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Research Article

Enhancing Mechanical Properties of Polypropylene Composites Reinforced with Date Palm Fiber Using Maleic Anhydride Grafted Polypropylene as a Compatibilizer

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ABSTRACT

This study investigates the effects of incorporating date palm fiber (DPF), polypropylene grafted maleic anhydride (PP-g-MA), and impact-modifying masterbatch on the tensile properties of polypropylene (PP) composites. Using a design of experiments (DOE) approach and analysis of variance (ANOVA), the interactions between these components were analyzed. The tensile strength of the composites increased by up to 21.08% compared to pure PP, reaching 19.6 MPa, while the elastic modulus improved by 54.78%, reaching 2.43 GPa, at 20 wt.% DPF and 5 wt.% PP-g-MA. Although the masterbatch enhanced impact resistance, its higher concentrations reduced tensile strength by up to 31.97% compared to formulations with minimal masterbatch content. The optimal composition—20 wt.% DPF, 5 wt.% PP-g-MA, and 1 wt.% masterbatch—exhibited the best overall mechanical performance, balancing tensile strength, elastic modulus, and impact resistance. This study highlights the synergistic effects of natural fibers and polymer compatibilizers, providing a pathway for the development of sustainable, high-performance bio-composites.

1. Introduction

Plastics are materials that find widespread use in various industries due to their ability to be converted into different products with diverse properties. [1]. PP is a type of plastic that is commonly employed across industries owing to its attributes such as low cost, good chemical resistance, low density, ultraviolet (UV) resistance, and a high melting point. [2] [3] [4]. PP is utilized in fields like water filtration, air purification, biomedicine, clothing, aerospace, recycling, packaging, and automotive applications. [5] [6]. However, pure PP suffers from poor mechanical properties. [7]And nowadays, various reinforcement materials are being added to improve their mechanical performance.

Al-Oqla and Thakur [8] used lignocellulosic parsley fibers as reinforcement to improve the mechanical properties of PP, and they treated the fibers with sodium chloride, phosphoric acid, and citric acid. Their findings revealed that sodium chloride treatment improved the tensile strength to 116 MPa at 20 wt.% fiber content, and with acid treatment at 40 wt.% fiber content, the

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tensile strength reached 162 MPa, while impact resistance increased by 22.3%. Zaman and Khan [9] examined PP composites reinforced with snake grass fibers (SGFs) and hydroxyethyl methacrylate (HEMA), reporting that the bio-composites reinforced with 10% HEMA demonstrated the best mechanical properties. Bhuyan et al. [10] explored the use of recycled polyethylene (rPE) and PP as matrices and jute as reinforcement in thermal insulation panels for building interiors. They found that the tensile and flexural strength of PP/jute composites was better than that of PE/jute composites, with PP/jute also exhibiting superior thermal insulation properties. Santosh et al. [11] studied PP composites reinforced with 20-30% sub-bituminous coal, reporting a 66% increase in tensile strength and a 55% improvement in flexural strength compared to pure PP.

Given the unique characteristics of natural fibers, such as biodegradability, low cost, low density, non-carcinogenic nature, and high specific strength, they have emerged as promising alternatives to synthetic fibers. [12] [13]. Among these natural fibers, DPF has garnered significant attention due to its low cost and environmental friendliness. DPF is produced annually in large quantities, and without proper utilization, it contributes to substantial waste. Its high strength-to-cost ratio makes DPF highly advantageous compared to other natural and synthetic fibers. [14] [15]. Kashizadeh et al. [16]Investigated the mechanical, water absorption, and flammability properties of phenolic resin reinforced with DPF. Their study showed that treating the fibers with NaOH led to improvements in flexural, tensile, and impact strengths by 19%, 14%, and 140%, respectively. However, water absorption also increased, while no significant change was observed in flammability. Djoudi et al. [17], examined the physical and mechanical properties of epoxy composites reinforced with different parts of date palm trees, showing that mechanical properties improved up to 10% fiber content, after which the properties declined at 15% due to poor fiber-matrix adhesion. Raghavendra et al. [18]Investigated hybrid epoxy composites containing date palm fibers and polyester, demonstrating that the hybrid composite with both date palm and polyester fibers exhibited the highest tensile strength (43.41 MPa) and flexural strength (84.83 MPa), which were 65.82% and 67.14% higher, respectively, compared to pure epoxy.

Although natural fibers exhibit unique advantages, they also have limitations, primarily their poor adhesion with polymer matrices. One of the common solutions to this problem is the use of coupling agents. According to various studies, PP-g-MA enhances fiber-matrix adhesion. [19]. This leads to improved mechanical properties, such as tensile strength, elastic modulus, and impact resistance. [20]. Additionally, PP-g-MA can enhance colorability, thermal properties, dimensional stability, and surface smoothness. [21]. The adhesion between fibers and the matrix plays a crucial role in enhancing the mechanical properties and performance of composites. Studies have shown that innovative approaches, such as bacterial surface treatment and the use of recycled materials, can improve this adhesion. [22], [23], [24]. These methods are particularly effective in natural fiber-based and recycled polymer-reinforced composites, leading to sustainable and durable materials.

Chaiwatinan et al. [25], examined the effect of PP-g-MA in a composite of recycled polyethylene terephthalate (rPET) as the matrix, and PP and wollastonite (WLN) as reinforcements. The composite formulations of 70/30/5 (w/w/phr) rPET/PP/PP-g-MA and 70/30/3/10 (w/w/phr) rPET/PP/PP-g-MA/WLN, with tensile strengths of 50.9 MPa and 50.3 MPa, respectively, showed the best results. Jauvinislavitis et al. [26]In a study on recycled polypropylene with recycled waste paper, researchers found that the presence of polypropylene coupled with maleic anhydride in the composition increases the mechanical properties and reduces water absorption. Andrzejewski et al. [27], investigated the effect of PP-g-MA on the mechanical properties of polypropylene composites reinforced with two natural fibers: wood and buckwheat husk. The presence of PP-g-MA in the composition reduced the stiffness of the sample but increased the tensile strength, which is attributed to the adhesive bonding provided by maleic anhydride. Mostafa et al. [28], studied the impact of PP-g-MA in a composite of polypropylene and hemp fibers. They found that the presence of 3% by weight of PP-g-MA increases fracture strength and tensile strength by 3.98–18.50%, which could be due to the enhanced adhesion between the matrix and the fibers.

