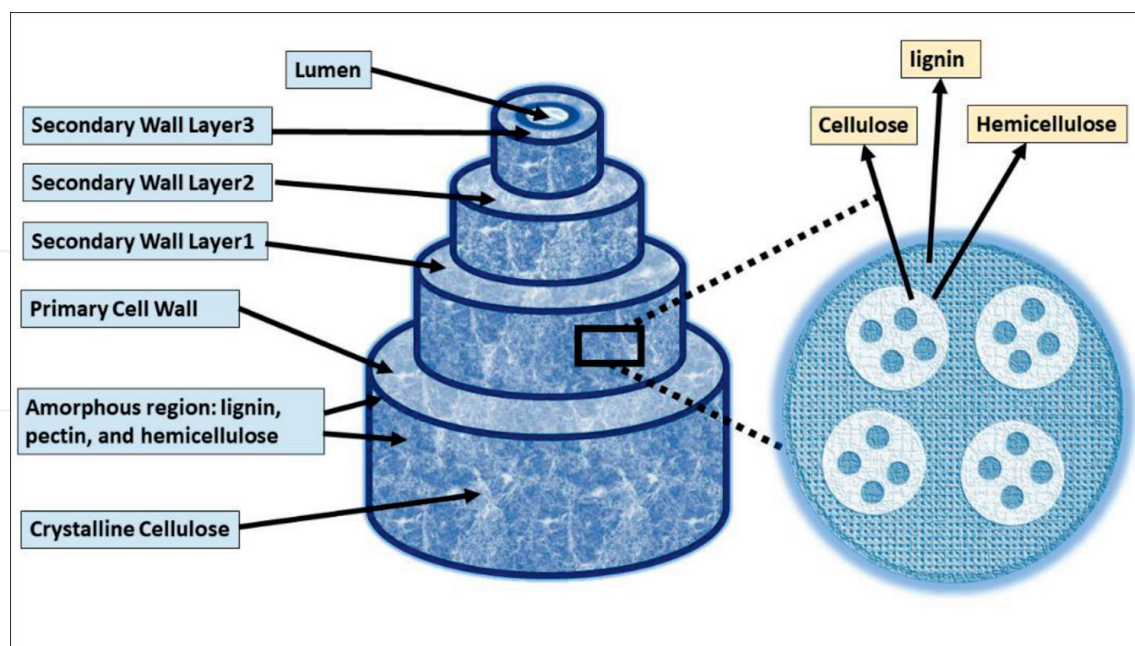


Figure 1.
Schematic representation of structure of natural fiber.

originated from plants, animals, or minerals. The major component of NFr generated from plants is cellulose fibrils embedded in lignin matrix. **Figure 1** demonstrates the structure of a biofiber. Three secondary cell walls and a primary cell wall make up the complicated layered structure of each fiber. The thick middle layer of secondary cell walls governs the mechanical characteristics of fiber. It is composed of a series of helical microfibrils generated from long-chain cellulose molecules. Each cell wall consists of three primary elements: cellulose, hemicelluloses, and lignin. Lignin-hemicelluloses serve as the matrix, whereas microfibrils (composed of cellulose molecules) serve as the fibers [20, 21]. Other constituents consist of pectins, oil, and waxes [21, 22]. The most important structural element of many NFr is cellulose, a natural polymer with three hydroxyl groups per repeating unit. Cellulose is resistant to hydrolysis, strong alkali and oxidizing agents. However, when exposed to chemical and solution treatments, cellulose degrades to some extent. Hemicelluloses are polysaccharides with a reduced molecular weight that act as a cementing matrix between cellulose microfibrils and are the fundamental structural component of the fiber cell. Because it is hydrophilic, weak acids and bases can quickly hydrolyze it. Lignin is a complex hydrocarbon polymer that provides plants their stiffness and aids in water transport. It is hydrophobic, resistant to acid hydrolysis and the assaults of most microbes, soluble in hot alkali, rapidly oxidized, and readily condensable with phenol [23].

3. Challenges for natural fiber as a reinforcement in polymer composites

3.1 Moisture absorption

Humidity aging is well acknowledged as a significant contributor to the long-term degradation of an organic matrix subjected to the environment or in contact with an aqueous medium. Moreover, humidity aging has a detrimental influence on the mechanical characteristics and dimensional stability of composites [24].

