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Research Article

Development and Characterization of Epoxy Composites Reinforced with Banana Peel Powder and Jute Fiber

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Abstract: Eco-friendly and sustainable composites materials have become a topic of great interest in the development of structural materials. Epoxy-based materials have been widely used for their inherent properties. However, thermal instability and the non-biodegradability are the main drawbacks of epoxy. This study incorporates natural fillers into the epoxy matrix with an aim to make them partially biodegradable while enhancing their mechanical and thermal properties. Banana peel powder-epoxy composites and jute fiber-epoxy composites of varying concentrations as well as a hybrid composite comprising of their best single filler loadings were fabricated using solution casting method. The optimum loadings for banana peel powder composites and jute fiber composites were determined to be 20 wt.% and 5 wt.% respectively as the maximum tensile strength of 27 MPa and 21.64 MPa and maximum flexural strength of 43.66 MPa and 42.06 MPa were observed respectively. The hybrid composite displayed both a higher tensile strength of 30.32 MPa and flexural strength of 44.5 MPa. The hardness was increased by increasing filler content up to a certain amount. The hybrid composite, however, displayed the lowest hardness value of 59.78 even compared to blank epoxy (68.11) making it more resilient and less likely to fail catastrophically. The hybrid composite also maintained an intermediary thermal stability among the samples. Water absorption of the hybrid composite was likewise intermediate but exhibited greater deterioration in soil.

Keywords: Epoxy Composite, Agro-Waste Filler, Hybrid Natural Reinforcement, Jute Fiber, Banana Peel Powder, Hardness.

1. INTRODUCTION

Biodegradable composites are a class of materials developed through innovative and ecologically conscious techniques of materials engineering that integrate sustainability, environmental responsibility, and technical performance. The potential of these composites made up of two or more materials with at least one biodegradable component, to break down into innocuous components while maintaining their mechanical, thermal, and functional qualities has drawn interest from a variety of industries [1]. The accumulation of plastic waste and environmental deterioration can be addressed with the use of these biodegradable composites. Currently, just 9% of plastic garbage is recycled, and 12 billion metric tonnes are predicted to wind up in landfills or marine areas by 2050. This is because the production of plastic waste is expected to quadruple over the next 20 years, posing a serious environmental threat [2-4]. Epoxy polymers, accounting for 7.1% of the world's plastic production in 2021, are crucial for creating fiber-reinforced polymers. These versatile synthetic polymers, known for their adhesive, mechanical, and electrical properties, are widely used in various industries. They distinguish themselves from conventional thermosetting polymers due to their unique attributes [5].

The biodegradability of epoxy resin is a significant issue as they can remain in the environment for extended periods if not handled properly [6]. As non-biodegradable epoxy-based

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composites worsen the problem of plastic waste; biodegradable composites are needed to address this issue [7]. Epoxy resins are often modified with fillers and additives like carbon nanotubes, plasticizers, reactive oligomeric compounds, low molecular weight polymers, and nanoparticles to enhance composite performance. Fibers, organic or inorganic, are crucial reinforcing elements in various applications [8]. Factors like fiber surface properties, length, modulus of elasticity, and material composition are essential for increasing tensile capacity [9]. The remarkable qualities of steel, glass, propylene, and carbon fibers made them the focus of research. However, these synthetic fibers have disadvantages such as increased stiffness, environmental impact, scarcity, and high costs. There are others who argue for natural fibers because they are inexpensive, easily accessible, environmentally friendly, and can occasionally lessen stiffness in certain composite applications [10].

As of today, many studies have utilized several kinds of reinforcements within the epoxy matrix to produce composites with comparable if not better mechanical, thermal and degradation characteristics. Ranjan *et al.* [11] created biodegradable epoxy composites using rice straw fibers, both treated and untreated as reinforcement. It was observed that while both type of fibers had increased strength than blank epoxy, the composite with rice straws treated with NaOH yielded the maximum strength. Treated and untreated kenaf fibers were also introduced in epoxy matrices, where the composite laminate with NaOH alkali treated kenaf fiber yielded superior thermal stability and less degradation, suitable for aerospace and automobile applications [12]. Similarly, epoxy-based composite with chemically treated luffa fiber showed better suitability for medium load structural applications as opposed to using untreated fibers [13]. Raghav *et al.* [14] extracted cellulose nanofibers from red coconut peduncle waste to reinforce epoxy sheets, producing composites with enhanced mechanical and thermal properties. Similarly, Yusuf *et al.* [15] extracted cellulose nanofibers albeit from a different source of oil palm produced epoxy-based composites with significantly improved mechanical properties and marginal decrement of thermal parameters. Several studies have utilized more than one reinforcement to produce hybrid epoxy-based composites. Shariff *et al.* [16] reinforced epoxy matrix with boron nitride or alumina with *Millettia pinnata* leaf powder and glass sheets. The observed increase of mechanical properties through this study opened the door for potential industrial applications of epoxy-based hybrid composites. Zeleke *et al.* [17] utilized sisal and glass fiber to create an epoxy hybrid composite that showed better mechanical strength than when only one of the reinforcements was introduced into the matrix. Arpitha *et al.* [18] incorporated sugarcane bagasse along with alumina micro fillers within an epoxy matrix which resulted in an increase in physical, thermal as well as mechanical properties. Ashok *et al.* [19] incorporated raw jute fibers and banana fibers in several weight ratios within epoxy and concluded that a 1:1 ratio of jute-banana fiber resulted in an improved mechanical and thermal properties with significant reduction in water absorption. Another study conducted utilized banana fiber and glass fiber as reinforcements in epoxy-based hybrid composites that were deemed suitable for lightweight structural and automobile applications [20]. Moreover, a separate study found hybrid composites composed of hybridized banana, jute, glass, and carbon fiber in epoxy resin matrix yielded lightweight materials with enhanced mechanical properties that are suitable for high-speed vehicles [21]. Corncob bio-waste and boron nitride particles were also introduced into epoxy matrices to produced hybrid composites with 2 to 3 time more tensile strength, suitable for lightweight applications [22]. Natural fiber-reinforced epoxy composites made from jute and powdered banana peels show promise in achieving a balance between biodegradability, sustainability, and performance [23].

Basalt, sisal, coconut, bagasse, hemp, jute, and banana peel have all been shown to improve the compressive and tensile strength of composite materials [24]. By incorporating these chopped natural fiber reinforcements, the composite's ability to absorb energy is increased, resulting in the transformation of brittle materials into more ductile ones. Furthermore, the application of continuous fiber reinforcement has resulted in the creation of a new class of building materials with enhanced ductility and tensile strength [2]. As reinforcing agents, natural fibers fill in the gaps in the matrix and transfer stress into it. Furthermore, the development of microcracks in composite materials is successfully prevented [25]. The natural plant-based fiber that is jute, also called the "Golden Fiber", is produced from the stems of the

Corchorus plant, which is grown readily in tropical places like Bangladesh and India with little fertilizer or pesticides [26, 27]. Biodegradable polymers and composites made of jute have been made possible by advancements in response to consumer demand for environmentally friendly products [28]. The remarkable tensile strength of jute fiber is one of its noteworthy features. Owing to its well-known durability, it can be used in a variety of contexts, such as construction, packaging, and textiles. It is especially useful when making durable sacks and bags to package agricultural goods. The peel of a banana has many uses and advantages, ranging from use in cooking to sustainable practices. In order to improve qualities of a polymer or resin for a variety of applications, dried and processed banana peels are mixed with a matrix material to make composite materials. Unripe banana peels have more fiber than ripe bananas do. When added to the matrix, the fiber can improve the material's overall performance, strength, durability which becomes more resilient to stress and deformation [1]. Because these peels naturally decompose over time, they lower pollution levels and promote a circular economy. Moreover, their affordability and abundance make this composite a cost-effective option in comparison to other synthetic substitutes [29].

The research aims to create biodegradable composites using jute fibers and banana peel powder, addressing the growing demand for environmentally friendly alternatives to traditional composites. It explores the use of natural fiber-reinforced epoxy composites, balancing engineering needs with environmental considerations, and contributes to the evolving field of materials science and engineering, where performance and sustainability can coexist. Although various studies have been conducted on the individual reinforcement of banana peel powder or jute fiber inside an epoxy matrix, research on a hybrid composite including both fillers simultaneously, focusing not only on the enhancement of strength but also increasing durability through reduction of hardness remain unexplored. The purpose of this work is to first optimise the loading of banana peel powder and jute fiber powder into epoxy-based composites. Next, a hybrid composite with the ideal loading of both fillers would be fabricated, and its properties would be compared to those of plain epoxy and the individual composites.

