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Research Article

Tea Stem Waste Powders for Epoxy-Based Composites: Processing, Mechanical Properties, and Fracture Behavior

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Abstract This study investigates the potential of mechanically processed tea stem waste powders as an environmentally friendly reinforcement for epoxy-based composites. Tea stem waste, a lignocellulosic byproduct of tea processing, was reduced in size by high-speed mixing and planetary ball milling without any chemical pretreatment, and incorporated into an epoxy system at varying weight fractions (1–10 wt.%). The composites were fabricated under controlled conditions and subjected to tensile, fracture toughness, hardness, thermal, and morphological evaluations. Mechanical testing revealed that tensile strength increased with filler loading up to an optimum of 7.5 wt.% (72.16 MPa), corresponding to a 14.8% improvement over neat epoxy, while higher content(10 wt.%) showed minor reduction due to potential filler agglomeration. The elastic modulus displayed a non-linear trend, decreasing slightly at low filler levels but reaching 1.30 GPa at 10 wt.%. Fracture toughness (K_{Ic}) exhibited a continuous increase, with a maximum of 2,41 MPa$\sqrt{m}$ at 10 wt.%—a 26.4% improvement compared to neat epoxy. Shore D hardness also improved progressively, with up to a 23% increase at the highest filler content. Thermal analysis confirmed that the addition of tea stem powder did not significantly affect the glass transition or initial degradation temperatures, while an increased char yield indicated enhanced thermal stability. FE-SEM fractography showed that fiber orientation strongly influenced crack propagation: longitudinal fibers remained intact, while transverse fibers fragmented and dissipated energy, thereby enhancing fracture resistance. These results confirm that tea stem waste powders, processed solely by mechanical means, can effectively reinforce epoxy matrices. Although samples made with 7.5% filler yield the best results in tensile testing, it has been observed that 10% content yields higher results in fracture toughness and hardness tests. The results of the study showed that the mechanical strength of the composite material made from this tea stem waste was higher than that of pure epoxy in all content variations tested here.

Keywords: Epoxy composites, Fracture toughness, Hardness, Natural fibers, Tea stem waste

1.INTRODUCTION

The rapid depletion of fossil-based resources and the environmental burden caused by petroleum-derived polymers have become critical global concerns. These synthetic polymers, despite offering excellent mechanical performance, thermal stability, and ease of processing, are inherently non-biodegradable and persist for decades in landfills and natural ecosystems, thereby contributing significantly to long-term environmental pollution and microplastic accumulation [1], [2]. In addition, the extraction and processing of petroleum feedstocks for polymer synthesis result in substantial greenhouse gas emissions and high energy consumption, further exacerbating global climate change. Such challenges have shifted the focus of materials science toward the development of sustainable and renewable alternatives that can provide comparable mechanical integrity, thermal performance, and durability while simultaneously minimizing ecological impact and supporting circular economy principles[3].

Synthetic fibers are increasingly being replaced with the natural fiber-reinforced composites, which are an attractive combination of mechanical and environmental properties [4]. Their inherently low density contributes to high specific strength, enabling lightweight yet mechanically robust materials suitable for demanding structural applications [5], [6]. Additionally, natural fiber composites exhibit excellent vibration damping characteristics and acoustic properties, making them ideal for noise reduction applications[7], [8]. Natural fibers composites in real-world applications have seen to be utilized the most in sectors like automotive, construction and consumer goods. The integration of fibers derived, for example, from flax, hemp, and jute were part of car interior and structural components enabling less weight in vehicles and better fuel economy [9], [10], [11].

Epoxy resins are well-known for their great strength and excellent resistance to chemicals, being used in high wear and tear industries as well as top performance demands [12]. With high thermal stability and good adhesion and moldability, these thermosetting polymers are employed in industrial applications for various types of composites (industrial and structural [13], [14]). However, conventional epoxy resins are almost entirely petroleum-derived—typically synthesized from precursors like epichlorohydrin and bisphenol A—raising critical sustainability concerns due to reliance on non-renewable feedstocks and associated environmental impacts [15].

Natural fiber-reinforced epoxy composites have been extensively studied for their mechanical and thermal properties, with significant findings across various fibers and fillers. The incorporation of bamboo fiber with nano SiO_2 in a hybrid composite showed a reduction in tensile, flexural, impact, and hardness strengths at 4 wt. % silica, highlighting an optimal limit of 3 wt.% [16]. Banana fiber composites with 0.75 wt% functionalized g-C_3N_4 exhibited enhanced tensile strength (126.8 MPa), flexural strength wt. %.9 MPa), and impact strength (26.9 J/m), suggesting potential for PCB applications [17]. Optimized banana/coir hybrid epoxy composites with a 65:35 fiber/matrix volume proportion, 10 mm fiber length, and 75:25 banana/coir ratio demonstrated superior tensile, compressive, impact, and flexural properties [18]. Cotton fiber composites achieved the highest tensile strength at 52.81 MPa, while coir composites showed the lowest at 15.34 MPa, with coir also exhibiting the highest specific heat (26.313 MJ/m^{3}K) for energy-saving insulation [19]. In another study, basalt-bamboo hybrid composites toughened with 4 vol.% echinoidea spike β-chitin absorbed the highest impact energy (17.4 J at 3 m/s), indicating improved impact resistance and thermal stability [20]. In a related work, it was found that adding areca fiber and pectin biofiller to epoxy led to a clear increase in tensile strength, rising from 65 MPa in neat epoxy to 107 MPa with areca fiber, and further up to 147 MPa when 3 vol.% pectin was included, before decreasing again at higher filler content due to agglomeration [21]. In the study by Singh and Rout (2023), the tensile strength of Borassus leaf fiber + rice husk nanoparticle epoxy composites increased from 9.24 MPa in raw fiber composites to 14.0 MPa at 0.45 wt. % RHN. Similarly, the tensile modulus improved from 471 MPa to 489 Mpa [22].

