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Effect of process variable on the mechanical and thermal behavior of a polypropylene composite reinforced with short bamboo fibers by hot compression

Efecto de variables de proceso en el comportamiento mecánico y térmico de un composite de polipropileno reforzado con fibras cortas de bambú por compresión en caliente

Leidy Quintero[1], Alexis García[2], Alejandro Alcaraz[1], Jorge Fajardo[3], Luis Cruz[1,*]

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Abstract

This study investigates the effect of fiber content and coupling agent concentration on the mechanical and thermal behavior of a polypropylene-based composite. The materials were fabricated via hot compression molding using pellets composed of polypropylene (PP) modified with maleic anhydride-grafted polypropylene (MAPP) and reinforced with short bamboo fibers derived from Guadua angustifolia Kunth (GAK). The fibers were previously extracted through the steam explosion technique. The research was carried out in two stages: first, the composite materials were produced; second, their mechanical and thermal properties were comprehensively characterized. The incorporation of GAK fibers and MAPP significantly altered the mechanical performance of the PP matrix, yielding stiffer composites with improved flexural strength and impact resistance. The optimal formulation, containing 50 wt% GAK fibers and 4 wt% MAPP, resulted in a 322% increase in elastic modulus (2.9 GPa) compared to neat polypropylene (0.7 GPa). Both variables, fiber content and compatibilizer concentration, were found to exert a substantial influence on the mechanical behavior of the resulting composites.

Keywords: Natural fibers, bamboo, polymeric composites, hot compression, mechanical characterization, thermal characterization.

Resumen

En este trabajo se estudió el efecto de la concentración del refuerzo y del agente de acople en el comportamiento mecánico y térmico de un material compuesto, procesado mediante la técnica de moldeo por compresión en caliente (MCC), a partir de una matriz de polipropileno (PP) modificada con anhídrido maleico injertado en polipropileno (MAPP) y reforzada con fibras cortas de bambú de la especie Guadua angustifolia Kunth (GAK). Las fibras fueron extraídas previamente mediante la técnica de *steam explosion*. La investigación se desarrolló en dos etapas. En la primera, se elaboraron los materiales compuestos poliméricos y, en la segunda, se realizó la caracterización mecánica y térmica de los mismos. La adición de las fibras de GAK y del agente de acople (MAPP) al polipropileno, modificó el comportamiento mecánico de la matriz, obteniéndose materiales más rígidos, con una mayor resistencia a la flexión y mayor absorción de la energía de impacto. La mejor configuración del material compuesto fue con el 50 % p/p de fibras de GAK y el 4 % p/p de MAPP, lo que permitió obtener un incremento sustancial en el módulo de elasticidad del 322 % (2,9 GPa) en relación con el PP virgen (0,7 GPa). Ambos factores tuvieron un efecto significativo en el comportamiento mecánico del *composite*.

Palabras clave: fibras naturales, bambú, composites poliméricos, compresión en caliente, caracterización mecánica, caracterización térmica

[1,*]Facultad de Ingeniería Mecánica, Universidad Pontificia Bolivariana, Colombia.
Corresponding author ✉: luis.cruz@upb.edu.co.

[2]Centro de diseño y manufactura del cuero - SENA, Colombia.

[3]Facultad de Ingeniería Mecánica, Universidad Politécnica Salesiana, Cuenca, Ecuador.

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1. Introduction

In recent decades, natural fibers such as kenaf, jute, and hemp have garnered increasing attention as renewable alternatives for the development of bio-based composite materials. Their appeal lies in the potential to replace non-biodegradable, difficult-to-dispose synthetic resources in the fabrication of functional components, where key performance attributes include high stiffness and low weight [1].

These bio-derived fibers offer multiple advantages, including low cost, reduced energy consumption during production, widespread availability, renewability, non-toxicity, low density, and high specific mechanical properties, comparable in some cases to those of glass fibers [2,3].

In particular, natural fibers derived from Guadua angustifolia Kunth (GAK) represent a promising reinforcement alternative for composite materials, owing to their high tensile strength and elevated modulus of elasticity. Furthermore, these fibers are environmentally sustainable and exhibit rapid growth, reaching maturity in approximately three years, a comparatively short cultivation cycle [4–6].