2. MATERIALS AND METHODS

2.1. Materials

Raw unripe bananas and raw jute collected from the local store were used for this study. For the matrix and hardener, Bisphenol A Diglycidyl Ether (BADGE) and diethylene triamine were used respectively. To make the mold, glass and aluminum foil were utilized while using petroleum Vaseline as the releasing agent.

2.2. Methodology

The process of making banana peel powder is given in Figure 1. Firstly, the peels were carefully removed from the bananas and thoroughly washed with distilled water to remove any dust or impurities. Subsequently, the banana peels were cut into small pieces and placed in an oven to dry for 24 hours at 60 °C. After the drying process, the peels were ground into a fine powder using a grinder. The resulting powder was sifted through a 1 mm sieve net multiple times to get the desired banana peel powder with average particle size less than or equal 1 mm. The process is analogous to previous similar studies [30, 31].

Figure 2 shows the making process of jute fiber. First, long jute fibers were separated from each other, cut into 6-inch lengths and thoroughly washed with distilled water. Then the jute fibers were treated with 1% NaOH solution, leaving them to soak within the solution for 1 hour, to ensure all fibers were fully submerged [32]. After that the fibers were removed from the solution and washed multiple times with distilled water to eliminate any remaining NaOH. The treated jute fibers were then placed in an oven and dried for 8 hours at 70 °C. Once dried, the jute fibers were meticulously separated and cut into approximately 10 mm lengths and the jute fibers were ready for use as reinforcement in epoxy composites [10, 32].

A glass measuring 20 inches in length, 16 inches in width, and 0.118 inches in thickness was used as the mold base. A transparent Rexene cloth was wiped with acetone and then affixed to the glass using Scotch tape. Four glass pieces, each 6 inches in length, 1 inch in width, and 0.236 inches in thickness, were selected and covered with aluminum foil. These wrapped glass pieces were

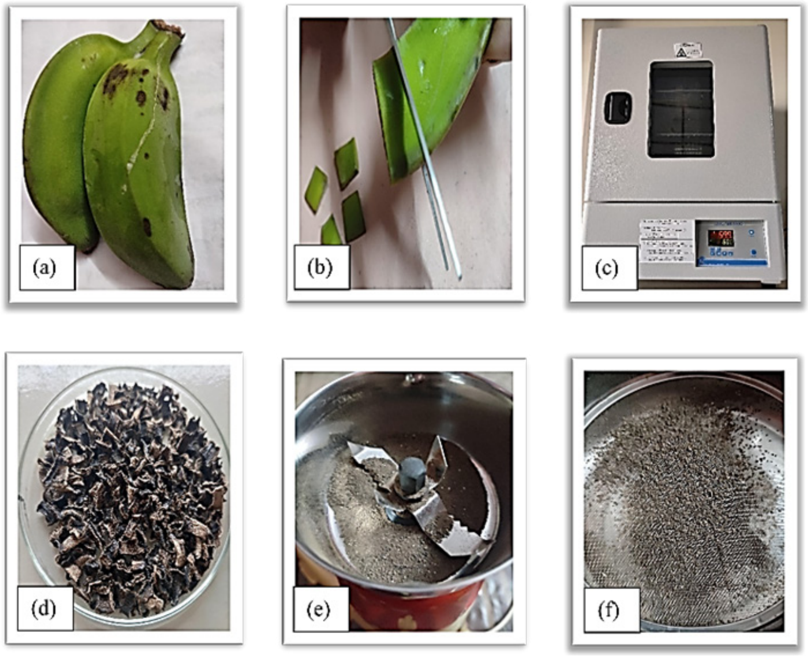

Fig. 1. Making banana peel powder, (a) Raw unripe banana, (b) Cutting banana peel, (c) Drying in oven, (d) Dried banana peel, (e) Grinding of banana peel, and (f) Sieving of powder.

Fig. 2. Jute fiber treatment, (a) Jute fiber cut into 6 inches, (b) Washing jute, (c) Weighing NaOH, (d) Jute soaked in NaOH, (e) Drying in oven, and (f) Cut into 10mm.

securely fastened together in a rectangular shape on top of the base glass using scotch tape to create the mold. A small amount of petroleum Vaseline was applied to the mold as a releasing agent [33].

To prepare the blank epoxy, a ratio of 3:1 epoxy and hardener were carefully measured, placed in a plastic cup and thoroughly mixed for 5 minutes using a popsicle stick. The epoxy-hardener mixture was subsequently poured into the glass mold. To release initial bubbles within the epoxy, the filled mold was lightly tapped on the table. All remaining bubbles were carefully removed by blowing through a straw. After bubble removal, the mold was left to cure for 48 hours. Once the curing process was completed, the solid epoxy was carefully removed from the mold [34].

For the preparation of banana peel powder-based epoxy composites the measured hardener and epoxy were mixed as mentioned before and 20 wt.% banana peel powder was added and mixed for an additional 10-15 minutes. Any bubbles that formed were carefully removed by blowing through a straw. Subsequently, the entire mixture was poured into a mold and cured for 48 hours. Once fully cured, the composite was removed from the mold. Similarly, composites with 25 wt.% and 30 wt.% banana peel powder were prepared following the same procedure.

Again, three different weight percentages of 5 wt.%, 6.5 wt.%, and 8 wt.% of jute fibers were added into the epoxy to prepare the composites. The epoxy-herdener mixture was prepared and half of the mixture was poured into the mold. Then the measured jute fibers (5 wt.%) were evenly distributed onto the epoxy layer and the remaining mixture was poured on top. The rest of the procedure was done as mentioned before. Similarly, jute fiber-epoxy composites with 6.5 wt.% and 8 wt.% jute content were prepared.

To fabricate the hybrid composite, combining banana peel powder and jute fibers, the filler contents were selected based on the best individual results observed from the banana peel powder-epoxy and jute fiber- epoxy composites. Based on the mechanical tests, the optimum compositions were determined to be 20 wt.% banana peel powder and 5 wt.% jute fiber. Initially, a mixture of epoxy, hardener and banana peel powder was prepared following the same procedure to produce banana peel powder- epoxy composites. Then half of the mixture was poured into the mold and the measured jute fibers were evenly distributed onto the composite mixture layer. The remaining mixture was poured into the mold, and the rest of the procedure was performed as mentioned as before. Figure 3 shows the fabricated mold, blank epoxy, epoxy-banana peel powder composite, epoxy-jute fiber composite and hybrid composite samples.

2.3. Characterization

2.3.1. Mechanical tests

To assess the mechanical properties of the composites, tensile test, flexural test, and Shore D hardness test were carried out. The flexural strength was measured using a universal testing machine (UTM, model: Instron) under a three-point loading condition according to ASTM D790 standard [35]. Tensile tests were also performed on the same UTM according to ASTM D3039 standard [36], with the samples securely held between the machine's grips, and the load was applied at a cross-sectional head speed of 5 mm/min. These tests were conducted on

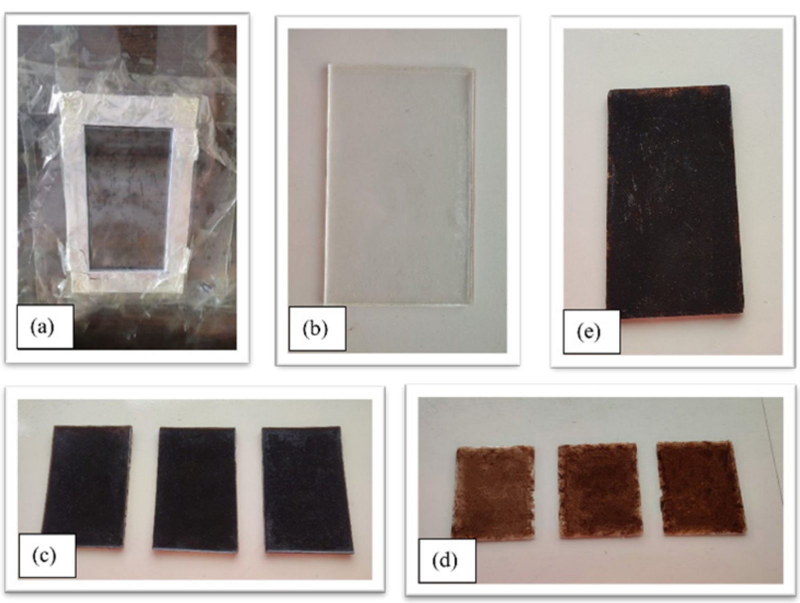

Fig. 3. (a) Mold making, (b) Blank epoxy, (c) Epoxy-banana peel powder composite, (d) Epoxy-jute fiber composite, and (e) Hybrid composite.

eight samples. Hardness was measured according to ASTM D2240 standard [37] using a Digital Shore D Durometer with a 10-second ball indentation time. To minimize errors, this test was repeated three times for each of the eight samples with the dimensions of 1 × 1 × 0.2 inches, and the average values were recorded. All tests were carried out at room temperature.

