



Compatibility of Polymer/Fiber to Enhance the Wood Plastic Composite Properties and their Applications

M. Hasanin ^a, M. E. Abd El-Aziz ^b, A. M. Youssef ^c



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^aCellulose and paper Department, National Research Centre, 33 El Bohouth St. (former El Tahrir St.), Dokki, Giza, P.O. 12622, Egypt.

^bPolymers and Pigments Department, National Research Centre, P.O. 12622, Giza, Egypt

^cPackaging Materials Department, National Research Centre, 33 El Bohouth St. (former El Tahrir St.), Dokki, Giza, P.O. 12622, Egypt

Abstract

Wood and non-woody fibers are abundant with different uses according to their composition and physical properties. Unfortunately, a huge amount of non-woody fibers was produced annually with negative environmental effects according to accumulations. Otherwise, the cellulose fibers were used as wood precursor material. Cellulosic materials are considered the most abundant natural, renewable and inexpensive polymer on the earth, considered the backbone of all woody and nonwoody fibers. Generally, the farmer tends to burn the agriculture wastes in the open air, and under uncontrolled conditions, that cause pollution to surrounding environments. These wastes are a rich source of cellulosic materials that shows great potential to be preferable used further with petroleum-based polymers. This review concerns with recycling various agricultural wastes such as rice straw, tree pruning, and cane bagasse... etc, by preparing cellulosic materials that can be used in different applications. Where composites based on recycled polymer and/or agricultural wastes were prepared to be used in various applications. The polymer wood composites are improving the single characterization of materials used and made the WPC biodegradable.

Keywords: WPC; Lignocellulose; Polymer; Compatibility; Biological treatment; Biodegradability.

1. Introduction

The main source of wood overall the world is cutting trees. With the increasing deforestation of wood around the world, where this process is going against the environment, researchers are constantly working to get new ideas to obtain wood-based alternatives to achieve the request for this natural resource and save future well-being. The alternative process to overcome the drawback of cutting trees is using wood-plastic composites (WPCs). The market demand for WPCs is growing rapidly every year, where it was 1728.9 kilotons in 2019. It can be used in many applications especially in the construction industry (such as window fitting, door frame, and flooring panel). It offers good strength and high modulus compared to commercial plastics. In this context, producers of WPC have started to integrate natural fiber produced from agricultural waste and

recycled plastic materials into WPC. Consequently, using natural fiber with synthetic polymers in WPC may enhance their degradability as well as be considered as a good environmental response. Unfortunately, the fibers and polymer compatibility play a valuable role in the properties of produced WPC. Usually, poor compatibility produces undesirable WPC [1-3].

Recently, the development of natural fiber-reinforced composites is one of the highly appealing research lines. Where, polymers replaced many of the classic materials due to their many advantages such as; ease of processing, as well as better and low-cost productivity. Also, their properties could be modified using fillers to achieve high strength and modulus requirements [4]. Moreover, the presence of the natural fiber in WPC has pushed up the biodegradation of plastic matrices where the natural fiber part of WPC is decomposed easily in

*Corresponding author e-mail: amyoussef27@yahoo.com.

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environments as well during degradation the plastic part of WPC is decomposed via degradation in parallel with degradation natural fibers where many wholes inside polymer matrices were acceleration the biological and physical degradation of plastic in comparison with neat plastic polymer [5].

Nowadays, wood-plastic composites (WPCs) have accepted enormous attention from industry, where it has shown an average yearly growth in the plastic industry with a rate of about 18% in Northern America and 14% in Europe [6]. The WPC expression mentions to any composite that contains natural fibers and synthetic polymers. WPC has good properties such as durability, low density, and stable dimensional under moisture exposure, excellent sound-absorbing capacity, high strength, and modulus of elasticity, as well as good fungi and termite resistance. Meanwhile, the characteristics of the composites decrease the friction during compounding, and the energy required for production and so the cost, which qualifies it to be used in multiple applications such as railway coaches, aerospace, military applications, building, packaging, and consumer products [7].