Tea processing generates substantial amounts of fibrous waste, including leaves, stems, buds, and other residues originating from harvesting, pruning, drying, and brewing operations [23]. In Türkiye, tea cultivation is carried out exclusively in the Eastern Black Sea Region, primarily in Rize, Trabzon, Artvin, Giresun, and Ordu with an annual fresh tea production of 1.357 million tonnes in 2023. During processing, approximately 203,483 tonnes of ITW(Industrial Tea Waste) are generated each year, corresponding to about 17.6% of the total harvested fresh tea mass [24]. Among the various components of ITW, tea stem waste stands out due to its high fiber content and complex lignocellulosic structure, rich in cellulose, hemicellulose, and lignin, which are conducive to reinforcement applications in composite materials[25]. The fibrous nature and rigidity of these stems offer inherent potential for mechanical reinforcement, such as enhancing stiffness and impact resistance when incorporated into polymer matrices [26]. However, despite these favorable properties, research on the utilization of tea stem waste, especially in the form of fiber-containing powders for thermosetting matrix composites remains scarce, highlighting a significant gap in valorization strategies for this underutilized agricultural residue[27].

In one study, industrial waste tea leaf fiber (WTLF) treated with 5% NaOH showed a tensile strength of 132–165 MPa. When 5 wt% WTLF was incorporated into hybrid epoxy composites, tensile, flexural, and impact strengths reached 70.81 MPa, 181.08 MPa, and 96 kJ/m², respectively. Higher WTLF contents reduced performance due to fiber agglomeration and poor resin wetting [28]. In another study, industrial tea waste (ITW) powder (1–250 μm) added to jute–unsaturated polyester composites showed the best performance at 9 wt%, with tensile and flexural strengths of 26.58 MPa and 40.58 MPa, respectively. Higher ITW contents caused agglomeration, reducing mechanical properties [29].

Waste tea fiber (WTF) reinforced bio-based epoxy composites, modified with maleic anhydride (MAH), achieved tensile strengths up to 16.1 MPa with elongation at break of 23.8%, and maintained good thermal stability up to 244 °C. These composites also showed remarkable durability, with tensile strength increases of up to 65.8% after heat aging and 49.5% after UV exposure[26]. A recent study utilized tea stem fiber (TSF) to reinforce polypropylene (PP) through conventional and microcellular injection molding. The best balance of strength and weight was obtained with 30 wt% TSF in foamed composites, delivering tensile, flexural, and impact strengths of 32.84 MPa, 51.31 MPa, and 6.94 kJ/m², alongside a ~6% density reduction. The enhanced performance was attributed to improved interfacial bonding from alkali treatment and maleic anhydride grafting, combined with a uniform microcellular structure [27].

The conversion of wastes into micro- and nanoparticles using a ball mill is relatively rare in the literature. For instance, Sharma et al. reported that rice straw remaining after harvest was ground with a ball mill to produce cellulose nanofibers (CNF), and although no composite was fabricated, the fiber microstructure was examined in detail [30]. Similarly, in a study with jute composites, ball milling not only reduced particle size but also activated the fiber surface, enhancing matrix adhesion and providing a low-cost alternative to chemical pretreatments [31]. While CNF production from agricultural residues often involves chemical pretreatments to enhance surface charge and dispersion, the present study demonstrates that mechanically processed tea stem waste reduced in size via high-speed mixing and subsequent ball milling without any chemical modification can still serve as an effective reinforcement in epoxy composites, combining simplicity, low cost, and environmental friendliness.

In this study, tea stem waste was selected as a lignocellulosic agricultural residue with potential for reinforcement in polymer composites. The waste was mechanically processed through high-speed mixing and planetary ball milling to obtain fiber-containing powders without the use of chemical pretreatments. These powders were then incorporated into epoxy matrices at different weight ratios to fabricate composite specimens. A systematic characterization program was conducted, including tensile testing, fracture toughness measurements, Shore D hardness evaluation, thermal analyses (DSC and TGA), and morphological examinations using FE-SEM. Through this comprehensive approach, the study aimed to establish a framework for the utilization of tea stem waste as a sustainable filler in epoxy-based composites, contributing to the broader valorization of agricultural residues in advanced material applications.

2. MATERIALS

The tea stem wastes used were obtained from a tea factory in Rize (Turkey) and no chemical treatment was applied. The tea stems photographed in Figure 1 are approximately 3 cm long and 2.5 mm in diameter.

Figure 1.Tea stem waste in its original form as supplied from the factory.

The epoxy system employed in this study consisted of two components supplied by Momentive. The A-component, designated as MGS-L285, is a lamination-grade resin with a viscosity of 600–900 mPa·s, formulated as a biphasic mixture containing 80–90 wt% diglycidyl ether of bisphenol A and 10–20 wt% aliphatic diglycidyl ether. The B-component, MGS-H285 curing agent, comprises 70–90 wt% cycloaliphatic amine and 10–30 wt% polyoxyalkyl amine, with a viscosity of 50–100 mPa·s. When mixed at the manufacturer-recommended ratio of 100:40 (by weight), the system exhibits a gelation time of approximately 2–3 h at room temperature.

3. METHODS

This section describes the preparation of tea stem waste powder, the fabrication of epoxy-based composites with varying filler contents, and the subsequent mechanical and microstructural characterizations performed to evaluate their performance.

3.1. PREPARATION OF TEA STEM WASTE POWDER

The raw stems, approximately 3 cm in length and 2.5 mm in diameter, were first dried at 70 °C for 6 h to remove residual moisture. The dried material was coarsely size reduced using a high-speed mixer (Retsch/GM200) operating at 10000 rpm for 2 min. The resulting coarse particles were then milled in a planetary ball mill (Retsch PM100) at 300 rpm for a total of 2 h, using 5mm diameter stainless steel balls at a ball-to-powder weight ratio of 10:1.