2.3.2. Thermal analysis

The thermal property of the composites was measured using TGA machine (Pyris STA 8000) maintaining a heating rate of 20 °C/min, reaching a maximum temperature of 750 °C. This test was conducted for four samples of blank epoxy composite, 20 wt.% banana peel-epoxy composite, 5 wt.% jute fiber-epoxy composite, and hybrid composite containing 20 wt.% banana peel powder and 5 wt.% jute fibers under air atmosphere where a flow rate of 200mL/min was maintained.

2.3.3. Water absorption test

Water absorption was assessed by quantifying the weight increase of composite specimens while immersing in water at ambient temperature, following the standard procedure outlined in ASTM D570 [38]. The water absorption test was conducted on four samples that were mentioned in the TGA test. For this evaluation, freshly cut samples of appropriate dimensions (1 × 1 inch) with a thickness of 0.2 inch were used as well as the corners of each sample were made to be curved for ensuring uniform water diffusion. The process involved measuring the initial weight of the samples using a precision weight balance machine. These samples were then submerged in a water bath maintained at an ambient temperature for 24 hours. After that the samples were carefully removed, dried using absorbent paper to eliminate the excess surface moisture, and reweighted. The weight gain of each sample, expressed as an increase in weight percentage, was calculated using Equation (1).

$$\text{Increase in wt.}\,\% = \frac{\text{Wet weight} - \text{Sample weight}}{\text{Sample weight}} \times 100 \qquad (1)$$

2.3.4. Soil burial test

The biodegradability of epoxy composite samples was observed through a simple soil burial test, simulating the natural biodegradation of this composite. This test was conducted according to [39] with some minor modifications for the four samples mentioned in TGA test. Four 1000 ml beakers with equal diameters were taken and filled with grey-colored soil from the garden. The pH of the soil was maintained at 7-7.5. The soil in the beakers was properly blended, and epoxy composites of uniform rectangular dimensions were placed in the middle of each beaker at a depth of 2 inches. Before being placed in the soil, the initial weight of each composite was measured with the help of a weight balance. The beakers were numbered separately for each sample. High relative humidity was maintained in the soil by regularly sprinkling water. The test was performed at an ambient temperature. The samples were first removed after 7 days, gently washed with water to remove adhered soil from their surfaces and weighed using a weight balance. Weight loss was calculated by employing Equation (2).

$$\text{Loss of wt.}\,\% = \frac{\text{Initail weight} - \text{Final weight}}{\text{Initial weight}} \times 100 \qquad (2)$$

In the same way, the samples were subjected to the test process for 14 days and 21 days, and weight loss was calculated. Weight loss of the sample concerning time was recorded as a measure of their biodegradation.

3. RESULTS AND DISCUSSION

3.1. Tensile Test

Tensile properties of prepared composite material are exhibited in Figure 4. The filler contents were determined through trial and error as well as comparative analysis with similar studies [30, 40]. The prepared epoxy-banana peel powder composites (20, 25, and 30 wt.%) along with the epoxy-jute fiber composites (5, 6.5, and 8 wt.%) were initially subjected to tensile testing to optimize their loading into epoxy- based composites. The graph revealed that the tensile strength of the composites decreased with the increase of fiber. The highest tensile strength of epoxy-banana peel powder composites was achieved at 20 wt.% reinforcement at 27 MPa. The tensile strength was reduced further to 24.27 MPa with a 25 wt.% addition of banana peel powder, and it was lowest at 18.41 MPa with

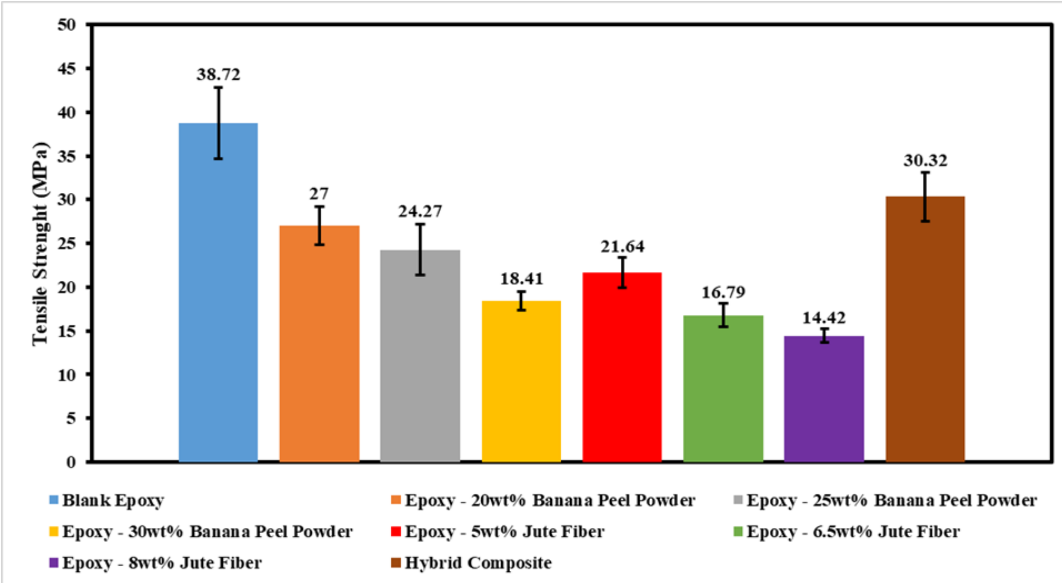

Fig. 4. Tensile strength of epoxy and epoxy-based composites.

a 30 wt.% addition of banana peel powder. The findings are in accordance to similar systems [30].

Similarly, for jute fiber-reinforced epoxy composites, the highest tensile strength was at 5 wt.% addition of jute fiber at 21.64 MPa, which reduced further to 16.79 MPa with 6.5 wt.% addition of jute fiber, the lowest being 14.42 MPa with reinforcement of 8 wt.% jute fiber. After reinforcing with banana peel powder and jute fiber, the optimum value of tensile strength was obtained at 20 wt.% for the banana peel powder-reinforced epoxy composites and at 5 wt.% for the jute fiber-reinforced epoxy composites. The hybrid composite containing both 20 wt.% for the banana peel powder and 5 wt.% for the jute fiber had a higher tensile strength of 30.32 MPa. Similar studies show the hybrid composites having superior tensile properties than single filler-based composites [41, 42]. However, it was found that the maximum tensile strength was obtained in the blank epoxy.

The tensile strength of a composite decreases with increasing fiber loading due to factors such as fiber clustering, poor adhesion between the fibers and the matrix, fiber misalignment, and reduced matrix contribution. Firstly, as fiber loading increases, fibers may begin to cluster or agglomerate, creating stress concentration points within the composite, potentially leading to premature failure. Secondly, inadequate adhesion between the fibers and the matrix can occur at high fiber loadings, weakening the matrix's ability to efficiently transfer stress to the fibers. Thirdly, maintaining a well-aligned fiber structure becomes challenging at high fiber loadings, and misaligned fibers cannot effectively contribute to load-bearing, resulting in reduced strength. Finally, when the fiber content is very high, the matrix material's contribution to load-bearing decreases significantly as the matrix becomes a smaller proportion of the composite. If the matrix itself is weak, this can further decrease the overall tensile strength [43, 44].

In the case of the hybrid composite, the higher tensile strength can be due to several factors. The presence of both the banana peel powder as well as jute fiber prevented the movement and deformation of the polymer chains. The reduction of voids, and therefore, a better adhesion between the matrix and fillers resulted in an improved load transfer of the fillers into the matrix [45, 46]. Moreover, the jute fibers improve the strength and toughness of the composite when cracks and subsequently, debonding between the filler-matrix interface occur, they keep the upper and lower part of the crack joined together due to the phenomenon known as "fiber bridging" [46, 47].