Fig. 1: Photos of various WPC profiles for different applications (Photos by the courtesy of JERUWERK GmbH & Co., Germany) [8].

Natural fibers are characteristic of renewable, abundant, biodegradable, and inexpensive. In addition, they have low density, high strength, and non-abrasiveness during processing which qualifies them to be used as reinforcement for synthetic polymers [1, 9, 10]. The most important source of natural fibers is wood fibers which are obtained from forests. But, the forests are declining at the frightening rate of approximately 13.0 million hectares per year [11]. For that, the researchers work to develop composites based on using agricultural byproducts or agro-waste materials (e.g., stalks of cereal crops, rice husks, coconut fibers, bagasse, maize cobs, peanut shells) [12-14]. Also, natural fibers such as the fibers of cotton, flax, hemp, jute, sisal, and sugarcane can be used as reinforcement materials for thermoplastics [15, 16]. Agricultural byproducts are good alternative waste materials that

replace wood due to they are plentiful, widespread, and easily available. Apart from their abundance and renewability, the utilization of agricultural wastes can be advantageous to the economy, environment, and technology [17].



Fig. 2. The life cycle of biodegradable, natural fibre reinforced [18].

The increase of wastes generated from the agricultural processes or polymeric materials is considered as a standout amongst the most significant issues that cause harm to the environment, in spite of the fact that it is lightweight, it occupies large areas. Furthermore, they are disposed of by landfilling or incineration, which is a damaging issue for the environment [14, 19]. Presently, new preservation policies are a force to reduce the emissions of carbon through management and improvement of carbon stocks. So this waste can be converted to useful raw material which can be used in many fields. The use of recycled agricultural and polymers waste as the raw material in manufacturing composites, that can be used in different applications, is cheap and environmentally friendly [16, 20-22].

The most important problems faced by researchers in this field are the compatibility between the natural fiber and the synthetic polymer, that mostly related to the high surface polarity of the cellulose fibers, which is the reason for (i) very low compatibility with non-polar matrices such as polyolefins (ii) moisture uptake and (iii) inter-fiber aggregation via hydrogen bonding. Various strategies have been developed to overcome these obstacles, mostly involving specific fiber surface treatments to reduce its polar character, which includes both physical and chemical modifications [23].

2. Natural fibers

Natural fibers are the plant fibers as well as all plant residues by-products biomass which are called

also lignocellulosic fibers that can be considered as composites. Lignocellulosic fibers consist of hollow cellulose fibrils that hold together by hemicellulose, lignin, wax, and resin, in addition, an inorganic material (called ash) which included mainly silica. Lignocellulose components were present in different ratios based on the type of plant. The length of cellulose chain molecules and their thickness determine the mechanical properties of the fibers. Cellulose is a natural polymer consisting of D-anhydro-glucose repeating units joined by β -1,4-glycosidic linkages at C1 and C4 positions. Each unit contains three hydroxyl groups that responded to form the hydrogen bond between the fibers which play a major role in directing the crystalline and the physical properties of cellulose. For that, the reinforcing efficiency of natural fiber is related to the nature and the crystallinity of cellulose [24]. Lignin is particularly important in the formation of cell walls, especially in wood and bark, because they lend rigidity and do not rot easily. Chemically, lignins are polymers made by cross-linking phenolic precursors. Hemicelluloses are included in the five-carbon sugars that have distinct compositions and structures [25].

The compatibility of fibers to mixing with polymer plastics was controlled by many factors. Hydrophobicity of natural fibers/plastic plays an important role in mechanical, physical, and chemical properties. Unfortunately, hydrophobic polymers/plastic are not a favorite category of polymer in WPC where they give the low mechanical, physical, and chemical properties with high water absorption properties which are against the main purpose of WPC manufacturing. Inhere, many articles were dealt with applied hydrophobic polymer/plastic with natural fibers [26].