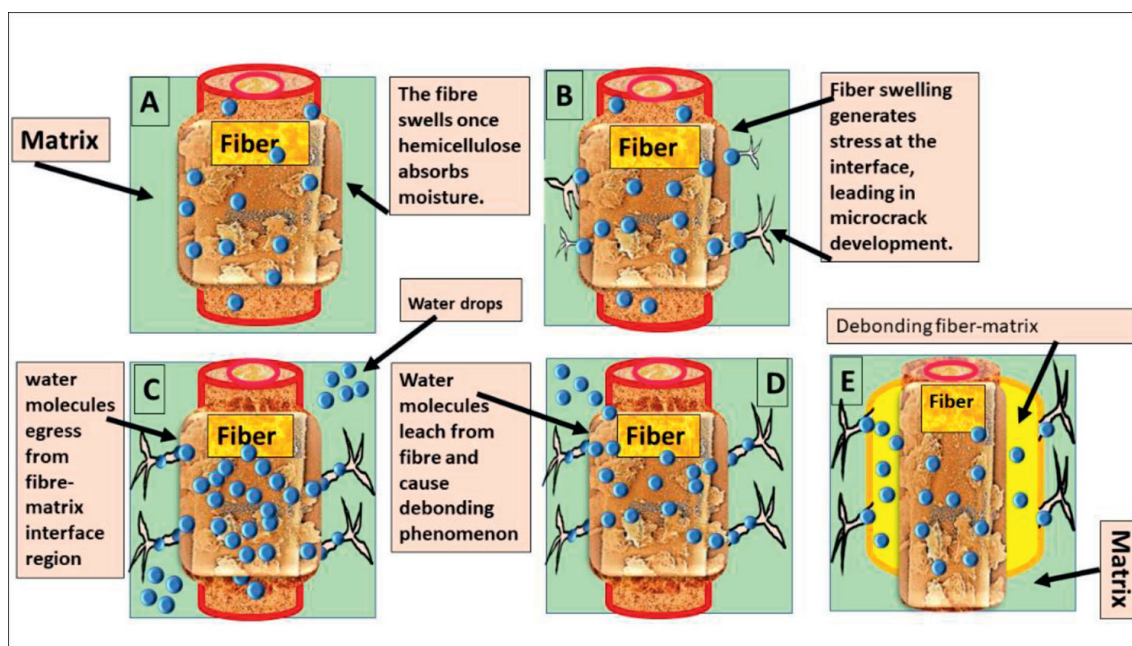


Figure 2.
Schematic representation of impact of moisture on Fiber-Matrix Interface.

Consequently, it is critical to research the moisture absorption behavior of NFr composites to determine the possible impacts of the absorbed water and the durability of the NFr composites utilized in the humidity environment [25, 26]. The majority of studies believe that moisture penetrates composite materials through three distinct mechanisms. The primary process is due to water molecules diffusing into the microgaps between polymer chains. The second mechanism includes capillary transportation through the holes and defects caused by insufficient wettability at the interfaces between the fiber and matrix. The third mechanism is the transfer through microcracks formed in the matrix during the combining process with fiber or due to fiber swelling [26, 27]. Moisture quickly hydrolyzes matrixes such as polyester, resulting in a reduce in molecular weight of polymer [24, 28]. Temperature and humidity have an impact on the rate of decomposition of NFr [28]. In a humid climate, this would significantly lose mechanical characteristics for NFr [29]. The loading of NFr has a significant impact on the moisture absorption characteristics. IAS et al. [30] evaluated the impact of fiber loading (10–40 wt%) on the moisture absorption capacity of a kenaf/polyester composite at ambient temperature. Moisture absorption increased with increasing fiber volume in composites, it was reported. The water uptake process of a NFr is shown in **Figure 2**.

4. Impact of surface treatment of natural fiber on moisture absorption

Numerous drawbacks of NFr include decreased strength, decreased interfacial adhesion, poor moisture absorption resistance, and reduced durability and dimensional stability. To overcome these constraints, different methods for NFr modification have been proposed [31]. Four different approaches are used for treating NFr, physical processes, chemical methods, biological methods, and nano enhance photocatalysis treatment. These revised techniques have varying degrees of efficacy in enhancing the mechanical properties of fibers, adhesion between matrix and fiber,

and improving various characteristics of the end products [32]. However, moisture absorption leads to debonding between NFr and the matrix, because of the high susceptibility of NFr to moisture, leading to a significant decrease in the mechanical characteristics of the NFr composite [27]. This is because NFr in nature is polar and hydrophilic due to the existence of non-cellulosic components (i.e., pectin, lignin, and hemicelluloses), because it makes moisture absorption possible through the availability of functional groups such as hydroxyl (OH) and carboxylic acid [33]. Low fiber bonding with a polymer matrix generates empty areas surrounding organic composite fibers, resulting in increased moisture absorption. Fiber modification through alkalization will minimize moisture content. Potassium hydroxide or sodium hydroxide is frequently employed to remove open groups of hydroxyls that bind to water molecules [22]. Additionally, it removes hemicelluloses and reduces the capacity of fiber to absorb moisture. This combination results in the formation of chemical and hydrogen bonds, which retards the degradation of the NFr-matrix interface caused by humidity [34].

There are certain limitations to utilizing the physical, chemical, and biological treatments, such as obtaining optimal chemical concentrations to avoid additional delignification of the NFr because greater concentrations might weaken and deteriorate the NFr, as reported by Alnaid et al. [35] and Dahham et al. [36]. The chemical compounds that are employed in treating NFr will continue to damage the fibers after exposure to weathering if they are not thoroughly cleaned after-treatment process, eventually leading to severe fiber swelling and disintegration. Furthermore, the NFr composites treated with these techniques have a low UV resistance, resulting in UV deterioration of composite components, such condition contributes to more inter-laminar delamination and more brittleness of the composites when placed under high loads [23].