Natural fiber-reinforced composite materials are well-suited for processing through various conventional techniques, including extrusion molding, injection molding, thermoforming, and hot compression molding. Moreover, they fulfill both technical and economic requirements for the production of functional components suitable for a wide range of industrial applications [7,8].

However, several challenges hinder the widespread adoption of these materials, including the variability in the mechanical properties of natural fibers [6], their susceptibility to moisture [9], and the poor interfacial adhesion between the fibers and the polymer matrix, an issue arising from the intrinsic incompatibility between the hydrophilic nature of the fibers and the hydrophobic character of the matrix [10].

With respect to this latter issue, it is important to note that the incompatibility between the hydrophilic fibers and the hydrophobic matrix not only presents processing challenges [5], but also significantly impairs the mechanical performance of the resulting composite material [11]. To address this, various chemical, physical, and biological surface treatments have been developed to reduce the hydrophilicity of natural fibers, enhance their surface area, and improve interfacial bonding with the polymer matrix [12–14].

Similarly, in composite materials, surface modification techniques such as esterification, etherification, and benzylation have been employed, along with the incorporation of compatibilizing agents during manufacturing processes. According to the scientific literature, the most commonly used compatibilizers for thermoplastic polymers reinforced with short natural fibers include maleic anhydride-grafted polypropylene (MAPP), maleic anhydride-grafted polyethylene (MAPE), and silanes [15].

Similarly, [16,17] developed polypropylene-based composite materials reinforced with bamboo fibers, applying surface treatments with NaOH and silanes, and calcium carbonate, respectively, to enhance their mechanical performance. The authors reported improvements in key properties such as tensile strength and elastic modulus.

In line with these approaches, [18,19] proposed alkaline treatments using NaOH and $NaClO_2$ to remove surface impurities from Guadua angustifolia Kunth (GAK) fibers and enhance polymer–fiber adhesion. These treatments also increased surface roughness and fiber crystallinity, while reducing both fiber weight and diameter.

In contrast, Kumar and Das [2] developed a composite laminate using an unsaturated polyester matrix reinforced with Guadua angustifolia Kunth (GAK) fibers, proposing its use in semi-structural components. They evaluated mechanical properties, including tensile strength, Young's modulus, flexural strength, and flexural modulus, and reported that all values decreased relative to the reference material. This reduction was attributed to the lack of fiber orientation control during fabrication, as well as the absence of coupling agents to mitigate the incompatibility between the hydrophilic nature of the fibers and the hydrophobic character of the polymer matrix.

Among the limited studies available on hybrid polymer matrices, the work of Ying-Chen et al. [20] is particularly noteworthy. The authors employed the extrusion technique to fabricate composite materials comprising a hybrid polypropylene/polylactic acid (PP/PLA) matrix reinforced with bamboo fibers. MAPP was introduced as a coupling agent to improve the fiber–matrix interfacial compatibility, and the resulting composites were evaluated for their morphological, thermal, and rheological properties.

The authors attributed the improvement in these properties to enhanced interaction at the hybrid fiber–matrix interface resulting from the incorporation of MAPP. They also reported an increase in the crystallinity of the composites compared to the unreinforced polymers, which was ascribed to the nucleating effect of natural fibers.

As highlighted in the literature, the behavior of short fiber-reinforced composite materials is governed by numerous factors, the most significant of which include: fiber type and content, coupling agent type and concentration, reinforcement orientation, fiber length, fiber–matrix interfacial adhesion, and processing technique [21].

It is noteworthy that the scientific literature lacks studies analyzing the fabrication of these materials via hot compression molding (HCM), as well as research

on the behavior of natural composites reinforced with short fibers extracted through the steam explosion technique.

To address this gap in the literature, this study investigated the effects of varying fiber content and coupling agent concentration (MAPP) on the mechanical and thermal behavior of a composite fabricated via hot compression molding (HCM), using polypropylene, MAPP, and short Guadua angustifolia Kunth (GAK) fibers. Mechanical tests (tensile, flexural, and impact) and thermal analyses (DSC and TGA) were conducted, and the optimal composite formulation was identified based on the results obtained.

2. Materials and Methods

The polymeric matrix used in this study was HOPELEN H1500 homopolymer polypropylene pellets (injection grade), with a density of 0.9 g/cm^3 and a melt flow index of 12 g/10 min, supplied by LOTTE CHEMICAL.

