EXPERIMENTAL INVESTIGATION ON MECHANICAL, MOISTURE UPTAKE AND BIODEGRADATION CHARACTERISTICS OF TULSI FIBER (*OCIMUM TENUIFLORUM*) AND MANGO (*MANGIFERA INDICA*) SEED PARTICLES REINFORCED COMPOSITES

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Natural composites have garnered attention for application in the automotive and construction industries due to their eco-friendly nature and lightweight properties. However, their strength is often limited, presenting challenges for such applications. The goal of this research was to develop a composite material with enhanced performance characteristics. The study focused on using Tulsi fiber as reinforcement in composite production. Additionally, mango seed particles were incorporated as a filler, alongside Tulsi fiber. The composites were fabricated using epoxy resin as the matrix, with varying amounts of Tulsi fibers as reinforcements, utilizing the conventional hand layup method. An optimal fiber-to-resin ratio was established through experimentation. The results indicated that a composition of 30 wt% Tulsi fiber and 70 wt% epoxy resin exhibited notable strength. Further reinforcement of this composite with different amounts of mango seed particles was conducted. Mechanical properties, water absorption, and biodegradation characteristics were assessed. The composite with 30 wt% Tulsi fiber and 20 wt% mango seed particles demonstrated superior performance in terms of tensile strength (60 MPa), flexural strength (90 MPa), and impact strength (26 kJ/m²). These improvements were attributed to the effective load transfer facilitated by the filler and fiber reinforcements. Moreover, the moisture absorption study revealed that the composite with 30 wt% Tulsi fiber and 30 wt% mango seed particles absorbed less water (7% over 10 days). During the biodegradation study, this same composite exhibited the least mass loss (34% over 60 days). In conclusion, the study successfully developed a composite material with enhanced mechanical properties by incorporating Tulsi fiber and mango seed particles into an epoxy matrix. These findings highlighted the potential applicability of these composites in automotive and construction applications.

Keywords: natural composites;, Tulsi fiber, mango seed, water absorption, biodegradation

INTRODUCTION

Natural composites are of interest to designers, scientists, engineers, and industrialists for various industrial applications, such as automotive, construction, marine, aerospace, and electronics.[1,2] These composites possess desirable characteristics, including low cost, ease of processing, non-toxicity, and environmental friendliness. Despite these positive characteristics, their strength is moderate and lower compared to conventional materials used in many industrial applications.[3,4] Addressing this limitation would be noteworthy to enable their use in diverse fields.

Generally, natural composites are made with natural fibers extracted from plants. Their properties depend on the source from which the fibers were extracted, such as the stem, fruit, root, branch, or seed. Moreover, natural composites are reinforced with multiple reinforcements to improve their performance. These additional reinforcements could include fibers, fruit peels, fruit seeds, and bark.

Recently, researchers have focused on fruit seed-based reinforcements and reported positive results on the composites' performance. For example, Senthilkumar *et al.* prepared biocomposites using Jujube fruit seeds and Indian almond fiber. Composites with 10 wt% Jujube fruit seed exhibited a 14% increase in tensile capacity and 23% upgrading in bending capacity. In addition, the same composite displayed a lower water intake.[5] Girimurugan *et al.* manufactured kenaf/kapok seed filler composites and studied their water absorption and mechanical properties. A composite with 25 wt% fiber and 10 wt% seed fillers produced an ultimate tensile strength of 28 MPa, a flexural strength of 58 MPa, and impact strength of 4.6 kJ/m².[6]

Babu *et al.* fabricated composites using neem seed and Indian almond. Composites with 7.5 wt% neem seed exhibited a maximum tensile strength of 68 MPa and a flexural strength of 110 MPa. Furthermore, the same composite revealed an impact strength of 3.78 kJ/m². Additionally, composites with 10 wt% neem seed showed low biodegradation and water absorption.[7] Karunakaran *et al.* developed biocomposites reinforced with tamarind seed powder. A composite with 20 wt% tamarind seed showed a tensile strength of 11.2 MPa. Also, the peak compression strength of 76 MPa was recorded for 30 wt% tamarind seed powder reinforced with epoxy.[8]

Rajkumar *et al.* created polypropylene/alpaca/palm seed composites. The Vickers hardness of polypropylene/alpaca fiber was recorded as 56. However, after including 20 wt% palm seed powder, the hardness improved by 40%. Further, the same composite showed a 43% increase in flexural strength.[9] Nagaprasad *et al.* fabricated vinyl ester and *Polyalthia longifolia* seed powder-reinforced composites and studied their wear behavior with respect to the weight fractions of seed powders. It was recorded that 25 wt% seed filler exhibited minimum wear loss at a 300 rpm sliding speed and a 10 N load. Further, a low coefficient of friction was observed for the same quantity of seed filler at a 700 rpm sliding speed and a 5 N load.[10]

