WOOD RESEARCH doi.org/10.37763/wr.1336-4561/69.3.417431
e-ISSN 2729-8906
69(3): 2024 417-431 pp.

EVALUATION OF PROPERTIES OF WOOD PLASTIC COMPOSITES MADE FROM SEVEN TYPES OF LIGNOCELLULOSIC FIBERS

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(RECEIVED JUNE 2024)

ABSTRACT

This article aims to investigate the characteristics of wood plastic composites (WPC) prepared from polyethylene (PE) reinforced with lignocellulosic fibers derived from the xylem and bark of Masson pine, fir, cypress, as well as from Moso bamboo. The surface polarity and elemental composition of fibers were determined through contact angle measurements and X-ray photoelectron spectroscopy (XPS). The lignocellulosic fiber/PE composites were manufactured through hot-pressing technique, and their water absorption, mechanical properties, and mildew resistance were evaluated. The results revealed that the surface free energy of xylem fibers was higher than that of bark fibers among the three conifer species. XPS analysis showed that the O/C ratio of bark was consistently lower than that of xylem fiber. Among the three conifers, the Masson pine bark had the lowest O/C ratio (22.25%), while its xylem fibers had the highest ratio of 41.64%. WPC made with bark fibers had better water resistance. Additionally, the composites reinforced with xylem fibers showed superior static bending strength, impact strength, and mildew-resistant properties as compared to the composites reinforced with bark fibers. WPC made from bamboo fibers exhibited the best water resistance, with a water absorption rate and thickness swelling rate of 1.83% and 1.42%, respectively. They also had the highest static bending strength, elastic modulus, and impact strength, at 41.31 MPa, 3.82 GPa, and 10.24 kJ/m^2, respectively. The WPC made from fir xylem fibers showed the most effective mildew resistance, with the smallest damage (0.50).

KEYWORDS: Coniferous wood, Moso bamboo, wood plastic composites, physical and mechanical properties, mildew resistance.

INTRODUCTION

Lignocellulosic biomass, as the most abundant renewable polymer resource on earth, has an annual global yield of up to 180 billion tons (Deng et al. 2023), and a significant amount of residues such as branches, sawdust, and other residues are generated during harvesting and processing. Currently, only a small portion of biomass wastes are used as low-quality fuels or crudely utilized as raw materials, leading in a low comprehensive utilization rate and failing to take advantage of the unique properties of natural plant fibers. By integrating these residues with a plastic matrix, it is possible to fabricate wood plastic composites (WPC) with excellent performance, cost-effectiveness, and wide applicability. This approach not only improves the effective utilization of agricultural and forestry biomass waste resources, but also contributes to the development of a circular economy and sustainable industry (Machado et al. 2016).

WPC are materials made by combining different types of lignocellulosic fiber, including wood, bamboo, straw, hemp, etc, with a variety of plastics such as polyethylene, polypropylene, polyvinyl chloride, polylactic acid, and polyhydroxyalkanoates. These components are proportionately mixed and converted into composites by manufacturing techniques such as hot pressing, extrusion, or injection molding. WPC can be used as a substitute for traditional wood in many applications, providing the dual advantages of enhanced strength and stiffness due to the reinforcement from the lignocellulosic fiber, while also reducing the costs of composites (Charlet et al. 2015, Zhang et al. 2018).

The properties of WPCs are influenced by the composition and inherent properties of the raw materials used. The characteristics of wood fibers, which acting as reinforcements, such as species, particle size, fiber morphology, chemical composition, surface roughness, and surface free energy, all play significant role in the mechanical properties and mildew resistance of WPC (Migneault et al. 2009, Ashori and Nourbakhsh 2010, Migneault et a. 2015, Delviawan et al. 2019). Kim et al. (2009) investigated the effects of 10 species of wood on the physical and mechanical properties of polypropylene WPC, and found that compared with maple, oak, and Osage orange, composites prepared with cedar and hickory exhibited higher tensile strengths. In addition, the dynamic mechanical properties of the composites seemed correlated with the crystallization behavior of the wood flour. Whereas, composites made with Eastern redcedar and Osage orange showed significantly lower water absorption and better mildew resistance compared to others. Migneault et al. (2014) observed a positive correlation between the intensity of surface-oxidized carbon (attributed to carbohydrates) on the surface of lignocellulosic fibers and the strength of WPC, and that the cellulose content of lignocellulosic fibers was correlated with bending modulus of elastic, bending modulus of rupture, and water absorption, while the correlation with the impact strength was not significant. Therefore, in general, the performance of WPC prepared with bark section fibers was poorer than that of WPC prepared with xylem section fibers of the same species (Alothman et al. 2020). Bouafif et al. (2009) found that increasing fiber size could improve the strength and stiffness of WPC, but it decreases their elongation and fracture energy, and compared to the influence of fiber origin and content, fiber size had a minimal effect on water absorption. Furthermore, research has indicated that high content of hydrophilic or lipophilic extractives in wood, such as rubberwood and pine wood, may affect the interfacial bonding properties between the fibers and plastic matrix, which in turn affects the mechanical properties and mildew resistance of WPC (Wang et al. 2020, Chen et al. 2014).

