Eco-Friendly Polypropylene Composite Reinforced with Natural Fillers: Mechanical Properties and Wear Resistance

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Abstract. Natural composite materials are gaining interest due to their low cost, recyclability, and availability. This study examines hemp-polypropylene (HPP) composites, where polypropylene (PP) is reinforced with 30 wt.% short hemp fibers (HF). The composites were produced via melt compounding using a twin-screw extruder, followed by injection molding. To improve adhesion between hydrophilic hemp fibers and the non-polar PP matrix, polypropylene-graft-maleic anhydride (PP-g-MA) was used as a coupling agent. Structural and mechanical properties were assessed using SEM, FTIR, tensile, and scratch tests. Results revealed a significant improvement in fiber-matrix adhesion with the use of PP-g-MA, demonstrating enhanced interfacial bonding. The hemp fibers were uniformly dispersed within the PP matrix, resulting in a dense and homogeneous composite structure. Mechanically, the addition of 30 wt.% HF markedly increased the stiffness and tensile properties of the composites. The Young's modulus and tensile strength of the HPP composites reached 3804 MPa and 28.07 MPa, respectively, compared to 1523 MPa and 22.98 MPa for neat PP. Scratch testing further supported these findings, showing a notable reduction in penetration depth upon the inclusion of hemp fibers. This study highlights the potential of hemp-reinforced polypropylene composites as a sustainable alternative in applications requiring enhanced mechanical performance.

Keywords: Hemp fillers, polypropelene, Composites, Mechanical Properties, Wear

1 Introduction

The increasing recognition of environmental sustainability and the limitations of synthetic materials have catalyzed a growing interest in natural fiber-reinforced polymer composites [1]. These materials provide several advantages, including a reduced environmental impact, cost-effectiveness, and ease of recycling. Among these composites, polypropylene (PP) stands out as one of the most widely used thermoplastic polymers due to its excellent chemical resistance, affordability, and lightweight characteristics [2]. However, to meet the demands of advanced applications, enhancements in mechanical and wear performance are often necessary. This enhancement can be achieved through the incorporation of natural fillers such as hemp fibers(HF).

Natural fibers, sourced from renewable resources, offer unique benefits as reinforcements, including biodegradability, low density, and favorable mechanical properties [3]. Composites made from polypropylene and natural fibers, such as flax, and wood fibers, exhibit improved mechanical properties compared to pure polypropylene. These composites are often referred to as biocomposites, which combine biodegradable or renewable materials with synthetic polymers to enhance sustainability and performance. Hemp fibers are particularly notable for their high tensile strength, stiffness, and availability [4]. Nevertheless, a significant challenge remains in the incompatibility between hydrophilic lignocellulosic fibers and the hydrophobic PP matrix, often resulting in weak interfacial bonding and poor load transfer [5]. To address this issue, coupling agents like polypropylene-graft-maleic anhydride (PP-g-MA) are frequently employed to improve fiber-matrix adhesion by facilitating chemical interactions [6]. Previous research has highlighted the potential applications of natural fiber-reinforced composites across various sectors, including automotive, construction, and consumer goods, where enhanced mechanical performance and wear resistance are crucial [7-9]. These composites also play a significant role in reducing dependence on non-renewable resources while minimizing environmental pollution. Despite this promising outlook, thorough evaluations of mechanical properties, structural integrity, and wear behavior are essential to confirm their practical viability and optimize performance. This study investigates eco-friendly hemp-polypropylene (HPP) composites, focusing on the effects of incorporating 30 wt.% hemp fibers and the influence of the PP-g-MA coupling agent on their structural, mechanical, and wear properties. Advanced characterization techniques, including scanning electron microscopy (SEM), tensile testing, and scratch testing, are employed to elucidate the structure-property relationships of these composites. The findings aim to advance the development of sustainable, high-performance materials suitable for various industrial applications.