3.2. Flexural Test

Figure 5 illustrates the flexural strength of banana peel powder and jute fiber reinforced epoxy

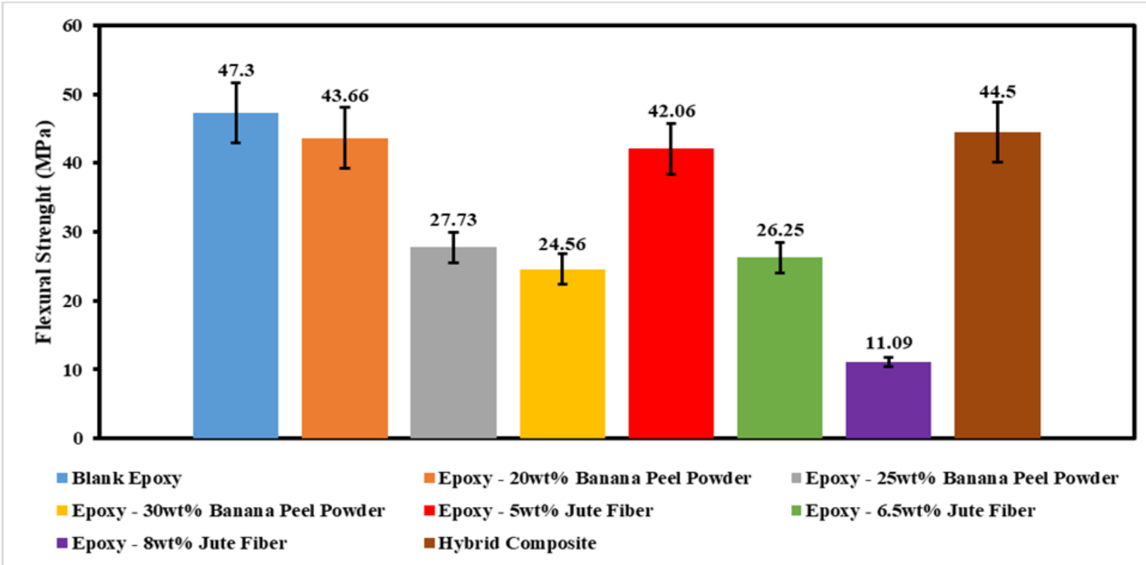

Fig. 5. Flexural strength of epoxy and epoxy-based composites.

composites at various fiber loadings compared to blank epoxy. The prepared epoxy-banana peel powder composites (20, 25, and 30 wt.%) as well as the epoxy-jute fiber composites (5, 6.5, and 8 wt.%) were initially subjected to flexural testing only to optimize their loading into the epoxy-based composites. Similar to the tensile strength, the flexural strength of the composites also showed a decline with the increase of fiber content.

The maximum flexural strength of epoxy-banana peel powder composites was achieved at 20 wt.% reinforcement at 43.66 MPa. The flexural strength was reduced further to 27.73 MPa with a 25 wt.% addition of banana peel powder, and it was lowest at 24.56 MPa with a 30 wt.% addition of banana peel powder. Similarly, for jute fiber-reinforced epoxy composites, the highest flexural strength was at 5 wt.% addition of jute fiber at 42.06 MPa, which reduced further to 26.25 MPa with 6.5 wt.% addition of jute fiber, the lowest being 11.09 MPa with reinforcement of 8 wt.% jute fiber. Hence, the optimum value of tensile strength was obtained at 20 wt.% for the banana peel powder-reinforced epoxy composites and at 5 wt.% for the jute fiber-reinforced epoxy composites. The hybrid composite containing both 20 wt.% for the banana peel powder and 5 wt.% for the jute fiber had a small increase in flexural strength to 44.5 MPa, which is greater than any of the single filler-based composites; this is in accordance to similar studies [41].

However, again it was found that the maximum flexural strength was obtained in the blank epoxy composite due to the strong adhesion between epoxy and hardener. With fiber loading adhesion between epoxy and hardener will be less. So, tensile strength and flexural strength both are decreased with fiber loading. At higher fiber content, a weak interface was created due to the increase in fiber-to-fiber interactions, the fibers not being perfectly aligned with matrix, voids, and dispersion problems [48].

The increased flexural strength of the hybrid composite may be the result of the same causes that increased the tensile strength. The polymer chains were stopped from moving and deforming by the presence of both jute fiber and banana peel powder. Stress transmission from the matrix to the fillers was enhanced as a result of the decrease in voids and increased adhesion between the matrix and fillers [45, 46]. Additionally, the jute fibers strengthen and toughen the composite through “fiber bridging” [46, 47].

3.3. Hardness Test

Figure 6 shows the hardness of banana peel powder and jute fiber reinforced epoxy composites at various fiber loadings compared to blank epoxy. It can be observed that the hardness increased up to a certain percentage with fiber loading for both banana peel powder and jute fiber reinforced epoxy composites, then began to decrease. Incorporation

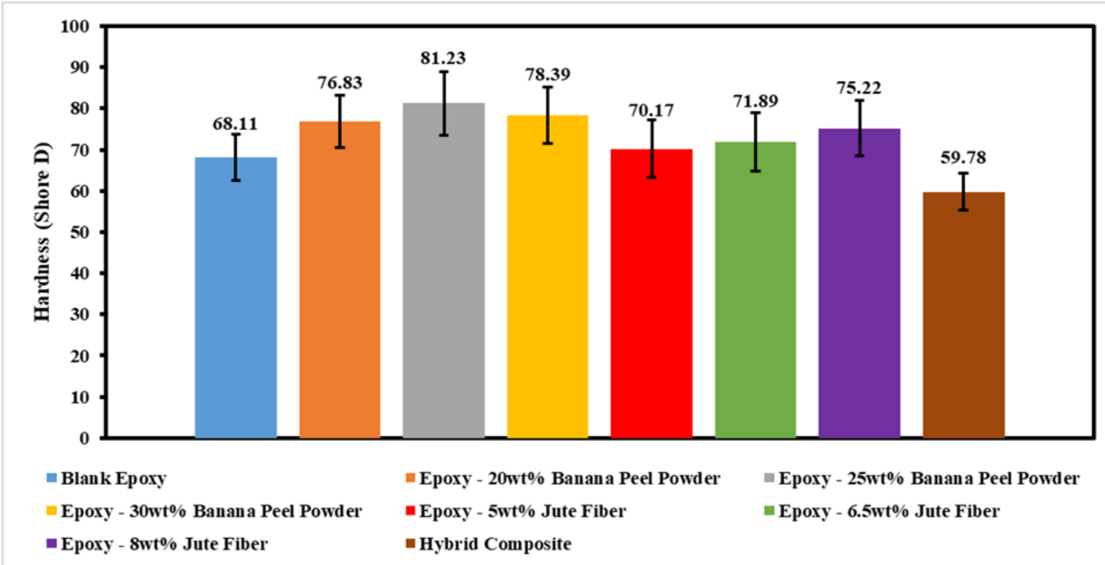

Fig. 6. Hardness of epoxy and epoxy-based composites.

of fiber into the matrix reduced the flexibility of the matrix resulting in more rigid composites. The addition of 20 wt.% banana peel powder and 5 wt.% jute fiber individually resulted in increased hardness values from 68.1 for blank epoxy to 76.83 and 70.17 respectively.

Due to the increase of stiffness of respective composite, the hardness of the composites showed a slight increasing trend with an increase in the fiber content as higher hardness values were observed for both 25 wt.% banana peel powder and 6.5 wt.% with 81.23 and 71.89 respectively. Better dispersion of the filler into the matrix with minimization of voids between the matrix and the filler also enhanced hardness. So, with fiber loading increased, average hardness also slightly increased [43]. However, as excessive fiber loading may lead to agglomeration or alignment issues, the effectiveness of reinforcement was reduced. Additionally, it could be due to a change in the material's overall structural integrity or other factors affecting its mechanical properties [49]. Hence, the hardness value for the 30 wt.% banana peel powder reinforced epoxy composite was reduced to 78.39. However, for 8.5 wt.% jute fiber reinforcement, the hardness value still increased to 75.22, indicating a better dispersion of the fibers within the matrix with minimization of voids.

The hardness value for the hybrid (20 wt.% banana peel powder + 5 wt.% jute fiber) composite was found to be 59.78. Since the tensile and flexural strengths of the hybrid composite increased compared to those of the banana-epoxy and jute-epoxy composites, the hardness was expected to decrease as strong and ductile fibers can enhance tensile strength but may simultaneously reduce the composite's hardness due to their increased susceptibility to localized deformation. Similar studies correlate the decrease of hardness to increased porosity and water absorption of the natural fibers which causes deterioration of the surface integrity and reduces the rigidity of the matrix [50]. Moreover, the weak interfacial wetting with increased fiber loadings has a softening effect on the composites as alluded in other similar systems [51]. The reduced hardness of the hybrid polymer composite enhances its toughness and decreases the probability of catastrophic failure, aligning with prior research on epoxy composites containing natural and particulate fillers [52].