Masson pine, Chinese fir, and cypress are important afforestation species in southern China, with areas of 8 million hm^2, 14 million hm^2, and 1.45 million hm^2 respectively, which represent 3.6%, 6.3%, and 0.6% of the total forest area in China (Jian et al. 2021, Xiang et al. 2022, Jin 2013). Bamboo is the fastest-growing plant on earth, and at present, China ranks first in the world in terms of bamboo forest area and stock volume. According to the report (Gao et al. 2024), the bamboo forest area in China has reached 7.56 million hm^2. These forest resources generate a large amount of waste such as wood chips during felling and processing. In this paper, focusing on the effective utilization of forest waste resources, seven different types of lignocellulosic fibers including xylem and bark fibers from Masson pine, Chinese fir, and cypress, as well as Moso bamboo fibers were selected to reinforce PE. The various lignocellulosic fiber/PE composite were fabricated by hot press molding method. The surface properties, including surface free energy and chemical element composition of the different lignocellulosic fibers were analyzed. Additionally, the physical, mechanical, and anti-mildew properties of the prepared WPC were assessed. These analyses are intended to provide a theoretical basis for the preparation of high-performance WPC, which are important for expanding the application scope of lignocellulosic biomass waste, improving the utilization of wood resources, and conservation forest resources.

MATERIAL AND METHODS

Materials

The xylem and bark of three coniferous wood species (Masson pine, Chinese fir, and cypress) and bamboo processing residues were collected from Guizhou Yuanhai Timber Processing Factory and Guizhou Xinjin Bamboo & Wood Products Co. Ltd. These materials were crushed into powders using a multipurpose pulverizer (Yongkang Boou Hardware Products Co., Ltd., 800-Y). The resulting powders was then passed through a vibrating sieve shaker (Shaoxing Shangyu District Daoxu Yuezhou Geotechnical Instrument Factory, 8411) to obtain particles of 20-80 mesh size. Polyethylene (PE-600, 100-150 mesh) was purchased from Suyuan Plastic Material Mall in Zhangmutou Town, Dongguan City. The compatibilizer of maleic anhydride grafted polyethylene (MAPE) with a grafting rate of 8%, was purchased from Shanghai Macklin Biochemical Technology Co., Ltd. In addition, the freeze-dried strain of *Aspergillus brasiliensis* (Production No. ATCC 16404) was acquired from the Microbiology Analysis and Testing Center of the Guangdong Academy of Sciences.

The preparation of WPC

Seven different types of lignocellulosic fiber, including Masson pine fiber (MP), Chinese fir fiber (CP), cypress wood fiber (CW), Masson pine bark (MB), Chinese fir bark (CB), cypress wood bark (CWB), and Moso bamboo fiber (BF), were dried to absolute dry state at 80°C in a blast oven. Lignocellulosic fiber, PE, and MAPE were weighed and thoroughly mixed in a mass ratio of 40:56:4. The resulting mixture was then placed into a homemade mold with dimensions of 220×220×4 mm and subsequently transferred to a flat vulcanizing machine (Yangzhou Zhengyi Experimental Machine Co., Ltd., XLB-100). The hot pressing was conducted at a temperature of 180°C for 8 min under a pressure ranging from 5 to 7 MPa. To prevent the mixture from adhering to the plates, a polytetrafluoroethylene film was used. After the hot pressing process, the panels were allowed to cool naturally in the mold for 12 h. The designed density of WPC was set as 1.0 g/cm^3.

