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RESEARCH ARTICLE

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Forming performance and environmental impact of bamboo fiber reinforced polypropylene composites based on injection molding process for automobiles

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Abstract

To explore the potential application of plant fiber reinforced composites for automotive component applications, this study prepared bamboo fiber (BF)/nano-talc/polypropylene (PP) composites based on the injection molding process, comprehensively evaluated the effect of reinforcement materials on the forming properties of composites, including thermal performance, mechanical properties, water absorption, etc. Furthermore, taking a certain automotive injection molded interior part as the object, a life-cycle assessment from production to the gate was conducted based on the real energy and material consumption during the composite preparation process. The results indicate that adding BF and talc powder increased the thermal stability, density, hardness, viscosity, and crystallinity of the composites while reducing the water contact angle on the surface. Surface-modified BF and PP showed good compatibility. Talc powder exhibited good dispersibility in PP, and the synergistic effect of BF and talc powder effectively enhanced the composite performance. The tensile, flexural, and impact strength of the composites were improved by 40.64%, 51.48%, and 66.51%, respectively, compared with pure PP. The modulus of the composite increased nearly 2 times compared with pure PP. Additionally, the composite demonstrated good friction and wear properties. The environmental impact of the BF composite manufacturing process was significantly higher than that of pure PP. The substantial consumption of electricity, chemicals, and water resources in the extraction and modification processes of BF were the main factors. The findings of this study contribute to achieving green, high-performance BF composite manufacturing and the expansion of its applications.

Highlights

- Composites have a higher environmental impact compared to PP.
- BF and talc can synergistically enhance the performance of composites.
- BF shows good compatibility with PP.
- Composites exhibit good friction and wear characteristics.

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KEYWORDS
bamboo fiber, injection molding, life cycle assessment, molding performance, nano-talcum

1 | INTRODUCTION

Fiber-reinforced composites, due to their low density, high ductility, and high strength have been widely used in the design and manufacturing of automotive components, such as carbon fibers and glass fibers.[1,2] However, they possess significant drawbacks, including high cost and lack of environmental friendliness. Currently, environmental degradation and resource depletion have become critical challenges affecting human development, with green and sustainable development being vital for the advancement and future of human civilization.[3] Nations worldwide have increased their commitment to environmental protection, enacting laws and regulations to constrain industrial production practices. Compared to synthetic fibers, plant fibers are lower in density, nontoxic, and biodegradable, making their application in manufacturing industries a means to effectively reduce environmental harm.[4,5] Consequently, plant fiber-reinforced composites exhibit notable environmental, economic, and social benefits.[6] Due to the excellent material properties of plant fiber-reinforced composites, their industrial application potential is high, with a trend towards gradually replacing traditional materials. Renowned automotive manufacturers such as Audi, Daimler-Benz, Ford, Volvo, and Toyota are increasingly incorporating plant fiber-reinforced composites in their vehicles, further expanding the market for these materials.[5,7–10]

Among the various plant fibers, bamboo fiber (BF) has significant development potential. Bamboo in nature grows rapidly, has a short growth cycle, and produces high-strength fibers, making it highly suitable as a reinforcement phase in composites.[11] China, with the richest bamboo resources globally, leads in bamboo species, area, and volume, with bamboo forests exceeding 7.01 million hectares, establishing China as a pioneer in the global bamboo industry.[12]

Among the various molding methods for BF-reinforced composites, injection molding, due to its process flexibility, high efficiency, and adaptability to product shapes, helps further expand the application range of composites.[13] To achieve BF-reinforced composites with desirable mechanical properties, surface treatment of BFs is usually performed before injection molding to form strong adhesion at the heterogeneous interface between BFs and the matrix, enhancing load transfer efficiency from the matrix to adjacent fibers.[12,14–16] Surface treatments for fibers are categorized into physical and chemical methods. Chemical methods are cost-effective and efficient, making them the most commonly used. The choice of chemical method depends on the type of fiber and matrix combination.[17] Reports suggest that combined chemical treatments often yield better results than single methods.[9] Generally, alkali treatment is the most common chemical method due to its simplicity and effectiveness in improving the interface bonding between the matrix and the plant fibers.[6] Alkali treatment reduces hydrophilic hydroxyl groups, removes impurities from the fiber surface, decreases fiber diameter, increases fiber aspect ratio and surface roughness, and improves thermal stability and adhesion with the matrix.[7,18] Additionally, maleic anhydride coupling agents form carbon–carbon bonds with the matrix and react with hydroxyl groups, coating long-chain polymers on the fiber surface to reduce hydrophilicity. By bridging fibers and the matrix, they form an effective interlock.[19,20] The combined treatment of alkali and maleic anhydride effectively improves the interfacial adhesion and enhances the molding performance of the composites.[21]

In polymer matrices, using plant fibers as the sole reinforcement phase often does not achieve satisfactory reinforcement effects. In automotive component manufacturing, inorganic particles are commonly used to reinforce polymer matrices. Compared to BFs, micro/nanostructures with smaller sizes provide a larger specific surface area for interactions with the matrix, resulting in better interactions. The uniform distribution of reinforcing particles effectively suppresses dislocation movements within the composites, hindering deformation behavior. The addition of particle-reinforced materials affects the thermal stability, melting point, crystallinity, mechanical performance, and mobility of polymers. Studies indicate that introducing a small amount of nanoparticle reinforcement into plant fiber composites enhances the required properties without affecting the composite's density.[7] Researchers typically use micro/nanoparticles and plant fibers together as reinforcements, resulting in excellent interface interactions, allowing loads to transfer fully from the matrix to the reinforcements, significantly enhancing composite performance.[22–24] Compared to PP composites reinforced solely by plant fibers, adding appropriate amounts and types of nanoparticles results in lower water absorption, higher strength, and modulus.[25,26] Nano-talc, with its good thermal stability and reinforcing effects, is abundant in nature, low in production cost, and widely used in industrial applications (e.g., transportation, construction). Blending nano-talc with BFs can effectively enhance the thermal stability

and mechanical performance of composites, warranting a more comprehensive evaluation.

