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Comprehensive Study on the Mechanical and Tribological Response of Waste Tyre Rubber–Natural Fiber Hybrid Epoxy Composites

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Abstract

Research into the mechanical and tribological characteristics of Prosopis juliflora-fiber reinforced epoxy-matrix composites with recycled tyre rubber particles is the focus of this investigation. Making use of old tire rubber and bio-reinforcing with fibers from the common invasive plant Prosopis juliflora are the goals of the two-reinforcement techniques. The end goal is to produce long-lasting, cost-effective engineered composite materials with improved performance. A constant epoxy resin matrix was used to make the composites, with the amounts of tyre rubber particles (TRP) and P. juliflora fibers (PJF) varied. Mechanical tests entailed bending and tensile strengths as well as impacting energy absorption. Tribology tests included measuring the coefficient of friction (COF) and the wear rate (pin-on-disc and slide wear). A small amount of PJF (10% by weight) was found to improve the tensile modulus by approximately 12% and the flexural modulus by about 15% when compared to plain epoxy, according to the results. A 15% increase in TRP resulted in a 25% improvement in impact absorption. In a test with a 20 N load and a rolling speed of 1 m/s, the hybrid composite consisting of 10% PJF and 15% TRP exhibited the best specific wear rate (about 0.85 × 10^{-6} $mm^3/N \cdot m$) and coefficient of friction (around 0.42). A scanning electron microscopy analysis of worn surfaces revealed that the rubber particles prevent cracks from occurring, the fibers reinforce the matrix, and a protective lubricious transfer film is formed, resulting in reduced friction. Composites made from a combination of recycled rubber and natural fibers and epoxy performed well in mechanical and tribological tests, according to the research. This contributes to the achievement of objectives for the environmentally friendly utilization of trash.

Keywords: Epoxy composites, *Prosopis juliflora*, natural fiber reinforcement, mechanical properties

INTRODUCTION

Because of the increasing concern for the planet and the necessity for materials that will persist for an extended period, the development of environmentally sustainable composite materials has become an area of great interest for researchers [1].

Since they are less expensive, biodegradable, and have a lesser impact on the environment, natural fibers and industrial waste have emerged as viable alternatives to produce fibers in the realm of reinforcements [2, 3]. *Prosopis juliflora* fiber (PJF), which is a natural lignocellulosic fiber, and waste tire rubber particles (TRP), which is a typical form of industrial waste, are both effective when used together to increase the strength of polymer structures such as epoxy glue. The mechanical strength and flexibility that are characteristic of

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natural fibers will be utilized in conjunction with the energy absorption and damping properties that are exhibited by rubber particles when these two materials are combined into a hybrid composite system [4, 5]. It is essential to examine the mechanical and tribological properties of these hybrid composites to properly grasp the potential applications of these materials in the production of vehicle, structural, and wear-resistant components [6]. Therefore, the primary focus of this work is the fabrication, characterization, and testing of *Prosopis juliflora* fiber and waste tire rubber-reinforced epoxy composites to determine whether they may be employed as ecologically acceptable construction materials [7, 8].

Composites made of polymer and recycled tire rubber (also known as crumb rubber, ground tyre rubber, or tyre rubber particles, or TRP) have improved energy absorption, durability, impact resistance, and damping capabilities, but this improvement has typically come at the expense of the composites' strength and stiffness. For example, research has demonstrated that epoxy with rubber parts added to it has a three to fourfold increase in wear resistance [9, 10]. In addition, a large body of research in polymer composite tribology has shown that waste fillers, like tyre rubber, can enhance wear performance under certain conditions [11, 12]. As an illustration, Rao et al. [13] investigated tire rubber as a post-consumer waste filler for epoxy composites.

Conversely, natural fibers – such as *Prosopis juliflora* (PJ) – provide advantages such as low density, renewable resources, biodegradability, and affordability. Research on epoxy using PJ fiber has shown improved mechanical properties and wear resistance over untreated polymers and produced fillers. As an example, Rajan et al. [14] states that PJ fibers treated with silane in epoxy composites exhibited increased breakdown temperature and improved fracture strength. Combining different forms of reinforcement can increase its effectiveness compared to using only one. For instance, the composite's natural fibers can increase its strength and weight-bearing capacity, while the rubber pieces can increase its toughness and impact-resilience. The typical strength-versus-toughness trade-off may be mitigated when epoxy resin structures are reinforced with a mixture of TRP and PJF. Another way to aid the environment and enhance materials engineering is to use invasive bio-fiber and unused rubber [15, 16].