Elkhouly *et al.* manufactured eco-friendly composites using PET and date seed powders. The addition of 0.75 wt% date seed powder helped decrease the wear loss of the composite by 74%. At the same time, the hardness of the composite increased by 75%. Further, the compressive strength of the composite was improved by 41%.[11] Stalin *et al.* studied the properties of vinyl ester/*Polyalthia longifolia* seed powder composite. The composite showed a peak tensile strength of 32 MPa and a tensile modulus of 1.23 GPa when added with 25 wt% seed powders. The same composite exhibited hardness, impact, and flexural strength of 36.5, 31.06 kJ/m², and 125 MPa, respectively. Further, the composite was stable up to 430 °C under thermal conditions. A literature survey revealed that seed-based fillers have great potential to enhance the performance of composites along with fiber reinforcement.[12]

Tulsi (*Ocimum tenuiflorum*) is a plant that belongs to the *Lamiaceae* family. It grows in Asia, Malaysia, Australia, and the Western Pacific regions. This plant is utilized in the medical field, but is often treated as a weed. Generally, the Tulsi plant grows to a height of 30 to 60 cm. In the engineering field, Tulsi fiber is relatively unexplored. Hence, there exists a research gap in focusing on Tulsi fiber for the development of composites. Mango fruit is the edible product of the *Mangifera indica* tree, mostly found in India, Bangladesh, and Myanmar. Mango fruit contains a large single seed that is strong and similar to stone-like material. This seed is often discarded as a waste after consuming the fruit. Hence, this seed could be used as filler for composite manufacturing. Thus, the aim of the present investigation has been to develop novel composites using Tulsi fiber and mango seed fillers and to study their mechanical, water absorption, and biodegradation characteristics.

EXPERIMENTAL

Materials

The composite was made from Tulsi fiber and mango seed particles, using epoxy resin as the binder. NaOH solution was used to treat the fiber, and silica release gel was used to assist in the manufacturing process. Tulsi fiber was developed from Tulsi plants collected locally.

The leaves and branches of the Tulsi plant were removed, and the main stem was soaked in stagnant water for about ten days. After that, it was exposed to sunlight for seven days for drying. Finally, fibers were separated using a decorticator machine (MD-300, Kovai Agro Tech, India). The fibers were alkalized before use to remove wax, sand particles, and other impurities. Additionally, the fibers were cut into approximately 10 mm length for composite manufacturing.

Mango seed particles were produced from mango seeds collected from a local market. The seeds were water retted and then dehydrated for one week in the sun. The dried seeds were converted into powder using a mechanical grinder (MG-750, Vijayalakshmi Engineering Works, India). To achieve uniformity, the powders were sieved through a 60-mesh size sieve. The properties of Tulsi fiber and mango seed particles are provided in Table 1 and Table 2, respectively. Table 3 details the properties of epoxy resin.

The chemical composition of both Tulsi fiber and mango seed particles was evaluated using standard biochemical analysis procedures. Cellulose, hemicellulose, and lignin contents were determined using the Van Soest method, which involves sequential extraction with neutral detergent, acid detergent, and sulfuric acid, followed by gravimetric analysis. Moisture content was measured by drying the samples in a hot air oven at 105 °C for 24 hours, and calculating the weight loss. The density of the materials was calculated using the mass-to-volume ratio, where the volume was measured via displacement method using a liquid of known density. The tensile strength and tensile modulus of the Tulsi fiber were measured in accordance with ASTM D3822 using a universal testing machine. Fibers were conditioned under standard laboratory conditions before testing, and the results were averaged over five replicates to ensure consistency.

Table 1
Properties of Tulsi fiber

Details	Tulsi fiber
Cellulose	8%
Hemicelluloses	10%
Lignin	35%
Moisture	9%
Density	1.1 g/cm^3
Tensile strength	390 MPa
Tensile modulus	13 GPa

Table 2
Properties of mango seed particles

Details	Value
Cellulose	3%
Hemicelluloses	14%
Lignin	2%
Moisture	8%
Density	0.9 g/cm^3

Table 3
Details of epoxy resin

Details	Values
Resin name	LY556
Manufacturer	Huntsman Advanced Materials, Mumbai, India
Viscosity (25 °C)	10,000–12,000 mPa·s
Gel time (25 °C)	45 minutes
Curing time	24 hours
Glass transition temperature	65–70 °C
Density	1.15 g/cm^3

Composite manufacturing

Composite manufacturing began with the preparation of a mixture of the matrix, hardener, Tulsi fiber, and mango seed particles. The epoxy was mixed with the hardener in a ratio of 10:1, followed by the addition of the fiber and seed particles. A mechanical mixer (Laboratory-Grade Overhead Stirrer, Model: RQ-127A/D, Remi Elektrotechnik Limited, India) was used for the mixing action, which was continued for about fifteen minutes at a speed of 300 rpm. The composite was developed via the hand layup method by filling the prepared mixture into a mold. The filling was carried out layer by layer. A level bar was used to level the surface of the mixture and ensure uniform flow in the mold. After every layer of the compound was deposited, a rolling tool was rolled over it to eliminate any encased gas. This process was continued until the required quantity of the mixture, as detailed in Table 4, was loaded. After completion, the mold was closed forcefully, and a 25 kg load was mounted on to provide force, which could improve the adhesive strength. After 24 hours, the mold was opened, and the composite was removed. The composite was kept under environmental conditions for 24 hours before further use. Finally, it was sliced to the required sizes for experimental purposes. The developed composites are shown in Figure 1.