3.4. Thermal Analysis

Thermal study was observed through TGA curves which indicate the weight loss of the composites in relation to rising temperature. For blank epoxy, a two step degradation is observed with the the onset thermal degradation beginning at around 275 °C as can be observed from Figure 7(a). This could be attributed to the depolymerization of the macromolecular network of epoxy resin while the latter could be due to further degradation of the carbon residue through oxidation at around 375 °C to 445 °C. The composites on the other hand showed one-step degradation curves as the fillers protected the epoxy resin from oxidation [53]. An initial weight loss can be observed before reaching the onset degradation temperature due to evaporation of moisture from the surface after which, the main weight loss could be attributed to the degradation and volatilization of the fillers and matrix. These findings are in accordance with similar studies [53, 54].

At lower temperatures, the composites experienced greater weight loss than the blank epoxy. The weight loss at 300 °C for blank epoxy was 7.12% while the weight loss for the composites were 13.56%, 21.22% and 31.22% for 20 wt.% BPP reinforced epoxy, hybrid epoxy and 5 wt.% jute fiber reinforced epoxy respectively. However at higher temperatures, the blank epoxy faced significantly more weight loss, leaving less char residue. At 500 °C, the weight loss for blank epoxy was 85.19% while the weight loss for the composites were 71.83%, 72.96% and 73.78% for 20 wt.% BPP reinforced epoxy, hybrid epoxy and 5 wt.% jute fiber reinforced epoxy respectively.

From the DTG curve, it can be observed that epoxy-based composites had lower onset as well as maximum degradation temperatures compared to blank epoxy as shown in Figure 7(b). However, while the blank epoxy exhibited a secondary degradation period between 375 °C to 445 °C due to oxidation, the composites showed no reactions. Table 1 compares the onset degradation and maximum degradation temperatures of the selected samples.

From the Figure 7 it is evident that the reinforcement in the epoxy composites initially experienced a greater weight loss but demonstrated more resistance to degradation at higher temperatures compared to the epoxy blank composite. Notably, the hybrid composite comprising 20 wt.% banana peel powder and 5 wt.% jute fiber displays a distinct weight loss curve that falls between the curves of the individual composites containing 20 wt.% banana peel powder and 5 wt.% jute fibers. This behavior can be attributed to the presence of treated jute fibers within the hybrid composite, which results in less degradation [55].

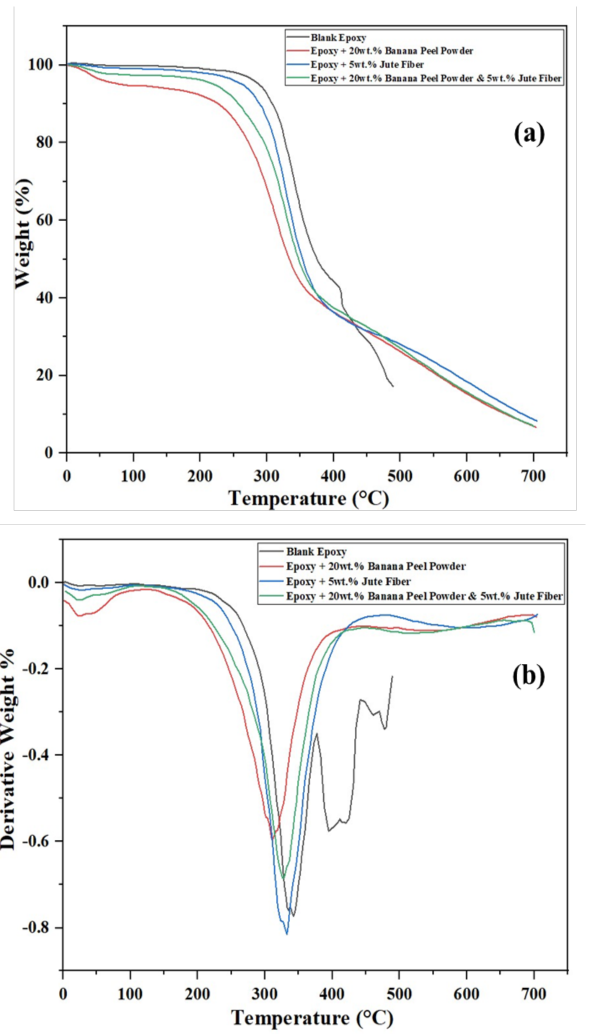

Fig. 7. Thermal analysis results of epoxy and epoxy-based composites (a) TGA and (b) DTG.

Table 1. Degradation temperatures of epoxy and epoxy-based composites.

Sample	Onset degradation temperature (°C)	Maximum degradation temperature (°C)
Blank Epoxy	275.42	342.34
20 wt.% BPP Reinforced Epoxy	200.22	311.04
5 wt.% Jute Fiber reinforced Epoxy	240.68	332.55
Hybrid Epoxy	225.54	326.94

3.5. Water Absorption Test

Biodegradable composites are designed to break down when exposed to environmental conditions, including moisture. Water absorption is a crucial step in the degradation process of biodegradable materials. As water penetrates the composite, it can initiate hydrolysis that breaks down the polymer chains leading to eventual degradation. The rate at which water is absorbed can vary depending on factors such as the type of biodegradable polymer and the composite's structure. Faster water absorption can lead to quicker biodegradation, which may be desirable in specific applications [56, 57].

The water absorption behavior of all four specimens was determined in terms of weight increase for composite specimen immersed in water at room temperature for 24 hours [58]. From Figure 8, it can be observed that the water absorption of the blank epoxy composite is nearly zero as the matrix material is hydrophobic, which restricts the interaction of the water molecules [34].

On the other hand, both the 20 wt.% banana peel powder-reinforced composite and the 5 wt.% jute fiber reinforced composite have higher water absorption compared to the blank epoxy composite, as the fillers are hygroscopic in nature, meaning they have a natural affinity to absorb moisture from the environment. This hygroscopic behavior can lead to increased water absorption in the composite. This is in accordance to similar studies [59]. However, the 20 wt.% banana peel powder-reinforced composite had the highest water absorption as the banana peel powder was non- treated while the jute fiber was treated [56]. Moreover, the water absorption of the hybrid composite was intermediate of the banana peel powder reinforced composite the jute fiber reinforced composite [34].

3.6. Soil Burial Test

Soil burial degradation tests were carried out by sandwiching the polymer films between two layers of commercial soil to simulate soil degradation after their use lifetime. Figure 9 illustrates the increasing weight loss values of different composites with time. This test was conducted to assess the biodegradability of the composite under both ideal and practical environmental conditions. While the presence of jute fiber and banana peel powder in the matrix may contribute significantly to the biodegradation of these composites, it's important to note that epoxy resin itself is not biodegradable. While the weight of the blank epoxy sample remained nearly unchanged throughout the burial period, the proportion of weight loss in the other test samples increased with time [60]. The increased weight loss with increasing filler content is consistent with similar systems [61].

Initially, the weight loss of the composites occurred at a gradual rate. However, after 7 days, a rapid weight loss was observed in the samples. This increased weight loss was likely due to various factors, including the presence of soil particles, moisture, and humidity in the environment [62]. The chemical components, such as cellulose, hemicellulose, and lignin, present in natural fibers,

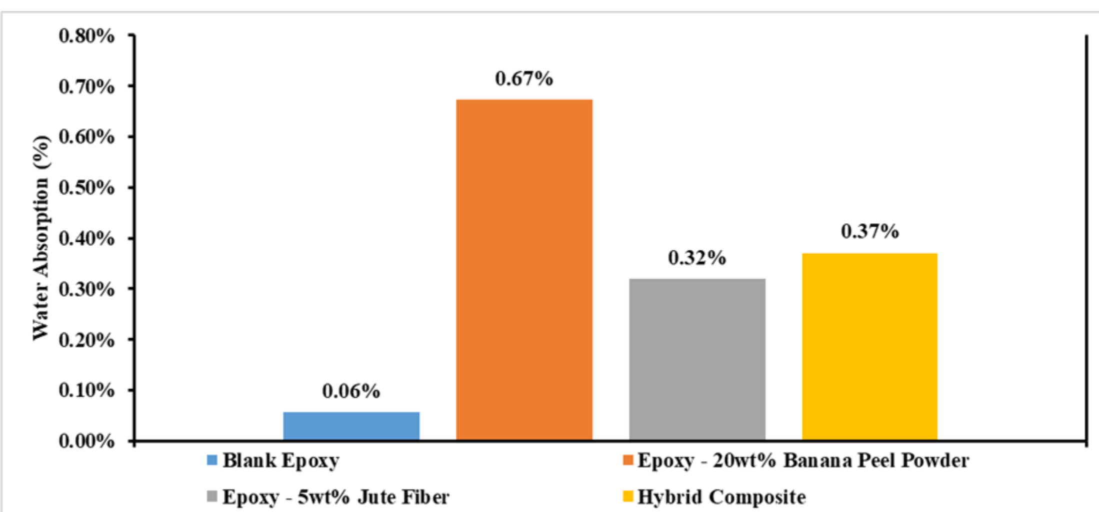

Fig. 8. Water absorption test of epoxy and epoxy-based composites.