2 Materials and Methods

Hemp fibers were employed as reinforcing agents in this study, while virgin polypropylene (PP), blended with a PP-g-MA (polypropylene-grafted-maleic anhydride) compatibilizing agent, served as the matrix material. The incorporation of PP-g-MA was essential to enhance interfacial adhesion between the hydrophilic hemp fibers and the hydrophobic PP matrix, thereby improving the composite's overall properties. The fabrication process began with the precise mixing of hemp fibers and PP pellets, along with the PP-g-MA compatibilizing agent (figure1). This mixture was fed into an extruder, where it underwent a controlled process of heating, mechanical mixing, and extrusion to create a homogeneous composite material. During extrusion, the combined effects of heat and shear ensured uniform dispersion of the fibers and improved bonding within the matrix. Once extruded, the composite material was cooled and pelletized into small, manageable pellets, ensuring ease of handling and consistent material quality. These pellets were then processed in an injection molding machine, where they were reheated and injected into molds to produce test specimens with specific shapes and dimensions.

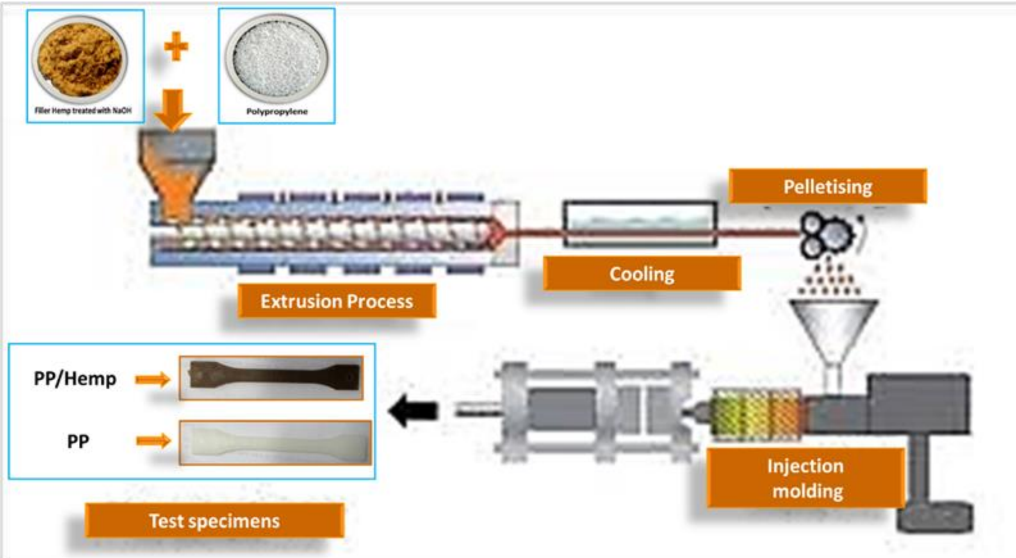

Fig. 1. Schematic illustration of Manufacturing Process of Polypropylene/Hemp Composite test Specimens

This standardized manufacturing approach facilitated the production of high-quality PP/hemp composite specimens, optimized for rigorous testing and detailed evaluation of their mechanical properties.

- The tensile tests were conducted on type 5A dumbbell-shaped specimens molded from the studied materials, in accordance with ISO 527-2 standards.
- The wear behavior of the fabricated composite was also investigated under constant loads of 1, 2, and 3 N through scratch tests equipped with a Rockwell HRC indenter featuring a 120° cone angle and a tip radius of 200 µm. This technique has shown efficiency in the study of wear in our previous work [10-12].
- The FTIR analysis was performed on the samples at room temperature using a Nicolet 560 spectrophotometer equipped with a diamond ATR accessory. The spectral range covered was 4000 to 400 cm^{-1}.