Table 4
Details of epoxy/Tulsi/mango seed composites

Composites	Epoxy (wt%)	Tulsi fiber (wt%)	Mango seed particles (wt%)
Epoxy/20wt% Tulsi (E20T)	80	20	0
Epoxy/30wt% Tulsi (E30T)	70	30	0
Epoxy/40wt% Tulsi (E40T)	60	40	0
Epoxy/30wt% Tulsi/10wt% mango seed (E30T10M)	60	30	10
Epoxy/30wt% Tulsi/20wt% mango seed (E30T20M)	50	30	20
Epoxy/30wt% Tulsi/30wt% mango seed (E30T30M)	40	30	30

Figure 1: Developed composites

Characterization tests

Tulsi fiber was examined using a Perkin Elmer Rx1 FTIR spectrometer. To prepare the samples, the fibers were first ground into a powder and then mixed with KBr. This mixture was pressed into pellets for spectrum absorbance measurement. The analysis spanned a spectral range from 4000 to 500 cm^{-1}. The scanning process featured 4 cm^{-1} steps and consisted of a total of 64 scans.

The characterization of mango seed particles was conducted using X-ray diffraction (XRD) with an XPert-3 diffractometer. The device utilized Cu–Kα radiation at a wavelength of 1.544 Å. Data were collected over a 2θ range from 5° to 90°, with a scan rate of 0.02° per minute. The instrument operated at a constant generator setting of 45 kV and 30 mA.

The tensile test on the composites was performed according to ASTM D3039 using a universal testing machine (UTM, Instron 5982, 100 kN). The speed of the test was set at 5 mm/min. The flexural test was conducted on the UTM following the ASTM D7264 procedure. Additionally, the impact strength of the composites was investigated using an Izod impact tester (FIT-300-I, pendulum type) as per the ASTM D256 procedure.

The water absorption examination was done by soaking the composites in distilled water for the required time and measuring the composite's water absorption capacity. This was calculated by measuring the composite's mass in dry and wet conditions using Equation (1):

$$\text{Water absorption} = \frac{\text{Composite mass at wet condition} - \text{Composite mass at dry condition}}{\text{Composite mass at dry condition}} \quad (1)$$

A biodegradation study was conducted on the developed composites to determine the material's degradation ability using a soil-burial test. A mud pot was used for this test, which was filled with soil, and the samples were buried in the soil. The container was covered with a polymer film to prevent the soil from drying. The soil was frequently moisturized by sprinkling water over it. The samples were periodically taken out, and their mass was assessed with an electronic scale after carefully removing sand particles deposited on them. Equation (2) was used to calculate the mass loss of the sample:

$$\text{Mass loss} = \frac{\text{Initial mass of composite} - \text{Final mass of composite}}{\text{Initial mass of composite}} \quad (2)$$

The density of the fabricated epoxy-based composites was determined using the Archimedes principle in accordance with ASTM D792-13 standard. The specimens were first weighed in air using a precision digital balance (accuracy ±0.001 g) and subsequently weighed while suspended in distilled water using a fine wire. The density was calculated using the formula:

$$\text{Density} = \frac{\textit{Weight of specimen in air}}{\textit{Weight of specimen in air} - \textit{Weight of specimen in water}} \times \textit{density of water} \quad (3)$$

Each density measurement was repeated three times for consistency, and the average value was reported. Standard deviations were calculated and presented as error bars in the corresponding plot.

The morphological analysis of the tensile-fractured composite surfaces was carried out using a scanning electron microscope (SEM). The equipment used for this analysis was a Zeiss SEM, operated at an accelerating voltage of 15 kV. The magnification range varied between 100× and 1000× depending on the features being examined. Prior to imaging, the fractured specimens were cleaned and then gold-coated using a sputter coater to enhance surface conductivity and prevent charging under the electron beam.

RESULTS AND DISCUSSION

FTIR analysis of Tulsi fiber

The FTIR analysis of Tulsi fiber revealed various functional groups, as illustrated in Figure 2. A peak at 3347 cm^{-1} indicated the presence of an amine group, attributed to N-H vibration. Another peak at 2914 cm^{-1} was due to the stretching vibrations of the aliphatic methyl group's C-H bonds. Additionally, a peak at 1654 cm^{-1} corresponded to the carboxyl group's C=O vibration. The amine group also manifested a peak at 1431 cm^{-1}. Furthermore, a peak at 1031 cm^{-1} was associated with the C-O-C group.