Surface free energy testing of lignocellulosic fibers

A small amount of lignocellulosic fibers was taken and pressed into flakes of uniform thickness at a pressure of 20-40 MPa using a powder tablet press machine for 2 min, and the contact angles of different lignocellulosic fibers were determined by a contact angle meter (Chengde City Jinhe Instrument Manufacturing Co., Ltd., JC2000A) with distilled water and ethylene glycol as the test liquids, respectively. The surface free energies were calculated according to Eqs. 1 and 2:

$$\gamma_1(1+\cos\theta) = 2\sqrt{\gamma_s^p \gamma_1^p} + 2\sqrt{\gamma_s^d \gamma_1^d} \quad (1)$$

$$\gamma_w = \gamma_s^p + \gamma_s^d \quad (2)$$

where: γ_1 - the surface energy of the test liquid, θ - the contact angle between the fiber and the test liquid, $\gamma^p{}_s$ - the polar surface energy component of the fiber, $\gamma^p{}_l$ - the polar surface energy component of the test liquid, $\gamma^d{}_s$ - the dispersion surface energy component of the fiber, $\gamma^d{}_l$ - the dispersion surface energy component of the test liquid, and γ_w - the surface free energy of the fiber.

Surface elemental analysis of wood fibers

The surface elemental (C, O) composition of lignocellulosic fibers was analyzed using an X-ray photoelectron spectrometer (Thermo Fisher, K-Alpha, USA).

Physical and mechanical properties testing of composites

In accordance with GB/T 17657-2013, the water absorption rate and thickness swelling of the WPC was assessed in an artificial climate chamber maintained at 20□ and 70% relative humidity over a 24 h period. The specimen size was 20×20×4 mm, and each test included six replicates. According to GB/T 9341-2008, the bending tests of WPC were carried out on an electronic universal testing machine (Xiamen Yi Shi Te Instrument Co., Ltd., LGS20K). The specimens' size was 80×13×4 mm, the span was 64 mm, and the bending speed was 1.9 mm/min. Six replicates were tested for each specimen type. With reference to GB/T 1043-2008, Charpy impact test was carried out on specimens sized 80×10×4 mm. The test utilized a pendulum energy of 7.5 J an impact speed of 3.8 m/s, and a span of 60 mm.

Anti-mildew property test of composites

Aspergillus niger was used to assess the mildew resistance of WPC according to GB/T 18261-2013. Specimens measuring 50×20×4 mm were inoculated and placed in a constant temperature and humidity chamber (Ningbo Jiangnan Instrument Factory, RXZ), and incubated at 28°C and 85% humidity for 28 days. The area of mold infection on the surface of the specimen was observed and the damage value of the sample was recorded (Tab. 1).

Tab. 1: Damage values of WPC.

Damage values	Area of mold on the surface of the specimen
0	＜5%
1	＜1/4
2	[1/4-1/2)
3	[1/2-3/4]
4	＞3/4

RESULTS AND DISCUSSION

Surface free energy analysis of the lignocellulosic fibers

Surface free energy, including its polar and dispersion components, is a fundamental thermodynamic property of solid surface. These properties have a great influence on the surface wettability, antibacterial properties, adsorption, and adhesion characteristics of materials (He et al. 2019, Martha et al. 2020). The surface free energy primarily reflects intermolecular forces and is intrinsically related to the wettability of solid surface. The wettability of wood fibers can be effectively characterized by determining their surface free energy and its respective components. Typically, the surface free energy is obtained by measuring the contact angle (θ) of fibers with liquids of different polarities (Li et al. 2014, Naum et al. 2021).

To analyze the surface polarity of the different lignocellulosic fibers, distilled water and ethylene glycol were used as probe liquids to measure their contact angles on the surfaces of various lignocellulosic fiber. These contact angles data were then used to calculate the polarity and dispersion component as well as the overall surface free energies. The results were summarized in *Tab. 2*.

Tab. 2: Surface contact angle and surface free energy of different lignocellulosic fibers.