Mahmoud M.A. Nassar et al. [29] enhanced the mechanical performance of PP and rPP by incorporating chemically treated date palm fillers. The treated fillers, prepared via a novel extraction and pulverization process, improved the tensile strength, crystallinity, and water resistance of the resulting bio-composites, particularly in rPP, where they acted as effective nucleation agents. Fabricated using extrusion and compression molding, the composites demonstrated superior performance compared to those with untreated fillers, while maintaining stable thermal degradation. This study highlights a sustainable approach for utilizing agro-residues

in bio-composites suitable for diverse industrial applications. Mehrdad Hossein Alizadeh et al. [30] investigated the energy absorption of Kevlar®/polypropylene (PP) weft-knitted hybrid composites produced via the co-air-textured yarn technique, focusing on optimizing production parameters for high-velocity impact resistance. Using the response surface method (RSM), the study identified optimal conditions for maximizing specific energy absorption. Key findings include a Kevlar/PP blend ratio of 1:2, full-milano knitting structure, higher stitch length, superior blending quality, molding pressure of 300 kg/cm^2, molding time of 20 minutes, and a lower molding temperature of 160°C. These optimized parameters ensure efficient energy absorption, making the composite suitable for high-performance applications.

Reza Eslami-Farsani [31] investigated the impact of DPF and its sodium hydroxide treatment on the mechanical properties of PP/EPDM polymer composites. Maleic anhydride grafted polypropylene (MAPP) was employed as a compatibilizer to enhance fiber-matrix bonding. Results showed that incorporating DPF improved tensile and bending strength but reduced impact strength. Treated fibers outperformed raw fibers, providing superior mechanical properties. Scanning electron microscopy confirmed that both MAPP and treated fibers enhanced interfacial adhesion between fibers and the polymer matrix.

S.M.R. Khalili et al. [32] investigated the mechanical properties of PP/ethylene-propylene-diene monomer (EPDM)/jute fiber composites under impact, tensile, and bending loadings. Composites with varying jute fiber contents (5–30 wt%) were fabricated using an injection molding machine, with MAPP employed as a compatibilizer to enhance fiber-matrix adhesion. The results indicated that adding EPDM to PP increased the impact strength (both notched and unnotched) and elongation at break, while tensile and bending strengths decreased. Increasing jute fiber content improved tensile strength but reduced impact and bending strength compared to pure PP. The study highlights the trade-offs between mechanical properties in designing such composites.

Numerous studies have been conducted on impact modifier masterbatches and their effects on the mechanical properties of composites. Hadi et al. [33], investigated the tensile properties of a composite made of recycled low-density polyethylene (rLDPE) as the matrix, and recycled carbon black and several other additives in the form of pigment masterbatch (PM) as reinforcements. Two types of processing aids were used. The first, labeled A, had the formula C38H76N2O2 in powder form, while the second, labeled B, was polyethylene wax. Both were combined with the composite. The addition of PM to rLDPE slightly improved the tensile properties, and processing aid B performed better than A. Furthermore, after water absorption, the tensile properties of the composites improved due to stronger bonding.

Tekay et al. [34], studied the mechanical properties of ternary nanocomposites of PP/maleic anhydride-grafted poly triblock copolymer (SEBS-g-MA) / halloysite nanotubes (HNT). The results showed that using the masterbatch (MB) method in composites led to improved toughness and yield strength. The use of MB also resulted in a 290% increase in impact strength compared to pure polypropylene. Al-Maqdisi et al. [35], examined the effect of two types of masterbatches with activated carbon platelet additives, named M1 and M2, on the mechanical properties of polyethylene composites with spruce and pine wood flour (WF). M1 contained 35 wt.% dispersed graphene nanoplatelets, while M2 contained 25 wt.%.% Graphene Black™ 3X. The results showed that M2 provided a more significant improvement in tensile and impact strength compared to M1 due to the smaller number of graphene layers and greater surface contact. This improvement continued up to 15 wt.% of nanoparticles, and in some cases, M2 outperformed M1 even at 6 wt.% of nanoparticles.

Despite the significant advances in natural fiber composites, improving the adhesion between natural fibers and polymer matrices remains a major challenge in enhancing the mechanical properties of composites. This study presents a detailed investigation into the mechanical properties of PP composites reinforced with natural DPF and compatibilized with PP-g-MA. Using a DOE approach, the research systematically examines the impact of varying DPF content (10-30 wt.%), PP-g-MA levels (1-5 wt.%), and masterbatch percentages (1-5 wt.%) on tensile strength and elastic modulus. Advanced statistical analysis, including analysis of variance, is employed to quantify the effects of each component and their interactions on the mechanical properties of the composites. The novelty of this study lies in the synergistic combination of DPF and PP-g-MA, which optimizes fiber-matrix bonding while minimizing negative effects associated with higher DPF content, such as fiber agglomeration. By identifying the composition that yields the highest mechanical performance, this research establishes a foundational understanding of how to enhance bio-composite materials for potential applications in automotive, packaging, and construction industries. These findings

contribute to the development of sustainable, high-performance composites that meet the growing industrial demand for eco-friendly alternatives to conventional synthetic-fiber composites.

2. Experimental Details

2.1. Materials

The EP548R homopolymer polypropylene (with a melt flow index of 21 g/min and a density of 0.9 g/cm^3) is produced and supplied by Eris Plast in Iran. Natural date DPF, which are used as a reinforcement in composites, have a density ranging from 0.9 to 1.2 g/cm^3, a length between 20 to 250 mm, and a diameter of 100 to 1000 µm [13]and are sourced from the orchards of Iranshahr County. The coupling agent used for composite preparation is PP-g-MA, branded as Aria Comp 1432, and is supplied by Arya Polymer Pishgam (Iran). This material has a melt flow index of 7.5 ± 2 g/min, a density of 0.91 g/cm^3, and a grafted maleic anhydride content in the range of 0.5 to 1 wt.%. Both PP and PP-g-MA were used in granule form in the production process.

Additionally, the impact modifier masterbatch, branded as Aria Comp 4203 (with a melt flow index of 0.27 ± 0.05 g/min, a density of 0.91 ± 0.01 g/cm^3, and a maleic anhydride content of 1 to 5 wt.%), was also sourced from Arya Polymer Pishgam.

2.2. Preparation of the Fiber-reinforced Composites

Initially, the long date palm fibers (approximately 40 cm in length) were cut into smaller pieces ranging from 2 to 10 mm using a cutter. Then, an oven was set to a temperature of 80°C, and the fibers were placed inside for 4 hours to dry and remove moisture. After the drying process was completed, the fibers were stored in ziplock bags to prevent them from reabsorbing moisture. The materials used were weighed using a laboratory digital scale, according to the percentages specified in Table 1. The parameter percentages used in the sample preparation were determined based on the DOE method, using the Box-Behnken design (BBD) approach with the Design Expert software.