These identified functional groups suggest the presence of cellulose, hemicellulose, and lignin within the fiber that significantly impact interfacial adhesion with polymer matrices. To assess the suitability of Tulsi fiber for composite applications, a comparative FTIR study was conducted using data from other natural fibers, such as jute, flax, banana, and hemp, shown in Table 5, which are widely used in fiber-reinforced composites.

This comparative analysis confirms that Tulsi fiber exhibits similar chemical functionality to traditional natural fibers. While the peak locations are broadly consistent, minor shifts in peak positions and intensities could imply variations in the relative content of cellulose, hemicelluloses and lignin. These compositional differences may influence key properties, such as moisture affinity (affected by hydroxyl content), thermal and oxidative stability (influenced by lignin content), fiber–matrix adhesion (enhanced by available polar groups for bonding).

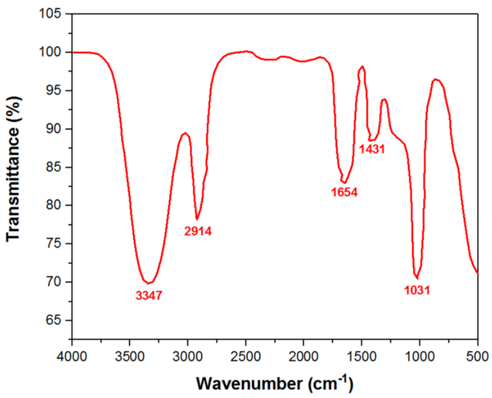

Figure 2: FTIR spectrum of Tulsi fiber

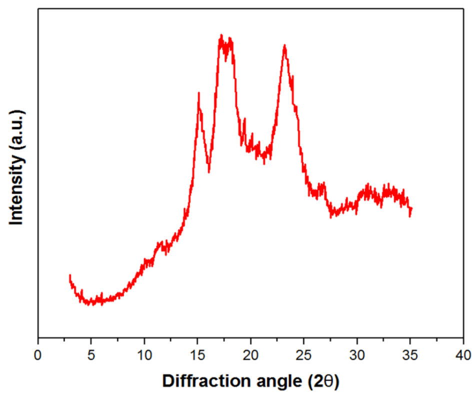

Figure 3: XRD pattern of mango seed particles

Table 5
Comparison of FTIR peak positions for Tulsi and other natural fibers

Fiber type	O-H/N-H (cm^{-1})	C-H (cm^{-1})	C=O (cm^{-1})	C-O/C-O-C (cm^{-1})	Reference
Tulsi	3347	2914	1654	1031	Present study
Jute	3435	2901	1733	1053	[20]
Flax	3419	2900	1735	1056	[21]
Banana	3379	2919	1602	1068	[22]
Hemp	3336	2887	1729	1048	[23]

XRD analysis of mango seed particles

The resulting XRD pattern of the mango seed particles, depicted in Figure 3, revealed peaks at 2θ angles of 15°, 17°, 18°, and 24°, suggesting the presence of A-type crystallinity starch. This indicates a high degree of chain packing, which could potentially enhance bonding strength when integrated into a matrix. Similar A-type crystallinity was reported in tamarind seed particles by Kaur *et al.*[13]

Tensile study of composites

A tensile study was conducted on epoxy/Tulsi/mango seed composites, and the results are shown in Figure 4. Tulsi fibers were mixed with epoxy resin in different quantities to investigate their effect on tensile strength. Experimental outcomes revealed that the epoxy/Tulsi composite showed a high tensile strength, of 55 MPa, when reinforced with 30 wt% Tulsi fiber. The added fiber facilitated good stress transfer along with the resin due to better bonding between the resin and fiber. However, increasing the fiber quantity beyond 30 wt% caused a decrease in tensile strength from 55 MPa to 53 MPa. This indicates that 30 wt% fiber is the optimal level for even distribution, promoting bonding strength and load transfer. A higher quantity (>30 wt%) resulted in agglomeration and weaker bonding strength.

Similar behavior has been reported in recent studies; for instance, an investigation on jute fiber-based epoxy composites found that an optimal fiber loading is crucial for maximizing tensile properties, with excessive fiber content leading to diminished strength because of poor dispersion and bonding issues.[14]

Further, the E30T composite (Epoxy/30 wt% Tulsi) was filled with different quantities of mango seed particles, and their effect on tensile strength was observed. Experimental outcomes showed that 20 wt% mango seed particles exhibited good strength. Beyond this limit (>20 wt% mango seed), the composite started to decrease in strength.