5. Mechanism of repellence moisture via photocatalysts nanoparticle

Photocatalysis is a viable environmental protection process because it can oxidize small quantities of organic contaminants into benign compounds [37, 38]. Photocatalysis employs PHNPs to perform a photo-induced oxidation reaction in order to degrade organic pollutants, inactivate microorganisms, and break down water molecules [39, 40]. **Figure 3** depicts the photocatalysis process. When photons with energies higher than the band gap energy of PHNPs are absorbed, the valence band (VB) electrons in PHNPs are excited to the conduction band, which opens up a variety of potential photoreactions. With sufficient photo energy, the photocatalytic surface produces a positive hole (h^+) in the valence band and an electron (e^-) in the conduction band (CB). The positive hole may either directly oxidize organic contaminants or generate highly reactive hydroxyl radicals (OH^\bullet). The major oxidants in the photocatalytic system [41] are the hydroxyl radicals (OH^\bullet), which oxidize organics. The electron in the conduction band decreases the amount of oxygen adsorbed by PHNPs. TiO_2 , ZnO , and Fe_2O_3 are only a few of the semiconductors that could be used as PHNPs. The band gap energy plays a crucial role in the photocatalytic process. The bandgap is defined as the void area that extends from the uppermost portion of the filled valence band to the lowest part of the unoccupied conduction band and is determined to be around 3.3 eV for ZnO nanoparticles in its crystalline state [42]. Thus, the light of a specific wavelength (i.e., ultraviolet radiation (UV)) contains enough energy to promote electrons (e^-) to the conduction band while leaving an

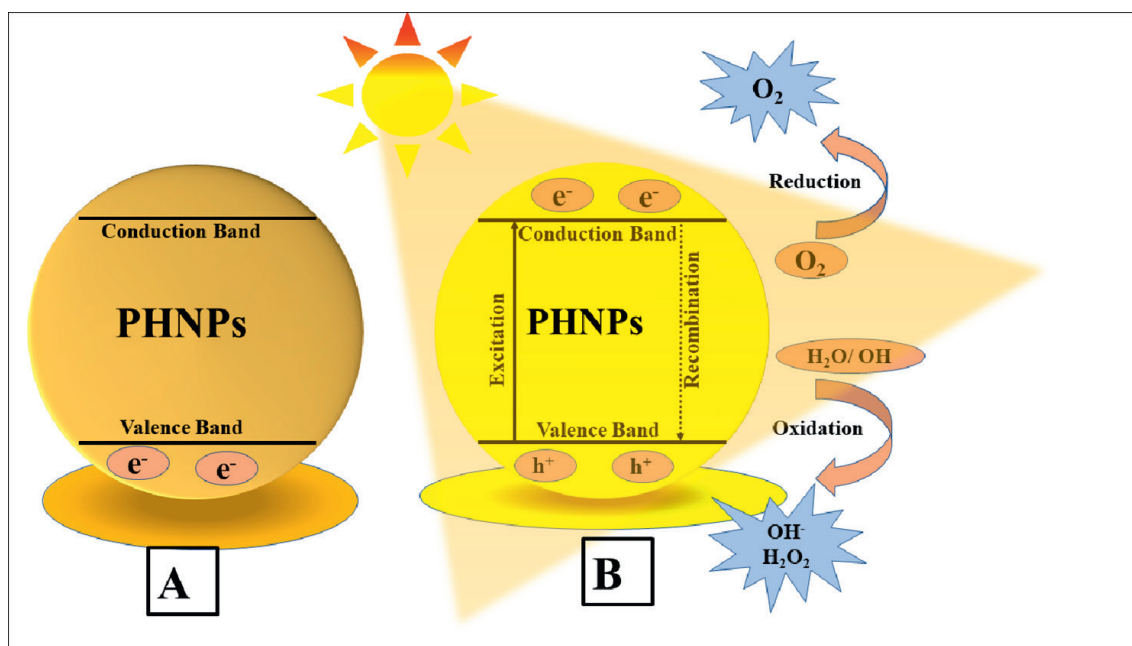


Figure 3. Schematic representation of the photocatalytic mechanism of ZnONPs (a) before exposure to UV, (b) after exposure to UV.

electron-hole (h^+) behind. Both the hole and electron can typically be recombined very quickly [43]. They can also migrate to the surface of the PHNPs as a result of their reaction with the adsorbed elements, initiating (i) the reaction between the electron and the oxygen and (ii) the reaction between the hole and the hydroxyl ion or H_2O molecule to form superoxide and hydroxyl radicals, as shown in **Figure 3** the photocatalysis process of PHNPs.

The majority of experts concur that there are five distinct mechanisms involved in the moisture-repelling action via photocatalyst nanoparticles. The first mechanism involves PHNPs were able to penetrate through the cell wall of the NFr and deposited mainly in the cell lumens and partly in the cell walls of the NFr. It is expected that the physical and mechanical characteristics of the resultant NFr would be altered to varying degrees since the PHNPs are present in both cell walls and lumens [44, 45]. Hygroscopicity of the modified NFr was reduced because the inorganic PHNPs were integrated into the cell wall and were likely occupying empty space (micropores) inside the cell wall that would otherwise be accessible to water molecules [46, 47]. By establishing hydrogen bonds with inorganic PHNPs, the hydroxyl groups of NFr cell wall components, which are principally responsible for water absorption, may have been inhibited, hence lowering the hygroscopicity of NFr. As similar study conducted by Mohammed et al. [48] showed that integration of zinc nano particle is proposed; the water repellent capability is good enough to achieve the high performance of the composite with proper system formulation during the modification process.