Short bamboo fibers from Guadua angustifolia Kunth (GAK), extracted via steam explosion at a severity factor of 3.3 [22], were used as the reinforcing material.

For compatibilization between the fibers and the polymer matrix, maleic anhydride-grafted polypropylene (MAPP) pellets, supplied by SIGMA-ALDRICH, were employed.

2.1. Processing of Composite Materials

The fibers extracted via steam explosion were dried at 105 °C for 2 hours to remove residual moisture. Subsequently, their size was reduced using a blade mill operating at 1440 rpm, with a 4 mm sieve used to retain the processed material. The milled fibers were then classified using a sieve shaker. For composite fabrication, fibers retained on mesh 60 (250 µm) and mesh 100 (150 µm) were selected, in accordance with ASTM E11 standards.

For the fabrication of the composite materials, the hot compression molding (HCM) technique was employed, with controlled variations in fiber content (30%, 40%, and 50% w/w) and MAPP concentration (0%, 4%, and 8% w/w), to evaluate the influence of these variables on the composites' mechanical and thermal behavior. Based on the test results, the optimal composite formulation was identified.

The percentages of reinforcing material and compatibilizer were established based on findings from the scientific literature. For example, studies such as [23] on bamboo fiber-reinforced polypropylene composites have demonstrated that incorporating fibers in the range of 30% to 50% w/w can lead to significant improvements in mechanical properties, including tensile strength and elastic modulus.

Similarly, studies such as [24] have reported that increasing the content of pineapple leaf fibers, which share structural similarities with Guadua angustifolia Kunth (GAK) fibers, enhances the elastic modulus. However, fiber contents exceeding 50% w/w may compromise the toughness of the composite.

In contrast, studies such as [25] have concluded that the use of coupling agents like maleic anhydride-grafted polypropylene (MAPP) enhances interfacial adhesion between the polypropylene (PP) matrix and natural fibers, thereby improving both mechanical strength and thermal stability. Specifically, a coupling agent concentration of 4% w/w has proven effective in promoting adhesion without adversely affecting the homogeneity of the mixture.

Thus, three levels of MAPP were established to evaluate potential improvements or saturation effects in the composite's properties.

Prior to sheet fabrication, the raw materials, manually pre-mixed, were fed into a single-screw extruder to produce homogeneous premixes corresponding to the different composite formulations.

The extruder's temperature profile was set to 170 °C, 180 °C, 190 °C and 200 °C. across its heating zones. The screw speed was maintained at 60 rpm. The extruder was equipped with a 3 mm diameter pelletizer, and the resulting pellets were cut into granules with an average length of 5 mm.

Subsequently, the pellets were hot-pressed in multiple stages using the hot compression molding (HCM) technique, as illustrated in Figure 1, to produce plates measuring $150 \times 100 \times 3mm$. Test specimens for mechanical characterization were then machined from these plates using a CNC router.

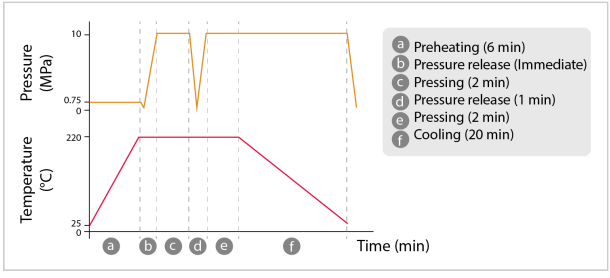

Figure 1. Temperature and pressure curves used in the hot compression molding process.

2.1.1. Mechanical Characterization of Composite Materials

Tensile tests were conducted using an INSTRON 5582 universal testing machine, in accordance with ASTM D638-14, employing Type IV specimens to determine tensile strength, elastic modulus, and maximum elongation at break. An Instron 2630-105 axial extensometer

with a gauge length of 25 mm was used to measure deformation.

Additionally, the fiber-matrix interface of the composites was qualitatively analyzed after tensile testing using a scanning electron microscope (SEM, JEOL JCM-6000Plus) operated at 15 kv under high vacuum conditions. Prior to imaging, the samples were coated by cathodic sputtering to ensure surface conductivity.

Three-point bending tests were conducted using an INSTRON 5582 universal testing machine, in accordance with ASTM D790-10, Procedure A, to determine flexural strength and flexural modulus.