Hence, it was confirmed from this study that the E30T20M (Epoxy/30 wt% Tulsi/20 wt% mango seed particles) composite performed well during the tensile test, showing a peak tensile value of 60 MPa that is 9% higher in relation with E30T composite. Felix Sahayaraj *et al.*[15] reported that adding 10 wt% *Tamarindus indica* seed particles to *Luffa cylindrica*-based composites enhanced tensile strength (67.83 MPa) due to improved matrix–fiber adhesion, supporting the findings of the present study.

Flexural study of composites

A flexural experiment was conducted on epoxy/Tulsi/mango seed composites, and the results are presented in Figure 5. Various quantities of Tulsi fiber mixed with epoxy resin showed significant differences in outcomes. For instance, the composite with 30 wt% Tulsi fiber exhibited the highest flexural strength of 85 MPa, followed by 83 MPa for the composite with 40 wt% Tulsi fiber. This demonstrated that 30 wt% Tulsi fiber was optimal for augmenting the flexural strength of the epoxy/Tulsi material. At this concentration, the interaction between the fiber and epoxy was optimal, improving the material's rigidity.

Additionally, the E30T composite (Epoxy/30 wt% Tulsi) was reinforced with different amounts of mango seed particles, and its performance was evaluated. The results showed that adding 20 wt% mango seed particles increased the flexural strength of the composite from 85 MPa to 90 MPa. This improvement can be attributed to the dispersion of mango seed particles within the epoxy matrix, which provided a bridging effect between the fiber and epoxy during stress transfer, thereby increasing the stiffness of the composite.

Therefore, this study concluded that the E30T20M composite (Epoxy/30 wt% Tulsi/20 wt% mango seed) performed well in the flexural experiment, showing a peak flexural strength of 90 MPa. Girimurugan *et al.* found that adding 15 wt% tamarind seed particles to sugarcane fiber composites enhanced flexural strength by 20% (37 MPa) due to improved matrix–filler interaction, aligning with the findings of the present study.[16]

Impact study of composites

An impact experiment was conducted on epoxy/Tulsi/mango seed composites to evaluate their performance under shock loads, and the results are presented in Figure 6. The outcomes indicated that the epoxy reinforced with 30 wt% Tulsi fiber (E30T) exhibited superior impact strength due to strong adhesion between the fiber and epoxy. This enhanced the material's ability to absorb shock energy effectively. However, when higher quantities of fiber (>30 wt%) were added, the adhesive strength weakened due to insufficient resin to adequately bond with the fiber. This resulted in fiber agglomeration and reduced bonding strength of the material.

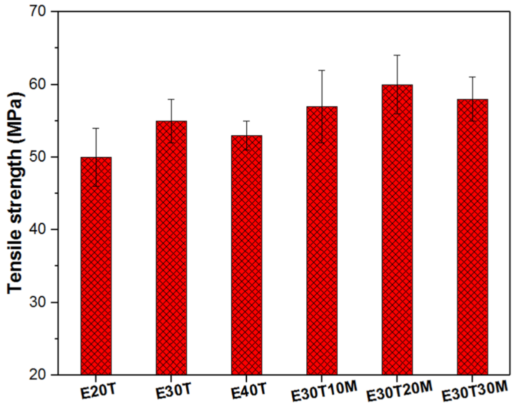

Figure 4: Tensile strength of epoxy/Tulsi/mango seed composites

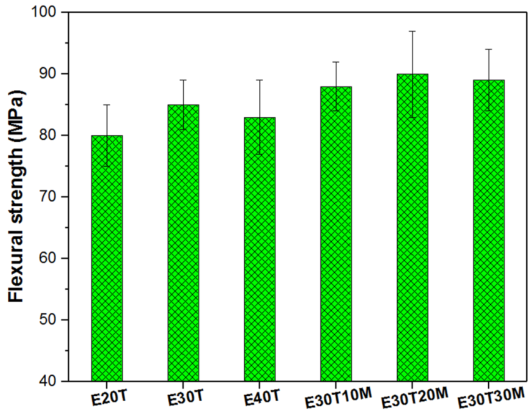

Figure 5: Flexural strength of epoxy/Tulsi/mango seed composites

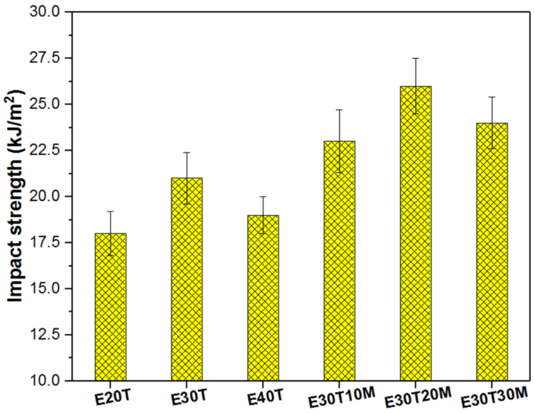

Figure 6: Impact strength of epoxy/Tulsi/mango seed composites

Additionally, the E30T composite was supplemented with varying amounts of mango seed particles, and the composite's performance was evaluated. The results showed that adding 20 wt% mango seed particles significantly improved the impact strength. Beyond this amount (>20 wt%), the impact strength began to decrease due to weak adhesive strength caused by particle clustering.