First, 3 grams of polypropylene were weighed, and then the other materials were added to it according to the desired weight percentage, and they were manually mixed. The internal mixer's temperature was set to 175°C. After the machine reached this temperature, a small amount of pure polypropylene was added to the machine to clean the chamber of any residues from previous materials. Initially, the rotor speed was set to 60 rpm, and the manually pre-mixed blend (without fibers) was poured into the mixer's chamber. After about 1.5 minutes, the rotor speed was increased to 70 rpm, and the fibers were added to the blend. The mixture was stirred for 7 minutes. Then, the machine was stopped, and the mixer chamber was opened for material discharge. The material was collected from the chamber walls and flattened using a weight.

Next, for sample preparation, a mold with dimensions of 10 by 15 cm was used. First, the mold was carefully cleaned with alcohol, and the material was placed between fire-resistant fabrics inside the mold. The temperature of the heated press plates had been pre-set to 190°C, and after reaching this temperature, the mold was placed under the press. The plates were brought together until they contacted the mold, and this position was maintained for 5 minutes to ensure the material was well heated and could flow in its molten state within the mold. Then, the mold was subjected to a pressure of 25 MPa for 1 minute. Afterward, the press plates were opened, and the mold was allowed to cool at room temperature for 10 minutes. Finally, the mold was opened to remove the samples. The rectangular sample was taken out, and the excess material around it was trimmed.

The rectangular samples were then cut into a dumbbell shape using a pneumatic cutter, preparing them for tensile testing. Figure 1 illustrates the composite preparation process, with each step contributing to the overall mechanical properties of the final composite. Fiber cutting and drying ensure the correct size and moisture content, vital for consistency in tensile testing. Mixing and pressing steps are crucial for achieving uniform distribution of fibers and additives, which directly impact tensile strength and elastic modulus. This process standardization aims to optimize composite quality and repeatability in properties.

Table 1. Information on composite samples.

Sample codes F: Fiber, G: PP-g-MA, M: Masterbatch	DPF (wt.% %)	PP-g-MA (wt. %)	Masterbatch (wt.% %)	Weight of tensile samples (g)
FGM-10-1-3	10	1	3	1.78
FGM-30-1-3	30	1	3	1.79
FGM-10-5-3	10	5	3	1.83
FGM-30-5-3	30	5	3	1.85
FGM-10-3-1	10	3	1	1.91
FGM-30-3-1	30	3	1	1.89
FGM-10-3-5	10	3	5	1.78
FGM-30-3-5	30	3	5	1.76
FGM-20-1-1	20	1	1	1.81
FGM-20-5-1	20	5	1	1.79
FGM-20-1-5	20	1	5	1.78
FGM-20-5-5	20	5	5	1.79
FGM-20-3-3	20	3	3	1.78
FGM-20-3-3 (2)	20	3	3	1.79
FGM-20-3-3 (3)	20	3	3	1.79

Fig. 1. The series of composite manufacture.

2.3. Tensile Test

The tensile test was conducted using a SANTAM STM-50 machine at room temperature with a speed of 5 mm/min, according to ASTM D638 (Type IV) standards. [36]. The detailed dimensions of the tensile test specimen are shown in Figure 2.

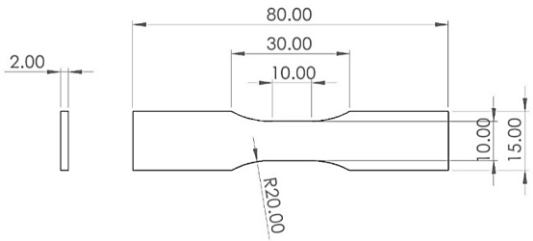


Fig. 2. The geometry of the tensile test specimen.

3. Results and Discussion

3.1. Tensile Test Results

To evaluate the mechanical properties of PP reinforced with DPF and impact modifier masterbatch, which were compatibilized with PP-g-MA, a tensile test was performed on the samples. The samples, as shown in Figure 3, were placed inside the machine grips. The sample after the tensile test is shown in Figure 4. Table 2 presents all the values for tensile strength and elastic modulus for all the samples.

This study investigates the effects of three parameters, including the weight percentage of date palm fibers, the weight percentage of the PP-g-MA compatibilizer, and the weight percentage of the impact modifier masterbatch, on the mechanical properties of polypropylene-based composite samples. The tensile test was conducted to evaluate two responses: ultimate tensile strength and elastic modulus. Statistical analysis was performed using the DOE method with the Design Expert software. The analyses included regression, ANOVA, and sensitivity analysis of the parameters and pairwise interactions of the parameters.

Table 2 presents tensile strength and elastic modulus values across all sample compositions. Notably, compositions with 5 wt.% PP-g-MA consistently exhibits higher tensile strengths due to the enhanced bonding interface between fibers and the polymer matrix. Comparisons between samples, such as FGM-10-5-3 and FGM-30-5-3, illustrate how higher fiber content with optimized PP-g-MA levels results in greater modulus, reinforcing the importance of component ratios for targeted mechanical properties.

The tensile test results demonstrate clear trends influenced by the percentages of DPF, PP-g-MA, and impact-modifying masterbatch. The optimal tensile strength of 19.6 MPa, observed at 20 wt.% DPF and 5 wt.% PP-g-MA represents a 21.08% improvement compared to pure polypropylene. This enhancement is attributed to the increased fiber-matrix adhesion facilitated by PP-g-MA, which improves stress transfer within the composite. However, at higher fiber content (30 wt.%), tensile strength decreased by approximately 12.12%, likely due to agglomeration of fibers and uneven distribution within the matrix, reducing the composite's uniformity and mechanical integrity.

The masterbatch content exhibited an inverse relationship with tensile strength. For instance, increasing the masterbatch from 1 wt.% to 5 wt.% in samples with 20 wt.%.% DPF resulted in a reduction of tensile strength by 31.97%. This decline can be attributed to the softening effect introduced by the masterbatch, which weakens the overall composite structure. These findings emphasize the importance of optimizing the balance between stiffness and toughness to achieve desirable mechanical performance.

The elastic modulus results, also presented in Table 2, highlight significant improvements when PP-g-MA is incorporated at higher concentrations. The peak modulus of 2.43 GPa, achieved with 30 wt.% DPF and 5 wt.% PP-g-MA corresponds to a 54.78% increase compared to pure polypropylene. This increase is primarily due to the enhanced stiffness provided by the fiber reinforcement and the improved interfacial adhesion from the PP-g-MA compatibilizer.

Interestingly, at lower compatibilizer levels (1 wt.%), the modulus decreased with increasing fiber content, as seen in the comparison between FGM-10-1-3 (1.942 GPa) and FGM-30-1-3 (1.735 GPa). This suggests that insufficient compatibilizer levels fail to adequately bond the matrix and fibers at higher fiber percentages, resulting in a less stiff composite.