3. Results

3.1. Structural properties of of PP and PP/HEMP composites

Figure 2a presents the FT-IR spectra of PP, hemp, and PP/hemp composites. The FT-IR spectra of the PP/hemp composites show that the structural integrity of the PP matrix is retained, as all the characteristic vibrational bands associated with PP are still present in the composite spectra. Additionally, the spectra of the PP/hemp composites exhibit characteristic stretching vibration bands associated with cellulose and hemicellulose, centered at 3100, 2935, and 2862 cm^{-1}, corresponding to the stretching vibrations of CH and CH_2 groups. Peaks at 1735 cm^{-1} and 1425 cm^{-1}, typical of the carboxylic functions of pectins, are also observed. However, a slight reduction in intensity and a shift to lower frequencies of these bands compared to the pure hemp spectra suggest an interaction between the polymer and the fibers, facilitated by the presence of the compatibilizing agent PP-g-MA.

The SEM analysis provides crucial insights into the microstructural differences between pure polypropene (PP) and the PP/Hemp composite. In Figure 2b, the surface of the pure PP appears relatively smooth and homogeneous, with minimal textural features, reflecting the typical structure of an unreinforced polymer. In contrast, Figures 2c and 2c' reveal the morphology of the PP/Hemp composite, highlighting a heterogeneous distribution of hemp fibers within the polymer matrix. The zoomed-in image (Figure 2c') shows a more detailed view of the interfacial regions, where fibers appear embedded within the PP matrix, suggesting good mechanical interlocking and partial adhesion between the two phases. The presence of surface irregularities and fiber pull-outs indicates localized interfacial debonding, which could impact mechanical properties. Overall, the SEM micrographs demonstrate the significant influence of hemp reinforcement on the composite's structural characteristics, potentially enhancing its strength and toughness while introducing defects that may require further optimization.

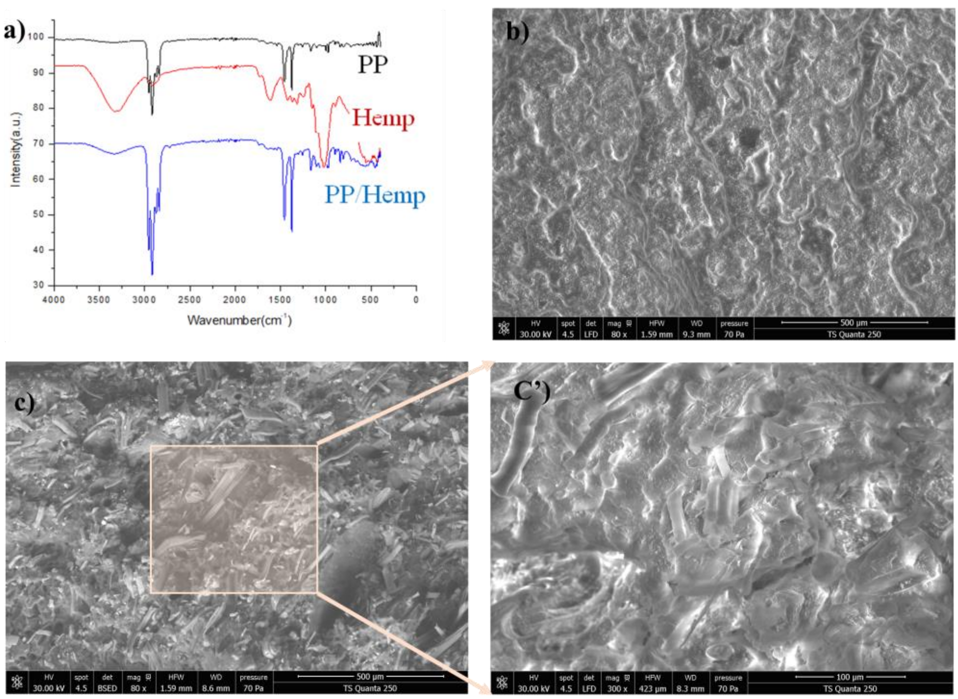

Fig. 2. FTIR spectra (a) and SEM of the b) PP and c,c' of PP/HEMP composites

3.2. Mechanical properties

Figure 3 presents the tensile test results for neat polypropylene (PP) and polypropylene reinforced with 30% short hemp fibers (PP/Hemp). The stress-strain curves reveal a significant enhancement in the mechanical properties of the reinforced composite. This improvement is evidenced by a marked increase in both the elastic modulus (stiffness) and tensile strength compared to pure PP.