Impact tests were conducted using an Izod-type pendulum impact tester (SATEC Systems), in accordance with ASTM D256-10.

For each composite formulation, eight replicates were tested.

Surface hardness was evaluated using a Shore D durometer (Bareiss) with an analog scale ranging from 0 to 100, following the procedure described in ASTM D2240-15. Prior to testing, the samples were conditioned at 22 °C and 55% relative humidity for 40 hours, as specified in ASTM D618-13.

2.1.2. Thermal Characterization of Composite Materials

Thermal properties of the composite materials, including melting temperature, crystallization temperature, and the enthalpies of melting and crystallization, were determined using differential scanning calorimetry (DSC).

Samples of approximately 6 mg were analyzed under an inert nitrogen atmosphere, with a flow rate of 50 mL/min and a heating rate of 10 °C/min.

It is important to highlight that, prior to data collection, a thermal erasure step was performed to eliminate the thermal processing history of the samples.

Additionally, thermogravimetric analysis (TGA) was used to determine the maximum thermal degradation temperature of the composite materials.

Samples of approximately 9 mg were analyzed under an inert nitrogen atmosphere, with a flow rate of 50 ml/min. The heating range extended from ambient temperature to 800 °C, with a heating rate of 30 °C/min.

3. Results and Discussion

Figure 2 presents the results of the tensile tests conducted on both the polypropylene matrix and the composite materials, with and without the coupling agent.

Regarding tensile strength, Figure 2a shows that the polypropylene (PP) matrix achieved the highest value, at 34.3 MPa. In contrast, uncompatibilized composites reinforced with 30% w/w fiber reached a maximum tensile strength of 18.6 MPa. Similarly, compatibilized composites with 50% w/w fiber and 4% w/w MAPP achieved a maximum of 24.8 MPa, representing reductions of 46% and 28%, respectively, compared to the NetApp matrix.

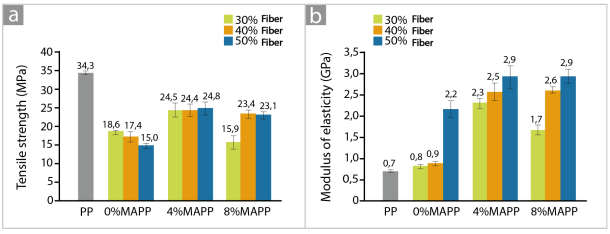

Figure 2. Tensile properties of composite materials with and without a coupling agent: a) Tensile strength and b) Elastic modulus.

As observed in the results, the tensile strength of composites without a coupling agent tends to decrease as the fiber content increases. This behavior is attributed to the hydrophilic nature of the fibers and the hydrophobic character of the polypropylene matrix, which results in poor interfacial compatibility and, consequently, weak fiber - matrix adhesion - an effect that becomes more pronounced at higher reinforcement levels [26, 27].

However, the addition of 4% w/w coupling agent to the composites results in improved tensile strength compared to the uncompatibilized formulations, as MAPP enhances fiber–matrix interfacial adhesion.

In contrast, increasing the MAPP content to 8% w/w does not yield further improvements; in fact, a slight decrease in tensile strength is observed. Fuqua and Ulven [28] attribute this behavior to the formation of weak van der Waals bonds between the residual coupling agent and the polypropylene matrix, which undermines the mechanical integrity of the composite.

Based on these results, none of the composites, reinforced, with or without a coupling agent, achieved the tensile strength exhibited by neat polypropylene. This outcome is attributed to the hot compression molding (HCM) technique, which does not promote fiber alignment in a preferred direction but instead produces a random fiber orientation. As a result, the reinforcing effect of the fibers is significantly reduced.

This same phenomenon has been reported by other authors [29], who attribute it to the random distribution of fibers within the matrix and the reduced aspect ratio (length-to-diameter) of the fibers after processing. During fabrication, the fibers experience significant breakage due to shear stresses generated by the processing equipment (e.g., mill and extruder), resulting in shorter fibers that limit efficient stress transfer within the composite.

Additionally, after processing, the fibers exhibit lengths shorter than the critical threshold required for effective reinforcement in the bamboo-PP system, which, according to [26], is approximately 3.5 mm.