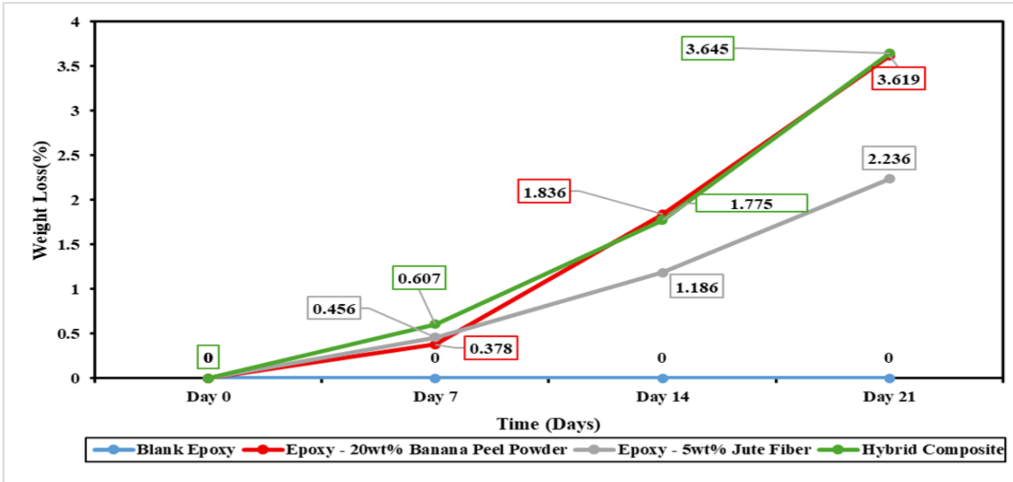

Fig. 9. Soil degradation of epoxy and epoxy-based composites.

promoted microbial activity in the composites during the soil burial test, ultimately resulting in their weight loss. Additionally, the hydrophilic nature of both banana peel powder and jute fiber may have played a significant role. The hydrophilic nature of these components tends to absorb moisture, causing them to swell within the polymer matrix. This swelling can lead to the formation of microcracks within the composite material. These microcracks provide pathways for external factors, such as moisture and microbes, to penetrate and interact with the composite. As these microcracks develop and expand, they create conditions that are conducive to the degradation process. Microbes and other factors can access the polymer matrix more readily through these openings, which can accelerate the degradation process. Importantly, while the formation of microcracks may enhance the rate of degradation, it does not fundamentally alter the overall mechanism of composite degradation [63].

In comparison to other composites, the biodegradability of the hybrid (20 wt.% banana peel powder and 5 wt.% jute fiber) epoxy composite is higher, and there is no degradation observed in the blank epoxy. Therefore, after its useful lifetime, disposing of the hybrid composite will result in relatively rapid degradation, with a somewhat reduced environmental impact.

4. CONCLUSIONS

This study aimed to create epoxy composites using banana peel powder and alkali-treated jute fiber. Different weight percentages of reinforcements were used; (20 wt.%, 25 wt.%, and 30 wt.% banana peel powder) and (5 wt.%, 6.5 wt.%, and 8 wt.% treated jute fiber). The tensile and flexural strength of the composites decreased due to fiber clustering, poor adhesion, fiber misalignment, and reduced matrix contribution. It was found that the highest tensile and flexural strength of the composites were achieved with 20 wt.% banana peel powder (27 MPa and 43.66 MPa) and 5 wt.% jute fiber (21.64 MPa and 42.06 MPa). These optimum loadings (20 wt.% banana and 5 wt.% jute) were incorporated into the epoxy matrix to produce a hybrid composite that displayed superior mechanical properties than the single-filler composites, with tensile and flexural strength of 30.32 MPa and 44.5 MPa. Moreover, the hybrid composite had a hardness value of 59.78 due to increased porosity and water absorption of the natural fibers, which is significantly less than the other composites and even the blank epoxy. Hence, it exhibited greater non-brittleness, resilience, and reduced risk of failure. The thermal analysis showed that the composites initially experienced greater weight loss compared to blank epoxy but demonstrated more resistance to degradation at higher temperatures as the fillers protected the epoxy resin from oxidation. The hybrid composite displayed a weight loss curve between the individual composite curves, indicating that the treatment of jute fiber resulted in less degradation compared to untreated banana peel powder. Similar trends were also observed in water absorption and soil burial tests. Therefore, the hybrid composite balances thermal stability and partial biodegradability while maintaining optimal mechanical properties, which could be a promising eco-friendly alternative to pure epoxy thermosets in structural applications such as automotive, construction and packaging.

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6. DATA AVAILABILITY

The datasets used and/or analysed during the current study are available from the corresponding authors.

7. CONFLICT OF INTEREST

The authors declare no conflict of interest.

8. ETHICAL STATEMENT

This work does not include any studies involving human or animal subjects.

9. DECLARATION

We confirm that the results in this manuscript are original and it has not been published elsewhere nor is it under consideration by another journal. All authors have approved the manuscript and agree that in case the article is accepted for publication, its copyright will be assigned to the *Pakistan Academy of Sciences*. Authors have obtained permission to reproduce, where needed, copyrighted material from other sources and ensured that no copyrights have been infringed upon.

10. REFERENCES

1. K. Papadopoulou, P.A. Klonos, A. Kyritsis, O. Mašek, C. Wurzer, K. Tsachouridis, A.D. Anastasiou, and D.N. Bikiaris. Synthesis and Study of Fully Biodegradable Composites Based on Poly (butylene succinate) and Biochar. *Polymers* 15(4): 1049 (2023). https://doi.org/10.3390/polym15041049
2. X. Zhou, S.H. Ghaffar, W. Dong, O. Oladiran, and M. Fan. Fracture and impact properties of short discrete jute fibre-reinforced cementitious composites. *Materials and Design* 49: 35-47 (2013). https://doi.org/10.1016/J.MATDES.2013.01.029
3. M.G. Kibria, N.I. Masuk, R. Safayet, H.Q. Nguyen, and M. Mourshed. Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management. *International Journal of Environmental Research* 17: 20 (2023). https://doi.org/10.1007/s41742-023-00507-z
4. United Nations Development Programme. Zero Plastic: Study of Plastic Waste in the Republic of Moldova. *UNDP Moldova*, (2023). https://www.undp.org/moldova/publications/study-plastic-waste-republic-moldova
5. T.D. Ngo. Introduction to Composite Materials (Chapter 1). In: Composite and Nanocomposite Materials - From Knowledge to Industrial Applications. T.D. Ngo (Ed.). *IntechOpen* pp. 1-27 (2020). https://doi.org/10.5772/intechopen.91285
6. A.P. Singh. Strength and permeability characteristics of steel fibre reinforced concrete. *International Journal of Civil and Environmental Engineering* 7(10): 733-738 (2013). https://www.semanticscholar.org/paper/Strength-and-Permeability-Characteristics-of-Steel-Singh/31af2139d7a91afaa63bc3a929ffff5ede93d326
7. G. Ramakrishna and T. Sundararajan. Impact strength of a few natural fibre reinforced cement mortar slabs: A comparative study. *Cement and Concrete Composites* 27: 547-553 (2005). https://doi.org/10.1016/j.cemconcomp.2004.09.006
8. T.A. Branca, V. Colla, D. Algermissen, H. Granbom, U. Martini, A. Morillon, R. Pietruck, and S. Rosendahl. Reuse and Recycling of By-Products in the Steel Sector: Recent Achievements Paving the Way to Circular Economy and Industrial Symbiosis in Europe. *Metals* 10(3): 345 (2020). https://doi.org/10.3390/met10030345
9. F.A. Silva, B. Mobasher, and R.D.T. Filho. Cracking mechanisms in durable sisal fiber reinforced cement composites. *Cement and Concrete Composites* 31(10): 721-730 (2009). https://doi.org/10.1016/J.CEMCONCOMP.2009.07.004
10. J. Ahmad, M.M. Arbili, A. Majdi, F. Althoey, A.F. Deifalla, and C. Rahmawati. Performance of concrete reinforced with jute fibers (natural fibers): A review. *Journal of Engineered Fiber Fabrics* 17: 1-17 (2022). https://doi.org/10.1177/15589250221121871
11. C. Ranjan, Z. Ahmed, S.R. Kumar, A. Kumar, A. Kumar, and K. Kumar. Fabrication and strength analysis of rice straw fibers reinforced epoxy biodegradable composite. *Materials Today: Proceedings* 46: 331-335 (2021). https://doi.org/10.1016/J.MATPR.2020.08.299
12. N.D. Muralidharan, J. Subramanian, S.K. Rajamanickam, and V. Gopalan. An experimental investigation of flame retardancy and thermal stability of treated and untreated kenaf fiber reinforced epoxy composites. *Journal of Polymer Engineering* 43(10): 865-874 (2023). https://doi.