Figure 2.Tea stem powder after ball-milling operation.

To prevent excessive heat generation from the grinding media, the milling process was performed in cycles of 15 min operation followed by 5 min cooling intervals. In one similar study, it was observed that bamboo-based cellulose nanofibers were produced at 500 rpm for 4 hours [32]. In yet another study, bamboo fibers were milled at 300 rpm with a 10:1 ball ratio for 3.6 and 12 hours. In this context, the values selected in this study are consistent with and appropriate for the literature[33]. Laser scatter analysis of the tea stem powder revealed an average particle size of 73.20 µm, with a median (D50) of approximately 71.9 µm. The particle size distribution was relatively broad, as 10% of the particles were smaller than 22.4 µm while 90% were below 142.6 µm. The resulting fiber-containing powder was stored in sealed containers at ambient conditions until composite fabrication. Figure 2 shows the resulting powder in the container.

3.2. COMPOSITE FABRICATION

In the composite fabrication stage, the micro-sized waste tea stem powder and epoxy resin (A-component), obtained from the preceding preparation processes, were utilized as the primary constituents. The waste tea powder, dried and sieved to the targeted particle size range, was incorporated into the epoxy resin without the addition of the curing agent, in accordance with the predetermined weight ratios presented in Table 1. This dry–wet blending process was carried out using a laboratory-scale mechanical stirrer with a rated power of 1000 W. The mixing speed was maintained at a constant 500 rpm for a duration of 20 minutes to promote effective wetting of the tea powder particles by the resin and to ensure their uniform dispersion throughout the viscous epoxy phase. The controlled shear provided by the stirrer facilitated the breakdown of any powder agglomerates and minimized localized resin-rich or fiber-rich regions, which are known to cause mechanical property inconsistencies in cured composites.

Table 1. Formulations of Epoxy–Waste Tea Stem Powder Composites

Sample Code	Epoxy Resin A [wt.%]	Hardener B [wt.%]	Waste Tea Stem Powder [wt.%]
E-0	60	40	0,00
E-1.0	59,4	39,6	1,00
E-2.5	58,5	39	2,50
E-5	57	38	5,00
E-7.5	55,5	37	7,50
E-10	54	36	10,00

For each formulation, an independent batch was prepared under identical processing conditions to maintain consistency across experimental variables. The homogenized suspensions, exhibiting a uniform particle distribution and stable viscosity, were then ready for the subsequent steps involving curing agent addition, mold casting, and thermal curing protocols, which ensured complete crosslinking and optimal network formation within the composite matrix.

Prior to casting, the epoxy–waste tea stem powder(Figure 3) mixtures were subjected to ultrasonic dispersion(Figure 3) using a 1000 W ultrasonic processor operated at 20% amplitude for 5 minutes. This additional step was employed to break down agglomerates and promote a more uniform distribution of the tea powder particles within the resin matrix. Ultrasonic energy generates localized high shear and cavitation, which enhances particle wetting and reduces the likelihood of particle clustering, thereby contributing to improved interfacial bonding and more consistent mechanical performance in the final composites.

Figure 3.Waste tea stem powder (left) and ultrasonic dispersion of epoxy–tea powder mixture using a 1000 W ultrasonic processor at 20% amplitude for 5 minutes (right).

3.3. PREPARATION OF TENSILE AND FRACTURE TEST SPECIMENS

The homogenized epoxy–waste tea stem powder mixtures were subsequently poured into steel molds designed for tensile and fracture specimens in accordance with the relevant ASTM standards, as illustrated in Figure 4. These molds were manufactured to meet the specified dimensions and tolerances required for the respective mechanical tests, ensuring consistency and comparability of the results. Care was taken during the pouring process to minimize air entrapment, as voids could serve as stress concentrators and adversely affect the mechanical performance of the cured composites.

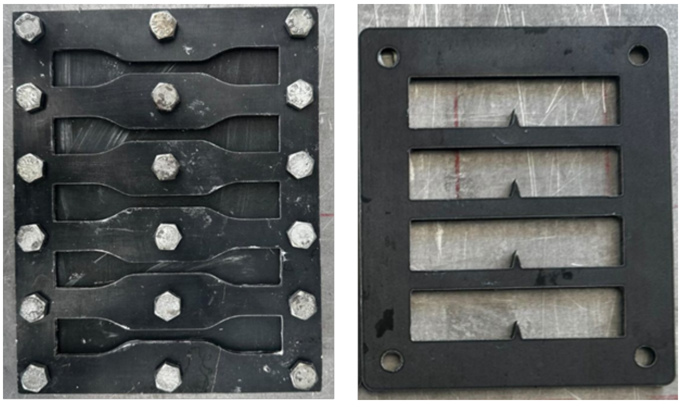

Figure 4.Steel molds for specimen fabrication: tensile test mold (left) and fracture test mold (right), manufactured in accordance with ASTM D638[34] & ASTM D5045[35] standards.

Following the initial casting, the composites were allowed to cure at room temperature for 8 hours to facilitate gelation and partial crosslinking of the epoxy matrix. Subsequently, a post-curing process was carried out in a laboratory oven, where the specimens were maintained at 80 °C for 2 hours to achieve complete crosslinking. This thermal treatment increased the crosslink density of the polymer network, resulting in improved mechanical strength, thermal stability, and overall composite performance. The curing parameters were selected in accordance with the epoxy resin manufacturer's recommended curing profile to ensure optimal material properties.