Overall, the study concluded that the E30T20M composite (Epoxy/30 wt% Tulsi/20 wt% mango seed) exhibited the highest impact strength of 26 kJ/m², which was 23.8% better than the impact strength of the E30T material. This indicates that the combined reinforcement of Tulsi fiber and mango seed particles effectively enhances the impact resistance of the epoxy composite. Srinivasan *et al.* found that Palmyra palm/tamarind seed powder composites showed higher impact strength than unfilled ones, attributed to improved interfacial bonding between fiber, filler, and matrix.[17]

Statistical analysis of mechanical properties

To assess the significance of the differences in mechanical properties among the various composite formulations, an analysis of variance (ANOVA) was performed on the tensile strength, flexural strength, and impact strength data, as detailed in Figure 7.

The ANOVA results indicated a statistically significant effect of the composite composition on mechanical performance. Specifically, the tensile strength exhibited an F-value of 7.90, with a corresponding p-value of 0.0017, confirming significance at the 1% level. Flexural strength analysis yielded an F-value of 4.00 and a p-value of 0.0229, while impact strength showed an F-value of 4.01 with a p-value of 0.0227, both significant at the 5% level.

These findings demonstrate that the reinforcement scheme, including the incorporation of Tulsi fiber and mango seed, significantly influences the mechanical properties of the composites.

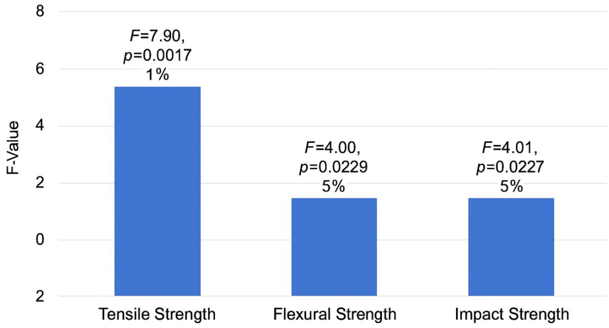

Figure 7: ANOVA results for mechanical properties of epoxy/Tulsi/mango seed composites

Water absorption study

A water absorption experiment was conducted on epoxy/Tulsi/mango seed composites, and the results are depicted in Figure 8, showing the relationship between water absorption percentage and soaking periods. It was observed that there is a correlation between the soaking time and water absorption, with higher water absorption percentages recorded for longer soaking periods. Natural fibers, such as Tulsi fiber, are prone to absorbing water due to capillary action, leading to increased water absorption over time. This trend continued until the 8th day, after which the plot leveled off, indicating that the material's water absorption reached a saturation point.

Interestingly, composites reinforced with mango seed particles demonstrated inferior water incorporation in relation with epoxy/Tulsi composites. This is attributed to mango seed particles filling the spaces between the fibers and epoxy, thereby reducing the overall water holding capacity of the material. For instance, during a 10-day soaking period, the E30T30M composite showed the lowest water absorption rate at 7%, which is 41.6% lower than the water absorption percentage recorded by the E30T composite.

In conclusion, the incorporation of mango seed particles into the epoxy/Tulsi composite effectively mitigates water absorption, demonstrating improved water resistance compared to composites without mango seed particles. Nath *et al.* reported an 18% reduction in water absorption in jute composites after adding 5 wt% cenosphere filler, attributing the improvement to the filler's ability to reduce voids and limit moisture ingress.[18]