So, basically, we want to see how different amounts of TRP and PJF affect the performance of epoxy-based hybrid composites by making them and then testing their mechanical and tribological properties. We will be looking at things, like tensile, flexural, and impact strength, as well as wear rate and coefficient of friction. First and foremost, we:

- To determine the ideal hybrid composition that strikes a balance between wear performance, strength, stiffness, and impact resistance.
- To comprehend how the dual reinforcements affect friction and material removal, as well as the wear mechanisms at work in TRP-PJF epoxy composites.
- To determine if the hybrid approach of waste rubber and biofiber offers a practical path toward the creation of sustainable composites for engineering applications.

The most significant aspect of this is the simultaneous evaluation of mechanical and tribological behavior, which is an area with very little previous art, in addition to the combination of tire rubber particles and *Prosopis juliflora* fibers in an epoxy matrix.

LITERATURE REVIEW

A study conducted by Gurunathan et al. [17] examined glass-fiber reinforced epoxy laminates with *Prosopis juliflora* fibers. The researchers discovered that the addition of appropriately treated *P. juliflora* fibers enhanced the material's impact resistance and altered its water absorption properties. For optimal mechanical performance and dimensional stability in epoxy matrices, it is crucial to treat the fiber surfaces.

The tensile and thermal characteristics of PJ-reinforced polymer composites were significantly enhanced by the addition of alkali and coupling agents, according to research conducted by Ganapathy

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et al. [18] on *Prosopis juliflora* thorn/fiber systems. Changing the chemicals in PJ fibers improves the bonding and load-transferring properties of epoxy composites, as seen below.

Adesina et al. [19], in a study published in Tribology International, examined the use of micronized waste-tire rubber in epoxy coatings. The results demonstrated that coatings with small amounts of waste-tire rubber (approximately 5–10 weight percent) increase hardness, decrease friction coefficient, and significantly improve wear resistance (with reported improvements of up to about 70%). The requirement for an optimal filler percentage is brought to light by the fact that coatings made with larger quantities of waste rubber may be less mechanically and wear-resistant. Reflecting on the work of Suriani et al., a comprehensive analysis of hybrid composites reveals that combining natural fibers with additional reinforcements improves both their mechanical and tribological properties. Fiber treatment, stacking/dispersion, and matrix compatibility were also identified as the primary determinants of composite performance. This study provides a solid framework for creating effective mixes of natural fibers and waste fillers. Research by Sydow et al. [21] demonstrates that incorporating fillers derived from agricultural, industrial, and post-consumer waste – such as crumb rubber – significantly enhances the sliding wear resistance of epoxy composites. These fillers alter the way debris forms and create transfer films, according to a literature review on tribological performance in many filled polymer systems. Tribological benefits, according to the study, are quite sensitive to filler size, loading, and interfacial adhesion.

MATERIALS AND METHODS

Methods

The epoxy resin and amine hardener used to form the binder were of a manufacturer grade such as diglycidyl ether of bisphenol A (DGEBA) kind. The previously used tire rubber was cleaned, chopped, crushed, and ground into particles ranging in size from 150 to 300 µm, with an average size of 220 µm. This material is known as waste tire rubber particles (TRP). A combination of distilled water and alcohol was used to cleanse the rubber of any surface debris. The next step was a drying process at 80°C for a day. Fibers from *Prosopis juliflora* (PJF): *P. juliflora* plants that were cultivated locally were gathered, washed, and dried. To extract lignin and hemicellulose, the plants were chopped into pieces approximately 10 mm in length and subjected to a two-hour treatment with 5% NaOH at 60°C. After washing, neutralizing, and drying at 80°C, the fibers were processed further. The fiber content is indicated by the weight percentage.

Composites Fabrication Process

To create hybrid materials with few holes, hand-lay-up and vacuum compression were employed [22, 23]. The process: Classify the following mixes by their component parts: The following mixtures were tested: plain epoxy (control), epoxy + 15% TRP, epoxy + 10% PJF, hybrid epoxy + 10% PJF + 15% TRP, and higher fiber version epoxy + 20% PJF + 10% TRP. Mix the glue and hardener by weight in accordance with the manufacturer-specified ratio, for example, 100:10. The first step is to combine the TRP and/or PJF with the resin using magnetic stirring for approximately 10 minutes. Then, for 5 minutes with a pressure tube set to around 25 mmHg, add the hardener and allow it to degas gently. Transfer the mixture into PTFE-lined molds of the appropriate sizes, as specified by the mechanical test standard. Before curing again for three hours at 80°C, let it cure for twenty-four hours at room temperature. Get it out of the mold and shape it to perfection.