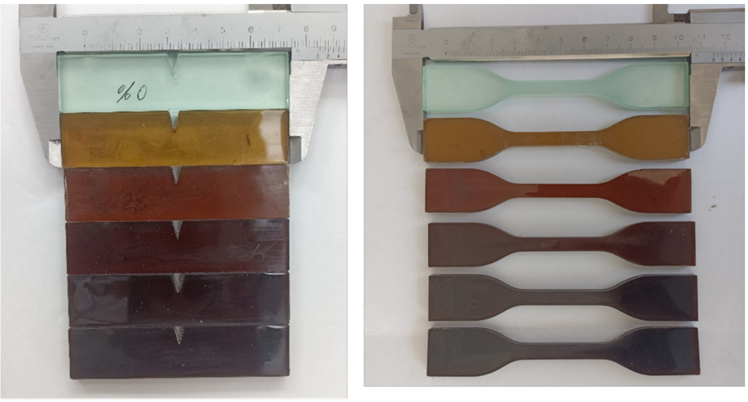

Figure 5.Fracture and tensile specimens with varying tea stem waste powder contents.

Figure 5 presents the sets of fracture (left) and tensile (right) test specimens produced with varying weight percentages of waste tea stem powder, as specified in Table 1. The specimens were fabricated in accordance with the relevant ASTM standards using steel molds to ensure precise geometry and dimensional accuracy. The gradual change in coloration across the series reflects the increasing filler content, which not only influences the visual appearance but is also expected to impact the microstructural characteristics, interfacial bonding, and consequently the mechanical performance of the composites. These specimens represent the final cured state after the complete curing cycle, including room-temperature pre-curing and oven post-curing, and were subsequently used for mechanical testing.

3.4. TENSILE TESTING

Tensile testing of the epoxy–waste tea stem powder composites was conducted using a Shimadzu universal testing machine with a load cell capacity of 10,000 N, as illustrated in Figure 6a. The specimens were mounted in standard wedge grips (Figure 6b, 6c), ensuring proper alignment to minimize bending stresses during loading. Tests were performed at a crosshead speed of 2 mm/min in accordance with ASTM D638, under controlled laboratory conditions at an ambient temperature of 23 ± 2 °C and relative humidity of 50 ± 5%. Load–displacement data were continuously recorded for the determination of tensile strength, elastic modulus, and elongation at break. The machine's high sensitivity and precise displacement control ensured reliable measurements across all composite formulations. The tensile tests were repeated for 3 samples of each tea stem powder loading composition.

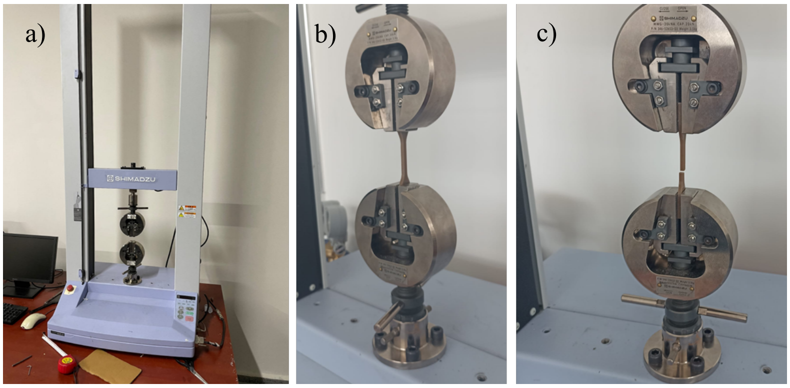

Figure 6.Shimadzu universal testing machine with a 10000N load cell (a), tensile specimen attached to the machine before testing (b), broken tensile specimen after testing (c)

3.5. FRACTURE TEST

Fracture toughness tests were performed in accordance with ASTM D5045-99 for the determination of plane-strain fracture toughness (K_{IC}) of plastic materials. All tests were carried out on a Shimadzu universal testing machine with a maximum load capacity of 10,000 N. Single-edge notched bend (SENB) specimens with a total length of 85 mm, width (W) of 20 mm, thickness (B) of 4 mm, and an initial crack length (a) of 9 mm were used. The notches were pre-formed during molding and subsequently sharpened using a fresh razor blade in a single controlled sliding motion to obtain the sharp crack tip geometry required by the standard.

The support span-to-width ratio (S/W) was maintained at 4, corresponding to an 80 mm span length. Tests were conducted at 23 ± 1 °C and 50 ± 5% relative humidity under displacement control, with a crosshead speed of 1 mm/min. Load–displacement curves were recorded, and the conditional stress intensity factor (K_Q) was calculated according to the equations provided in ASTM D5045-99. Three repeats were performed for each sample set for fracture toughness tests. The validity of the K_Q values was checked against the size requirements of the standard to determine whether they qualified as K_{IC}.

Figure 7.Shore D hardness tester (UVE Measurement Equipment) with Novotest durometer used for composite specimen hardness measurements.

3.6. SHORE-D HARDNESS TEST

Shore D hardness measurements of the composite specimens were conducted using a UVE Measurement Equipment setup equipped with a Novotest Shore D durometer. The test procedure followed the guidelines specified in ASTM D2240[36], which is the standard method for determining the indentation hardness of rigid plastics. Prior to testing, all specimens were conditioned at room temperature (approximately 23 ± 2 °C) and relative humidity of 50 ± 5% for at least 24 hours to ensure thermal and moisture equilibrium. Each specimen was placed on a flat, rigid support surface, and the indenter was applied perpendicularly to the sample surface without impact, maintaining firm contact for 15 seconds before recording the hardness value. For each formulation, a minimum of five measurements were taken at different locations on the specimen surface to account for local variations, and the average Shore D hardness was calculated and reported.