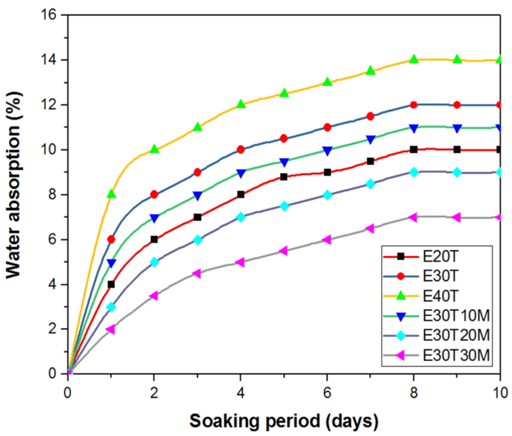

Figure 8: Water absorption results of epoxy/Tulsi/mango seed composites

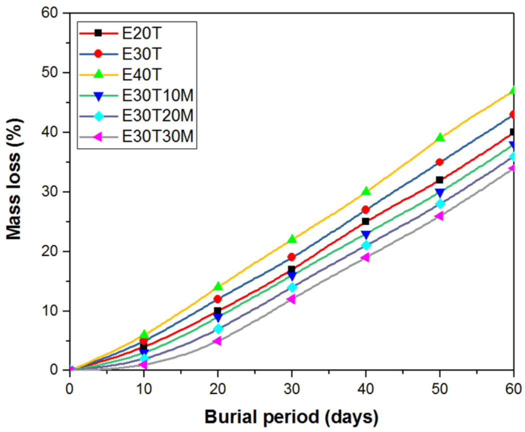

Figure 9: Biodegradation results of epoxy/Tulsi/mango seed composites

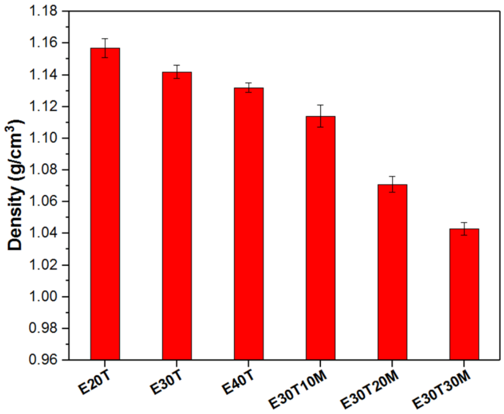

Figure 10: Density results of epoxy/Tulsi/mango seed composites

Biodegradation study

A biodegradation study was conducted on epoxy/Tulsi/mango seed composites by burying the materials for 60 days and calculating the percentage of mass loss. Figure 9 shows the biodegradation outcomes for epoxy/Tulsi/mango seed composites. The plot of mass loss versus burying time showed a steep curve, indicating that the degradation of the material increased with longer burying times. This increase in degradation could be attributed to prolonged exposure to humidity and bacterial attack. Composites with higher fiber content exhibited greater mass losses. For instance, the E40T composite showed a mass loss of 47%, while the E20T composite exhibited a mass loss of 40%. This confirms that higher amounts of fiber in composites led to more severe degradation. When a material contained more fiber, its water absorption capacity increased due to the hydrophilic nature of natural fibers and resulted in swelling of the material. This swelling of the material can result in reduced bonding strength and provided a suitable environment for bacterial growth, leading to accelerated degradation. However, composites containing mango seed particles showed a slowdown in the degradation process due to reduced water absorption, as discussed in the water absorption study. The presence of mango seed particles interrupted water absorption pathways, thereby mitigating bacterial attack and reducing degradation.

In conclusion, the study determined that the E30T30M composite exhibited the least mass loss of 34% during the 60-day burying period. This suggests that the combination of 30 wt% Tulsi fiber and 30 wt% mango seed particles effectively balances mechanical properties with reduced susceptibility to degradation in environmental conditions. Dinesh *et al.* observed slower biodegradation in jute/wood dust composites with fillers, findings consistent with the present study's results.[19]

Densities of composites

The bar chart shown in Figure 10 presents the density (g/cm³) of various epoxy composite formulations reinforced with different weight fractions of Tulsi fibers and mango seed particles. The formulations include single-fiber composites (E20T, E30T, E40T) and hybrid composites (E30T10M, E30T20M, E30T30M), where the labels indicate the corresponding fiber and filler weight percentages.

The density of the composites decreases progressively with increasing mango seed particle content. The E20T composite (80 wt% epoxy and 20 wt% Tulsi fiber) exhibited the highest density at approximately 1.16 g/cm³. In contrast, the lowest density (1.04 g/cm³) was recorded for the E30T30M composite (40 wt% epoxy, 30 wt% Tulsi fiber, and 30 wt% mango seed particles). The reduction in density with the addition of mango seed particles is attributed to the inherently lower density of the organic filler compared to the epoxy matrix and the increased volume fraction of low-density reinforcements displacing the denser matrix material.

Morphological analysis

Morphological analysis was conducted on the tensile fractured composites, and the micrographs are presented in Figure 11. In the E30T20M composite, a clear fiber breakage was observed, with the resin surface appearing smooth. However, there was evidence of gaps at the interface between the fiber and resin, likely caused during loading due to fiber movement. This suggests that the composite exhibited sufficient strength to withstand the applied load, attributed to good bonding strength.

In contrast, the E30T30M composite showed fiber pullout, indicating that the composite experienced more severe forces, compared to the E30T20M composite, because of weaker interfacial bonding strength. This resulted in fibers being pulled out from the resin matrix.

Therefore, the morphological investigation confirmed that the E30T20M composite performed better than the E30T30M composite. This finding aligns with the mechanical properties discussed previously, where the E30T20M composite demonstrated superior performance in terms of tensile strength and impact resistance.