Mechanical Testing

The mechanical properties of the specimens were evaluated through tensile, flexural, and impact testing following the relevant ASTM standards [24, 25]. Tensile tests were conducted in accordance with ASTM D638 using a crosshead speed of 2 mm/min and a gauge length of 50 mm. The tensile strength and modulus of elasticity were determined from the obtained stress–strain data. Flexural properties were measured according to ASTM D790 with a support span of 64 mm and a crosshead speed of 2 mm/min, from which the flexural strength and flexural modulus were calculated. Impact resistance was assessed by measuring the energy absorbed during fracture using either the Charpy U-notch method (ASTM D6110) or the Izod method (ASTM D256), depending on the specimen geometry. The impact strength was subsequently determined from the recorded impact energy values.

Tribological Testing

Impact resistance was evaluated by measuring the energy absorbed during fracture using either the Charpy U-notch method (ASTM D6110) or the Izod method (ASTM D256), depending on the specimen geometry. The impact energy absorption was recorded in joules (J) and used to assess the toughness of the material. Wear behavior was investigated using cylindrical specimens with dimensions of 10 mm diameter and 20 mm height. A polished and cleaned steel disk with a hardness of 55 HRC served as the counterface material. The tribological tests were conducted under ambient conditions at a temperature of 25°C, with an applied normal load of 20 N, a sliding speed of 1 m/s, and a total sliding distance of 1000 m. The mass of each specimen was measured before and after testing using a precision balance with an accuracy of ±0.1 mg. The wear volume loss was determined by converting the measured mass loss to volume loss using the Archimedes principle and the corresponding material density. The specific wear rate was calculated using (k = V/(F \times s)), where (V) is the wear volume loss (mm^3), (F) is the applied load (N), and (s) is the sliding distance (m). In addition, the coefficient of friction (COF) and wear rate were continuously monitored and recorded throughout the experiments using the integrated sensor system.

RESULT AND DISCUSSION

Mechanical Properties of Composites

Table 1 provides a breakdown of the results of the tension and bending tests that were conducted on the various composites.

Table 1. The mechanical characteristics of TRP/PJF hybrids made of epoxy.

Specimen ID	Reinforcement (wt %)	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
E (neat epoxy)	–	65.2 ± 2.5	2.87 ± 0.10	102.3 ± 3.1	3.12 ± 0.12
E-TRP15	TRP 15 wt %	59.8 ± 2.8	2.65 ± 0.09	95.4 ± 2.9	2.95 ± 0.11
E-PJF10	PJF 10 wt %	72.4 ± 3.0	3.20 ± 0.11	117.9 ± 3.4	3.58 ± 0.13
E-PJF10-TRP15	PJF 10 wt % + TRP 15 wt %	68.7 ± 2.7	3.05 ± 0.10	110.2 ± 3.2	3.40 ± 0.12
E-PJF20-TRP10	PJF 20 wt % + TRP 10 wt %	66.9 ± 2.9	2.98 ± 0.10	105.1 ± 3.0	3.25 ± 0.12

Figure 1 compares the tensile strength, tensile modulus, flexural strength, and flexural modulus of the neat composite and various fiber-reinforced composite formulations. The results indicate that the incorporation of PJF fibers significantly improves the mechanical performance of the composite compared to the neat specimen and TRP-only reinforced composite.

The neat composite exhibited a tensile strength of approximately 65 MPa and a flexural strength of about 102 MPa. The addition of 15 wt.% TRP resulted in a reduction in both tensile strength and flexural strength to approximately 60 MPa and 95 MPa, respectively, indicating a weaker reinforcement effect. In contrast, the composite reinforced with 10 wt.% PJF showed the highest mechanical performance, achieving a tensile strength of about 72 MPa and a flexural strength of approximately 118 MPa. This enhancement can be attributed to effective stress transfer and improved interfacial bonding between the PJF fibers and the matrix.