The curves demonstrate that PP/Hemp composites exhibit improved toughness, reflected in extended strain and greater stress absorption before failure. This enhancement indicates better energy dissipation due to the reinforcement provided by the fibers. Specifically, the addition of hemp fibers results in a significant increase in the elastic modulus from 1523 MPa to 3804 MPa, indicating a considerable improvement in stiffness. Simultaneously, the tensile strength increases from 22.98 MPa to 28.07 MPa, demonstrating an enhanced capacity to bear loads.

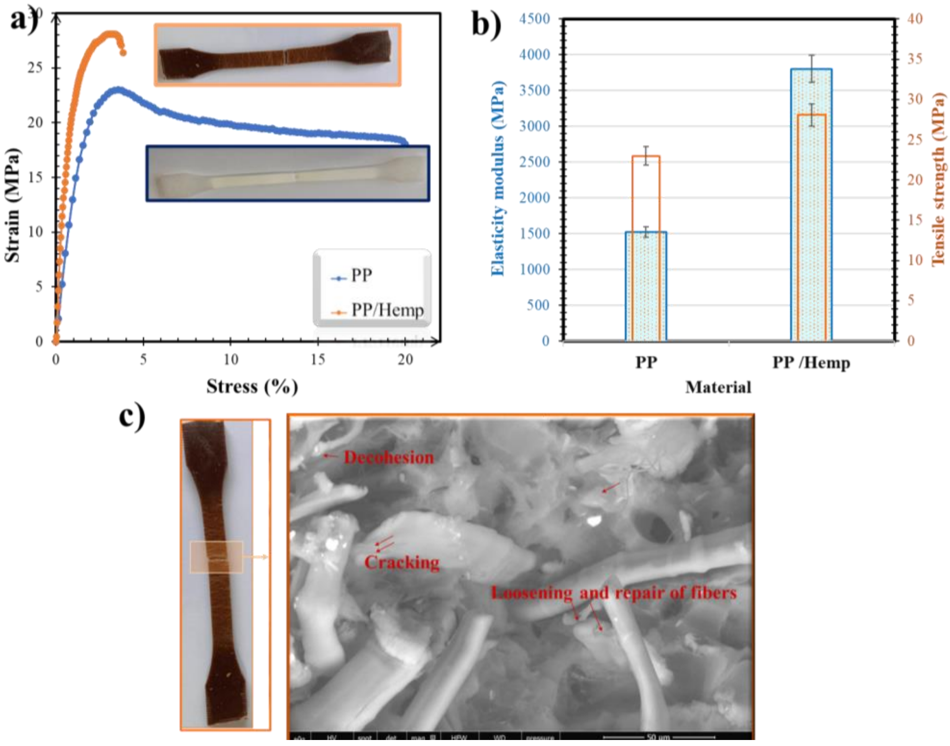

Fig. 3. Tensile test on polypropylene specimens and reinforced with 30% short hemp fibers.

However, this reinforcement comes at the expense of ductility, as evidenced by a significant reduction in elongation at break (A%) from 19.39% to 3.83%. These findings illustrate that while hemp fiber reinforcement effectively improves the strength and stiffness of the composite, it reduces flexibility, making PP/Hemp composites more suitable for applications prioritizing rigidity and strength over ductility.

Scanning Electron Microscope (SEM) analysis (fig 3c) of the fractured surfaces reveals critical failure mechanisms, such as fiber-matrix decohesion, cracking, and fiber pull-out. These mechanisms highlight the importance of the fiber-matrix interface in determining the composite's overall performance. Despite these challenges, hemp fibers play a vital role in bridging cracks and delaying catastrophic failure, thus contributing to improved mechanical behavior.