Regarding the elastic modulus (figure 2b), a significant increase is observed upon incorporation of short GAK fibers into the polypropylene matrix, an effect that is further enhanced by the addition of the coupling agent (MAPP).

Quantified relative to virgin polypropylene (0.7 GPa) , the elastic modulus increased by 212% (reaching 2.2 GPa) with 50% w/w fiber, and up to 322% (2.9GPa) when an additional 4% w/w MAPP was incorporated at the same fiber concentration. These results are consistent with the findings reported by [30].

These authors attribute this improvement to the intrinsic rigidity of the fibers and the high reinforcement content in the composite, as the elastic modulus is strongly influenced by the fiber volume fraction.

Additionally, the incorporation of the coupling agent results in higher elastic modulus values compared to composites without a compatibilizer. This improvement is attributed to the formation of covalent bonds between the anhydride groups of MAPP and the hydroxyl groups of the GAK fibers, as well as interactions between the non-polar segments of MAPP and the polypropylene matrix, as reported by Chattopadhyay et al. [23].

This enhanced interfacial adhesion between the fiber and the matrix facilitates more efficient stress transfer from the matrix to the fibers [23].

However, despite the positive effects associated with the addition of the compatibilizer, increasing the MAPP content to 8% w/w does not result in further improvements; in fact, it may lead to a slight reduction in this property, as previously reported [28].

Additionally, a qualitative analysis of the fiber-matrix interface of the composites was conducted using SEM imaging of the fracture surfaces following tensile testing to identify potential interfacial defects or failure mechanisms.

As shown in figures 3a and 3b, the incorporation of the coupling agent resulted in improved matrix wettability and enhanced fiber impregnation, as clearly observed in the compatibilized composite (figure 3b).

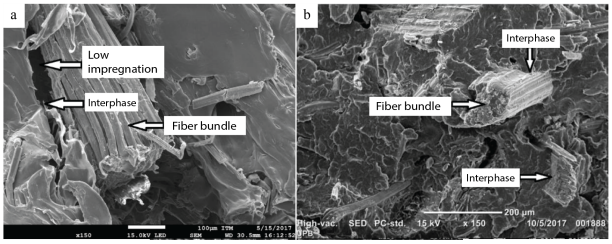

Figure 3. Scanning electron microscopy (SEM) images of the fracture surfaces of the composite materials after tensile testing: (a) 30% w/w fiber and 0% w/w MAPP; (b) 30% w/w fiber and 4% w/w MAPP.

The addition of MAPP modifies the fiber-matrix interface by enhancing interfacial interactions between the two phases, thereby improving stress transfer from the matrix to the fibers and ultimately enhancing the mechanical performance of the compatibilized composites.

Figure 4 presents the results of the three-point bending tests conducted on virgin polypropylene (PP) and the reinforced composite materials, both with and without the coupling agent. The highest flexural strength value, 34.0 MPa (figure 4a), was observed in the formulation containing 40% w/w fiber and 4% w/w MAPP.

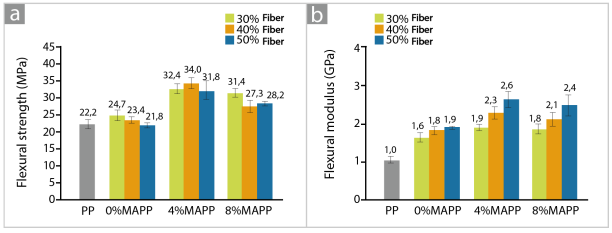

Figure 4. Flexural properties of the composite materials with and without a coupling agent: a) Flexural strength, and b) Flexural modulus.

In the case of the composites reinforced without a coupling agent, an 11.46% increase in flexural strength was observed with 30% w/w fiber, reaching 24.7 MPa. In contrast, with the addition of 40% w/w fiber and 4% w/w MAPP, the improvement rose to 53.34% (34.0 MPa) relative to virgin PP.

Flexural strength shows a slight increase with rising fiber content in composites without compatibilization; however, this trend reverses when the fiber loading exceeds 40% w/w. This decline has also been reported by other authors [27], who attribute it to the incompatibility between the hydrophobic polymer matrix and the hydrophilic reinforcement, as well as to less uniform fiber distribution at higher concentrations.

In contrast, compatibilization of the matrix with MAPP leads to a significant improvement in flexural strength, attributed to enhanced interfacial adhesion between the fiber and the matrix, which facilitates

more efficient stress transfer along the fiber-matrix interface [23].