Sample types	Lignocellulosic fiber						
	MP	CP	CW	MB	CB	CWB	BF
Contact angle of distilled water/ °	59.00 	61.00 	54.50 	65.00 	65.50 	69.50 	53.00 
Contact angle of ethylene glycol/ °	31.50 	33.00 	30.00 	40.00 	32.50 	33.50 	37.00 
Surface free energy/mJ·m^{-2}	42.66	41.52	45.53	38.22	41.07	40.32	47.36
Polarity component/mJ·m^{-2}	23.97	21.67	30.48	19.67	15.00	11.29	37.99
Dispersion component/mJ·m^{-2}	18.69	19.83	15.05	18.56	26.07	29.03	9.37

The data indicated that for the same species, the contact angle with distilled water was larger than that with ethylene glycol, suggesting that the fibers were more prone to infiltration by ethylene glycol. It was also found that the xylem fibers of all three species had a higher polarity component than the bark fibers. This difference likely stems from a higher carbohydrates content in xylem fibers, enhancing their hydrophilicity (Bouafif et al. 2008). Moreover, free energy measurements results showed that among the three types of xylem fibers, fir fiber showed the highest dispersion component at 19.83 mJ/m², followed by Masson pine and cypress. Among the seven different types of lignocellulosic fibers, Moso bamboo displayed the lowest dispersion component at 9.37 mJ/m², indicating the best hydrophilicity and the highest polar component at 37.99 mJ/m².

Elemental analysis of different lignocellulosic fibers surface

X-ray photoelectron spectroscopy (XPS) can qualitatively analyze the elemental composition, molecular structure, and chemical state of material surfaces. This study analyzed the relative contents of the two main elements, carbon (C) and oxygen (O), as well as the differences in the valence states of carbon on the surfaces of different lignocellulosic fiber. The wide-scan XPS spectra are presented in Fig. 1, and the corresponding elemental contents and oxygen-to-carbon (O/C) ratios are summarized Tab. 3. The O/C ratio is an initial indicator of surface oxidation and usually an indicator of lignin content (Johansson et al. 2004). Among the fibers analyzed, Moso bamboo had the highest O/C ratio at 45.86%. followed by Masson pine wood fiber, fir wood fiber, and cypress wood fiber, with O/C ratios of 41.64%, 35.87%, and 32.43%, respectively. These ratios were 19.39%, 8.50%, and 6.44% higher than those of their respective bark fibers, indicating that the O/C ratios of xylem fibers were higher than those of barks fibers. This finding aligns with research finding that bark fiber contained relatively high lignin and extractive contents but low cellulose content (Mohammad et al. 2020).

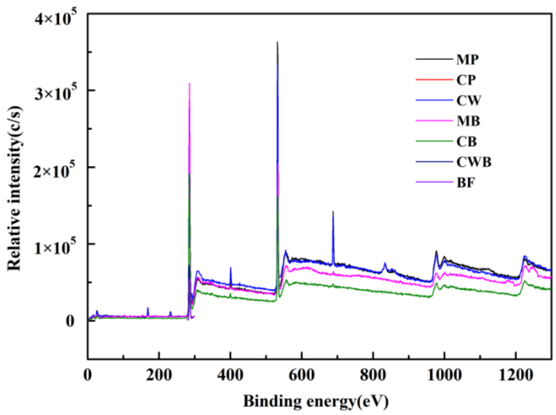


Fig. 1. XPS wide scan spectra of different types of lignocellulosic fiber surfaces.

Tab. 3. Elemental C and O content and O/C ratio values of different lignocellulosic fibers.

Sample types	C1s (%)	O1s (%)	O/C (%)
MP	29.40	70.60	41.64
CP	26.40	73.60	35.87
CW	24.49	75.51	32.43
MB	18.20	81.80	22.25
CB	21.49	78.51	27.37
CWB	20.61	79.39	25.96