The second mechanism involves the incorporation inorganic PHNPs into cell walls of the fiber decreases the capacity of the cell wall to swell owing to bulking, therefore increasing the dimensional stability of the impregnated NFr. Indeed, only inorganic PHNPs integrated into the cell wall are predicted to affect the hydrophilicity and dimensional stability of NFr significantly. In contrast, those deposited in the cell lumen are anticipated to have a negligible effect [49]. Moreover, by incorporating inorganic PHNPs into the NFr cell wall, the cell wall elements are expected to be coated with water-repellent inorganic PHNPs, which may stop water molecules

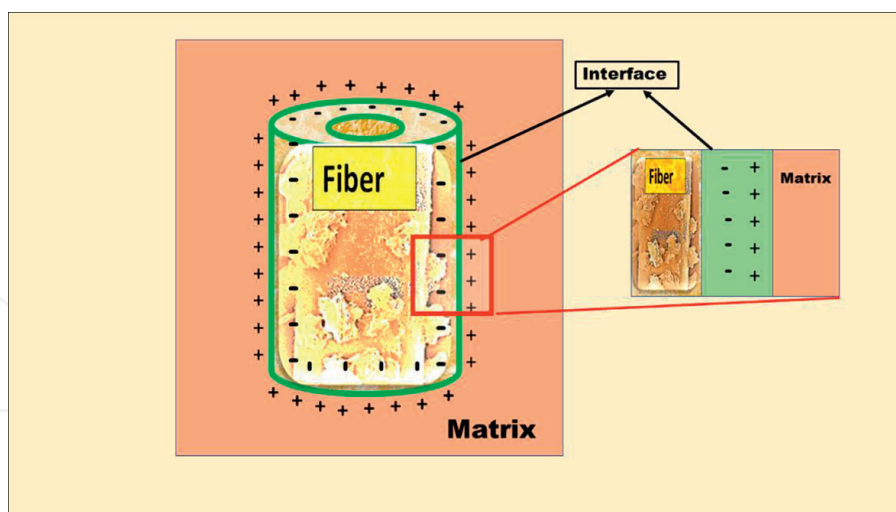


Figure 4.
Schematic representation of electrostatic adhesion mechanisms between Fiber and matrix.

and moisture from reaching them, thus slowing swelling of NFr and improving NFr dimensional stability [48, 50, 51].

Due to the presence of inorganic PHNPs in the cell wall and on the fiber surface, the third mechanism includes strong static electric forces that may attract the nonpolar polymer surface to the NFr. As a result of the compatibility between the NFr and the polymer matrix, the mechanical characteristics of the composites will be improved and their moisture absorption will be reduced. Electrostatic adhesion is a common bonding mechanism in which opposite charges (cathode and anode) are formed on the fiber and matrix surfaces. This results in two layers of opposite charges at the interface, which enhances the attraction between the fiber and matrix of the composite [52, 53]. Electrostatic discharge treatments were applied to the surfaces of polymer and electrostatic fibers to promote electrostatic adhesion at the interface region between matrix and NFr, thereby improving the transfer the stress from matrix to NFr leading to enhancing performance of the NFr composites [54]. In other words, the incorporation of the inorganic PHNPs into the micropore structure of the fiber cell walls can diminish the microvoid volumes in the fiber, as well as decrease air bubble formation during the composite manufacturing process [55]. **Figure 4** illustrates schematic representation of interfacial electrostatic bonding mechanisms between fiber and matrix.

According to Stark [56], moisture penetration increases as the number of moisture channels within NFr composites increases; consequently, the fourth mechanism refers to the addition of inorganic PHNPs as an additive to close these pathways and reduce moisture absorption. However, greater density NFr composites have lower moisture content and less swelling than untreated NFr composites [57]. This is because the inorganic PHNPs enhance the density of the composite. Therefore, by incorporating inorganic PHNPs, it is possible to lower the loading of NFr present in composites while simultaneously rising the tensile strength of the NFr composites [45, 58]. According to specific research, reducing the fiber loading improves the tensile strength of composites, whereas rising the fiber loading results in increased moisture absorption of composites depend on NFr as ingredients [59, 60].

PHNPs play two key roles in the water repellence mechanism of NFr composites via the fifth mechanism. **Figure 5** shows that when NFr absorbs a water molecule, the critical radius of PHNP atomic structures increases, pushing NFr molecules to press outward and be released to the composite surface, which is warmed by UV absorption [44]. Second,