As carbon-negative materials, plant fibers are often considered to have environmental advantages. Under the global carbon neutrality context, the application of plant fiber-reinforced composites in industry is regarded as an effective carbon reduction measure. However, the environmental impact of plant fiber composites is still controversial considering the large energy consumption during the extraction and pretreatment of plant fibers. Studies have found that plant fiber composites exhibit higher resource consumption and environmental impact compared to pure PP.[27] However, for flax short fiber composites and banana fiber composites, the life-cycle carbon dioxide emissions gradually decrease as the plant fiber content increases.[28,29] Life cycle assessment (LCA) can help analyze the environmental impact of products, aiding in achieving economic, social, and environmental balance, and promoting a sustainable future. There is still a huge research gap on the environmental impact of plant fiber-reinforced composite components for automotive use during the manufacturing process.

To explore the potential application of BF-reinforced composites in automotive components, this study prepared BF/nano-talc/ polypropylene (PP) composites based on injection molding, comprehensively evaluating the influence of reinforcement materials on the molding properties of composites, including thermal properties, mechanical properties, and water absorption. Particularly, friction and wear characteristics, water absorption, and other crucial features affecting the application of composites in bearings, seals, and other industrial fields, which were often overlooked by researchers, were also considered. Furthermore, we conducted a cradle-to-gate life cycle assessment based on actual energy and material consumption during composite preparation, targeting an automotive injection-molded interior part. The findings of this study contribute to achieving green, high-performance BF composite manufacturing and the expansion of its applications.

2 | MATERIALS AND METHODS

2.1 | Materials

BFs extracted from bamboo were supplied by Sichuan Bamboo Silk New Material Technology Co., Ltd (Yibin, China). PP (HP500N) was purchased from LyondellBasell Industries NV (Hoofddorp, Netherlands). Alkali and acetic acid were supplied by Hubei Zhongshui Chemical Co., Ltd (Wuhan, China). Maleic anhydride grafted polypropylene was purchased from Beijing Petrochemical Group Co., Ltd (Beijing, China). Nano-talc was obtained from Shanghai Haofu Chemical Co., Ltd (Shanghai, China).

2.2 | Preparation of the composites

BFs were surface-treated using a 5 wt % NaOH solution at room temperature for 2 h. After treatment, the fibers were sequentially washed with running water and 1 wt% acetic acid solution, followed by another rinse with running water until a neutral pH was achieved to remove impurities from the fiber surface. The surface-modified BFs were air-dried and then oven-dried at 100°C for 4 h to remove residual moisture. The BFs were then ground into 200-micron powder for later use. According to the experimental plan, different ratios of PP and additives were blended, extruded, pelletized, and finally injection-molded. The temperature of the die head of the twin-screw extruder (SHJ-20, Nanjing Giant Machinery Co., Ltd. (Nanjing, China)) was set to 185°C, and the temperatures in zones I-IV were set to 190, 190, 190, and 190°C, respectively. For the twin-screw injection molding machine (HDX50, Ningbo Haida Plastic Machinery Co., Ltd. (Ningbo, China)), the temperatures in zones I-IV were set to 180, 190, 190, and 180°C, respectively. As shown in Figure 1, eight groups were set up in this experiment: pure PP, different contents (10–40 wt%) of BFs, and various contents (3–9 wt%) of talc at a BF content of 30 wt%. Except for pure PP, all other experimental groups included 6 wt% maleic anhydride grafted polypropylene (MAPP). The compositions used in this study are shown in Table 1. Additionally, Figure 1 illustrates the LCA model system boundary for a specific automotive door interior panel established according to LCA standards. This system reflects the resource and environmental impacts of producing an automotive door interior panel made from BF-reinforced composites from "cradle" to "gate." The process includes BF extraction and surface treatment, raw material blending, and composite forming. Specifically, for BF preparation, including harvesting, transport, extraction, chemical treatment, drying, and grinding, and for composite preparation, including blending, extrusion, pelletizing, drying, and injection molding, considering both material and energy consumption.

2.3 | Characterization of the composites

2.3.1 | Physical properties

Hardness

Measured using a Shore D hardness tester (HV-1010A, Laizhou Huayin Testing Instrument Co., Ltd. (Yantai, China)), with an indentation distance of 5 mm.

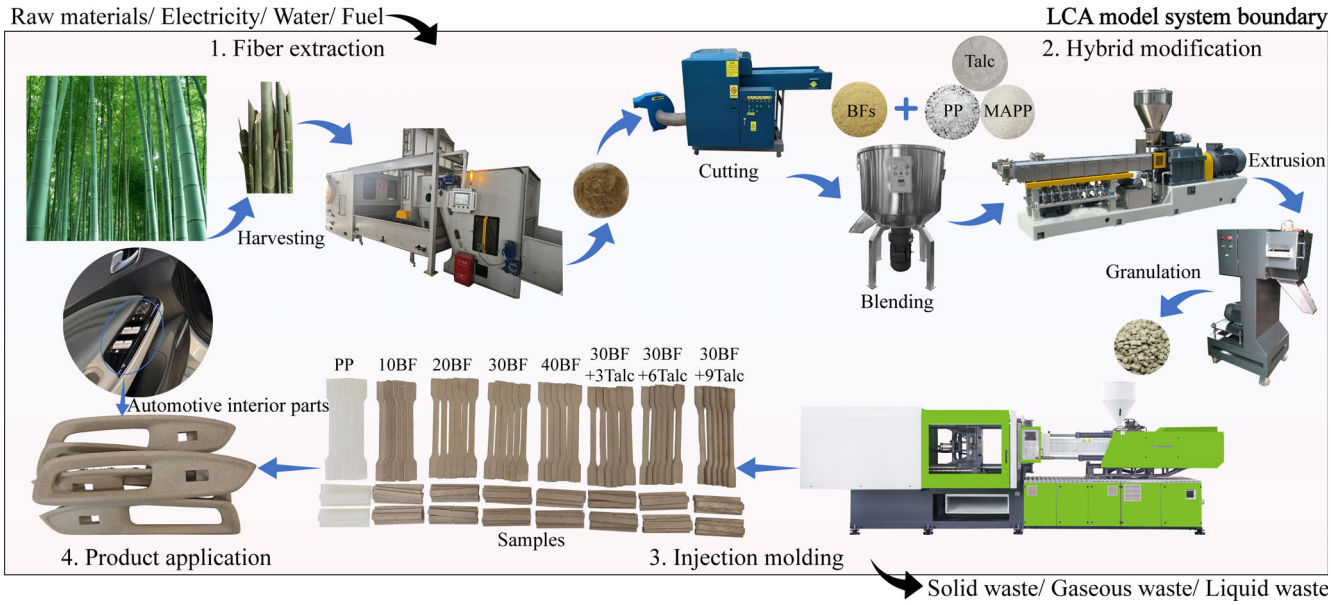

FIGURE 1 Preparation process of the composites and system boundary of the LCA model.