However, increasing the MAPP concentration to 8% w/w results in a slight decrease in flexural strength, a trend similar to that observed for tensile strength [28].

Regarding flexural modulus (figure 4b), the composites without a coupling agent exhibited a maximum increase of approximately 83% (1.9 GPa), while the compatibilized composites reached a 154% increase (2.6 GPa) both relative to virgin polypropylene (1.0 GPa).

These results highlight the improvement in flexural modulus achieved through fiber reinforcement, which increases significantly with the addition of the coupling agent.

According to the findings reported in [30], the behavior of the flexural modulus mirrors that of the elastic modulus, both increasing with the incorporation of MAPP. This indicates that these properties are sensitive to interfacial adhesion between the GAK fibers and the polypropylene matrix. A similar trend was also observed in [9], supporting the idea of more efficient stress transfer from the matrix to the fibers, along with increased composite stiffness. This is attributed to the inherently high elastic modulus of GAK fibers, which, at higher reinforcement levels, requires greater force to achieve equivalent deformation.

However, as previously noted, the coupling agent at a concentration of 8 wt% does not positively influence this property. This behavior is attributed to residual MAPP molecules that do not form covalent bonds with the fibers and the matrix [17].

Figure 5 presents the results of the impact strength tests, with a maximum value of 47.2 J/m observed for the composite containing 50 wt% fiber and 0 wt% MAPP. This corresponds toan increase of approximately 50% compared to virgin polypropylene (31.4 J/m).

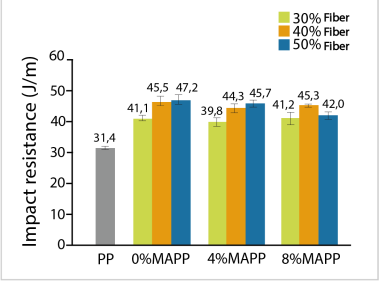

Figure 5. Impact strength of the manufactured composite materials.

According to the literature, the increase in impact strength is associated with mechanical interlocking at the fiber–matrix interface, which promotes more efficient stress transfer between the two phases. Additionally, the linear increase in this property with fiber content is attributed to the greater interfacial area available for stress distribution [23].

Likewise, the addition of reinforcement enhances energy absorption, driven by fracture mechanisms such as fiber pull-out, sliding, fragmentation, and partial fracture of the matrix material [31, 32].

However, the composites compatibilized with 4 wt% MAPP exhibit slightly lower impact strength compared to those without accoupling agent.

According to [33], this reduction is consistent with enhanced interaction and adhesion at the fiber–matrix interface, driven by the formation of a stronger chemical bond that replaces the previous mechanical interlocking. As interfacial bonding increases, a more rigid and cohesive composite structure is formed, resulting in greater stiffness and hardness but reduced toughness, thereby requiring less energy to initiate fracture.

Similarly, higher MAPP contents (8 wt%) do not enhance impact strength. According to [34], an excess of coupling agent may lead to the formation of a macromolecular layer within the composite, generating a weak region rich in MAPP that facilitates crack initiation and reduces the material's overall toughness.

Figure 6 presents the surface hardness results for the fabricated composites. The composite containing 50 wt% GAK fiber and no MAPP exhibited a 5% increase in hardness (78.13 Shore D) compared tovirgin polypropylene (74.13 Shore D).

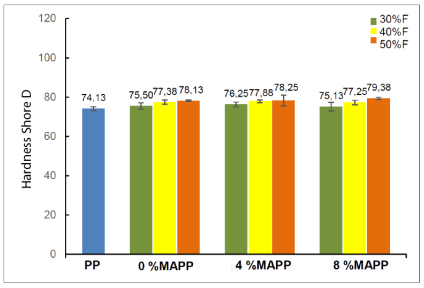

Figure 6. Shore D surface hardness of the fabricated composite materials.

This increase is attributed to the reinforcing effect of the GAK fibers embedded in the polymer matrix. When 8 wt% MAPP is incorporated as a compatibilizing agent, at the same fiber loading, a progressive increase in hardness is observed, reaching a maximum value of 79.38 Shore D. This represents a 7% improvement compared to virgin polypropylene.