Fig. 3. Tensile sample of PP/DPF composite undergoing tensile test inside the clamps of the machine.

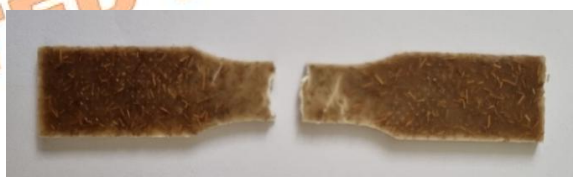


Fig. 4. PP/DPF sample after tensile test.

Table 2. Tensile strength and elastic modulus values of the samples

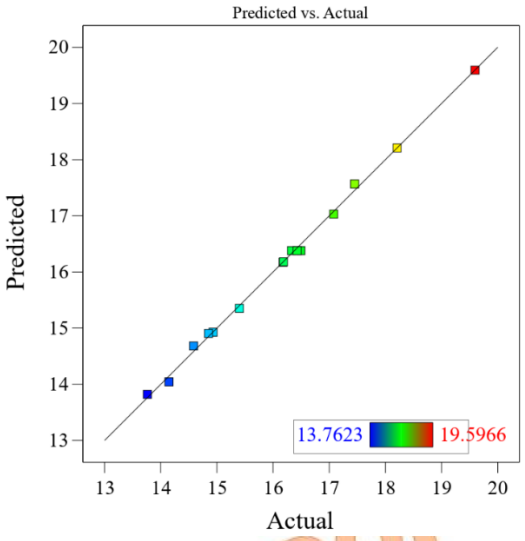
Samples	Tensile strength (MPa)	Elastic modulus (GPa)
FGM-10-1-3	15.4012	1.942
FGM-30-1-3	14.9318	1.735
FGM-10-5-3	17.0795	1.884
FGM-30-5-3	16.1775	2.437
FGM-10-3-1	18.2087	2.307
FGM-30-3-1	17.4516	2.383
FGM-10-3-5	14.5852	1.57
FGM-30-3-5	14.1474	1.587
FGM-20-1-1	16.1848	2.177
FGM-20-5-1	19.5966	2.12
FGM-20-1-5	13.7623	2.114
FGM-20-5-5	14.8488	1.895
FGM-20-3-3	16.4942	2.083
FGM-20-3-3 (2)	16.3278	2.031
FGM-20-3-3 (3)	16.4295	2.016

3.2. Analysis of Variance (ANOVA)

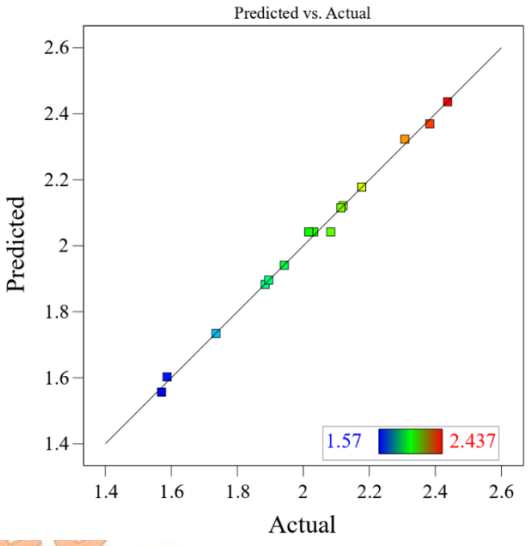
The ANOVA results for tensile strength and elastic modulus confirm the statistical significance of the models obtained. In Table 3, the analysis of variance for tensile strength shows an F-value of 408.50 and a p-value of less than 0.0001, indicating that the regression model is generally significant. In this model, the parameters of DPF, PP-g-MA, and the impact modifier masterbatch are all significant, with strong effects on the ultimate tensile strength. Furthermore, the interaction between PP-g-MA and the impact modifier masterbatch also has a significant effect on this response.

Similarly, in Table 4 for the elastic modulus, the F-value is 112.26, and the p-value is less than 0.0002, confirming that the model is significant and capable of predicting the response. In this model, parameters B (PP-g-MA) and C (impact modifier masterbatch) have the most significant effects on the elastic modulus, while the interactions AB (DPF and PP-g-MA) and A^2C (DPF squared and impact modifier) show the highest influence on the response. This indicates that changes in these parameters directly affect the elastic modulus.

Figures 5a and 5b present the graphs of actual values versus predicted values by the model for tensile strength and elastic modulus, respectively. As shown in these graphs, the proximity of the points to the 45-degree diagonal line indicates the high accuracy of the model.



a)



b)

Fig. 5. Scatter diagram of responses of the DOE, a) tensile strength, b) elastic modulus

Table 3. The results related to the variance analysis of the tensile strength

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	34.71	8	4.34	408.50	< 0.0001	significant
A-Fiber	0.8232	1	0.8232	77.50	0.0001	
B-PP-G-MA	5.06	1	5.06	476.23	< 0.0001	
C-Masterbatch	24.84	1	24.84	2338.88	< 0.0001	
AB	0.0468	1	0.0468	4.40	0.0806	
BC	1.35	1	1.35	127.26	< 0.0001	
A^2	0.2420	1	0.2420	22.78	0.0031	
B^2	0.2422	1	0.2422	22.80	0.0031	
A^2B	0.3098	1	0.3098	29.17	0.0017	
Residual	0.0637	6	0.0106			
Lack of Fit	0.0497	4	0.0124	1.76	0.3929	not significant
Pure Error	0.0141	2	0.0070			
Cor Total	34.78	14				
			Std. Dev.	0.1031	R^2	0.9982
			Mean	16.11	Adjusted R^2	0.9957
			C.V. %	0.6398	Predicted R^2	0.9860

Table 4. The results related to the variance analysis of the elastic modulus.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.9437	10	0.0944	112.26	0.0002	significant
A-Fiber	0.0022	1	0.0022	2.57	0.1840	
B-PP-G-MA	0.0190	1	0.0190	22.66	0.0089	
C-Masterbatch	0.0207	1	0.0207	24.67	0.0077	
AB	0.1444	1	0.1444	171.79	0.0002	
BC	0.0066	1	0.0066	7.81	0.0491	
A^2	0.0232	1	0.0232	27.66	0.0063	
B^2	0.0047	1	0.0047	5.61	0.0769	
A^2B	0.1058	1	0.1058	125.87	0.0004	
A^2C	0.1938	1	0.1938	230.50	0.0001	
AB^2	0.0080	1	0.0080	9.52	0.0367	
Residual	0.0034	4	0.0008			
Lack of Fit	0.0009	2	0.0004	0.3598	0.7354	not significant
Pure Error	0.0025	2	0.0012			
Cor Total	0.9470	14				
			Std. Dev.	0.0290	R^2	0.9964
			Mean	2.02	Adjusted R^2	0.9876
			C.V. %	1.44	Predicted R^2	0.9830

3.3. Tensile Strength

Figure 6 shows that composites with 10 wt.% fiber content achieve higher tensile strength compared to those with 30%, suggesting that higher fiber concentrations may cause clumping and reduce uniformity in the composite. The stress-strain diagrams further illustrate this behavior, as samples with lower DPF percentages exhibit better stress distribution under tension. As reported, composites with 10 wt.% fibers performed better in all cases compared to those with 30 wt.% fibers. Specifically, the tensile strength of the samples FMG-10-1-3, FMG-10-3-5, and FMG-10-5-3 was 3.14%, 3.09%, and 5.57% higher than that of the samples FMG-30-1-3, FMG-30-3-5, and FMG-30-5-3, respectively.