TABLE 1 Compositions used in this research.

Composition	PP (wt %)	BFs (wt %)	MAPP (wt %)	Talc (wt %)
PP	100	-	-	-
10BF	84	10	6	-
20BF	74	20	6	-
30BF	64	30	6	-
40BF	54	40	6	-
30BF+3Talc	61	30	6	3
30BF+6Talc	58	30	6	6
30BF+9Talc	55	30	6	9

The average value from six measurements at room temperature was recorded. The test standard was GB/T 3398.

Density

Measured using an electronic balance (FA2240B, Techcomp Co., Ltd. (Hong Kong, China)) at room temperature. The average value from six measurements was recorded.

Melt flow index (MFI)

Measured using an MFI tester (MFI-1211, JJ-TEST Materials Testing Industry Co., Ltd. (Chengde, China)) at 230°C with a load of 2.16 kg, using a sample interval of 60s. The average value from six tests was recorded. The test standard was GB/T 3682.

X-ray diffraction (XRD)

Tested using an x-ray diffractometer (SmartLab, Rigaku Co., Ltd. (Tokyo, Japan)) with a voltage of 40 kV and a current of 100 mA. The scanning range for 2θ diffraction peaks was 5°–30° with a scanning rate of 5°/min.

Water contact angle (WCA)

Measured the static water contact angle on the composite surface using a water contact angle tester (OCA20, DataPhysics Instruments GmbH (Filderstadt, Germany)) and averaged over 4 tests. The water droplet volume was 3 μL.

Differential scanning calorimetry (DSC)

Tested using a differential scanning calorimeter (DSC 214, NETZSCH Instruments Manufacturing GmbH (Selb, Germany)) with heating and cooling rates of 20°C/min and 10°C/min, respectively, holding the peak temperature of 230°C for 5 min.

2.3.2 | Mechanical properties

Testing was performed at room temperature using friction and wear tester (HT-1000, Lanzhou Zhongke Kaihua Technology Co., Ltd. (Lanzhou, China)) under dry sliding conditions. The tests were conducted with a load of 15 N,

a sliding radius of 5 mm, a rotational speed of 700 r/min, and a test duration of 10 min. The test standard was GB/T 10006.

The tensile, flexural, and impact tests were conducted at room temperature with six replicates for each sample to obtain an average value and the test standards were ISO 527-1, ISO 178, and ISO 180, respectively. Tensile and flexural tests were performed using a universal testing machine (CMT6104, Meister Industrial Systems (China) Co., Ltd. (Shanghai, China)). The tensile and flexural rates were set at 50 mm/min and 2 mm/min, respectively. Impact tests were conducted with an Izod impact tester (XJUD-5.5, Chengde Jinjian Testing Instruments Co., Ltd. (Chengde, China)), with an impact energy of 2.75 J.

2.3.3 | Micromorphology

Samples were immersed in liquid nitrogen for 10 min for low-temperature fracture treatment, then sputter-coated with platinum to enhance conductivity. Scanning electron microscopy (JSM-IT300, Nippon Electron Co., Ltd. (Tokyo, Japan)) images were taken at an accelerating voltage of 10 kV. The test area was located in the middle of the standard specimen.

2.3.4 | Life cycle assessment

For the injection molding process of a specific Chinese automotive interior part with a functional unit of 1 kg, an LCA was conducted based on ISO 14040 to evaluate resource and environmental impacts from cradle to gate. The LCA model was established using Simapro 9.0, with evaluation methods ReCiPe 2016 and IPCC (GWP 100a). The LCA assessment scenarios were consistent with the eight experimental groups shown in Figure 1. The evaluation results were normalized to cover carbon emissions and impacts on water, air, and soil. Further sensitivity analysis quantified the impact of significant variables on the results. Data reliability was crucial for the evaluation's value.[31] Background data for the analysis were sourced from the Ecoinvent database embedded in Simapro and the China Life Cycle Database (CLCD). Foreground data came from the actual material and energy consumption in our experiments, publicly available data from local government reports and research papers, and data obtained through collaboration with equipment and raw material suppliers. For energy consumption, adjustments were made to reflect the actual development conditions in various regions of China, ensuring that the analysis data closely matched actual production conditions. Additionally, considering the complex working conditions during the injection molding stage, this paper referenced our group's previous research on the application of digital twin technology[27] and the standardization of injection molding energy consumption.[30]

3 | RESULT AND DISCUSSION

3.1 | Physical properties

The density and hardness of composites depend on the relative hardness and density of their components. Figure 2A illustrates the effect of fiber and talc content on the density of the composites. The density of the composite increases with the addition of fiber and talc, indicating that the inclusion of BF does not result in a lightweight polymer. At a fiber content of 40 wt%, the density of the composite reaches its maximum, showing a 13.33% increase compared to pure PP. Additionally, a minor amount of talc has a negligible effect on the density of the composite. Similarly, as the content of BF and talc increases, the hardness of the composite also gradually increases, achieving a maximum improvement of 41.39%, as shown in Figure 2B. This suggests that both BF and talc are harder than PP, with talc contributing more significantly to the hardness even at minimal concentrations. The greater the hardness and density of the composite, the higher the molecular mass it typically indicates, resulting in increased viscosity when in a molten state. As shown in Figure 2C, the MFI of the composite is inversely proportional to the content of the reinforcing phase (BF and talc). With 30 wt% BF and 9 wt% talc, the MFI of the composite is only 38.83% of that of PP. The main reasons for the reduction in the MFI of the composite are the interactions between the internal reinforcement phases of the polymer and the obstruction of polymer chain movement by the reinforcement phase. As the content of fiber and talc increases, their collisions and the friction at the interfaces during the melting process intensify, leading to an increase in composite viscosity, resulting in higher shear stress during the molding of the composite. However, the addition of a minimal amount of talc (3 wt%) has a negligible effect on the MFI of the composite. This may be because the nanoscale talc fills the micro-gaps between fiber and resin, without significantly hindering its melt flow behavior.