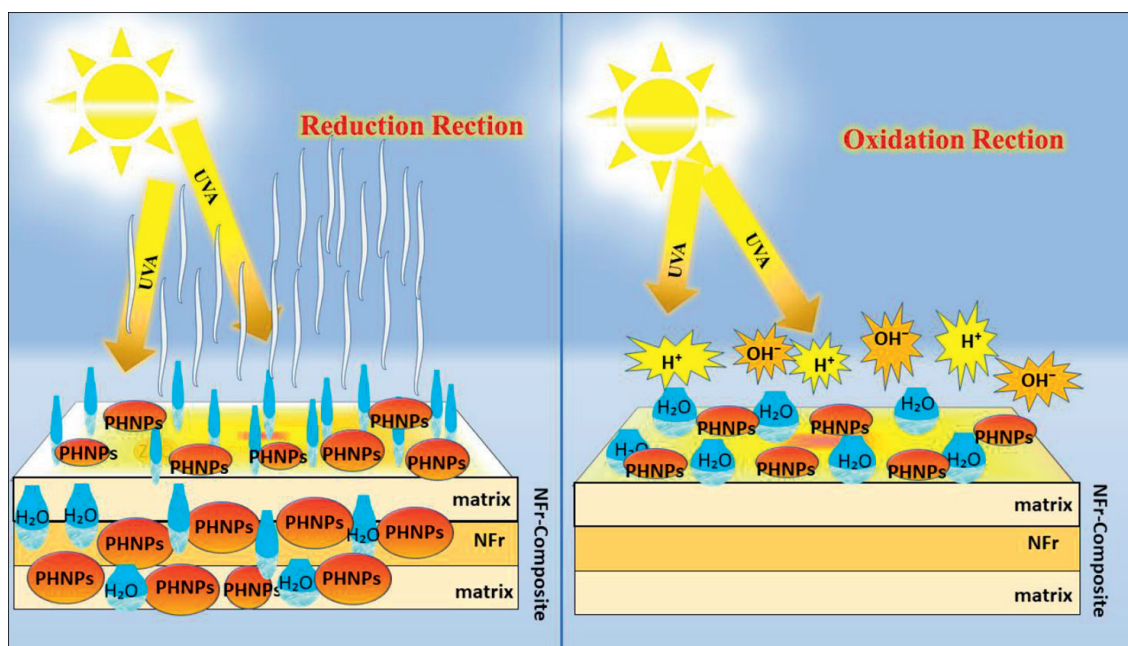


Figure 5.
 Illustration proposed reduction and oxidation reactions by PHNPs.

suppose the water molecule is straight or near the composite surface. In that case, PHNPs will initiate an oxidation process with the assistance of radiated energy, resulting in the breakdown of the water molecule into H^+ and OH^- [44].

Raghupathi et al. [61] revealed that enhanced Active Oxygen Species (ROS) generation from PHNPs during UV exposure resulted in higher PHNPs activity, which regenerated the NFr water repellency mechanisms. These reactive species include anion of superoxide (O_2^-), peroxide of hydrogen (H_2O_2), and hydroxide (OH^-). The formation of ROS during the dark has been noticed by Hirota et al. [62] who tested ZnO-NPs toward E. Coli. They observed that activity might occur in the dark, which is consistent with the findings of Jones et al. [63] such unambiguous findings imply that new methods for producing reactive species in the absence of light and the dark are likely to be discovered in the future.

The activation of PHNPs by UV light can be represented by the following steps:



In this reaction, h^+ and e^- are powerful oxidizing and reductive agents respectively. The oxidative and reductive reaction steps are expressed as:

Oxidative reaction:



Reductive reaction:



6. Conclusions

This chapter reviewed the research on NFr-reinforced composites and the constraints that have emerged in their development and serviceability. These constraints must be addressed in order to utilize the potential of NFr successfully. To begin, a suitable surface treatment of the fiber should be performed. Additionally, the study discusses the literature on NFr treatments that researchers have employed to decrease the moisture absorption of NFr composites and increase the compatibility of NFr with the polymer matrix. Many surface treatments are available, such as sodium chlorite, methacrylate, silane, peroxide, enzyme, plasma, ozone treatment, etc. Furthermore, the study describes how surface treatments-based photocatalysts nanoparticle could increase NFr adhesion to their matrix and reduce NFr moisture absorption. Therefore, surface treatments with PHNPs can be regarded for modifying the characteristics of NFr. Moisture resistance and fiber-matrix adhesion can be improved by including specific PHNPs, such as Zinc oxide, titanium dioxide, and copper oxide, inside the cell wall and on the surface of NFr. In addition, these PHNPs exert a high electric static attraction on the nonpolar polymer surface, enhancing the compatibility of the fibers with the polymer matrix. Water-repelling inorganic PHNPs are projected to cover the cell wall components, which could prevent water molecules from accessing the wall components, delaying their swelling and decreasing moisture absorption rate of NFr. The review is given here will aid researchers in better comprehending the many characteristics of NFr composites, therefore facilitating the development of novel green materials with enhanced performance. However, research in this field is extensive, and the current literature discusses using photocatalysts nanoparticle in reducing the moisture uptake by NFr. As a result, it is essential to do a thorough analysis of the current literature to understand the pros and cons of photocatalysis treatment for the specific requirements. In light of this review, it is advised that more research be conducted to determine the impact of matrix modification and fiber length on the characteristics of NFr composite materials.