Nourbakhsh [11] illustrated that the application suitability of agro-waste materials (such as corn stalk, reed stalk, and oilseed stalk) as reinforcement for thermoplastics improves the tensile and flexural properties of the prepared composites. Also, the oilseed fibers enhanced the mechanical properties as a result of their chemical characteristics. Flores-Hernández [7] studies the effect of white oak flour with different particle sizes and content on the properties of polystyrene. The prepared WPC has shown good mechanical properties that are strongly dependent on wood flour content and their particle size. Yao et al. [12] used four rice straw components (rice husk, straw leaf, and straw stem, plus the whole rice straw) and natural fibers to prepare composite with virgin and recycled high-density polyethylene (VHDPE and RHDPE, respectively) using melt compounding and compression molding. They found that rice straw fibers can work well as reinforcing filler for both VHDPE and RHDPE. In addition, the different rice straw components had no significant impact on the composites' mechanical properties [27, 28].

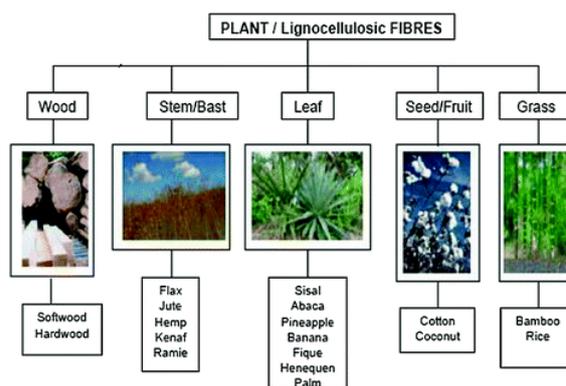


Fig. 3. Classification of plant-based natural fibers used as reinforcement in composites [29].

3. Treated fibers

The treating of fibers is generally the process goal to increase the fiber compatibility with polymer. Many natural fibers can be used as fiber-reinforced for polymer composites. But the high surface polarity of cellulose and the presence of pectin and wax in the composition of the natural fiber make their compatibility with non-polar polymers is limited. This un-compatibility can form debonding and voids in the prepared composites due to fiber aggregation as a result of inter-fibers hydrogen bond formation. [23]. Besides, it causes underprivileged interfacial adhesion strength among fibers and the matrix. This debonding and voids decreased the mechanical properties of the prepared composites. For that, the wax and pectin covering the fiber's surface should be removed beforehand [30]. Natural fibers can be undergoing to different surface treatments to increase their compatibility with the polymer matrix [30, 31]. Surface treatments comprise (i) physical modifications, such as solvent extraction; (ii) Physico-chemical treatments, like the use of corona or plasma discharges as well as bombing by laser, γ -ray, or UV; and (iii) chemical modifications, include direct condensation of the coupling agents onto the cellulose surface, etherification, and by its grafting by free-radical or ionic polymerizations [24, 32, 33].

Many researchers worked to develop specific methods to decrease the hydrophilicity of fibers against the hydrophobicity of polymers [34, 35]. Chemical treatment of natural fiber such as using alkali can be used to modify and purify the surface of the fibers, and encourage interfacial adhesion [36]. Also, graft copolymerization is a possible approach to significant increases in mechanical properties. Furthermore, the acylation treatment of cellulose fibers using fatty acids represents an interesting strategy to modify the cellulose surface due to the renewable and biodegradable nature of fatty acids also their non-polar nature [37, 38]. Physical treatments such as stretching, calendaring and thermal treatment can also make the fibers' surface

hydrophilic or hydrophobic via changes in surface energy with no alteration of the fibers' chemical structure [39-41]. A coupling agent can be used to increase the compatibility between fibers and matrix by improving the water resistance of fibers [42].

Generally, the collected fibers were cleaned by water to remove dirt and any contaminant then dried within an oven at 70°C. After that, they were ground into a short fiber via a mechanical grinder then sieving. Chun et al. were used durian husk fiber after cutting and sieving through a sieve with a mesh size of 600 μ m as a reinforcement material for the preparation of WPC with polystyrene foam waste [1].