Although the measured hardness values remain close to that of virgin polypropylene, this is expected since the test assesses only the surface of the composite, where PP is the dominant phase. Nonetheless, the slight increase suggests that the compatibilizer enhances interfacial adhesion between the fibers and the matrix, contributing to improved surface cohesion and greater resistance to penetration and wear.

Figure 7 presents the DSC thermograms of the fabricated composite materials, both with and without the coupling agent, using virgin polypropylene as a reference.

These tests were used to assess the influence of fiber content and MAPP concentration on the thermal behavior of the composites.

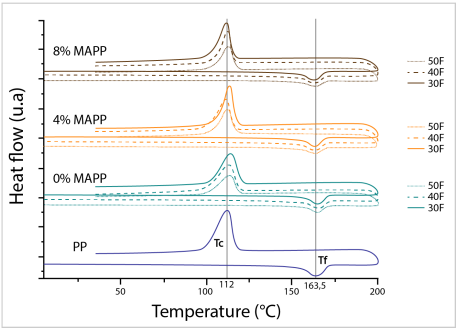

Figure 7. DSC curves of the fabricated composite materials.

The melting and crystallization temperatures of virgin polypropylene were observed around 163.5 °C and 112 °C, respectively. Upon incorporating the reinforcement and the coupling agent, no significant change in melting temperature was observed compared to virgin PP, with only a slight increase of about2 °C.

This slight increase is attributed to the fibers' higher heat absorption capacity compared to the polymer. However, the addition of MAPP at 4 wt% and 8 wt% did not havea significant effect on this property [9], [35, 36].

Regarding crystallization temperature, an increase in fiber content results in a slight upward shift in this property, as the fibers serve as heterogeneous nucleation sites that accelerate the crystallization process [9], [37]. Additionally, incorporating higher amounts of bamboo fiber reduces the free volume available for polymer chain mobility, thereby promoting crystallization at higher temperatures during the cooling cycle [38].

However, as shown in Table 1, the enthalpy of fusion decreases with increasing reinforcement content, as the fibers act as inert fillers and, additionally, reduce the proportion of polypropylene in the composite, thereby lowering the energy required to induce melting [39].

Nevertheless, this thermal property exhibits higher values in composites compatibilized with 4 wt% MAPP compared to those with 0 wt% and 8 wt%, indicating that, at this concentration, fiber–matrix interactions are enhanced, thereby improving the thermal stability of the composites.

On the other hand, when MAPP is added at a concentration of 8 wt%, the presence of residual coupling agent in the matrix reduces thermal stability, as MAPP has a lower melting temperature than virgin polypropylene [35].

A similar trend is observed for crystallization enthalpy, which decreases with increasing reinforcement content due to the lower proportion of polypropylene in the composite, as shown in Table 1 [35].

Table 1. Fusion and crystallization enthalpies of the fabricated composite materials.

Sample	Fusion enthalpy (J/g)	Crystallization enthalpy (J/g)
PP	114.5	104
30 % p/p F/0 % p/p MAPP	79.95	78.16
40 % p/p F/0 % p/p MAPP	65.32	75.44
50 % p/p F/0 % p/p MAPP	55.11	51.7
30 % p/p F/0 % p/p MAPP	75.95	71.21
40 % p/p F/0 % p/p MAPP	72.69	83.39
50 % p/p F/0 % p/p MAPP	77.8	72.9
30 % p/p F/0 % p/p MAPP	72.04	81.51
40 % p/p F/0 % p/p MAPP	71.94	60.96
50 % p/p F/0 % p/p MAPP	58.94	49.88

In the composites compatibilized with 4 wt% MAPP, crystallization enthalpy follows a similar trend to that observed for fusion enthalpy, indicating improved interfacial adhesion between the fibers and the matrix.

At a MAPP concentration of 8 wt%, the same trend observed for fusion enthalpy is maintained.

Figure 8 presents the DTG curves obtained from TGA analyses performed on a sheet of virgin polypropylene and on reinforced composites with and without the coupling agent, all evaluated at a heating rate of 30 °C/min.

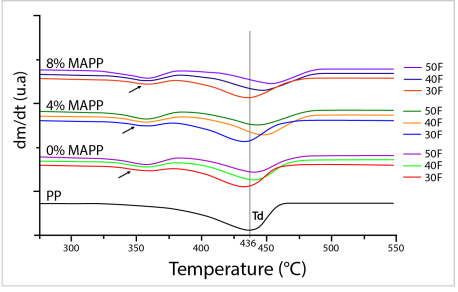

Figure 8. DTG curves of the fabricated composite materials.