org/doi:10.1515/polyeng-2023-0128
13. B.N. Sharath, T.G.Y. Gowda, P. Madhu, C.B.P. Kumar, N. Jain, A. Verma, M.R. Sanjay, and S. Siengchin. Fabrication of raw and chemically treated biodegradable Luffa aegyptica fruit fibre-based hybrid epoxy composite: a mechanical and morphological investigation. *Biomass Conversion and Biorefinery* 15: 8473-8486 (2025). https://doi.org/10.1007/s13399-024-05570-w
14. G.R. Raghav, R.A. Kumar, N.K. Jawaharlal, C. Vignesh, F. Sahayaraj Arockiasamy, and E. Syafri. Effect of Cellulose Nanofibers from Red Coconut Peduncle Waste as Reinforcement in Epoxy Composite Sheets. *Cellulose Chemistry and Technology* 57(7-8): 855-866 (2023). https://doi.org/10.35812/cellulosechemtechnol.2023.57.75
15. J. Yusuf, S.M. Sapuan, U. Rashid, R. A. Ilyas, and M.R. Hassan. Thermal, mechanical, and morphological properties of oil palm cellulose nanofibril reinforced green epoxy nanocomposites. *International Journal of Biological Macromolecules* 278(3): 134421 (2024). https://doi.org/10.1016/J.IJBIOMAC.2024.134421
16. M.M. Shariff, G.R. Arpitha, N. Jain, U. Shankar, A. Verma, and N.D. Shivakumar. A comparative study on the effect of reinforcing boron nitride/alumina in epoxy-based hybrid composite with Millettia pinnata leaf powder and glass sheets: Experimental fabrication, mechanical and micro-structural characterization. *Hybrid Advances* 4: 100095 (2023). https://doi.org/10.1016/J.HYBADV.2023.100095
17. A. Zeleke and H.S. Gebremedhen. Characterization of Sisal-Glass Fiber Reinforced Epoxy Hybrid Composite. *8th EAI International Conference, ICAST 2020, Proceedings, Part II, (October 2nd - 4th, 2020), Bahir Dar, Ethiopia* (2021). http://dx.doi.org/10.1007/978-3-030-80618-7_23
18. G.R. Arpitha, H. Mohit, P. Madhu, and A. Verma. Effect of sugarcane bagasse and alumina reinforcements on physical, mechanical, and thermal characteristics of epoxy composites using artificial neural networks and response surface methodology. *Biomass Conversion and Biorefinery* 14(11): 12539-12557 (2024). https://doi.org/10.1007/s13399-023-03886-7
19. K.R. Ashok, K.A. Ramesh, S. Durairaj, and R.C. Sakthi. Morphological and mechanical evaluation of epoxy hybrid composites reinforced with banana and jute cellulose. *Journal of Mechanical Science and Technology* 40: 455-461 (2026). https://doi.org/10.1007/s12206-025-1237-7
20. G.R. Arpitha, N. Jain, and A. Verma. Banana biofiber and glass fiber reinforced hybrid composite for lightweight structural applications: mechanical, thermal, and microstructural characterization. *Biomass Conversion and Biorefinery* 14(11): 12589-12598 (2024). https://doi.org/10.1007/s13399-023-04300-y
21. M.A. Based. Extraction of banana fiber and characterization analysis of hybrid (banana, jute, carbon and glass) reinforced composite materials. *Results in Materials* 28: 100803 (2025). https://doi.org/10.1016/j.rinma.2025.100803
22. G.R. Arpitha, N. Jain, A. Verma, and M. Madhusudhan. Corncob bio-waste and boron nitride particles reinforced epoxy-based composites for lightweight applications: fabrication and characterization. *Biomass Conversion and Biorefinery* 14(11): 12531-12538 (2024). https://doi.org/10.1007/s13399-022-03717-1
23. P. Agrawal, A.K. Kundu, D. Purohit, P. Sahu, N. Gautam, A. Sharma, and V. Patil. A review paper of composite materials: advantages and applications. *International Journal of Advances in Engineering and Management* 4: 369 (2022). https://doi.org/10.35629/5252-0411369370
24. H. Jamshaid, R.K. Mishra, A. Raza, U. Hussain, M.L. Rahman, S. Nazari, V. Chandan, M. Muller, and R. Choteborsky. Natural cellulosic fiber reinforced concrete: influence of fiber type and loading percentage on mechanical and water absorption performance. *Materials* 5(3): 874 (2022). https://doi.org/10.3390/ma15030874
25. M.S. Islam and S.J. Ahmed. Influence of jute fiber on concrete properties. *Construction and Building Materials* 189: 768-776 (2018). https://doi.org/10.1016/J.CONBUILDMAT.2018.09.048
26. M.R. Islam, M.M. Kamal, M.R. Kabir, M.M. Hasan, A.R. Haque, and S.M.K. Hasan. Phenolic compounds and antioxidants activity of banana peel extracts: Testing and optimization of enzyme-assisted conditions. *Measurement: Food* 10: 100085 (2023). https://doi.org/10.1016/J.MEAFOO.2023.100085
27. K.Z.M.A. Motaleb, A. Ahad, G. Laureckiene, and R. Milasius. Innovative Banana Fiber Nonwoven Reinforced Polymer Composites: Pre- and Post-Treatment Effects on Physical and Mechanical Properties. *Polymers* 13(21): 3744 (2021). https://doi.org/10.3390/polym13213744
28. J. Zhang, H. Dong, L. Tong, L. Meng, Y. Chen, and G. Yue. Investigation of curing kinetics of sodium carboxymethyl cellulose/epoxy resin system by differential scanning calorimetry. *Thermochimica Acta* 549: 63-68 (2012). https://doi.org/10.1016/J.