3.7. POST-FRACTURE MORPHOLOGICAL ANALYSIS WITH FE-SEM

The fracture surfaces of the tested specimens were examined using a Zeiss Gemini SEM 500 Field Emission Scanning Electron Microscope (FE-SEM) to investigate the microstructural features and failure mechanisms induced by tensile and fracture toughness testing. The imaging was performed at an accelerating voltage of 5 kV, with a working distance (WD) ranging from 5 to 6 mm depending on the topography of the observed region. High-resolution micrographs enabled the identification of matrix–filler interfacial characteristics, fiber pull-out phenomena, and the extent of fiber–matrix adhesion. Distinct fracture morphologies were observed depending on the waste tea stem powder content, including regions of brittle cleavage, ductile tearing ridges, and resin-rich areas. The dispersion of filler particles and the presence of voids or agglomerates were also analyzed, as these microstructural features can act as stress concentrators and significantly influence the mechanical performance.

3.8. THERMAL ANALYSIS BY DSC AND TGA

The thermal properties of the epoxy-based composites were characterized using DSC and TGA. Two representative specimens were analyzed: neat epoxy (sample mass: 12.91 mg) and epoxy reinforced with 10 wt.% waste tea stem powder (sample mass: 11.07 mg).

Both DSC and TGA measurements were performed under a nitrogen atmosphere with a flow rate of 50 mL/min to prevent oxidative degradation. For DSC, each sample was heated from 25 °C to 250 °C at a constant rate of 10 °C/min, cooled back to room temperature, and then reheated under the same conditions. The glass transition temperature (T_g) was determined from the midpoint of the heat capacity change during the second heating cycle. For TGA, the heating range was from 25 °C to 800 °C at a rate of 10 °C/min. From the TGA curves, the onset decomposition temperature (T_{onset}), the maximum decomposition temperature (T_{max}), and the residual char content at 800 °C were recorded. The total run time for each TGA analysis was approximately 70 minutes.

4. RESULTS AND DISCUSSION

This section presents and interprets the experimental findings obtained from the mechanical, thermal, and morphological characterization of epoxy-based composites reinforced with varying weight percentages of waste tea stem powder. The results are organized to first address the influence of filler content on the tensile and fracture properties, followed by an evaluation of the composites' hardness performance. Subsequently, the thermal stability and glass transition behavior are analyzed through DSC and TGA measurements, providing insights into the effects of the lignocellulosic filler on the thermal performance of the epoxy matrix. Finally, FE-SEM fractographic examinations are discussed to elucidate the underlying failure mechanisms, focusing on fiber–matrix interfacial bonding, fracture surface morphology, and filler dispersion characteristics.

4.1. HARDNESS TEST RESULTS

As can be seen in the box plot presented in Figure 7, the distribution and variation of Shore D hardness values clearly demonstrate the reinforcing effect of tea stem powder on the epoxy matrix. The neat epoxy (E-0) exhibited a median hardness of approximately 79, with relatively narrow variability across replicates. At 1 wt.% filler (E-1.0), the hardness remained nearly unchanged (~80), indicating that such a low content does not provide a significant stiffening effect. A remarkable improvement was observed at 2.5 wt.% (median ~93), representing a ~17% increase compared to the neat epoxy, suggesting effective load transfer and surface densification. At 5 wt.% (median ~91), the hardness slightly decreased but remained significantly higher than the neat epoxy, likely due to localized agglomerates influencing indentation resistance. The 7.5 wt.% and 10 wt.% composites exhibited the highest hardness values, ~96 and ~98 respectively, corresponding to ~20–23% improvements relative to the control. The narrow interquartile ranges for these groups further confirm the uniform reinforcement effect at higher filler contents.

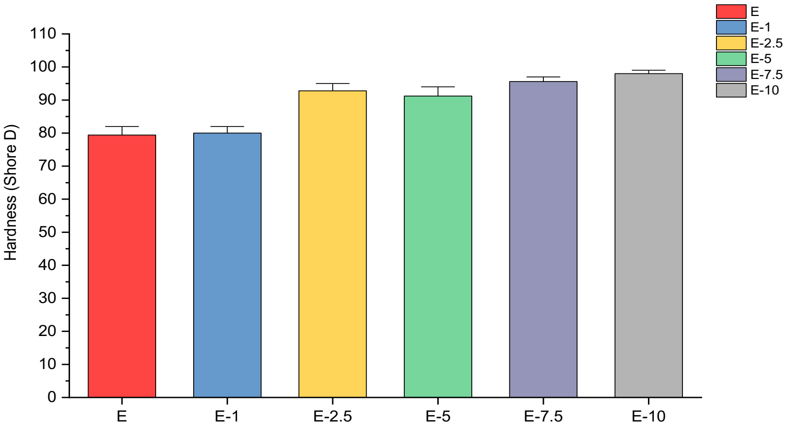

Figure 8.Shore D hardness of epoxy–tea stem composites with varying filler contents.

4.2. TENSILE TEST RESULTS

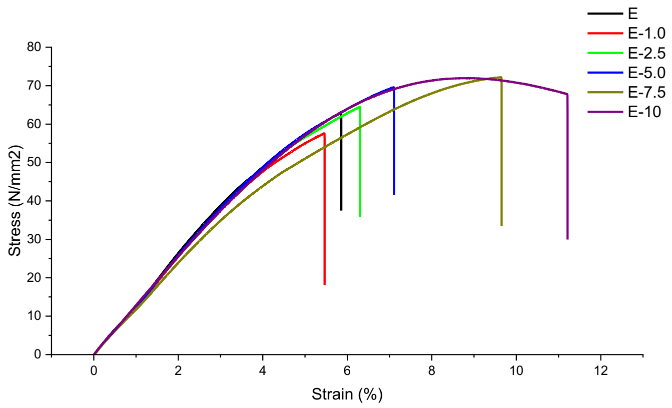

Figure 9.Tensile test results of epoxy-tea stem composite tensile specimens in accordance with ASTM standards.