Moisture absorption is one of the major limitations of plant fiber-reinforced composites.[8] Figure 2D shows the effect of BF and talc content on the static WCA on the surface of the composite. With the increase of fiber content, the surface WCA of the composite decreases gradually. As the fiber content is less than 20 wt%, the decrease is relatively small, but it begins to decrease rapidly when the fiber content exceeds 20 wt%. However, the WCA is still above

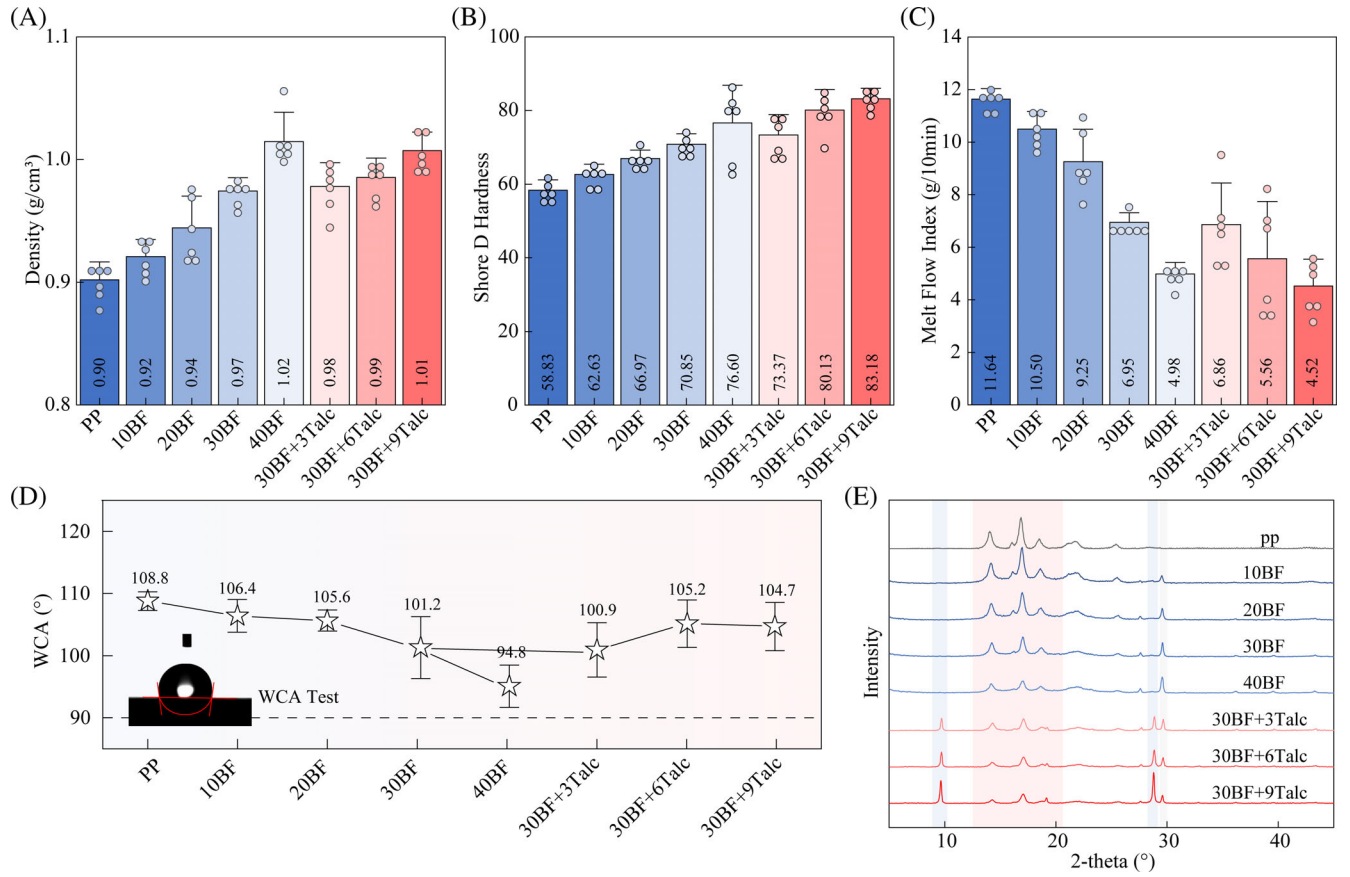

FIGURE 2 Effects of BF and talc content on the composite's density (A), hardness (B), melt index (C), surface water contact angle (D), and XRD spectra (E).

90°, indicating the hydrophobicity of the composite, which is mainly due to the surface modification of the fibers. When plant fiber is added to the polymer, the likelihood of it being exposed to the surface of the composite increases with its content. On one hand, this exposes more hydrophilic groups on the composite surface, increasing the material's affinity for water molecules. On the other hand, it enhances the roughness and surface energy of the composite, promoting easier spreading of water on its surface, thereby reducing the surface WCA. With the addition of talc, the surface WCA of the composite gradually increases. In minimal amounts, these fillers can fill the voids between the matrix and fiber, reducing the chance of fiber exposure on the surface and lowering the water absorption of the composite.[9] As the talc content further increases, it affects not only the surface roughness but also alters the surface chemistry, imparting its inherent hydrophobicity to the composite, ultimately increasing the surface WCA.