This phenomenon can be attributed to the uneven distribution of fibers throughout the composite at higher fiber percentages, leading to fiber clumping in various areas. [37]. Figure 7 shows stress-strain curves that compare the influence of the fiber content on the composite's performance.

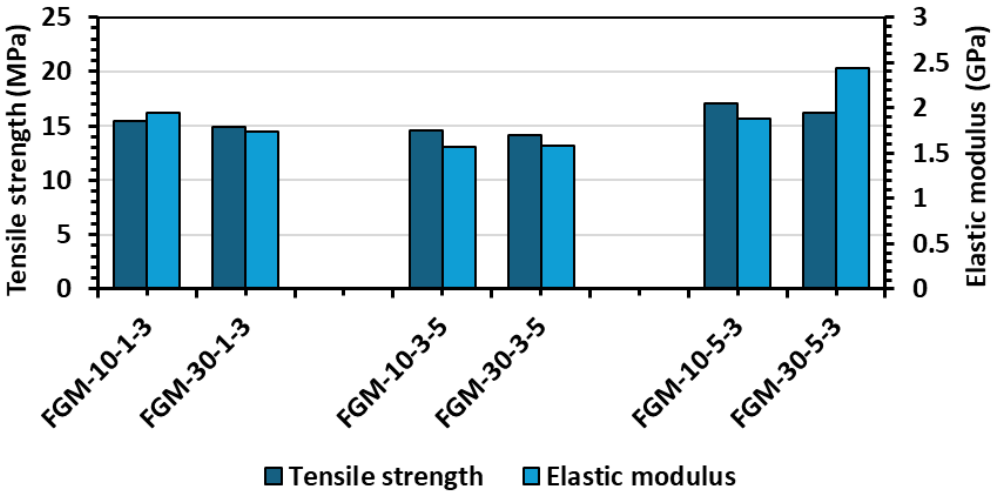


Fig. 6. The effect of DPF on tensile strength and elastic modulus in fixed percentages of PP-g-MA and Masterbatch

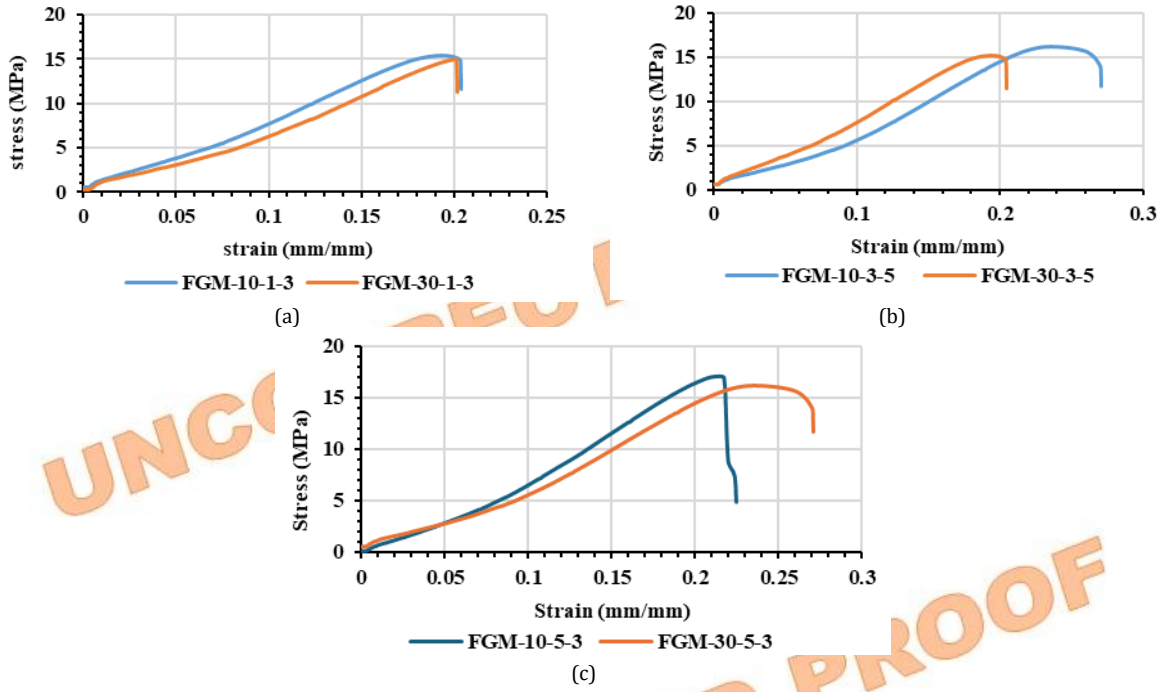


Fig. 7. Stress-strain diagram of polypropylene/DPF composite in different fiber percentages

In Figure 8a, the simultaneous effect of the weight percentage of DPFs and PP-G-MA on the tensile strength of the composite is depicted. It is observed that as the weight percentage of PP-G-MA increases from 1 to 5 wt.%, and the weight percentage of DPF rises from 10 to 20 wt.%, the tensile strength significantly improves, reaching a maximum value of about 19.6 MPa. These results highlight the strong influence of PP-G-MA in enhancing the bond between the fibers and the polypropylene matrix. Conversely, when the fiber content increases to 20 wt.% and PP-G-MA is less than 2 wt.%, the tensile strength decreases to about 13.76 MPa. These variations clearly demonstrate the importance of the optimal combination of these two parameters to achieve desirable mechanical strength. Figures 8a and 8b demonstrate that tensile strength improves as PP-g-MA increases from 1 to 5 wt.%, with DPF levels between 10 and 20 wt.%. This enhancement is attributed to improved adhesion between the polypropylene matrix and DPF fibers due to PP-g-MA, which optimizes load transfer and stress distribution. However, fiber content exceeding 20 wt.% without sufficient PP-g-MA, causes a reduction in tensile strength, likely due to incomplete bonding within the matrix.