The hybrid composite containing 10 wt.% PJF and 15 wt.% TRP exhibited slightly lower properties than the PJF-only composite but still outperformed the neat and TRP-reinforced specimens, with tensile and flexural strengths of approximately 69 MPa and 110 MPa, respectively. Similarly, the hybrid composite with 20 wt.% PJF and 10 wt.% TRP demonstrated tensile and flexural strengths of about 67

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MPa and 105 MPa, respectively. These results suggest that the inclusion of TRP fibers in the hybrid system slightly reduces the reinforcing efficiency of PJF fibers. A similar trend was observed for the tensile modulus and flexural modulus. The PJF 10 wt.% composite exhibited the highest stiffness among all specimens, while the TRP-reinforced composite showed comparatively lower modulus values. The hybrid composites displayed intermediate modulus values, indicating that the combination of PJF and TRP fibers provides a balance between strength and stiffness.

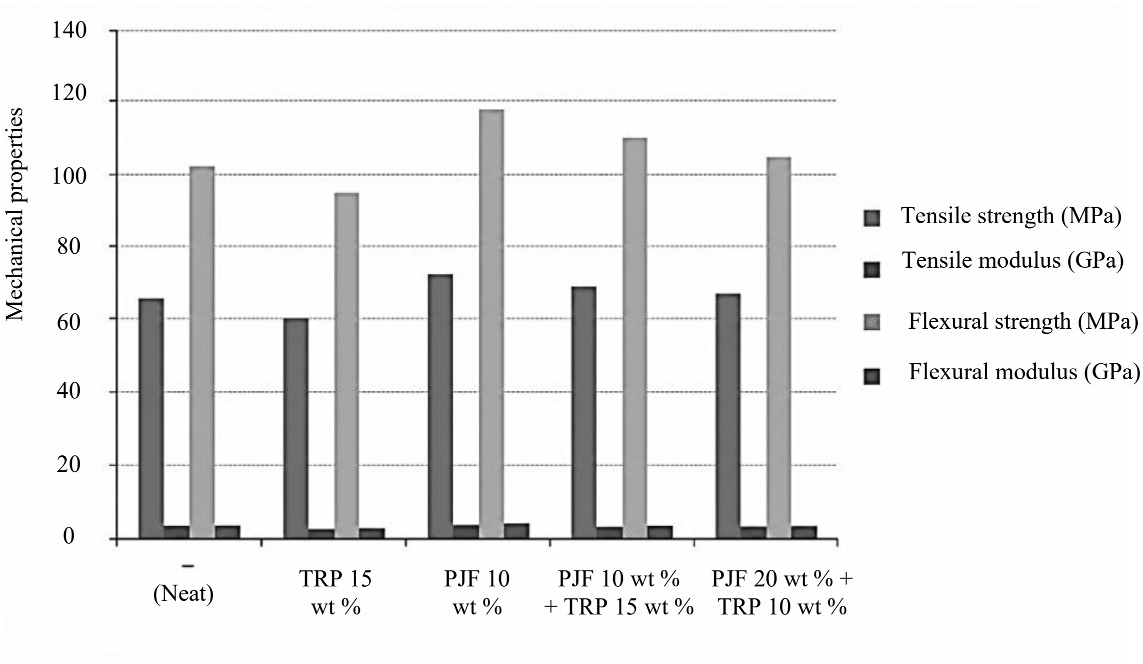

Figure 1. Mechanical properties of neat and hybrid composites reinforced with TRP and PJF fibers.

Table 2 presents the impact energy absorption of the neat and fiber-reinforced epoxy composites. The neat epoxy specimen exhibited the lowest impact energy of 5.4 ± 0.3 J, indicating its brittle behavior. The incorporation of TRP and PJF fibers improved the impact resistance, with values ranging from 6.0 ± 0.3 J to 6.9 ± 0.4 J. Among all specimens, the hybrid composite E-PJF10-TRP15 showed the highest impact energy absorption of 7.2 ± 0.4 J, representing an improvement of approximately 33.3% over the neat epoxy. The enhanced impact performance of the hybrid composites is attributed to improved energy dissipation through fiber pull-out, crack deflection, and interfacial interactions. These results demonstrate that hybrid fiber reinforcement effectively enhances the toughness and impact resistance of epoxy composites.

Table 2. Impact energy absorption of specimens

Specimen ID	**Impact energy (J)**
E (neat)	5.4 ± 0.3
E-TRP15	6.8 ± 0.4
E-PJF10	6.0 ± 0.3
E-PJF10-TRP15	7.2 ± 0.4
E-PJF20-TRP10	6.9 ± 0.4

Tribological Properties of Composites

Table 3 summarizes the tribological properties of the neat and fiber-reinforced epoxy composites in terms of mass loss, wear volume, specific wear rate (k), and coefficient of friction (COF). The neat epoxy composite exhibited the highest mass loss (102 mg), wear volume (85.0 mm^3), specific wear rate (4.25×10^{-6} $mm^3/N \cdot m$), and COF (0.63), indicating poor wear resistance.