The XRD spectra of the composites are shown in Figure 2E. When BF and talc are added, new diffraction peaks appear at 9.7°, 28.8°, and 29.6°. The diffraction peaks at 9.7° and 28.8° correspond to the characteristic crystal structures of magnesium silicate minerals in talc at these angles, and their intensity increases with increasing talc content. The diffraction peak at 29.6° is attributed to crystalline cellulose in BF. The dispersion of talc in the matrix partially obscures the crystalline cellulose, causing the intensity of the 29.6° diffraction peak in the XRD spectra to decrease with increasing talc content. Pure PP exhibits diffraction peaks between 14° and 22°, with the peaks at 14.1°, 16.9°, 18.6°, and 21.8° corresponding to the (110), (040), (130), and (140) crystal planes of the α-crystal type, respectively. With adding BF and talc, these diffraction peaks gradually decrease and slightly shift towards higher angles. The primary reason is that the addition of fillers causes disturbance in the crystalline structure of pp, altering the spacing between crystal planes and resulting in the shift of diffraction peak angles. Fillers may act as heterogeneous nucleating agents, modifying the crystallization process of PP, potentially leading to the formation of new crystal defects or a reduction in crystal size, thereby affecting the position and intensity of the diffraction peaks.[31] In addition, as the content of BF and Nano-talc increases, the content of PP decreases, further leading to a decrease in the intensity of the diffraction peaks.

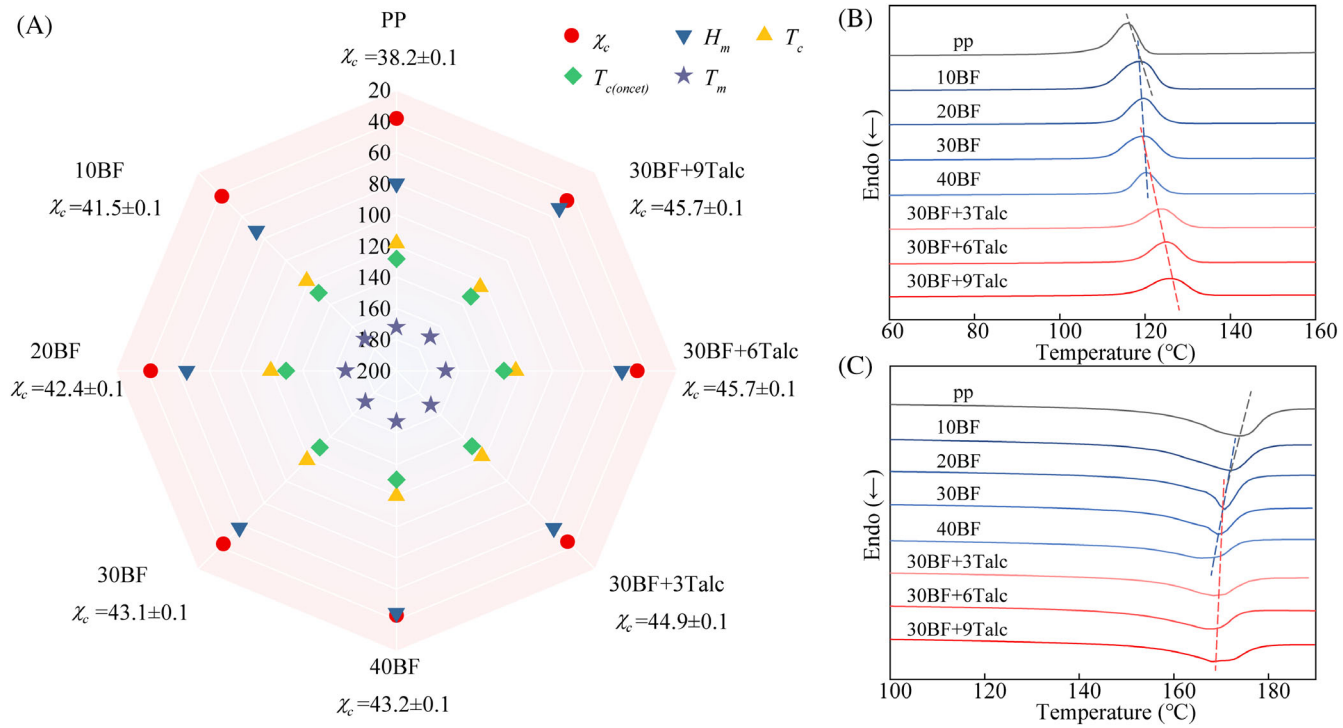

FIGURE 3 Effects of BF and talc content on the thermal properties of the composite: (A) DSC data, (B) crystallization temperature curves, (C) melting temperature curves.

Figure 3 illustrates the influence of BF and talc content on the thermal properties of the composites. The addition of BFs and talc significantly enhances the crystallinity (X_c) of PP, showing an increasing trend with the higher filler content. These fillers act as heterogeneous nucleating agents, providing more nucleation sites for the crystallization of PP molecules, which accelerates the crystallization process and reduces the required crystallization time. The crystallization temperature (T_c) and onset crystallization temperature ($T_{c(onset)}$) of PP are 118.3 and 122.3°C, respectively. With the addition of fibers and talc, these temperatures increase, with the crystallization temperature and onset crystallization temperature of the composites ranging from 118.6 to 124.2°C and 126.4 to 132.6°C, respectively. This indicates that the addition of BFs enhances the thermal stability of the composites. Similarly, fibers from durian peel,[32] rice straw,[33] flax,[18] and wood[22] have also shown positive effects on the thermal stability of polymers. As the reinforcement content in the composites increases, the proportion of PP significantly decreases, leading to a substantial reduction in the melting enthalpy (H_m) values. The melting temperatures (T_m) of the composites are lower than that of PP (172.1°C), ranging between 167.5 and 171.8°C. The fillers affect the heat transfer within the composites and the uniformity of the internal structure, resulting in an overall influence on the melting behavior and promoting melting at lower temperatures.

3.2 | Mechanical properties

The effect of BF and talc content on the mechanical performance of the composites is shown in Figure 4. When the fiber content is 30 wt% and 40 wt%, the composites achieve the best tensile and flexural strength, with values of 38.13 MPa and 68.4 MPa, respectively, representing increases of 14.95% and 42.92% compared with pure PP. The addition of BFs to PP forms a good interfacial bond, effectively transferring stress and thus enhancing the tensile and flexural strength of the composites, as shown in Figure 4C. Related studies have also shown that the mechanical properties of the composites are best when the plant fiber content is 20–30 wt%.[34,35] Adding talc further improves the tensile and flexural strength, achieving optimal results at a small content (3 wt%), with improvements of 40.64% and 51.48%, respectively, compared to pure PP. This is mainly due to the good compatibility of talc with PP, which fills the voids in the composites, increasing material density and mechanical properties. Adding fillers significantly enhances the tensile and flexural modulus of the composites, primarily because both talc and BFs have high rigidity and modulus.