BF	31.44	68.56	45.86

The C1s signal can be typically decomposed into four components (C1, C2, C3, and C4) based on the degree of oxidation (Fig. 2). These components provide insights into the chemical environment surrounding the carbon atoms in lignocellulosic fiber, thus providing valuable information for understanding their chemical structure. Among them, C_1 represents carbon atoms bonded to C and H atoms (*e.g.*, -C-H, -C-C), which are mainly from lignin, fatty acids, and fats. C_2 corresponds to carbon atoms bonded to one oxygen atoms (*e.g.*, -C-O-), which originates from cellulose, as well as the hydroxyl and ether bonds in lignin. C3, which represents a higher oxidation state, includes structures such as -O-C-O-O- or C=O, typically arising from oxidized chemical components on the lignocellulosic surface. C_4 (*e.g.*, -O-C=C-) represents organic acid within lignocellulosic fiber with the highest oxidation state but is present in minimal amounts (Gustafsson et al. 2003, Watts and Goacher 2022). Previous literature (Abdelwahab et al. 2021) indicated a positive correlation between the O/C ratio and the mechanical properties of WPC, such as flexural strength, elongation at break, and impact energy. Higher O/C ratio signified a higher proportion of carbohydrates on the surface of fiber, which not only enhances the strength of fiber, but also provides a greater number of available polar sites (e.g. OH), which can lead to stronger esterification reaction with the compatibilizer MAPE. The peak-fitted C1s spectra of different lignocellulosic fibers were analyzed using XPS analysis software, and the results are presented in Fig. 2 and Tab. 4. Among the seven lignocellulosic fibers, bamboo fiber exhibited the lowest content of C1 and C4, but the highest of C2 and C3. In addition, bark fibers of the three tree species showed higher C1 and C4 content, and lower C2 and C3 content compared to xylem fibers, indicating that bark fibers contain more lignin and extractives and less carbohydrates compared to xylem fibers.

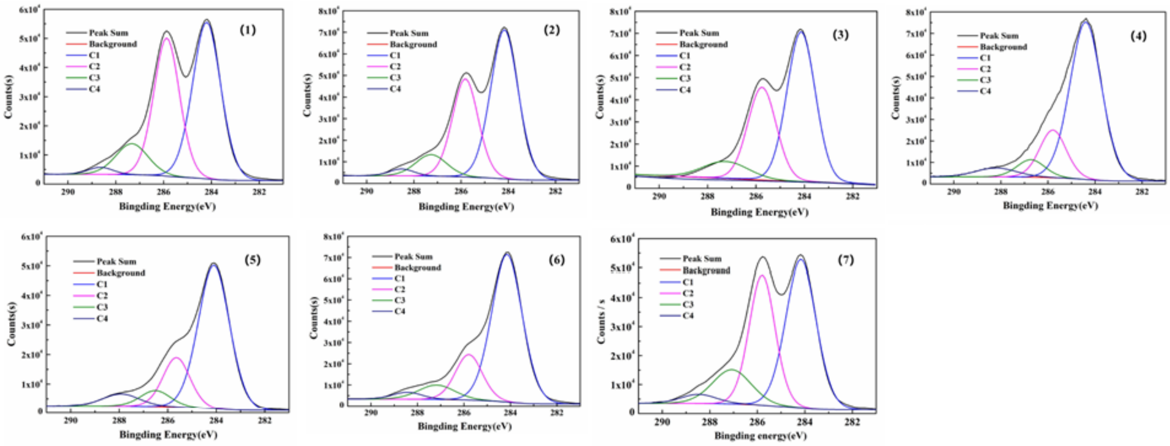


Fig. 2. C1s XPS spectra of lignocellulosic fiber surfaces, (1) MP, (2) CP, (3) CW, (4) MB, (5) CB, (6) CWB, (7) BF.

Tab. 4: Percentage of carbon in different chemical states for lignocellulosic fibers.

Sample types	Peak position/eV				Relative content/%			
	C1	C2	C3	C4	C1	C2	C3	C4
MP	284.20	285.87	287.33	288.64	48.30	38.90	10.91	1.89
CP	284.17	285.82	287.27	288.52	54.87	33.95	8.93	2.25
CW	284.14	285.75	287.25	289.25	53.29	33.04	9.57	4.10
MB	284.40	285.79	286.73	288.21	70.05	17.87	6.92	5.15

CB	284.10	285.64	286.51	287.92	66.33	19.86	7.18	6.63
CWB	284.15	285.79	287.18	288.44	69.77	19.00	7.09	4.14
BF	284.16	285.80	287.07	288.47	45.04	37.51	14.02	3.43

Water resistance of different lignocellulosic fiber/PE

Water absorption is one of the key factors in assessing the quality of composites. The water-absorption nature of WPC primarily relies on the ability of its surface groups to engage in hydrogen bonding with water molecules and the number of pores in the composite.