Figure 8b illustrates the effect of the weight percentages of date palm fiber (DPF) and the masterbatch on the tensile strength of the composite. The results indicate that increasing the DPF content from 10 wt.% to 20 wt.% improves tensile strength, reaching a maximum of 19.6 MPa at 20 wt.% DPF and 1 wt% masterbatch. However, a further increase in DPF content to 30 wt.% causes a decrease in tensile strength, likely due to fiber agglomeration and poor distribution within the matrix. Similarly, as the masterbatch content increases from 1 wt.% to 5 wt.%, tensile strength decreases significantly. This effect is more pronounced at higher DPF percentages, indicating that excessive masterbatch weakens the matrix-fiber bonding, leading to reduced mechanical performance.

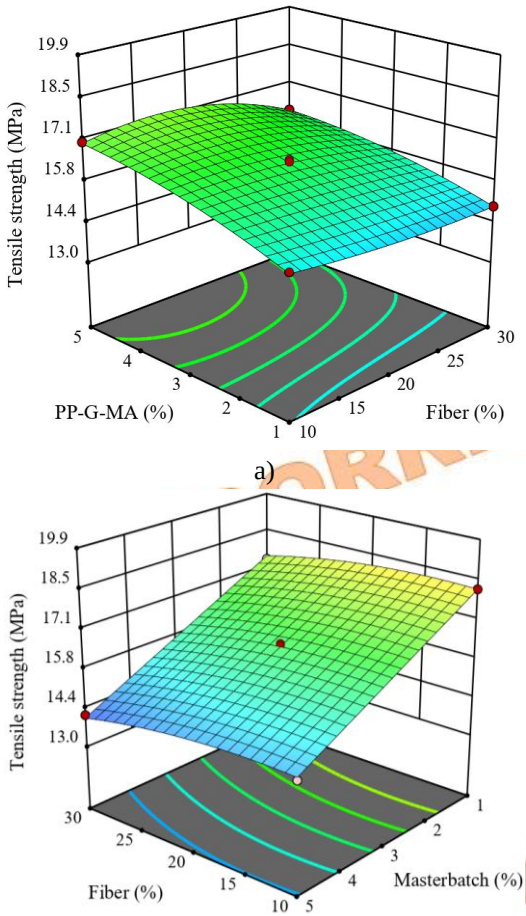


Fig. 8. a) Effect of weight percentage of date palm fibers and PP-G-MA on tensile strength. b) Effect of weight percentage of date palm fibers and masterbatch on tensile strength.

To address the incompatibility and lack of adhesion between PP and DPF, using a compatibilizer coupled with maleic anhydride can resolve these issues. [38] [39] [40]. The impact of PP-g-MA on the tensile strength and elastic modulus of the samples is illustrated in the bar chart in Figure 9. Although 1 wt.% of PP-g-MA in the composites increases the adhesion between the matrix and fibers, a concentration of 5 wt.%.% further enhances this adhesion, improving the overall compatibility. This increased adhesion between PP and DPF leads to better stress transfer from the matrix to the fibers, ultimately increasing the tensile strength. As a result, the tensile strength of the samples FGM-10-5-3, FGM-20-5-5, FGM-30-5-3, and FGM-20-5-1 is 10.89%, 7.89%, 8.34%, and 21.08% higher, respectively, compared to their counterparts with 1 wt.% PP-g-MA.

Figure 10 shows the effect of masterbatch in weight percentages ranging from 1 to 5 wt.%. As observed, in all cases, the tensile strength decreases as the masterbatch content increases, negatively affecting the tensile test results. For example, the tensile strength of FGM-20-1-1, which is 16.1848 MPa, decreases by 17.60% when the masterbatch is increased to 5 wt.%. In other samples, this reduction is even more pronounced. In samples FGM-10-3-1 and FGM-30-3-1, as the masterbatch content increases from 1 to 5 wt.%, the tensile strength decreases from 18.2087 MPa and 17.4516 MPa to 14.5852 MPa and 14.1474 MPa, respectively. The tensile strength of FGM-20-5-5 decreases by 31.97% compared to its counterpart with 1 wt.% masterbatch, marking the largest reduction in tensile strength among the samples. Figures 9 and 10 reveal that the optimal PP-g-MA content (5 wt.%) significantly enhances tensile strength by promoting better stress transfer between fibers and matrix, while excessive masterbatch content reduces tensile strength due to matrix softening.

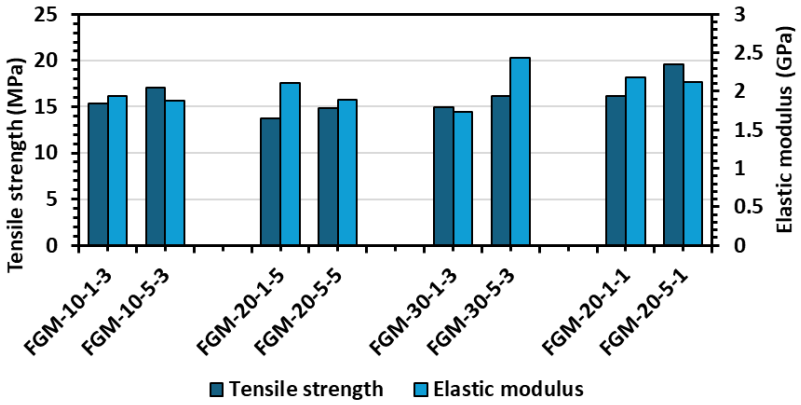


Fig. 9. The effect of PP-g-MA on tensile strength and elastic modulus at fixed percentages of DPF and masterbatch.

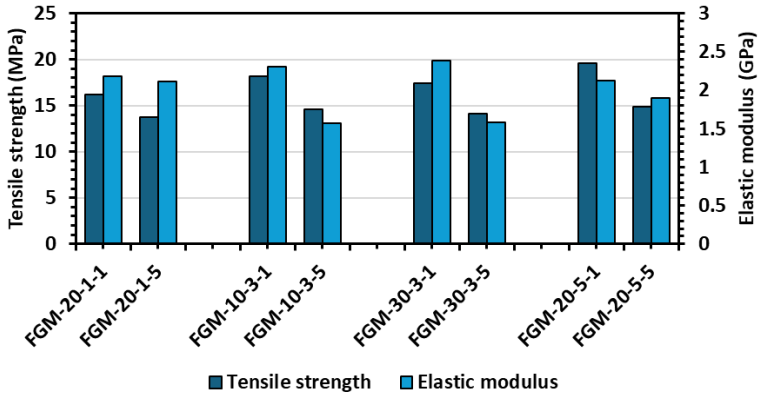


Fig. 10. The effect of masterbatch on tensile strength and elastic modulus at fixed percentages of DPF and PP-g-MA.