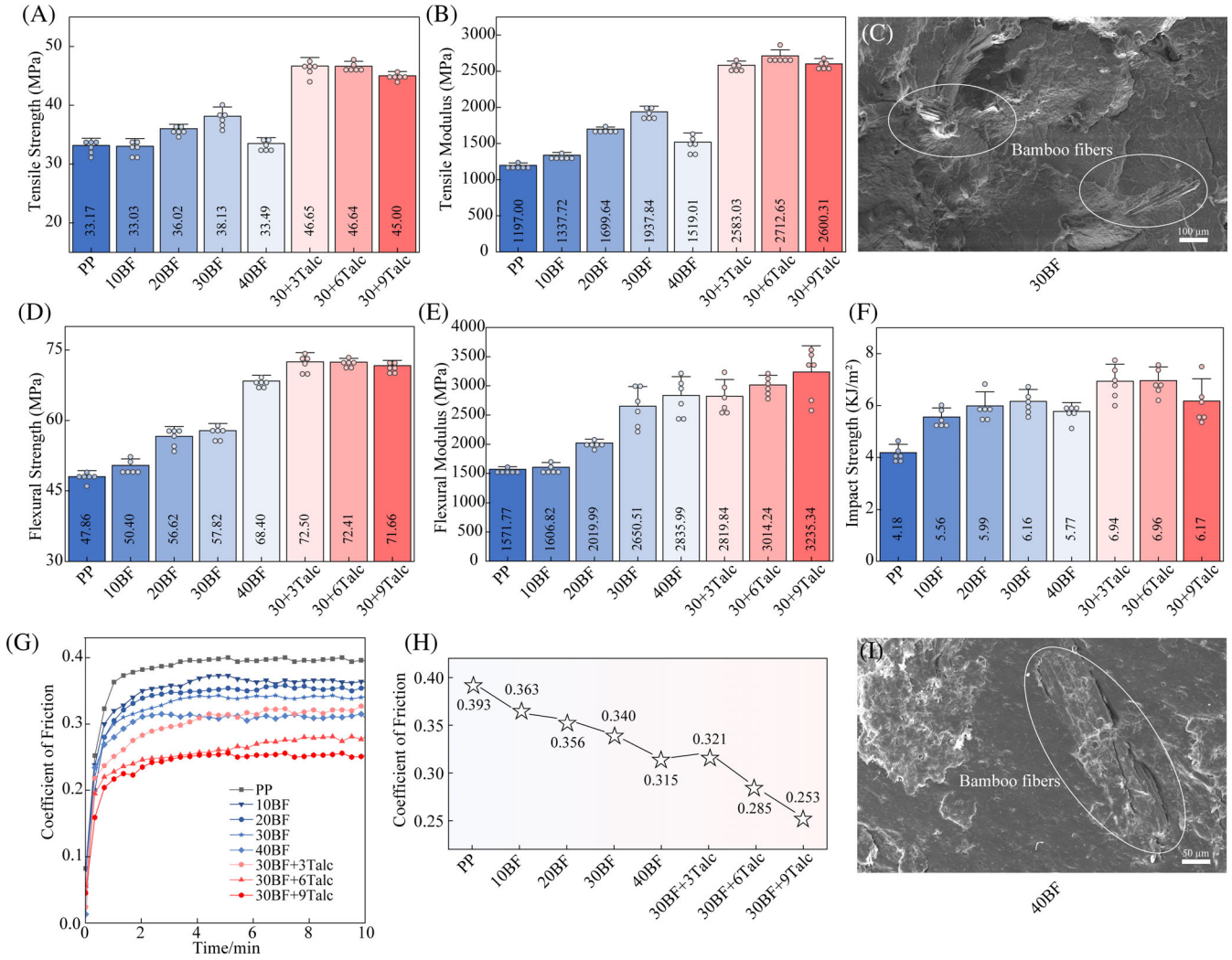

FIGURE 4 Effects of BF and talc content on the mechanical performance of the composite: (A) tensile strength, (B) tensile modulus, (C) impact fracture morphology, (D) flexural strength, (E) flexural modulus, (F) impact strength, (G) friction coefficient versus time curves, (H) friction coefficient, (I) wear surface morphology.

When compounded with PP, they significantly improve the rigidity and modulus of the composites. At a BF content of 30 wt%, the impact strength of the composites is 6.16, representing an increase of 47.37% compared to PP. However, when the fiber content exceeds 30 wt%, the impact strength slightly decreases due to poor interfacial bonding between fibers, which leads to stress concentration areas and reduces impact strength. Adding talc does not significantly enhance the impact strength of the composites, mainly because the filler content has already reached a high level, and the composites exhibit high rigidity and evident brittle fracture behavior. As the filler content increases, the coefficient of friction of the composites gradually decreases, with the composite containing 40 wt% BF having the lowest coefficient of friction at 0.315, a maximum reduction of 19.85%. The addition of talc further reduces the coefficient of friction, with a maximum reduction of 35.62%. This is mainly due to the poor thermal conductivity of the fillers, which weakens the thermal effect during the friction process. Additionally, the presence of fillers prevents excessive wear of PP during friction. Microscopic images of the surface (Figure 4I) show that the wear debris of fillers fills the microcracks formed during surface friction, Improving the friction and wear characteristics of the composites.[36,37]

3.3 | Micromorphology

The microstructure of the composites with different filler contents is shown in Figure 5. As the BF content increases, the amount of exposed fibers in the composite cross-section gradually increases. Fibers the role of the skeleton in molded composites, enhancing the ability of the composites to resist external forces. However, increased fiber content also intensifies interactions between fibers,