In tensile test, each composite variation was tested using three replicate specimens, and the representative results presented here correspond to the median values among the triplicates. The average standard deviation across all groups was approximately ±1.2 MPa, indicating good reproducibility of the measurements. As shown on Figure 9, based on the results, the neat epoxy (E-0) exhibited a maximum strength of 62.84 MPa. The incorporation of 1.0 wt.% waste tea stem powder (E-1.0) led to a reduction of approximately 8.5 % in tensile strength, decreasing to 57.51 MPa, likely due to insufficient filler content to effectively reinforce the matrix and potential particle–matrix interfacial imperfections. Conversely, a slight filler loading of 2.5 wt.% (E-2.5) improved the tensile strength to 64.37 MPa, corresponding to a 2.4 % increase compared to the neat epoxy. A more pronounced enhancement was observed for E-5.0, which reached 69.58 MPa (a 10.7 % increase), indicating more efficient stress transfer between the matrix and the dispersed filler. The highest tensile strength was recorded for E-7.5 at 72.16 MPa, representing a 14.8 % improvement over the neat epoxy, suggesting that this composition provides the optimum filler-to-matrix balance for mechanical reinforcement. A slight decrease was observed for E-10 (71.91 MPa, 14.5 % above neat epoxy), which, although still high, may be attributed to the onset of particle agglomeration and micro-defect formation at higher filler contents, partially offsetting the reinforcing effect. These results confirm that 7.5 wt.% is the optimal filler content for maximizing tensile strength in the studied epoxy–waste tea stem composites.

4.3. EVALUATION OF TENSILE ELASTIC MODULUS

The elastic modulus values were determined by considering the 0.5–1.0% strain interval within the elastic deformation region. The calculated results for each formulation are presented in Figure 10.

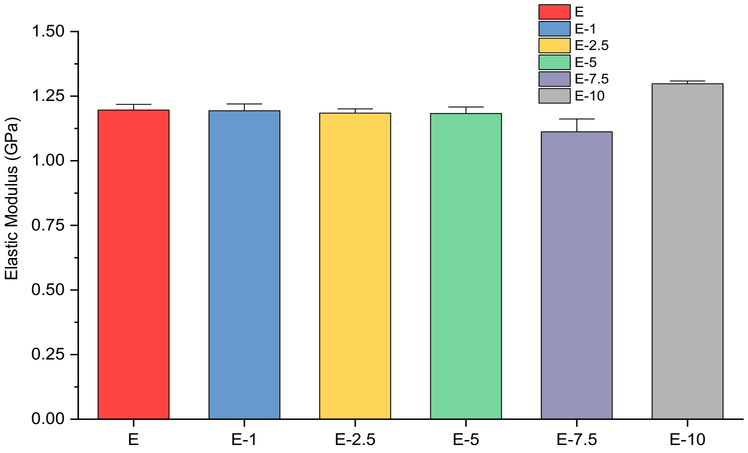

Figure 10.Variation of elastic modulus of epoxy–tea stem powder composites with different filler contents (GPa).

The elastic modulus values of the epoxy–tea stem powder composites exhibit a non-linear trend with increasing filler content. While the neat epoxy (E) shows a modulus of approximately 1.21 GPa, the addition of 1–7.5 wt.% filler results in a slight decrease, indicating a modest reduction in stiffness. At 10 wt.% filler loading (E-10), however, a significant increase in modulus is observed, reaching nearly 1.30 GPa.

Consistent with reports in the literature, the absence of a significant improvement in elastic modulus with fiber addition can be explained by several microstructural and processing-related factors. In short and randomly oriented fiber composites, residual stresses often accumulate at the fiber ends, and local shear stresses develop around the fibers. More importantly, the orientation of fibers tends to change during melt processing, where the material is subjected to both extensional and shear flow. Under extensional flow, fibers rotate toward the direction of extension, whereas in shear flow, some fibers align with the shear direction while others rotate oppositely. Such variations in orientation reduce the effective alignment of fibers along the loading direction, thereby limiting stress transfer efficiency. Combined with the critical fiber length requirement and the dominant role of the matrix in load bearing at low fiber content, these factors collectively explain why the elastic modulus does not increase appreciably despite fiber incorporation [37], [38].

4.4. FRACTURE TEST RESULTS

The fracture toughness (K_{IC}) results (Figure 11) demonstrated that the addition of tea stem powder improved the crack resistance of the epoxy matrix. Compared with neat epoxy, the composite with 2.5 wt.% filler showed a slight increase of about 2%. More pronounced enhancements were observed at higher loadings: 5 wt.% and 7.5 wt.% resulted in gains of roughly 12% and 14%, respectively. The highest increase was achieved at 10 wt.% filler, with an improvement of nearly 26% over the neat epoxy.

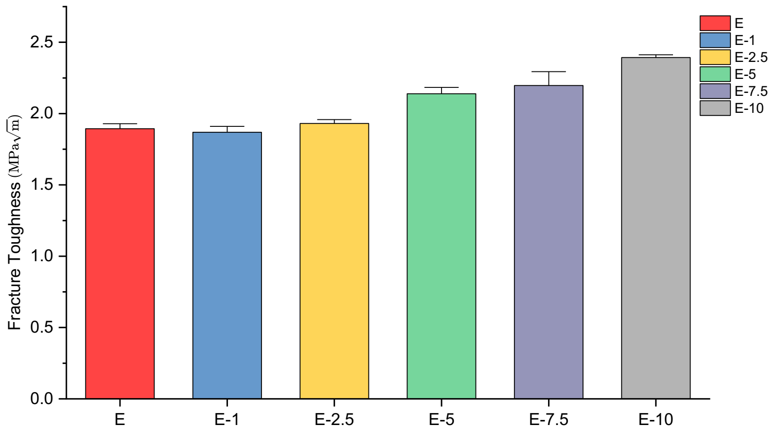

Figure 11. Fracture toughness values of epoxy–tea stem powder composites.