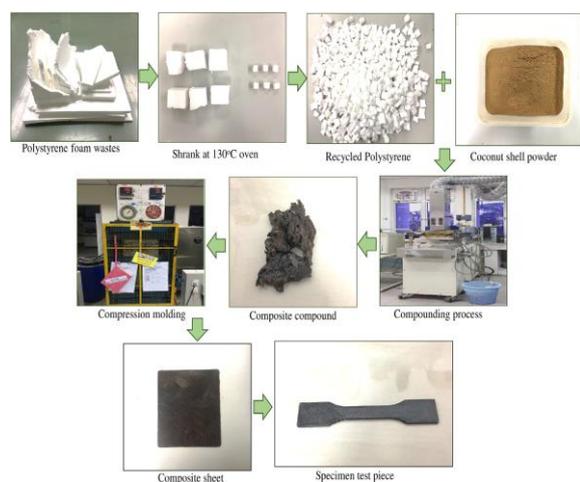


Fig.4. Process flowchart of composites made from post used PS foam and CS. [43]

3.1. Physical modification

Physical modification of natural fibers which may be called physical pretreatment was included all treatments use physical factors starting from washing, grinding to radiation. This section of treatment methodology was considered as green and eco-friendly techniques [44, 45]. Grinding usually use to cut the long discarding fibers to homogeneous length via mechanical grinding.[46]. In addition, the thermal treatment was involved in the physical methods used in the treatment of natural fibers with high efficacy which could change the fiber's chemical composition as well as can be used as an extraction method to extract the active components of fibers as dual role treatment method [10]. Consequently, physical radiation included ultrasonic, plasma, irradiation treatments [47]. It well knows that these all-previous methods used basically to modify the surface of the fiber to enhance the compatibility with plastic polymer. However, all physical treatments except mechanical and thermal treatments are non-promising according to the hazards of irradiation as well as coast effective [48].

3.2. Chemical modification

The aim of the chemical treatment for natural fibers not only removes non-desirable components but also adds functional groups to improve their bonding in polymer composites via decreasing the hydrophilicity of the fibers. The natural fibers were treated using a specific percentage of chemical solutions to modify their surface making it less hydrophilic with a unique surface texture to enhance the natural fibers and plastic compatibility [35, 49]. Haque et al. [31] modified palm and coir fiber via chemical treatment using benzene diazonium salt where the hydroxyl groups convert into the diazo group and the result is 2,6-diazo cellulose. The modified fibers were more compatible with the polypropylene matrix where the mechanical properties of composites prepared using modified fibers are higher than that prepared using untreated fiber.



Fig.5. Composites preparation: (a) Banana fiber extraction, (b.1) Banana fiber untreated and (b.2) alkali-treated, (c) Knife milling of fibers, (d) K-Mixer processing, (e) Production of plates banana fiber-TPE composites in the compression molding [50].

Arrakhiz et al. [35] modified alfa fiber using alkali treatment and etherification treatment to be used as reinforcement for polypropylene matrix. Furthermore, they [51] used three chemical treatments (silane, sodium hydroxide, and dodecane bromide) to modify the surface of coir fiber to increase their interface adhesion with the polyethylene matrix. They found that the treated fiber improves the mechanical properties of the prepared composite more than untreated fibers.

Freire et al. [23] were used modified bleached Kraft pulp by esterification with different fatty acids (eg. hexanoic, dodecanoic, octadecanoic, and docosanoic acids) and the unmodified pulp as reinforcement cellulosic fibers in Low-density polyethylene. They illustrated that the modified pulp by fatty acids enhanced the interfacial adhesion with the polymer matrix and improve the mechanical

properties of the composites and reduce their ability to water uptake capacity. But, the degree of substitution (DS) plays a mean role in the mechanical properties of the prepared composites, where the low DS gave composites with preferable mechanical properties.