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References

- [1] Gholampour A, Ozbakkaloglu T. A review of natural fiber composites: Properties, modification and processing techniques, characterization, applications. *Journal of Materials Science*. 2020;**55**:829-892. DOI: 10.1007/s10853-019-03990-y
- [2] Negawo TA, Polat Y, Buyuknalçaci FN, Kilic A, Saba N, Jawaid M. Mechanical, morphological, structural and dynamic mechanical properties of alkali treated Ensete stem fibers reinforced unsaturated polyester composites. *Composite Structures*. 2019;**207**:589-597. DOI: 10.1016/j.compstruct.2018.09.043
- [3] Saba N, Tahir PM, Jawaid M. A review on potentiality of nano filler/ natural fiber filled polymer hybrid composites. *Polymers*. 2014;**6**:2247-2273. DOI: 10.3390/polym6082247
- [4] Srinivasan T, Suresh G, Ramu P, Ram VG, Giresh M, Arjun K. Effect of water absorption of the mechanical behavior of banana fiber reinforced IPN natural composites. *Materials Today: Proceedings*. 2021;**45**:1334-1337. DOI: 10.1016/j.matpr.2020.06.024
- [5] Lu N, Oza S, Tajabadi MG. Surface modification of natural fibers for reinforcement in polymeric composites. *Surface Modification of Biopolymers*. 2015;**1**:224-237. DOI: 10.1002/9781119044901.ch9
- [6] Edeerozey AM, Akil HM, Azhar AB, Ariffin MZ. Chemical modification of kenaf fibers. *Materials Letters*. 2007;**61**:2023-2025. DOI: 10.1016/j.matlet.2006.08.006
- [7] Baiardo M, Frisoni G, Scandola M, Licciardello A. Surface chemical modification of natural cellulose fibers. *Journal of Applied Polymer Science*. 2002;**83**:38-45. DOI: 10.1002/app.2229
- [8] Njuguna J, Pielichowski K, Desai S. Nanofiller-reinforced polymer nanocomposites. *Polymers for Advanced Technologies*. 2008;**19**:947-959. DOI: 10.1002/pat.1074
- [9] De Azeredo HM. Nanocomposites for food packaging applications. *Food Research International*. 2009;**42**:1240-1253. DOI: 10.1016/j.foodres.2009.03.019
- [10] Schadler LS, Brinson LC, Sawyer WG. Polymer nanocomposites: A small part of the story. *Journal of Metals*. 2007;**59**:53-60. DOI: 10.1007/s11837-007-0040-5
- [11] Haq M, Burgueño R, Mohanty AK, Misra M. Hybrid bio-based composites from blends of unsaturated polyester and soybean oil reinforced with nanoclay and natural fibers. *Composites Science and Technology*. 2008;**68**:3344-3351. DOI: 10.1016/j.compscitech.2008.09.007
- [12] Mohammed M, Rozyanty R, Mohammed AM, Osman AF, Adam T, Dahham OS, et al. Fabrication and characterization of zinc oxide nanoparticle-treated kenaf polymer composites for weather resistance based on a solar UV radiation. *BioResources*. 2018;**13**:6480-6496. DOI: 10.15376/biores.13.3.6480-6496
- [13] Camargo PH, Satyanarayana KG, Wypych F. Nanocomposites: Synthesis, structure, properties and new application opportunities. *Materials Research*. 2009;**12**:1-39. DOI: 10.1590/s1516-14392009000100002
- [14] Musa L, Rozyanty AR, Zhafer SF. Effect of modification time of kenaf

bast fiber with maleic anhydride on tensile properties of kenaf-glass hybrid fiber unsaturated polyester composites. In: Solid State Phenomena. Vol. 280. Switzerland: Trans Tech Publications Ltd.; 2018. pp. 353-360. DOI: 10.4028/www.scientific.net/ssp.280.353

[15] Mohan TP, Kanny K. Compressive characteristics of unmodified and nanoclay treated banana fiber reinforced epoxy composite cylinders. Composites Part B: Engineering. 2019;169:118-125. DOI: 10.1016/j.compositesb.2019.03.071

[16] Abdel-Hakim A, Awad EH, El-Nemr KF, El-Basheer TM. Impact of gamma radiation and multi-walled carbon nanotubes on the mechanical and acoustical properties of reinforced sisal fiber/polyester resin composites. Radiation Physics and Chemistry. 2021;189:109768. DOI: 10.1016/j.radphyschem.2021.109768

[17] Prasad V, Joseph MA, Sekar K, Ali M. Flexural and impact properties of flax fibre reinforced epoxy composite with nano TiO₂ addition. Materials Today: Proceedings. 2018;5:24862-24870. DOI: 10.1016/j.matpr.2018.10.285

[18] Wang D, Xuan L, Han G, Wong AH, Wang Q, Cheng W. Preparation and characterization of foamed wheat straw fiber/polypropylene composites based on modified nano-TiO₂ particles. Composites Part A: Applied Science and Manufacturing. 2020;128:105674. DOI: 10.1016/j.compositesa.2019.105674

[19] Mysamy B, Palaniappan SK, Subramani SP, Pal SK, Aruchamy K. Impact of nanoclay on mechanical and structural properties of treated Coccinia indica fibre reinforced epoxy composites. Journal of Materials Research and

Technology. 2019;8:6021-6028. DOI: 10.1016/j.jmrt.2019.09.076

[20] Dittenber DB, GangaRao HV. Critical review of recent publications on use of natural composites in infrastructure. Composites Part A: Applied Science and Manufacturing. 2012;43:1419-1429. DOI: 10.1016/j.compositesa.2011.11.019

[21] John MJ, Thomas S. Biofibres and biocomposites. Carbohydrate Polymers. 2008;71:343-364. DOI: 10.1016/j.carbpol.2007.05.040

[22] Wong KJ, Yousif BF, Low KO. The effects of alkali treatment on the interfacial adhesion of bamboo fibres. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 2010;224:139-148. DOI: 10.1243/14644207jmda304

[23] Azwa ZN, Yousif BF, Manalo AC, Karunasena W. A review on the degradability of polymeric composites based on natural fibres. Materials & Design. 2013;47:424-442. DOI: 10.1016/j.matdes.2012.11.025

[24] Yew GH, Yusof AM, Ishak ZM, Ishiaku US. Water absorption and enzymatic degradation of poly (lactic acid)/rice starch composites. Polymer Degradation and Stability. 2005;90:488-500. DOI: 10.1016/j.polymdegradstab. 2005.04.006

[25] Merdas I, Thominette F, Tcharkhtchi A, Verdu J. Factors governing water absorption by composite matrices. Composites Science and Technology. 2002;62:487-492. DOI: 10.1016/S0266-3538(01)00138-5

[26] Kim HJ. Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites. International Journal of Fatigue.