The polypropylene sheet exhibits single-stage thermal decomposition, initiating at approximately 365 °C and completing around 436 °C. When bamboo fibers are incorporated, a second degradation stage appears at lower temperatures (see arrow), corresponding to the thermal decomposition of the reinforcement. This secondary stage becomes more pronounced with increasing fiber content, due to the breakdown of low-molecular-weight constituents in the natural fibers, primarily cellulose and hemicellulose, which are more abundant at higher reinforcement levels [35].

However, as shown in the graph and previously discussed, increasing the fiber content slightly enhances

the thermal stability of the composites [9] [35]. Additionally, the degradation temperatures of the reinforced composites, both with and without the coupling agent, are slightly higher than those of virgin polypropylene, indicating a slower degradation process. This behavior is attributed to the greater heat absorption capacity of the reinforcement, which is further amplified in composites compatibilized with MAPP, reflecting improved interfacial adhesion due to more effective fiber–matrix bonding [35], [37].

4. Conclusions

The tensile strength of the fabricated composites decreased with increasing fiber content. In contrast, the elastic modulus increased significantly up to 322% with the incorporation of 4 wt% MAPP.

Scanning electron microscopy confirmed that the incorporation of MAPP enhances the fiber–matrix interface by promoting stronger interactions between the two phases. This finding aligns with the tensile test results, which showed improved mechanical performance in compatibilized composites.

Flexural strength and flexural modulus also improved relative to the neat polypropylene matrix, with maximum increases of 55% and 154%, respectively, observed in composites containing MAPP. Similarly, impact resistance increased by up to 50% with the addition of GAK fibers, even in the absence of the coupling agent, specifically in the formulation with 50 WT% fiber and 0 wt% MAPP.

Regarding surface hardness, a slight increase of 7% was observed compared to virgin polypropylene in the composite containing 50 wt% fiber and 8 wt% MAPP. This result highlights the reinforcing effect of the GAK fibers and also suggests that the compatibilizer enhances fiber–matrix interfacial adhesion, contributing to improved resistance to penetration and wear.

The incorporation of GAK fibers and MAPP had little effect on melting and crystallization temperatures. However, fusion and crystallization enthalpies tended to decrease with increasing fiber and compatibilizer content, likely due to the reduced proportion of polypropylene available for these phase transitions.

The degradation temperatures of the polymer increased slightly with the incorporation of GAK fibers and MAPP. This effect is attributed to the higher energy absorption capacity of the fibers and the improved interfacial adhesion between the fiber and matrix provided by the compatibilizer. Together, these factors contribute to a greater energy requirement for the thermal degradation of the polymer.

Overall, higher MAPP concentrations (8 wt%) did not lead to further improvements in mechanical or thermal performance, confirming that 4 wt% is the optimal compatibilizer content.

The addition of GAK fibers and the coupling agent (MAPP) to polypropylene modified the mechanical behavior of the matrix, resulting in stiffer composites with enhanced flexural strength and greater energy absorption capacity under impact. Based on the results of this study, the best-performing formulation corresponds to the composite containing 50 wt% GAK fiber and 4 wt% MAPP.

This composite material is recommended for application in the automotive industry for the fabrication of semi-structural components, including door panels, seat backs, trunk linings, floor trays, and dashboards, which are traditionally manufactured from neat polypropylene in many vehicle models.

Reinforcing these components with GAK fibers would improve their mechanical performance relative to the virgin polypropylene matrix, while also contributing to overall vehicle weight reduction.

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Contributor Roles

- **Leidy Quintero:** Conceptualization, investigation, methodology, validation, formal analysis, writing – original draft, writing – review and editing, visualization.
- **Alexis García:** Writing – original draft, writing – review and editing, formal analysis, validation.
- **Alejandro Alcaraz:** Writing – original draft, writing – review and editing, formal analysis, validation.
- **Jorge Fajardo:** Review and editing, formal analysis, validation.
- **Luis Cruz:** Conceptualization, writing – original draft, writing – review and editing, project administration, supervision, funding acquisition.

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