4.5. FRACTURED PARTS MORPHOLOGY ANALYSIS

When the surface morphology of the neat epoxy was examined at 1000× magnification (Figure 12a), a homogeneous curing structure with minimal inclusions or foreign particulates was observed, indicating uniform crosslinking of the polymer matrix. Furthermore, the fracture surface of the neat epoxy at 500× magnification (Figure 12b) revealed predominantly brittle fracture features, characterized by smooth cleavage regions [39].

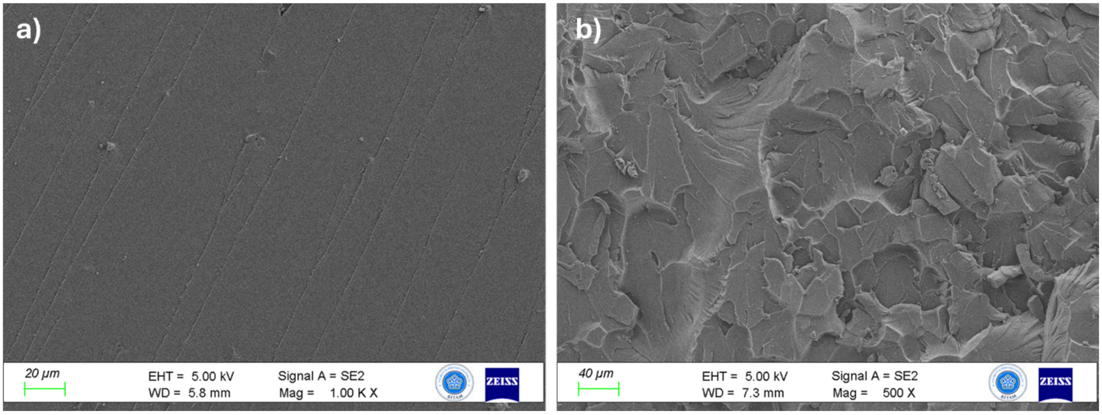

Figure 12. FE-SEM micrographs of neat epoxy: (a) surface morphology of the untested neat epoxy at 1000× magnification, and (b) fractured surface morphology after testing at 500× magnification.

In certain localized zones, mixed-mode features combining tearing ridges[40] and quasi-brittle[41] fracture patterns were also evident, reflecting limited plastic deformation prior to final failure.

Figure 13 shows the fracture surface of the epoxy composite containing 10 wt.% tea stem waste. The fracture morphology reveals distinct lamellar (step-like) structures and river patterns, which are characteristic of crack propagation in brittle polymeric systems. It is observed that fibers aligned parallel to the crack propagation direction largely remain as long and intact fragments, whereas fibers oriented perpendicular to the fracture direction tend to break into multiple shorter segments. This fragmentation increases interfacial friction and energy dissipation within the matrix, thereby hindering crack propagation and contributing to higher fracture resistance.

These microstructural features are consistent with the mechanical results, where the 10 wt.% composite exhibited the highest fracture toughness. The coexistence of intact and fragmented fibers demonstrates that increasing fiber content not only enhanced crack resistance but also supported the strengthening trend observed in tensile performance, confirming the beneficial role of fiber addition in improving both strength and toughness.

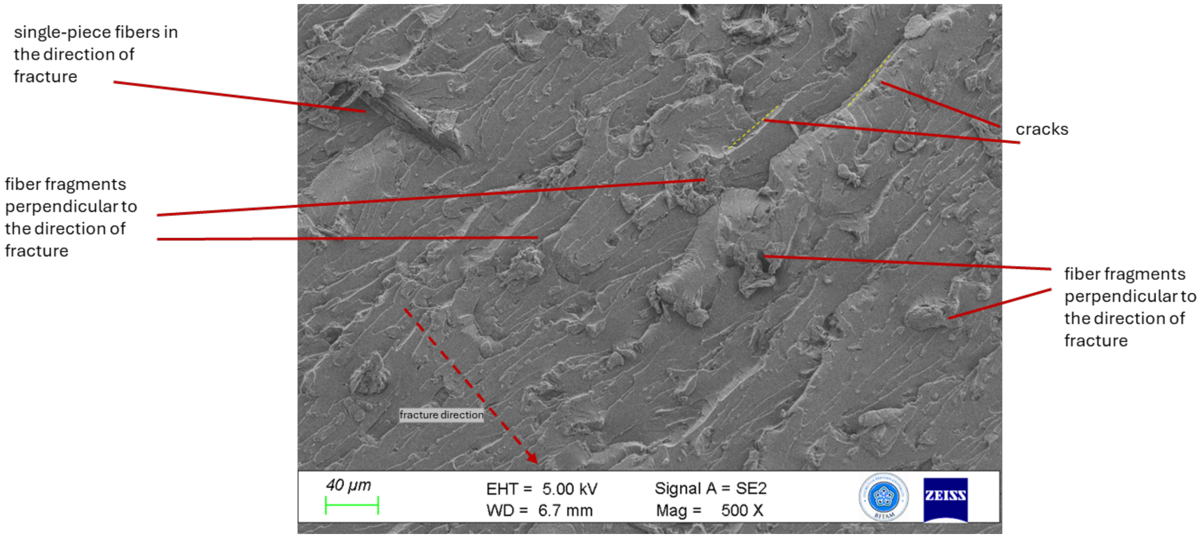

Figure 13.FE-SEM micrograph of the fracture surface of the epoxy composite containing 10 wt.% tea stem waste at 500× magnification.