The sensitivity analysis chart for tensile strength, shown in Figure 11, demonstrates that increasing the weight percentage of PP-G-MA plays a decisive role in improving the tensile strength of polypropylene composites. The best results are obtained when the weight percentage of PP-G-MA is in the upper range (5 wt.%) and the DPF content is around 15-20 wt.%. On the other hand, the impact modifier masterbatch continuously and linearly reduces tensile strength.

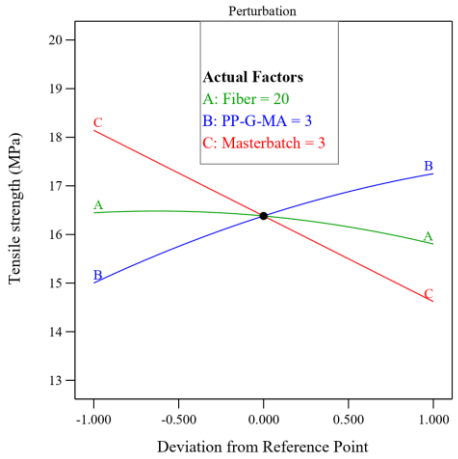


Fig. 11. Sensitivity analysis of parameters on the tensile strength.

4. Elastic Modulus

In Figure 12a, the combined effect of the weight percentage of DPFs and PP-G-MA on the elastic modulus is examined. Increasing the weight percentage of PP-G-MA from 1 to 5 wt.% clearly results in an increase in the elastic modulus from 1.57 GPa to 2.43 GPa at higher fiber percentages. However, the compatibilizer has little effect on the elastic modulus at lower fiber percentages. Additionally, when the PP-G-MA content is low, increasing the DPF weight percentage up to about 25 wt.% improves the elastic modulus, but at higher fiber contents (above 25 wt.%), the elastic modulus decreases to approximately 2 GPa. This suggests that an optimal combination of both factors can lead to better mechanical properties.

The elastic modulus of sample FMG-30-1-3 (1.73 GPa) is 10.56% lower than that of sample FMG-10-1-3, indicating that 1 wt.% PP-g-MA does not provide adequate adhesion for 30 wt.% fibers, leading to reduced stiffness [41]. The similar elastic modulus values in samples FMG-10-3-5 and FMG-30-3-5 (1.57 and 1.58 GPa, respectively) show that 3 wt.% PP-g-MA creates relatively stable stiffness in the samples. Furthermore, the results indicate that the elastic

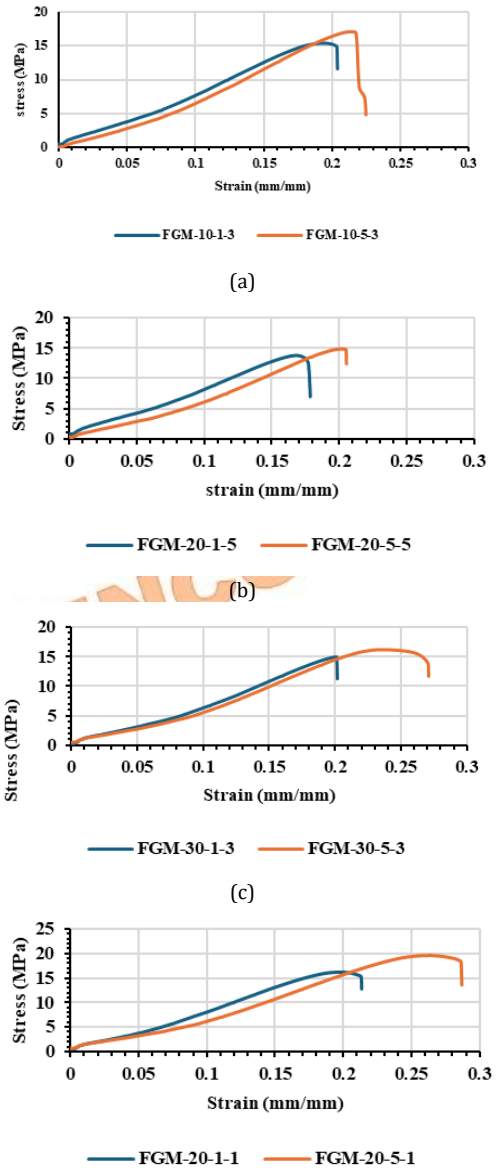


Fig. 13. Stress-strain diagrams of polypropylene/DPF composites at different PP-g-MA percentages.

modulus of FMG-30-5-3 is 29.35% higher than FMG-10-5-3, showing that 5 wt.% PP-g-MA has successfully enhanced adhesion for 30 wt.% fibers [42].

In Figure 12b, the effect of the weight percentage of DPF and masterbatch on the elastic modulus is evaluated. The results show that as the DPF content increases from 10 to 30 wt.% at low masterbatch percentages, the elastic modulus initially decreases but then rises. However, at higher masterbatch contents, the elastic modulus first increases, reaching a peak, and then declines.

The smallest reduction in elastic modulus is observed in sample FGM-20-1-1, which decreases by only 2.98% when the masterbatch content is increased to 5 wt.%. However, sample FGM-30-3-5 shows the largest reduction in elastic modulus compared to FGM-30-3-1, with a decrease of 50.15%. The reduction in the elastic modulus for samples FGM-10-3-5 and FGM-20-5-5 also falls between 2.98% and 50.15%. These findings suggest that the masterbatch used in this study softened the samples, reduced strength, and decreased compatibility between the matrix and the fibers, which can also be observed in the stress-strain curves of the samples in Figure 13.

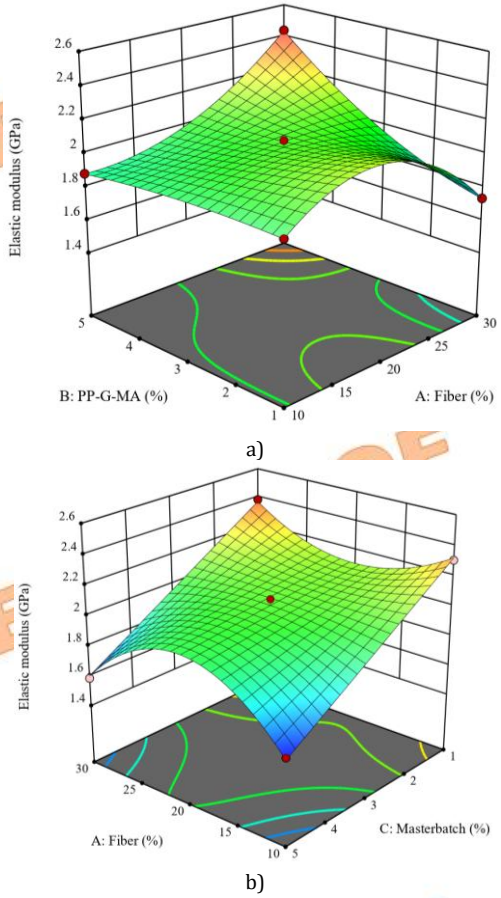


Fig. 12. a) Effect of DPF and PP-G-MA on the elastic modulus. b) Effect of DPF and masterbatch on the elastic modulus.