The 24 h water absorption and thickness swelling of seven different lignocellulosic fiber/PE composites are presented in Fig. 3. As can be seen, the composites made of Moso bamboo fiber/PE showed the lowest 24 h water absorption rate (1.83%) and thickness swelling rate (1.42%), signifying superior water resistance. Additionally, WPC derived from bark fibers had lower water absorption rates (ranging from 1.61% to 2.15%) and thickness swelling (ranging from 1.28% to 3.05%) compared to those made from xylem fibers, which is in line with the results of a previous study that the bark confers composites with better water resistance (Avci et al. 2018, Pokhrel et al. 2021). Combined with the analysis of the surface polarity and elements of different lignocellulosic fibers, the excellent water resistance of WPC made from xylem fiber may be attributed to the high proportion of hydrophobic substances such as lignin and extractives, and a low proportion of hydrophilic substances like hemicellulose and cellulose in the bark fibers (Vercher et al. 2020).

The contact angles and surface free energy of the seven lignocellulosic fiber/PE composites are presented in Tab. 5. As can be observed, Moso bamboo fiber/PE composites showed the highest contact angle values for both distilled water and ethylene glycol (85° and 70°, respectively) and the lowest surface free energy (22.03 mJ·m^{-2}). Additionally, the surface free energies of the bark fiber/PE composites (23.40 mJ·m^{-2}, 22.72 mJ·m^{-2}, and 22.38 mJ·m^{-2}, respectively) were lower than those of their corresponding xylem fiber/PE composites, which is line with the trend observed in water absorption and thickness swelling.

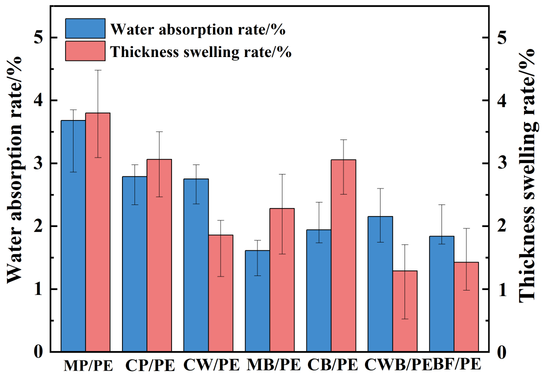


Fig. 3: 24 h water absorption and the thickness swelling *of lignocellulosic fiber/PE composites.*

Tab. 5. Contact angle and surface free energy of lignocellulosic fiber/PE composites.

Sample types	Contact angle of distilled water/°		Contact angle of ethylene glycol/°		Dispersion component/ mJ·m^{-2}	Polarity component/ mJ·m^{-2}	Surface free energy/ mJ·m^{-2}
MP/PE	80.00		68.67		6.85	18.24	25.09
CP/PE	83.33		68.33		9.88	13.20	23.09
CW/PE	83.33		67.00		11.15	12.29	23.44

MB/PE	83.17	[redacted]	67.33	[redacted]	10.67	12.73	23.40
CB/PE	84.50	[redacted]	68.17	[redacted]	11.13	11.59	22.72
CWB/PE	85.17	[redacted]	68.67	[redacted]	11.28	11.09	22.38
BF/PE	85.00	[redacted]	70.00	[redacted]	9.85	12.18	22.03

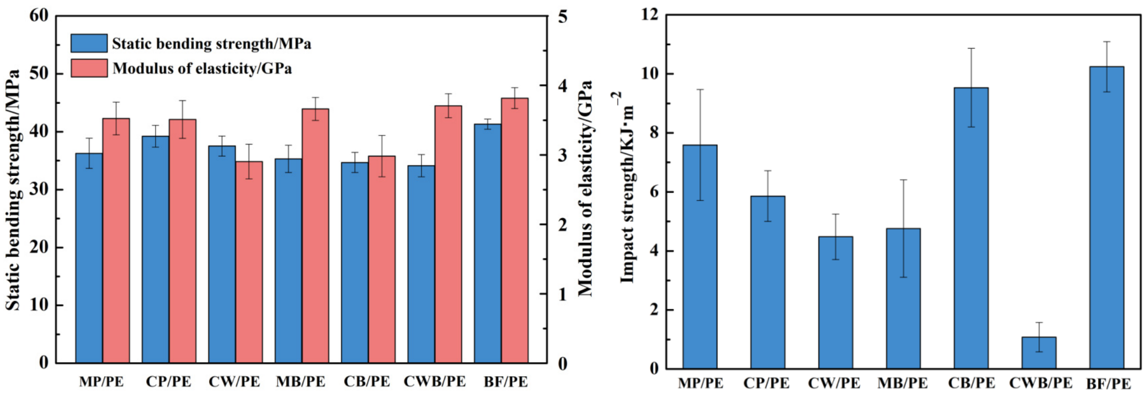
Mechanical properties of different lignocellulosic fiber/PE