3.3. Biological treatment

The term of biological treatment is the global expression referred to the techniques used by a living organism. On the other hand, the treatment of natural fiber biologically via microorganisms themselves and/or microbial enzymes was intensively studied. The biological treatment is mainly used to enhance the surface properties of fibers to increase their suitability incorporated with plastic matrix [52] which is considered as the most eco-friendly, green treatment technique[53]. Herein, the treatment of plastic via a biological system cannot be performed where the plastic materials produced from non-biological systems and cannot be attached to microorganisms or their enzymes easily. In this context, the biological treatment of natural fiber is considered an ecofriendly, green, sustainable, economic, and usable process to enhance the combability between natural fibers and polymer plastic where is hazardous chemical less use as well as no by-products accumulated in the environment [52].

Moreover, the synthetic plastic materials and WPC included chemically modified fibers are difficult degradation in the environment [5]. Hence, the addition of biologically treated fibers to WPC systems is improving biodegradation. Moreover, the biological treatments are making the fibers more contact and adhered with a plastic matrix which not only enhanced the WPC biodegradability but also improves the mechanical properties [54]. In addition, the biological treatments are considered as a green and eco-friendly process which is used generally without any hazards by- products. The biological treatment term is used basically for any process that involved biological costive agents. The natural fibers treatment biologically is included two main types [55, 56].

3.3.1. Types of biological treatments

The biological treatments are included in situ treatment using whole microorganisms as well as enzyme treatments using crude enzymes, partially pure or pure.

i- Microorganism treatment

In this method, the whole microorganism is used as a costive agent to treat the fibers via its cells or mycelium [52]. The fibers are used as the sole carbon

source and in many cases as the sole nitrogen source also in the microbial media contents. Also, the microorganism usually produced unique enzymes which affect the surface and structure of the fiber [52]. As it's known that the WPCs are based on lignocellulosic materials. Besides the effect of microorganism cells, the microbes produced enzymes called lignocellulosic enzyme clusters (Lignin peroxidases, laccases, xylanases, and cellulases). These enzymes have the ability to modify the surface of the fiber and increase its affinity to couple the plastic matrix. In this method, the fibers are affected by two factors the microorganism physical effect as well as enzyme effect. Moreover, the produced enzymes affect the composition of the fiber where each enzyme affects a specific component [58]. The advantage of this method is the fibers affect by dual stress the microorganism physical effect where for example fungal treatments occurs its mycelium into fibers and penetrate the fibers and break down their structure. On the other hand, the enzymes affect the component of lignocellulosic fibers and eliminate the undesired construction. The main disadvantage of this method is the separation of the microorganism cells and treated fibers well as no electability.

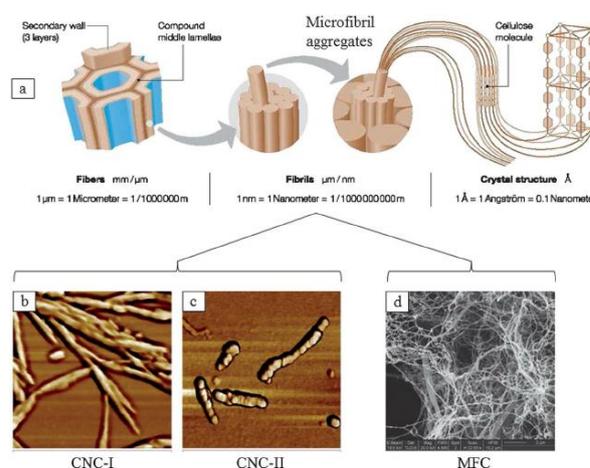


Fig. 6. Scheme illustrating the arrangement of cellulose units in the plant cell wall. (b and c) AFM images of cellulose I and cellulose II nanocrystals (CNC-I and CNC-II, respectively). (Adapted from ref. 21. Copyright 2012 American Chemical Society.) (d) SEM image of microfibrillated cellulose (MFC) [57].

ii- Crude enzymes treatment

In this method, the microorganism is grown in the reference or modified medium. The medium is extracted after complete microorganism growth. The extract is used as the crude solution to treat the fibers in an additional step. The fibers were treated in the crude extract without any previous purification. This method's advantage is the fibers produced without needed for separations from the microbial cells. While the disadvantages include the period is too