These results align with previous research on natural fiber composites, underscoring the potential of fibers like hemp to enhance material properties while promoting sustainability. Hemp fibers are renewable, biodegradable, and cost-effective, making them a viable option for eco-friendly polymer composites. However, further optimization—such as surface treatments to improve fiber-matrix adhesion—will be necessary to fully exploit the benefits of these natural reinforcements.

3.3. Wear properties

Figure 4 (A, B, and C) illustrates the influence of varying applied loads (1 N, 2 N, and 3 N, respectively) on the penetration depth (Pd) and residual depth (Rd) of polypropylene (PP) and PP reinforced with hemp fibers (PP/Hemp). The results clearly show that PP exhibits higher Pd values under load compared to the composite, indicating its relatively lower resistance to penetration and wear. In contrast, the PP/Hemp composite demonstrates higher resistance to penetration due to the reinforcing effect of the hemp fibers.
However, PP consistently exhibits lower Rd values, highlighting its superior elastic recovery after unloading. Conversely, the PP/Hemp composite displays higher Rd values, suggesting a greater tendency toward plastic deformation with limited recovery. As the applied load increases, this contrast becomes more pronounced (Figure 4C), with the PP/Hemp composite showing significant residual deformation, indicative of a ductile response.
These findings suggest that PP is better suited for applications requiring resilience, elastic recovery, and dimensional stability. On the other hand, the PP/Hemp composite may be advantageous in applications where energy absorption or plastic deformation is prioritized. These trends align with previous studies on polymer composites and natural fibers, which emphasize the balance between elasticity and plasticity in mechanical performance.
Additionally, the larger fluctuations in depth observed for PP/Hemp may be attributed to the intrinsic structural heterogeneity of the hemp fibers, as noted in [3]. These results have practical implications for material selection in load-bearing applications, sustainable construction, and impact-resistant designs, where trade-offs between elastic recovery and plastic deformation must be carefully evaluated.

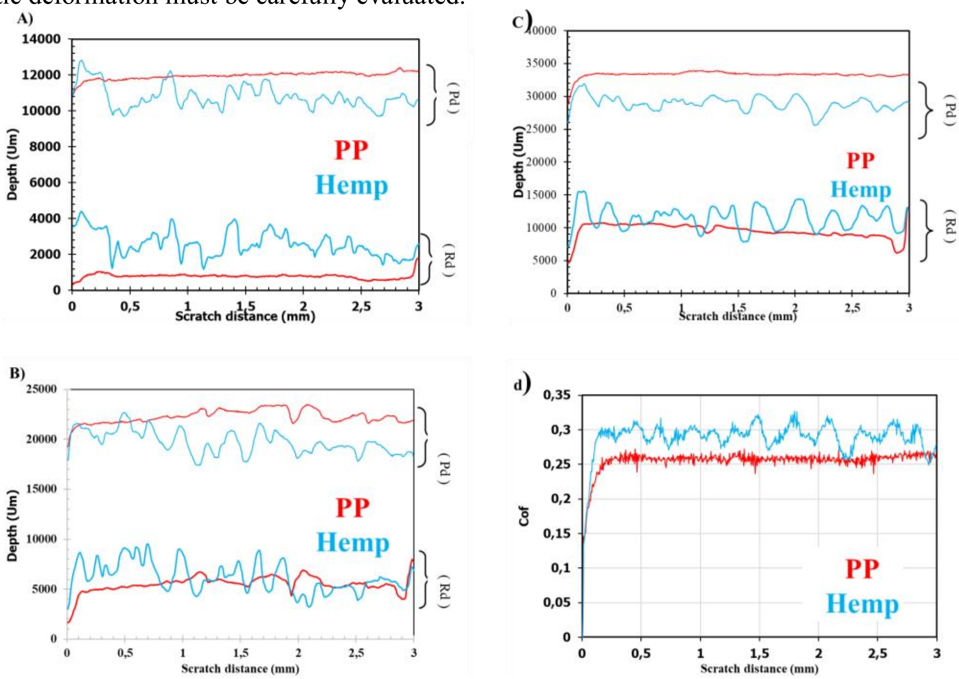

Fig. 4. Scratch Resistance at an applied load 1N(a), 2N(b), and (c)3N 1n and Coefficient of Friction (d) Analysis for PP and PP/Hemp Composites