2006;**28**:1307-1314. DOI: 10.1016/j.ijfatigue.2006.02.018

[27] Dhakal HN, Zhang ZA, Richardson MO. Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. *Composites Science and Technology*. 2007;**67**:1674-1683. DOI: 10.1016/j.compscitech.2006.06.019

[28] Garlotta D. A literature review of poly (lactic acid). *Journal of Polymers and the Environment*. 2001;**9**:63-84. DOI: 10.1023/A:1020200822435

[29] Paul A, Joseph K, Thomas S. Effect of surface treatments on the electrical properties of low-density polyethylene composites reinforced with short sisal fibers. *Composites Science and Technology*. 1997;**57**:67-79. DOI: 10.1016/s0266-3538(96)00109-1

[30] Salem IA, Rozyanty AR, Betar BO, Adam T, Mohammed M, Mohammed AM. Study of the effect of surface treatment of kenaf fiber on chemical structure and water absorption of kenaf filled unsaturated polyester composite. In: *Proceedings of the International Conference on Applications and Design in Mechanical Engineering (ICADME 2017)*; 21-22 August 2017; Penang, Malaysia: In *Journal of Physics: Conference Series*. 2017. p. 012001

[31] Mohammed M, Rozyanty AR, Beta BO, Adam T, Osman AF, Salem IA, et al. The weathering effect in natural environment on kenaf blast and unsaturated polyester composite. In: *Proceedings of the International Conference on Applications and Design in Mechanical Engineering (ICADME 2017)*; 21-22 August 2017; Penang, Malaysia: In *Journal of Physics: Conference Series*. 2017. p. 012003

[32] Mohammed M, Rozyanty AR, Adam T, Betar BO. Study of the weathering effect in a natural environment on the hybrid kenaf bast/glass fibre-filled unsaturated polyester composite. In: *Proceedings of the 3rd Electronic and Green Materials International Conference 2017 (EGM 2017)*; 29-30 April 2017; Krabi, Thailand: *AIP Conference Proceedings*. 2017. p. 020201

[33] Akil HM, Cheng LW, Ishak ZM, Bakar AA, Abd Rahman MA. Water absorption study on pultruded jute fibre reinforced unsaturated polyester composites. *Composites Science and Technology*. 2009;**69**:1942-1948. DOI: 10.1016/j.compscitech.2009.04.014

[34] Salem IA, Rozyanty AR, Betar BO, Adam T, Mohammed M, Mohammed AM. Study of the effect of surface treatment of kenaf fibre on mechanical properties of kenaf filled unsaturated polyester composite. In: *Proceedings of the International Conference on Applications and Design in Mechanical Engineering (ICADME 2017)*; 21-22 August 2017; Penang, Malaysia: In *Journal of Physics: Conference Series*. 2017. p. 012002

[35] Alnaid A, Noriman NZ, Dahham OS, Hamzah R, Sudin S, Idrus SS, et al. Effects of sodium hydroxide treatment on LLDPE/DS composites: Tensile properties and morphology. In: *Proceedings of the International Conference on Green Design and Manufacture (IConGDM 04)*; 29-30 Apr 2018; Saigon, Vietnam: *Journal of Physics*. 2018. p. 012061

[36] Dahham OS, Noriman NZ, Hamzah R, Al-Samarrai MN, Idrus SS, Shayfull Z, et al. The influences naoh treatment on polypropylene/cyperus odoratus (pp/cy) composites: Tensile and morphology. In: *Proceedings of*

the International Conference on Green Design and Manufacture (IConGDM 04); 29-30 Apr 2018; Saigon. Vietnam: Journal of Physics. 2018. p. 012057

[37] Srinivasan SS, Wade J, Stefanakos EK, Goswami Y. Synergistic effects of sulfation and co-doping on the visible light photocatalysis of TiO₂. *Journal of Alloys and Compounds*. 2006;**424**:322-326. DOI: 10.1016/j.jallcom.2005.12.064

[38] Vijayaraghavan S, Goswami DY. Photocatalytic oxidation of toluene in water from an algae pond with high dissolved oxygen content. *Journal of Solar Energy Engineering*. 2003;**125**:230-232. DOI: 10.1115/1.2871871

[39] Goswami DY, Trivedi DM, Block SS. Photocatalytic disinfection of indoor air. *Journal of Solar Energy Engineering, Transactions of the ASME*. 1997;**119**:92-96. DOI: 10.1115/1.2871871

[40] Rehman S, Ullah R, Butt A, Gohar ND. Strategies of making TiO₂ and ZnO visible light active. *Journal of Hazardous Materials*. 2009;**170**:560-569. DOI: 10.1016/j.jhazmat.2009.05.064

[41] Ahmed S, Rasul MG, Martens WN, Brown R, Hashib MA. Heterogeneous photocatalytic degradation of phenols in wastewater: A review on current status and developments. *Desalination*. 2010;**261**:3-18. DOI: 10.1016/j.desal.2010.04.062

[42] Lany S, Osorio-Guillén J, Zunger A. Origins of the doping asymmetry in oxides: Hole doping in NiO versus electron doping in ZnO. *Physical Review B*. 2007;**75**:241203. DOI: 10.1103/physrevb.75.241203

[43] Rasmussen JW, Martinez E, Louka P, Wingett DG. Zinc oxide nanoparticles

for selective destruction of tumor cells and potential for drug delivery applications. *Expert Opinion on Drug Delivery*. 2010;**7**:1063-1077. DOI: 10.1517/17425247.2010.502560

[44] Mohammed M, Betar BO, Rahman R, Mohammed AM, Osman AF, Jaafar M, et al. Zinc oxide nano particles integrated kenaf/unsaturated polyester biocomposite. *Journal of Renewable Materials*. 2019;**7**:967-982. DOI: 10.32604/jrm.2019.07562