Flexural properties

The static bending strength and modulus of elasticity of the WPC prepared from different lignocellulosic fibers are illustrated in Fig. 4a. It was observed that under the same hot-pressing conditions, composites made by Moso bamboo fibers exhibited superior static bending strength and modulus of elasticity, at 41.31 MPa and 3.82 GPa, respectively.

Within the same tree species, composites prepared from xylem fibers consistently exhibited higher static bending strength compared to those prepared from bark fibers. This discrepancy primarily arises from several factors related to the surface polarity and elements composition of the lignocellulosic fibers. Firstly, the total surface free energy of xylem fibers was higher than that of bark fibers from the same species (Lopez et al. 2022). Secondly, xylem fibers had a higher oxygen-carbon ratio than bark fiber, which facilitated the formation of ester bonds between lignocellulosic fibers and the compatibilizer MAPE. These two factors collectively improve the interfacial compatibility between the xylem fibers and PE 17(Hu et al. 2022), thereby improving interfacial bonding, reducing stress concentration within the composites, minimizing defect occurrence, and improving resistance to external stresses (Jian et al. 2022). Additionally, studies had shown that the inherent strength of bark fibers is lower than that of xylem fibers, which is another reason for the difference in static bending strength (Yemele et al. 2010).

The figure also reveals that composites made from bark fibers tended to have a higher modulus of elasticity compared to those made from xylem fibers within the same tree species. Adhikary et al. (2011) suggested a notable positive correlation between the extractives content of lignocellulosic fiber and their modulus of elasticity. Elemental analysis of the lignocellulosic fiber surfaces revealed that bark fibers contain higher levels of C1 and C4 compared to xylem fibers, suggesting that higher extractive content in bark fibers contributes to higher modulus of elasticity of the composites.



a) *b)*

Fig. 4: a) Static bending strength and modulus of elasticity, b) impact strength of lignocellulosic fiber/PE composites.

Impact performance

Impact strength is the amount of energy absorbed by the material per unit area when subjected to impact force until fracture. It serves as a mechanical strength indicator used to assess the impact capability of materials, or to determine their brittleness and toughness (Effah et al. 2018). Generally, higher energy absorption indicates greater material toughness. The impact properties of composites prepared from different lignocellulosic fibers were analyzed, and the results are presented in Fig. 4b. It is evident that the composites made of Moso bamboo exhibited the best impact performance, with an impact strength value of 10.24 kJ/m². Following this, in descending order, were composite made from fir xylem fibers, cypress xylem fibers, Masson pine xylem fibers, fir bark fiber, cypress bark fibers, and Masson pine bark fiber. This ranking generally aligns with trends observed in static bending strength. The interfacial bonding strength between the lignocellulosic fiber and the matrix resin is a crucial factor affecting the impact strength of the composites. Preferable interfacial bonding facilitates effective dispersion of external stress throughout the matrix and transfers some stress to the lignocellulosic fibers (Chaudhari et al. 2018). The inferior impact performance of composites made from Masson pine xylem and bark fibers might be due to the presence of rosin and other extractives, which weaken the interfacial adhesion between the fibers and PE resin.

Anti-mildew properties of different lignocellulosic fiber/PE

The mold resistance of lignocellulosic fibers from different tree species, along with their interfacial bonding properties with the plastic matrices, significantly influences the anti-mildew characteristics of WPCs composed of these fibers. To assess the anti-mold performance of various lignocellulosic fiber/PE composites, samples were incubated in *Aspergillus niger* culture medium for 4 weeks and subsequently examined. The visual appearance and damage value levels are shown in Fig. 5 and Fig. 6.