TCA.2012.09.015

29. G.A. Sabirova, R.R. Safin, N.R. Galyavetdinov, and A.R. Shaikhutdinova. Research of biodegradable wood completed composite materials based on polylactide. *Journal of Physics: Conference Series* 1399(4): 044117 (2019). https://doi.org/10.1088/1742-6596/1399/4/044117
30. A.L. Naidu, D. Raghuveer, and P. Suman. Studies on characterization and mechanical behavior of banana peel reinforced epoxy composites. *International Journal of Scientific & Engineering Research* 4(6): 844-851 (2013). https://www.researchgate.net/publication/344151239_Studies_on_Characterization_and_Mechanical_Behavior_of_Banana_peel_Reinforced_Epoxy_Composites
31. A. Kumar, S. Kumar, D. Kumar, V.K. Mahakur, and S. Bhowmik. Utilization of banana peel as bio-filler to develop bio-composite materials and characterize their physical, mechanical, thermal, and tribological characteristics. *Polymer Bulletin* 81: 16175-16196 (2024). https://doi.org/10.1007/s00289-024-05464-x
32. X. Liu. Surface modification and micromechanical properties of jute fiber mat reinforced polypropylene composites. *Express Polymer Letters* 1: 299-307 (2007). https://doi.org/10.3144/expresspolymlett.2007.43
33. M. Kumar, A. Sachdeva, S. Singh, and A.P. Singh. Prediction of Mechanical Properties and Morphological Characterization of the Reinforced Hybrid Natural Fiber Polymer Composites using the Bidirectional Sisal Fiber and Woven Jute. *International Journal of Mechanical Engineering* 5(5): 27-31 (2018). https://doi.org/10.14445/23488360/IJME-V5I5P105
34. M. Boopalan, M. Niranjanaa, and M.J. Umapathy. Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites. *Composites Part B: Engineering* 51: 54-57 (2013). https://doi.org/10.1016/J.COMPOSITESB.2013.02.033
35. Test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials *ASTM International, West Conshohocken, PA* (2017). https://doi.org/10.1520/D0790-17
36. Standard test method for tensile properties of polymer matrix composite materials. *ASTM International, West Conshohocken, PA* (2014). DOI: 10.1520/D3039_D3039M-08
37. Test method for rubber property-durometer hardness. *ASTM International, West Conshohocken, PA* (2015). DOI: 10.1520/D2240-15R21
38. Test method for water absorption of plastics. *ASTM International, West Conshohocken, PA* (2022). https://doi.org/10.1520/D0570-22
39. R. Kumar, M. Yakubu, and R. Anandjiwala. Biodegradation of flax fiber reinforced poly lactic acid. *Express Polymer Letters* 4(7): 423-430 (2010). https://doi.org/10.3144/expresspolymlett.2010.53
40. M.K. Gupta, R.K. Srivastava, and H. Bisaria. Potential of jute fibre reinforced polymer composites: a review. *International Journal of Fiber and Textile Research* 5: 30-38 (2015). https://www.researchgate.net/publication/282073854_Potential_of_Jute_Fibre_Reinforced_Polymer_Composites_A_review
41. B. Sandeep, H.N. Divakar, and K.S. Keerthiprasad. Coupling strength and synergy: exploring the mechanical properties of epoxy hybrid composites with s-glass and basalt fibers. *Scholars International Journal of Chemistry and Material Sciences* 7: 45-59 (2024). DOI: 10.36348/sijcms.2024.v07i05.001
42. N. Saba and M. Jawaid. Epoxy resin based hybrid polymer composites. *Hybrid Polymer Composite Materials: Properties and Characterisation* pp. 57-82 (2017). https://doi.org/10.1016/B978-0-08-100787-7.00003-2
43. M.R. Rahman, M.M. Huque, M.N. Islam, and M. Hasan. Improvement of physico-mechanical properties of jute fiber reinforced polypropylene composites by post-treatment. *Composites Part A: Applied Science and Manufacturing* 39(11): 1739-1747 (2008). https://doi.org/10.1016/J.COMPOSITESA.2008.08.002
44. M. Haque, N. Islam, M. Huque, M. Hasan, S. Islam, and S. Islam. Coir Fiber Reinforced Polypropylene Composites: Physical and Mechanical Properties. *Advanced Composite Materials* 19(1): 91-106 (2010). https://doi.org/10.1163/092430409X12530067339325
45. T. Yokozeki, Y. Iwahori, and S. Ishiwata. Matrix cracking behaviors in carbon fiber/epoxy laminates filled with cup-stacked carbon nanotubes (CSCNTs). *Composites Part A: Applied Science and Manufacturing* 38: 917-924 (2007). https://doi.org/10.1016/j.compositesa.2006.07.005
46. S. Dehrooyeh, M. Vaseghi, M. Sohrabian, and M. Sameezadeh. Glass fiber/Carbon nanotube/Epoxy hybrid composites: Achieving superior mechanical properties. *Mechanics of Materials* 161: 104025 (2021). https://doi.org/10.1016/j.mechmat.2021.104025
47. K.G. Dassios. A review of the pull-out mechanism in the fracture of brittle-matrix-fibre-

reinforced composites. *Advanced Composites Letters* 16(1): 17-24 (2007). https://doi.org/10.1177/096369350701600102
48. M. Davindrabrabu, P.S. Januar, B. Dandi, M.R. Mohd Ruzaimi, and T. Cionita. Effect of fibre loading on the flexural properties of natural fibre reinforced polymer composites. *Applied Mechanics and Materials* 695: 85-88 (2014). https://doi.org/10.4028/www.scientific.net/AMM.695.85
49. S. Siddika, F. Mansura, and M. Hasan. Physico-mechanical properties of jute-coir fiber reinforced hybrid polypropylene composites. *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering* 7(1): 60-64 (2013). https://doi.org/10.5281/zenodo.1328564
50. H.M. Khdier, W.M. Salih, A.H. Ali, and K.A.F. Husham. Comparative study between properties of composite polymer blend reinforced within two kinds of natural fibers. *Journal of Materials Science: Materials in Engineering* 21: 10 (2026). https://doi.org/10.1186/s40712-025-00368-8
51. B. Neher, M.M.R. Bhuiyan, H. Kabir, M.R. Qadir and M.A. Gafur, and F. Ahmed. Study of mechanical and physical properties of palm fiber reinforced acrylonitrile butadiene styrene composite. *Materials Sciences and Applications* 5(1): 39-45 (2014). https://doi.org/10.4236/msa.2014.51006
52. S.C.D. Sharma, P.B. Nishan, M.M. Islam, and A.M. Hossain. Study of Mechanical Properties of Glass Fiber Reinforced Epoxy Composites using Chemically Modified Carbon Nanoparticles as Nano-Fillers. *International Journal of Engineering Research & Technology* 14(12): 18053145 (2025). https://doi.org/10.5281/zenodo.18053145
53. M. Cui, L. Zhang, P. Lou, X. Zhang, X. Han, Z. Zhang, and Z. Shuhua. Study on thermal degradation mechanism of heat-resistant epoxy resin modified with carboranes. *Polymer Degradation and Stability* 176: 109143 (2020). https://doi.org/10.1016/j.polymdegradstab.2020.109143
54. M.K. Lila, G.K. Saini, M. Kannan, and I. Singh. Effect of fiber type on thermal and mechanical behavior of epoxy based composites. *Fibers and Polymers* 18: 806-810 (2017). https://doi.org/10.1007/s12221-017-1147-0
55. S.R. Islam, A. Alassod, M.K. Patoary, T. Naveed, M.A. Ali, and J. Jiang. Study on thermal, thermo-mechanical, and flexural properties of jute fiber surface modification and its reinforced composite. *American Association of Textile Chemists and Colorists Journal of Research* 8(5): 11-17 (2021). https://doi.org/10.14504/ajr.8.5.2
56. S. Sanjeevi, V. Shanmugam, S. Kumar, V. Ganesan, G. Sas, D.J. Johnson, M. Shanmugam, A. Ayyanar, K. Naresh, R.E. Neisiany, and O. Das. Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. *Scientific Reports* 11(1): 13385 (2021). https://doi.org/10.1038/s41598-021-92457-9
57. T. Väisänen, O. Das, and L. Tomppo. A review on new bio-based constituents for natural fiber-polymer composites. *Journal of Cleaner Production* 149: 582-596 (2017). https://doi.org/10.1016/J.JCLEPRO.2017.02.132
58. B. Dan-asabe. Thermo-mechanical characterization of banana particulate reinforced PVC composite as piping material. *Journal of King Saud University - Engineering Sciences* 30(4): 296-304 (2018). https://doi.org/10.1016/j.jksues.2016.11.001
59. O.O. Daramola and O.S. Akintayo. Water absorption characteristics of Epoxy matrix composites reinforced with green silica particles. *Leonardo Electronic Journal of Practices and Technologies* 32: 215-232 (2018). https://www.academia.edu/74417933/Water_absorption_characteristics_of_Epoxy_matrix_composites_reinforced_with_green_silica_particles
60. A. Mahmud, C. Dev, M.T. Meem, M.A. Gafur, and M.A. Hoque. Preparation and mechanical properties of green epoxy/chitosan/silver nanocomposite. *Green Materials* 10(3): 110-118 (2021). https://doi.org/10.1680/jgrma.21.00020
61. S. Dixit. Degradation analysis of lignocellulosic fillers infused coir epoxy composites in different environmental conditions. *International Journal of Lignocellulosic Products* 1(2): 160-179 (2014). https://doi.org/10.22069/ijlp.2014.2073
62. M. Milošević, A. Krkobabić, M. Radoičić, Z. Šaponjić, T. Radetić, and M. Radetić. Biodegradation of cotton and cotton/polyester fabrics impregnated with Ag/TiO2 nanoparticles in soil. *Carbohydrate Polymers* 158: 77-84 (2017). https://doi.org/10.1016/j.carbpol.2016.12.006
63. H. Wang, D. Wei, A. Zheng, and H. Xiao. Soil burial biodegradation of antimicrobial biodegradable PBAT films. *Polymer Degradation and Stability* 116: 14-22 (2015). https://doi.org/10.1016/J.POLYMDEGRADSTAB.2015.03.007