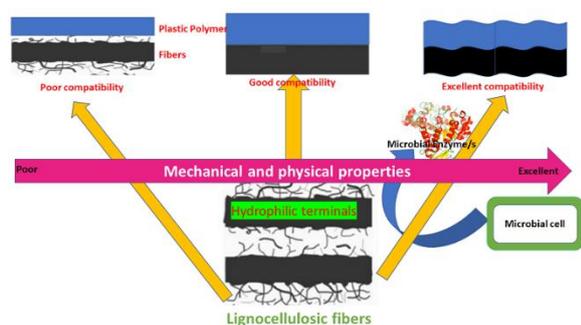
long, as well as the effect of the microbial cells and selectability is lacked [44].

iii- Purified enzymes treatment

This method is including the application of the pure enzyme. In this method, each enzyme of lignocelluloses clusters enzyme can be used alone to treated the one component of the lignocellulose structure. This method's advantage is tractability and selectability where in this method one undesired component can be eliminated. The main disadvantage of this method is the high cost [59].

4. Biodegradability of WPC

Biodegradation is the biological process in which the breakdown of organic matter by microorganisms via enzymatic action [60]. However, the biodegradation of native synthetic plastic matrix may take place for decades to forever [61]. Moreover, the accumulation of plastics materials in the environment can be changed to highly hazardous materials described as a toxin for the animal and marine organisms called microplastics [62]. In this context, the degradability rate is the restricted factor to maintain the natural material properties. Natural wood has a high rate of degradation so that the surface of natural wood must be covered by finishing polymers to prevent degradation. In contrast, the addition of the natural fibers in WPC made it easy to degrade in nature by the controlled rate in which the usability of WPC can be taken and the end of role can be controlled without negative feedback towered the environment. Furthermore, the accumulations of the native plastic materials lead to an increase in environmental destructions as shown in (Scheme 1).



Scheme 1: biological treatments of wood plastic composite.

4.1. Evaluation of biodegradability

4.1.1. Soil burial and compost conditions

In this method the enzymes produced by the soil microorganisms included algae, molds and bacteria which can occur under aerobic and anaerobic

conditions, leading to complete or partial degradation of polymeric material to carbon dioxide and water [63]. The rate of degradation was affected by the crystallinity of the material where the degradation rate was decreased with an increase in the crystallinity. In addition, the humidity and temperature were playing a striated role in this process [64]. The soil burial biodegradability was carried out by our previous work by the standard conditions in which the evaluation of biodegradation was estimated accurately [65].

4.1.2. Test with river water

Likewise, the river water method was similar to the soil burial biodegradability which depended on the microbial floral of the river water which covers all surfaces of the specimen and is attached with the microbial enzymes [66]. Additionally, this method is not suitable to carry out all types of specimens.

4.1.3. Aerobic test

The aerobic biodegradability of organic compounds in an aqueous medium was evaluated by determining the oxygen requirement in a closed respirometer (Germany standard ISO 9408:1999. In this method the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were used to calculate the degradation rate using the following equation [67]:

$$\text{The degradation rate} = \text{BOD} / \text{COD} * 100.$$

In the strict sense of the word, each mentioned above method is offered to evaluate the biodegradability rate with different techniques and requirements. Whereas, according to the sample type and blend the suitable method can be used.

5. Conclusion

Wood Plastic Composites (WPCs) are new and rapidly evolving products which combine recycle polymer with wood fibers generating a material with the characteristic properties of wooden whilst having a number of additional benefits. WPCs are not as susceptible as woody to changing moisture levels in the environment, eliminating the opportunity of the material immobilizing and splitting. Moreover, WPCs provide a number of advantages, including flexibility of manufacture and the use of recycled material to create a recyclable product also the negative impacts caused by plastic materials in the environment remains a main threat. Despite the wide array of possible finished forms, the manufacture of WPCs is relatively simple and uniform. Wood Plastic Composites have become well-established building materials, particularly for housing flooring, and are

likely to be used for a wider array of applications in the future.

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