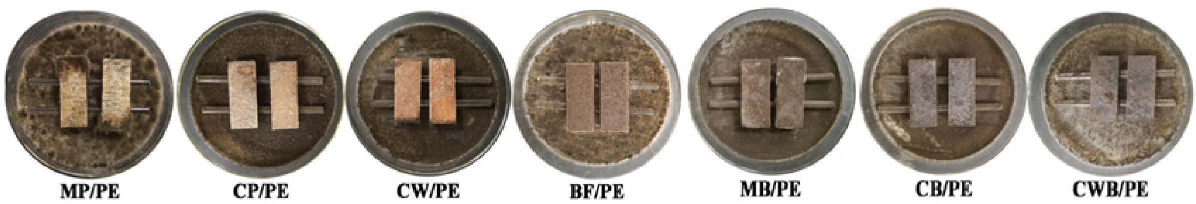


Fig. 5: Effect diagram of anti-mold for lignocellulosic fiber/PE composites.

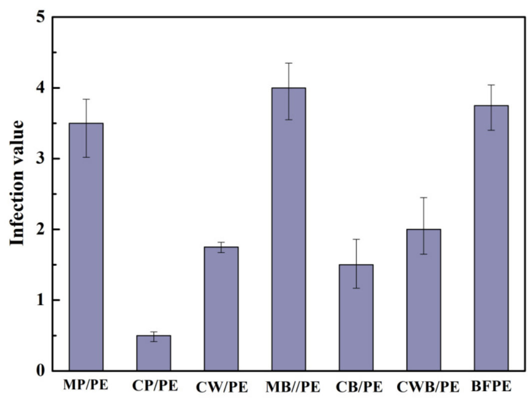


Fig. 6: Damage values of lignocellulosic fiber/PE composites.

Overall, discrepancy was noted in the anti-mold effects of composites prepared from different fibers, primarily due to variations in the proportions of cellulose, hemicellulose, and lignin in the fibers, as well as differences in the compositions of inclusions, which affected the susceptibility to *Aspergillus niger*. Observations showed varying degrees of fungal invasion on the surfaces of the seven different lignocellulosic fiber/PE composites. Among these, the composite made from Masson pine bark fiber showed the most severe susceptibility to *Aspergillus niger*, with a damage value of 4. In contrast, composites prepared from fir xylem fibers exhibited the lowest susceptibility to mold, with a damage value of 0.5, indicating superior anti-mildew properties. Following closely were composites made from fir bark fibers, with a damage value of 1.5. This enhanced resistance in fir-derived composites could be attributed to specific extractives present in fir xylem and bark, such as 8-propoxycedrane, manool, and α-cedrene, which have been shown to enhance the biological durability of the biomass (Xu et al. 2015). The study suggested that composites made from xylem fibers of the three investigated tree species generally displayed better mildew resistance compared to those made from bark fibers. This difference may be due to the higher sugar and protein content in bark fibers, rendering them more prone to mold growth (Feng and Zhao 2022).

CONCLUSIONS

(1) The polarity of xylem fibers in Masson pine, fir and cypress was found to be higher than that of the bark fibers from the same species. The O/C ratios of the bark fibers were lower than those of the xylem fibers, indicating that bark fibers contained relatively high levels of lignin and extractives. *(2)* The 24 h water absorption and thickness swelling of bark fiber/PE composites were lower than those of xylem fiber/PE composites for these tree species. Among the seven types of lignocellulosic fibers studied, bamboo fiber/PE composites showed the best water resistance, with water absorption rate of 1.838% and thickness swelling rate of 1.427%. *(3)* Under the same hot-pressing conditions, the xylem fiber/PE composites from the three tree species exhibited higher static bending and impact strengths than those made from xylem fiber. Whereas, the modulus of elasticity was generally higher in bark fiber/PE composites. WPC prepared from bamboo fibers demonstrated the highest static bending strength (41.31 MPa), modulus of elasticity (3.82 GPa), and impact strength (10.24 kJ/m^2). *(4)* The mildew resistance of xylem fiber/PE composites from the three species was generally better than that of bark fiber/PE composites. Specifically, the fir xylem fiber/PE composite was virtually unaffected by *Aspergillus niger*, with a damage value of 0.50, representing excellent mildew resistance.

ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (32160413 and 32060324), the Natural Science Foundation of Guizhou Province (No. Qiankehe ZK [2022] General 067, ZK [2021] General 161), the International Joint Research Center for Biomass Materials, (Southwest Forestry University) (2023-GH06), and the 111 Project (D21027), Guizhou Provincial Department of Human Resources and Social Security high-level talent innovation and entrepreneurship project (2022-06).

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