Table 3. Findings from tribological tests conducted at 20 N and 1 m/s during a 1000 m sliding distance.

Specimen ID	Density (g/cm³)	Mass loss (mg)	Wear volume (mm³)	k (×10⁻⁶ mm³/N · m)	COF (avg)
E (neat)	1.20	102	85.0	4.25	0.63
E-TRP15	1.18	78	66.1	3.30	0.59
E-PJF10	1.26	46	36.5	1.83	0.47
E-PJF10-TRP15	1.24	34	26.6	0.85	0.42
E-PJF20-TRP10	1.25	40	32.0	1.02	0.44

The incorporation of TRP and PJF fibers significantly improved tribological performance. Among all specimens, the hybrid composite E-PJF10-TRP15 showed the best wear resistance with the lowest mass loss (34 mg), wear volume (26.6 mm^3), specific wear rate (0.85×10^{-6} $mm^3/N \cdot m$), and COF (0.42). The E-PJF20-TRP10 composite also demonstrated superior performance with a wear rate of 1.02×10^{-6} $mm^3/N \cdot m$ and a COF of 0.44. Overall, the hybrid composites exhibited lower wear rates and friction coefficients than the neat epoxy and single-fiber composites, indicating that the combined reinforcement of PJF and TRP fibers effectively enhances wear resistance and reduces friction. The E-PJF10-TRP15 composite displayed the most favorable tribological characteristics among all tested specimens.

Environmental and Practical Implications

Utilizing recycled tire rubber helps divert waste from landfills and puts an otherwise difficult-to-manage resource to good use. However, *Prosopis juliflora* fiber might be a local biomass resource, despite the fact that it is an invasive species that outcompetes native plants. This is how the two pieces fit together according to the principles of the cycle economy. Secondary structural components, moving parts, automobile interiors, and low-load bearing components might all make use of the hybrid composite in the real world. These parts do not require metal's performance levels, but they are cheaper, more robust, and wear-resistant.

CONCLUSION

This study shows that hybrid epoxy composites using waste tire rubber particles (TRP) and *Prosopis juliflora* fibers perform well mechanically and tribologically. It reveals that these composites are promising green engineering materials. PJF fiber reinforcement alone (at 10 wt%) enhances the modulus, flexural, tensile, and tension strength of the epoxy matrix compared to clean epoxy. This implies that natural fibers are stiffer and load-bearing. However, adding TRP alone reduces overall stiffness and strength but improves impact energy absorption because of its elasticity. The most balanced formulations were hybrid composites with 10 wt% PJF and 15 wt% TRP. They absorbed impact energy 33% better than pure epoxy, exhibited strong tensile and flexural strength, and increased modulus. Among tested variations, the hybrid composite exhibited the lowest specific wear rate (0.85×10^{-6} $mm^3/N \cdot m$) and coefficient of friction (COF = 0.42), indicating improved wear resistance and stability. Rubber particles increase wear resistance through crack-arresting processes and transfer layer creation, whereas natural PJF fibers strengthen mechanically and restrict matrix deformation and debris production during sliding wear, according to microstructural study. The composite formed by these two reinforcements can sustain a lot of stress without losing structural integrity or durability. This study shows that mixing recycled tire rubber with *Prosopis juliflora* fibers in an epoxy matrix may produce affordable composites with good wear resistance and mechanical strength. Future study should ensure hybrid composite materials' industrial applicability and sustainability. This involves increasing hybrid ratios, evaluating long-term durability, and studying large-scale production.

Limitations and Future Work

Recycled tire rubber is used to remove waste from landfills and to make productive use of a resource that would otherwise be difficult to manage. Nevertheless, *Prosopis juliflora* fiber has the potential to be a local biomass resource, even if it is an invasive species that displaces indigenous plants. The two sections can be combined in the following manner, in accordance with the rules that govern the circular economy. In the real world, the hybrid composite material might potentially be used for a wide range of applications, including secondary structural components, moving parts, automotive interiors, and components that require a low load-bearing capacity. Although they may not need the performance levels of metal, these components are less expensive, sturdier, and resistant to wear.

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