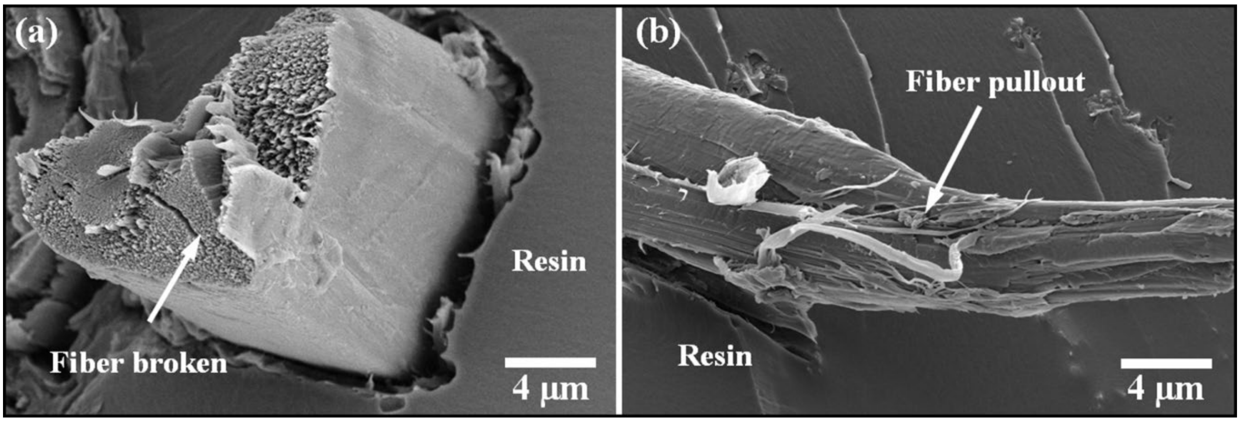

Figure 11: Tensile fractured composites, (a) E30T20M, (b) E30T30M

Table 6
Comparison of mechanical properties of epoxy/Tulsi/mango seed composites with other composites

Composites	Tensile strength (MPa)	Flexural strength (MPa)	Reference
Epoxy/Tulsi/mango seed	60	90	Present study
Epoxy/Indian almond/neem seed	69	113	[7]
Epoxy/groundnut shell	18	28	[24]
Epoxy/luffa/groundnut	39	58	[24]
Epoxy/Indian almond/jujube fruit seed	66	63	[5]
Epoxy/tamarind seed	28	-	[25]
Epoxy/Tamarind case	48	47	[26]
Epoxy/*Erythrina variegata*	108	112	[27]
Epoxy/date seed	50	-	[28]

Comparison results

The performance of the epoxy/Tulsi/mango seed composite was compared with other composites reported in the literature, as detailed in Table 6. The epoxy/Tulsi/mango seed composites exhibited a tensile strength of 60 MPa and flexural strength of 90 MPa, which were comparable to the results for epoxy/Indian almond/neem seed and epoxy/Indian almond/jujube fruit seed composites. Apart from these materials, all other composites showed lower strength values. Additionally, groundnut shell and tamarind seed-based composites exhibited notably lower strengths compared to the epoxy/Tulsi/mango seed composites. From this analysis, it was observed that mango seed in the epoxy/Tulsi composite demonstrated performance similar to jujube fruit seed and neem seed-based composites.

The epoxy/Tulsi/mango seed composite, which exhibited a tensile strength of 60 MPa and a flexural strength of 90 MPa, demonstrates mechanical characteristics suitable for light to moderate load-bearing applications. These values are comparable to those reported for epoxy/Indian almond/neem seed and epoxy/jujube fruit seed composites, which have been proposed in earlier studies for use in automotive interior panels, low-load structural components, and consumer products that benefit from biodegradable and lightweight materials.

Based on the achieved mechanical performance, the epoxy/Tulsi/mango seed composite is suitable for potential applications in areas such as automotive components (including dashboards, door panels, and trims), furniture parts, enclosures for electronic devices, packaging and decorative panels in construction, as well as in consumer goods like helmets and luggage. In contrast, composites such as those reinforced with groundnut shell or tamarind seed, which showed significantly lower tensile and flexural strengths, are more appropriate for non-structural or semi-structural uses, such as insulation, packaging, or decorative items.

Therefore, considering its mechanical properties and its environmentally friendly composition, the epoxy/Tulsi/mango seed composite developed in this study shows strong potential for use in eco-conscious industrial applications, where moderate strength and sustainability are important design criteria.

CONCLUSION

The developed epoxy composites reinforced with Tulsi fiber and mango seed particles exhibit a well-balanced combination of mechanical strength, moisture resistance, and biodegradability. The incorporation of 30 wt% Tulsi fiber and 20 wt% mango seed particles led to optimal tensile, flexural, and impact properties, making the composite suitable for moderate load-bearing applications.

The composites showed reduced water absorption and improved dimensional stability, indicating suitability for environments exposed to humidity or occasional moisture. Biodegradation studies confirmed partial environmental degradability, supporting the composite’s use in eco-friendly and disposable product applications.

The material's performance positions it as a strong candidate for use in automotive interior components, lightweight furniture, electronic casings, and sustainable packaging solutions where both mechanical integrity and environmental impact are critical.

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