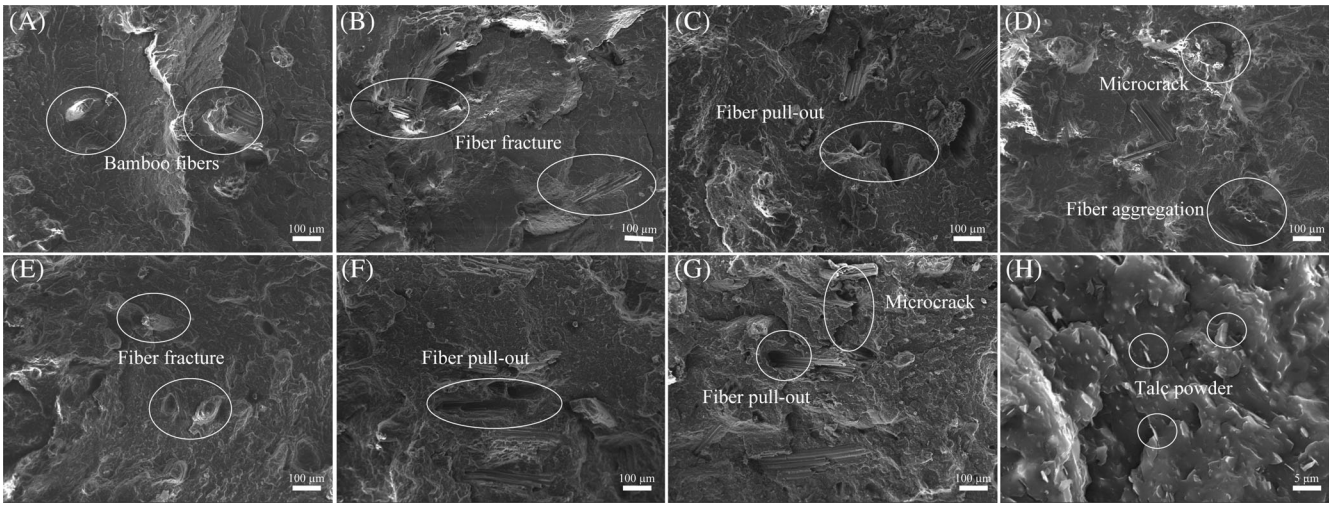

FIGURE 5 Microstructure of the composites: (A) 10 wt% BF, (B) 20 wt% BF, (C) 30 wt% BF, (D) 40 wt% BF, (E) 30 wt% BF and 3 wt% talc, (F) 30 wt% BF and 6 wt% talc, (G) 30 wt% BF and 9 wt% talc, (H) distribution of talc.

making it difficult to uniformly disperse them within the composites. In this study, microcracks and fiber agglomeration phenomena appear when the fiber content exceeds 30 wt%, making it difficult to achieve uniform filling during the molding process and maintain structural integrity under higher loads. The damage modes of BFs mainly include fiber fracture and fiber pull-out, with fiber fracture being predominant. Fiber pull-out mainly occurs in fiber aggregation areas, significantly damaging the molding performance of the composites. Talc can be uniformly dispersed within PP, effectively filling areas lacking fibers and microvoids in the matrix, preventing fiber agglomeration and forming a more uniform composite microstructure. This uniform distribution helps reduce stress concentration, lowering the likelihood of crack formation. This indicates that BFs and talc have a synergistic effect, forming a more uniform and stable microstructure within the composites. This improvement enhances the mechanical properties while reducing the negative impact of fiber damage on material performance during molding. Additionally, by reasonably controlling the content of BFs and talc, an optimal balance between mechanical properties and molding processes can be achieved.

3.4 | LCA analysis

Figure 6A–C presents the environmental toxicity analysis during the manufacturing process of BF-reinforced composites. The terrestrial ecosystem toxicity is significantly higher than that of freshwater and marine ecosystems. The environmental toxicity of the composites gradually increases with increasing BF content and is significantly higher than that of pure PP. Adding talcum powder does not cause any noticeable change in the environmental impact of the composites, indicating that trace amounts of talcum powder have a similar effect on the environment as PP. The main factors influencing environmental toxicity include electricity, petroleum, water resources, and the use of chemical reagents. Among these, extensive use of water has the greatest impact on terrestrial eco-toxicity, while the use of electricity and chemical reagents predominantly influences the toxicity to freshwater and marine environments. Figure 6D,E illustrate the effects of the composites on the ozone formation potential and terrestrial acidification of the terrestrial ecosystems. As fibers are added, the amount of PP used gradually decreases, thus reducing its environmental impact. The heavy use of electricity remains the main factor causing environmental harm, followed by petroleum, water, chemical reagents, and PP. Particularly for terrestrial acidification, electricity accounts for nearly 40 wt% of the impact. Preventing eutrophication of water bodies is essential for water resource protection. The study assessed the influence of phosphorus and nitrogen content in the manufacturing process of the composites on freshwater eutrophication, as shown in Figure 6F. The primary factors contributing to environmental impact remain the usage of chemical reagents, electricity, and water. Similarly, the increased addition of plant fibers raises the risk of water pollution. The concept of eco-carbon emphasizes achieving a balance between ecology and carbon in socio-economic development to minimize negative environmental impacts. Within the current international context of carbon neutrality, this has become a crucial concept in the manufacturing process of automotive components. Figure 6G evaluates the carbon emissions during the manufacturing process of composites with different raw materials, where the area of the circles represents the significance of each factor.