4.6. THERMAL ANALYSIS RESULTS

The DSC and TGA analyses of the neat epoxy and the 10 wt.% tea stem powder-reinforced composite are presented in Figure 14. The DSC thermograms (upper curves) reveal that both materials exhibit a similar primary endothermic transition, corresponding to the glass transition temperature (Tg), followed by an exothermic region attributable to residual crosslinking reactions of the epoxy matrix. The incorporation of tea stem powder did not significantly shift the Tg, indicating that the filler did not substantially alter the segmental mobility of the epoxy network. However, a slightly higher heat flow was observed in the composite beyond Tg, which can be associated with the presence of lignocellulosic constituents contributing additional reaction enthalpy or altering the effective heat capacity of the system [16], [42], [43].

The TGA curves (lower plots) show comparable onset degradation temperatures for both materials, approximately around 300 °C, confirming that the addition of tea stem powder does not markedly compromise the initial thermal stability of the matrix. Nevertheless, the composite exhibited a marginally faster mass loss in the early stages of degradation, reflecting the lower thermal stability of the lignocellulosic filler compared to the epoxy resin. Furthermore, the composite retained a higher char residue at the end of the test, which is attributed to the inorganic ash content and the enhanced carbonization tendency of the tea stem powder.

The increased char yield observed in the thermogravimetric analysis is not only indicative of improved thermal stability but also has direct implications for application performance. A higher char content can contribute to the formation of a dense, carbonaceous protective layer during combustion, which serves as an effective barrier to heat and oxygen transfer [44]. This phenomenon enhances the fire resistance and flame-retardant behavior of the composites. Such characteristics are particularly desirable in applications where fire safety is critical, including automotive interiors, building materials, and electrical insulation systems [44], [45].

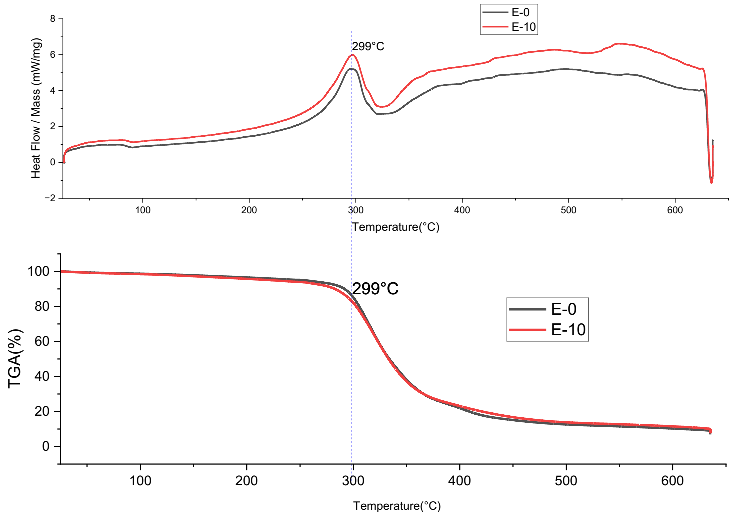

Figure 14.DSC and TGA curves of neat epoxy and 10 wt.% tea stem composites.

5. CONCLUSION

This study demonstrated the feasibility of utilizing mechanically processed tea stem waste powders as a sustainable reinforcement for epoxy-based composites without requiring any chemical pretreatment. Comprehensive mechanical, thermal, and morphological evaluations consistently revealed the reinforcing capability of the filler.

Tensile strength results indicated that the optimum reinforcement level was achieved at 7.5 wt.% filler content, yielding a 14.8% increase compared to neat epoxy, while 10 wt.% still maintained high values but showed slight reductions due to agglomeration effects. Elastic modulus analysis revealed a non-linear trend, with modest decreases at low filler contents but a significant increase at 10 wt.% (≈1.30 GPa), demonstrating the stiffening potential of high filler loading.

Fracture toughness (K_{IC}) values exhibited a clear and continuous improvement with increasing filler content, reaching a maximum enhancement of 26.4% at 10 wt.%, which highlights the role of tea stem fibers in impeding crack propagation. Shore D hardness measurements further confirmed these findings, showing progressive increases with filler content and achieving up to a 23% improvement in indentation resistance at 10 wt.% loading.

Thermal analysis by DSC and TGA demonstrated that filler incorporation did not significantly alter the glass transition temperature or onset decomposition temperature of the epoxy, while the higher char residue confirmed improved thermal stability associated with the lignocellulosic filler. Morphological examination via FE-SEM revealed distinct fracture features: fibers aligned parallel to the crack propagation direction remained intact, whereas transversely oriented fibers fragmented, thereby enhancing crack resistance by increasing interfacial friction and energy dissipation.

The results confirm that waste tea stem powders, processed solely by mechanical means, provide a low-cost, environmentally friendly, and effective reinforcement for epoxy composites. While the optimum composition for tensile strength was identified at 7.5 wt.% filler content, the 10 wt.% loading exhibited superior performance in fracture toughness, hardness, and thermal stability, indicating that the best overall reinforcement effect is achieved at higher filler contents. These findings not only establish a valorization pathway for agricultural residues but also contribute to the development of sustainable polymer composites with reduced environmental footprints.

Beyond these fundamental outcomes, the developed composites show strong potential for use in automotive interior components, furniture, building materials, and other cost-sensitive engineering applications where mechanical robustness and sustainability are both required. For future work, it would be valuable to explore surface modification strategies to further improve interfacial adhesion, hybridization with other natural or synthetic fillers, and scalability studies for industrial processing. Additionally, evaluating long-term durability, water uptake, and fire-retardant behavior would strengthen the applicability of these composites in safety-critical and outdoor environments.

Authors' Contributions

Hüseyin Kaya was responsible for specimen preparation, experimental testing, and data processing. Mürsel Ekrem contributed to the manuscript through critical review, editing, and supervision. Yasin Uslugil carried out the manuscript writing and data analysis.

Competing Interests

The authors declare that they have no conflict of interest.

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