[45] Wang X, Liu J, Chai Y. Thermal, mechanical, and moisture absorption properties of wood-TiO₂ composites prepared by a sol-gel process. *BioResources*. 2012;**7**:0893-0901. DOI: 10.15376/biores.7.1.0893-0901

[46] Soltani M, Najafi A, Yousefian S, Naji HR, Bakar ES. Water repellent effect and dimension stability of beech wood impregnated with nano-zinc oxide. *BioResources*. 2013;**8**:6280-6287. DOI: 10.15376/biores.8.4.6280-6287

[47] Kathirvelu S, D'souza L, Dhurai B. A comparative study of multifunctional finishing of cotton and P/C blended fabrics treated with titanium dioxide/zinc oxide nanoparticles. *Indian Journal of Science and Technology*. 2008;**1**:1-12. DOI: 10.17485/ijst/2008/v1i7/29597

[48] Mohammed M, Rozyanty AR, Osman AF, Adam T, Hashim U, Mohammed AM, et al. The weathering effect in natural environment on KenafBast filled unsaturated polyester composite and integration of Nano zinc particle for water repellent. *Micro and Nanosystems*. 2017;**9**:16-27. DOI: 10.2174/1876402909666170531075138

[49] Tshabalala MA, Libert R, Schaller CM. Photostability and moisture uptake properties of wood veneers coated with a combination of thin sol-gel films

and light stabilizers. *Holzforschung*. 2011;**65**:215-220. DOI: 10.1515/hf.2011.022

[50] Li Z, Wang Y, Cheng L, Guo W, Wu G. Effect of Nano-CaCO₃ on the structure and properties of holocellulose-fiber/polypropylene biomass composites. *Journal of Wood Chemistry and Technology*. 2017;**37**:62-74. DOI: 10.1080/02773813.2016.1235586

[51] Ibrahim ID, Jamiru T, Sadiku ER, Kupolati WK, Agwuncha SC. Impact of surface modification and nanoparticle on sisal fiber reinforced polypropylene nanocomposites. *Journal of Nanotechnology*. 2016;**2016**:1-9. DOI: 10.1155/2016/4235975

[52] Heath CJ, Bond IP, Potter KD. Integrating electrostatic adhesion to composite structures. In: *Industrial and Commercial Applications of Smart Structures Technologies* 2015. USA: SPIE; 2015;**9433**:95-105. DOI: 10.1117/12.2084073

[53] Heath CJ, Bond IP, Potter KD. Electrostatic adhesion for added functionality of composite structures. *Smart Materials and Structures*. 2016;**25**:025016. DOI: 10.1088/0964-1726/25/2/025016

[54] Yamamoto T, Uematsu K, Irisawa T, Tanabe Y. Controlling of the interfacial shear strength between thermoplastic resin and carbon fiber by adsorbing polymer particles on carbon fiber using electrophoresis. *Composites Part A: Applied Science and Manufacturing*. 2016;**88**:75-78. DOI: 10.1016/j.compositesa.2016.05.021

[55] Mai C, Militz H. Modification of wood with silicon compounds. *Inorganic silicon compounds and sol-gel systems: A review*. *Wood Science and Technology*.

2004;**37**:339-348. DOI: 10.1007/s00226-003-0205-5

[56] Stark NM. Effect of weathering cycle and manufacturing method on performance of wood flour and high-density polyethylene composites. *Journal of Applied Polymer Science*. 2006;**100**:3131-3140. DOI: 10.1002/app.23035

[57] Tuduce Trăistaru AA, Crina Anca Sandu I, Cristina Timar M, Lucia Dumitrescu G, Sandu I. SEM-EDX, water absorption, and wetting capability studies on evaluation of the influence of nano-zinc oxide as additive to paraloid B72 solutions used for wooden artifacts consolidation. *Microscopy Research and Technique*. 2013;**76**:209-218. DOI: 10.1002/jemt.22155

[58] Farahani MR, Banikarim F. Effect of nano-zinc oxide on decay resistance of wood-plastic composites. *BioResources*. 2013;**8**:5715-5720. DOI: 10.15376/biores.8.4.5715-5720

[59] Li X, Tabil LG, Panigrahi S. Chemical treatments of natural fiber for use in natural fiber-reinforced composites: A review. *Journal of Polymers and the Environment*. 2007;**15**:25-33. DOI: 10.1007/s10924-006-0042-3

[60] Stark N. Influence of moisture absorption on mechanical properties of wood flour-polypropylene composites. *Journal of Thermoplastic Composite Materials*. 2001;**14**:421-432. DOI: 10.1106/udky-0403-626e-1h4p

[61] Raghupathi KR, Koodali RT, Manna AC. Size-dependent bacterial growth inhibition and mechanism of antibacterial activity of zinc oxide nanoparticles. *Langmuir*. 2011;**27**:4020-4028. DOI: 10.1021/la104825u

[62] Hirota K, Sugimoto M, Kato M, Tsukagoshi K, Tanigawa T, Sugimoto H. Preparation of zinc oxide ceramics with a sustainable antibacterial activity under dark conditions. *Ceramics International*. 2010;**36**:497-506. DOI: 10.1016/j.ceramint.2009.09.026

[63] Jones N, Ray B, Ranjit KT, Manna AC. Antibacterial activity of ZnO nanoparticle suspensions on a broad spectrum of microorganisms. *FEMS Microbiology Letters*. 2008;**279**:71-76. DOI: 10.1111/j.1574-6968.2007.01012.x