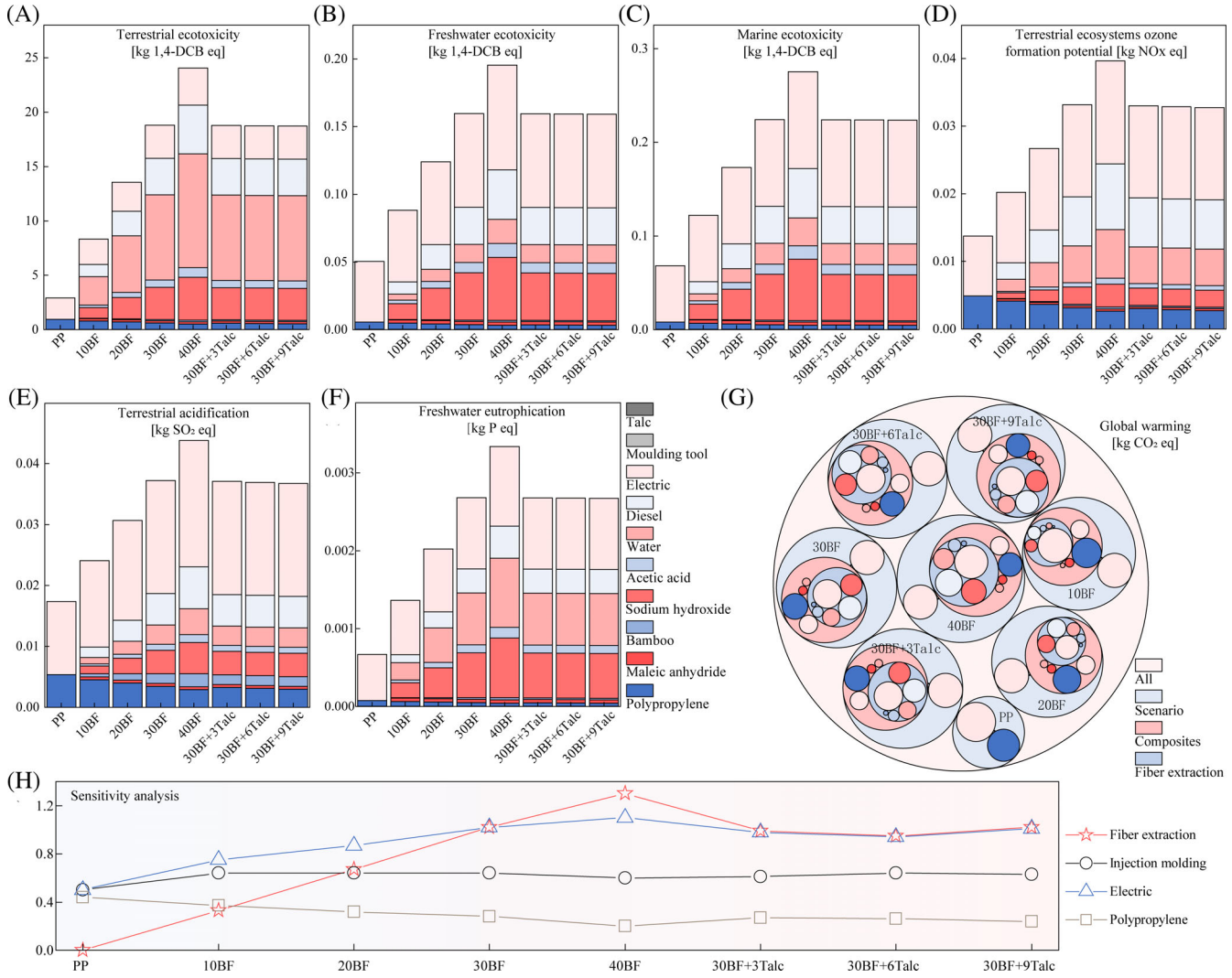

FIGURE 6 Environmental impact of composites made from different raw materials: (A) terrestrial ecotoxicity, (B) freshwater ecotoxicity, (C) marine ecotoxicity, (D) terrestrial ecosystem ozone formation potential, (E) terrestrial acidification, (F) freshwater eutrophication, (G) global warming (carbon emissions), (H) sensitivity analysis.

The carbon emissions are lowest in the forming process of pure PP and highest in the forming process of 40 wt% BF composites. The extraction of BF and the consumption of electricity are the primary contributors to carbon emissions. Carbon emissions from the injection molding process are similar across different raw materials. Furthermore, this study assessed the sensitivity of several key factors—such as fiber extraction, injection process, and the usage of electricity and PP—on the carbon emissions during the manufacturing process of the composites, to validate the accuracy of the evaluation model. By increasing or decreasing these factors by 10% and calculating the differences, where a difference close to 0 indicates lower sensitivity, results are shown in Figure 6H. With increasing plant fiber content, the sensitivity of fiber extraction to carbon emissions during the composite forming process gradually increases. Additionally, electricity remains a major factor. When the plant fiber content is below 30 wt%, electricity shows the highest sensitivity. Over 30 wt%, fiber extraction becomes more sensitive, while at exactly 30 wt%, both factors exhibit similar sensitivity. Hence, it can be concluded that electricity and fiber extraction processes significantly contribute to the increase in carbon emissions during the manufacturing of composites and are major factors causing environmental harm, consistent with the findings illustrated in Figure 6A–G.

In summary, the significant environmental impact observed during the manufacturing of BF composites, compared with PP, is primarily owing to the substantial consumption of electricity, chemical reagents, and water resources during the fiber extraction and modification processes.[38] Therefore, developing efficient fiber extraction techniques and clean fiber modification methods are future challenges to address. Additionally, replacing traditional

thermal power with cleaner energy sources like wind, hydro, solar, and nuclear power to optimize the energy structure is crucial for environmental protection. This shift towards clean energy is also the primary reason for China's accelerated transition to cleaner energy sources.

4 | CONCLUSION

To explore the potential application of BF composites in automotive parts, this study prepared BF/nano talc/PP composites based on injection molding technology and comprehensively evaluated the forming performance and environmental impact of the composites. The main findings are summarized as follows:

The addition of BF and talc powder increased the thermal stability, density, hardness, viscosity, and crystallinity of the composites while reducing the surface water contact angle.

Surface-modified BFs showed good compatibility with PP. Talc powder exhibited good dispersion within the PP matrix, effectively limiting the formation of microcracks.

The synergistic effect of BF and talc powder significantly improved the composite performance. The tensile, flexural, and impact strengths of the composites increased by 40.64%, 51.48%, and 66.51% respectively, compared to pure PP. Owing to the high rigidity and modulus of talc powder and BFs, the modulus of the prepared composites was nearly doubled compared to pure PP. Additionally, the inclusion of fillers endowed the composites with excellent friction and wear properties, which is beneficial for expanding the application range of the composites.

The environmental impact of the manufacturing process for BF composites is significantly higher than that for PP. The main factors are the large amounts of electricity, chemical reagents, and water resources consumed during the extraction and modification of BFs. Developing cleaner fiber modification methods and clean energy sources are future challenges that need to be addressed.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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