In Figure 4c, the incorporation of hemp fibers into polypropylene demonstrates an increase in the coefficient of friction (CoF). This increase is primarily due to the rougher surface texture provided by the fibers. Hemp fibers, when embedded in polypropylene, create a

textured surface that enhances the material's ability to resist sliding against another surface. The natural irregularities of the hemp fibers promote greater frictional forces, which can be beneficial in applications requiring higher grip or resistance to wear, such as in automotive or industrial materials.
Figure 5 illustrates the damage mechanisms of pure polypropylene (PP) and polypropylene reinforced with hemp fibers (PP/HEMP). In (a), pure PP typically undergoes micro-cracking or plastic deformation due to its smooth structure, with cracks propagating along the polymer chains under stress, leading to material failure. In (b), the incorporation of hemp fibers into PP improves tensile strength but introduces new failure mechanisms such as fiber pull-out, debonding, or fiber rupture at the fiber-matrix interface. While the hemp fibers enhance the material's resistance to crack propagation, they also create localized weak spots that alter the overall damage behavior, resulting in a different failure pattern compared to pure polypropylene.

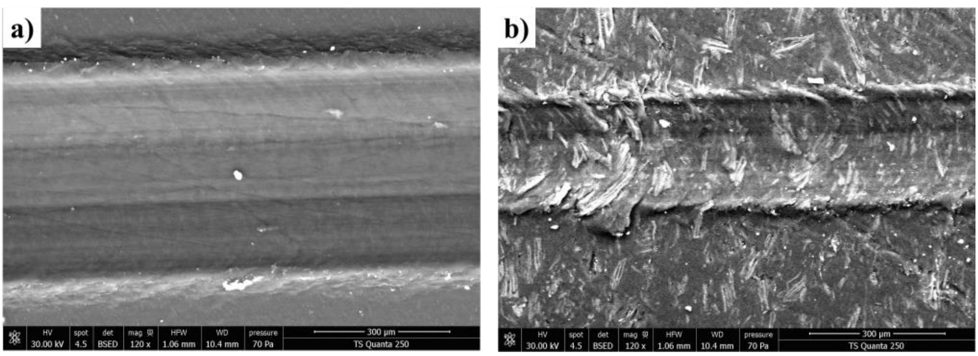

Fig. 5. Damage mechanisms of PP (a) and PP/HEMP (b)

4. Conclusion

In conclusion, this study demonstrates the potential of hemp-polypropylene (HPP) composites as a sustainable and high-performance material. The incorporation of 30 wt.% short hemp fibers into polypropylene significantly enhances the mechanical properties, including stiffness and tensile strength, as evidenced by the marked increase in Young's modulus and tensile strength compared to pure polypropylene. The use of a compatibilizing agent (PP-g-MA) improved the fiber-matrix adhesion, facilitating a more homogeneous composite structure with enhanced mechanical interlocking. While the hemp fibers improved the material's scratch resistance, they also introduced new failure mechanisms such as fiber pull-out and debonding at the fiber-matrix interface. The study highlights the potential of hemp fibers as a natural, cost-effective reinforcement for polypropylene, offering a promising alternative for applications requiring improved mechanical performance and wear resistance, while also contributing to environmental sustainability. Further optimization of the interface between hemp fibers and the polymer matrix is recommended to maximize the composite's properties for broader industrial applications.

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