The sensitivity analysis chart for elastic modulus, shown in Figure 14, indicates that increasing the weight percentage of PP-G-MA plays a critical role in improving the elastic modulus of polypropylene composites. In general, the presence of PP-G-MA and the masterbatch reduces the elastic modulus, but as shown in Figure 15, the interaction between DPF and PP-G-MA increases the modulus at higher fiber and compatibilizer percentages. The best results are achieved when the PP-G-MA content is in the upper range (5 wt.%) and the DPF content is around 15-20 wt.%. On the other hand, the impact modifier masterbatch continuously and linearly reduces tensile strength.

Based on the results, increasing the fiber content within a specific range leads to an increase in elastic modulus, while higher amounts of masterbatch and PP-G-MA reduce the

modulus. However, in specific combinations of these parameters, mechanical property improvements were observed, suggesting an optimal point for each parameter. The findings from this research can assist in optimizing the production of PP composites reinforced with fibers and provide solutions for enhancing the mechanical properties of these materials.

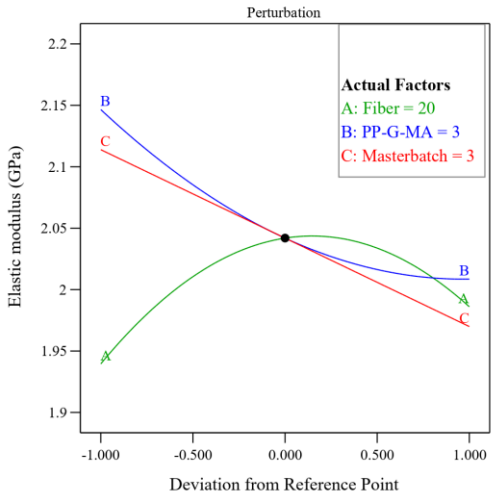


Fig. 14. Sensitivity analysis of parameters on the tensile modulus.

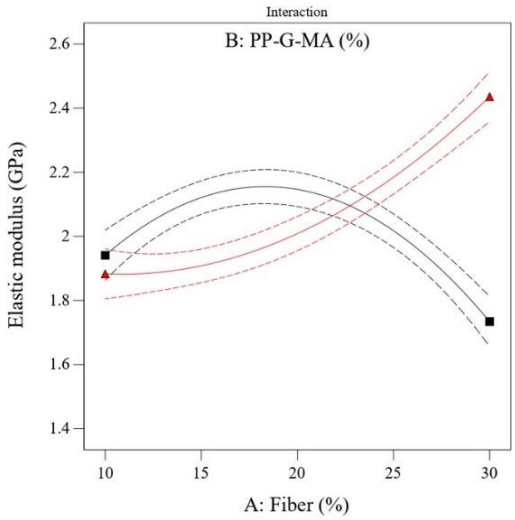


Fig. 15. Interaction between fiber percentage and compatibilizer on the elastic modulus response.

The findings of this study, particularly the enhanced mechanical properties achieved through the optimal combination of DPF and PP-g-MA, suggest promising applications for these composites in several industries. For instance:

In the automotive sector, components that require high tensile strength and stiffness, such as interior panels, door trims, and under-the-hood applications, could benefit from the lightweight and durable properties of PP/DPF composites. These materials not only reduce vehicle weight but also support sustainability goals by incorporating natural fibers.

In packaging, particularly for products that require high-impact resistance and strength, such as containers and crates, the addition of PP-g-MA compatibilizer in the composite enhances durability, which could extend the lifespan of packaging materials and reduce environmental impact through increased reusability.

In the construction industry, PP/DPF composites could be utilized in non-load-bearing structures, such as insulation panels and interior decorative elements, where improved impact resistance, stiffness, and tensile properties are critical. Additionally, the use of natural fibers like DPF aligns with the industry's push toward eco-friendly building materials.

5. Conclusions

This study investigated the mechanical properties of PP composites reinforced with DPF and compatibilized with PP-g-MA, incorporating an impact-modifying masterbatch. Using a design of experiments approach, the study identified optimal material compositions for enhanced tensile strength and elastic modulus. The key findings are as follows:

- The tensile strength of the composite increased by up to 21.08% compared to pure PP, reaching a maximum value of 19.6 MPa at 20 wt.% DPF, 5 wt.% PP-g-MA, and 1 wt.% masterbatch.
- The elastic modulus showed a maximum improvement of 2.43GPa, representing an increase of 54.78% from lower percentages of PP-g-MA.
- While enhancing impact resistance, it caused a reduction of tensile strength by 31.97% at higher levels (5 wt.%), showing the highest decrease in strength, indicating the need for optimization in impact-enhancing formulations.
- DPF at 15-20 wt.% concentration led to the highest mechanical properties. Tensile strength improved by 19.6 MPa, and elastic modulus was optimized at 2.43 GPa.
- However, DPF at 30 wt.% resulted in slightly reduced mechanical properties, suggesting that fiber distribution and interaction with the matrix at higher percentages may lead to agglomeration, reducing composite performance.
- The interaction between PP-g-MA and masterbatch was crucial in optimizing mechanical properties, with the best results seen when both were used at their upper limits.
- The highest tensile strength reached 19.6 MPa, while elastic modulus peaked at 2.43 GPa, showing a clear correlation between optimized material ratios and performance.

- The elastic modulus improved by 54.78%, reaching 2.43 GPa at 30 wt.% DPF, 5 wt.% PP-g-MA, and 3 wt.% masterbatch.
- The masterbatch enhanced impact resistance but reduced tensile strength by up to 31.97% at higher concentrations (5 wt.%) compared to compositions with 1 wt.% masterbatch.
- Optimal mechanical performance was achieved at 20 wt.% DPF, 5 wt.% PP-g-MA, and 1 wt.% masterbatch, striking a balance between tensile strength (19.6 MPa) and elastic modulus (2.12 GPa).
- Higher DPF content (30 wt.%) led to reduced mechanical properties, likely due to fiber agglomeration and uneven distribution in the matrix.

6. Ethics Approval and Consent to Participate

The authors provided informed consent to enrolment in the study.

7. Consent for Publication

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8. Availability of Data and Materials

The data supporting the outcomes of this study are available based on request from the corresponding author.

9. Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

10.Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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