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Synergistic Enhancement of the Mechanical Properties of Epoxy-Based Coir Fiber Composites through Alkaline Treatment and Nanoclay Reinforcement

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Abstract: This study explores the synergistic effects of incorporating coir fibers and nanoclay into epoxy resin composites. Coir, a renewable and cost-effective natural fiber, undergoes an alkaline treatment to influence its ability to form strong interfacial bonding with the epoxy matrix. To further enhance the mechanical properties of the composite, montmorillonite nanoclay, surface-modified with aminopropyltriethoxysilane and octadecyl amine, is introduced. The research investigates different combinations of coir fiber content (20, 30, and 40 wt%) and nanoclay loading (0, 2, and 4 wt%) with epoxy resin. The composites are fabricated through an open molding process, and the mechanical properties are evaluated using tensile and flexural tests according to the ASTM D638 and D7264 standards, respectively. The tensile and flexural strengths of the 40 wt% coir fiber-reinforced epoxy composite are found to be 77.99 MPa and 136.13 MPa, which are 44% and 23% greater than pure epoxy, respectively. Furthermore, the strengths displayed a 23% improvement in tensile strength with 4 wt% and a 31.4% improvement in flexural strength with 2 wt% nanoclay as additional reinforcement. Scanning electron microscopy is employed for fractographic analysis of the fractured specimens from the tensile test. The study underscores the importance of understanding the interplay between natural fibers, nanoclay, and epoxy resin for optimizing the composite's performance in real-world applications.

Keywords: coir fiber; nanoclay; polymer composite; alkaline treatment; mechanical properties; SEM analysis

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1. Introduction

Fiber-reinforced polymer (FRP) composites are gaining prominence in various applications due to their high strength, stiffness, and reduced environmental impact. Researchers are increasingly motivated by growing environmental awareness to develop eco-friendly materials. Natural fibers from sources like coir, oil palm, sisal, bamboo, banana, rice husk, jute, and kenaf are considered environmentally friendly and serve as excellent reinforcements in polymer matrices, reducing the composite's density and cost [1–3]. In recent years, these natural fibers have emerged as alternatives to glass and carbon fibers in polymer composite production, making composites with natural phases highly desirable and an actively evolving field in material engineering [4]. Biocomposites, including natural vegetable fibers, are considered promising materials for future applications [5,6].

Epoxy resins are commonly used as the matrix material in FRP composites. The performance of epoxy resins is influenced by factors like the curing temperature, the environment in which they are used, and the amount of hardener mixed with the resin. These variables can be adjusted to optimize the resin's performance for specific applications [7,8]. Epoxy resins find application in various industries, including the automotive, aerospace, construction, oil and gas, and marine sectors.

General casting provides a simple and advantageous manufacturing process for polymer composites [9]. This process makes fabricating composites with improved mechanical qualities easier by pouring a combination of polymer matrix and reinforcing fibers into a prepared mold. The ability to customize the product to meet unique needs is made possible by the versatility of the materials, such as epoxy or polyester matrices reinforced with natural or synthetic fibers as reinforcements [10]. The procedure is made accessible by a simple mold preparation technique, dispensing the polymer mixture, and the subsequent curing [11]. The efficiency is increased by demolding and optional post-curing. Considering all these aspects, general casting is an ideal option for producing high-performance components due to its ease and versatility.

1.1. Coir Fiber-Reinforced Polymer Composites

Coir, a renewable secondary natural resource, is a particularly advantageous natural fiber due to its high cellulose content, strength, high strain at break, and affordability. It is a tough, biodegradable lignocellulosic fiber derived from the coconut fruit's fibrous mesocarp, constituting approximately 25% of the coconut [12]. It is commonly found in tropical countries like Thailand, India, and Sri Lanka. Coir fibers are renowned for their high lignin content, which imparts durability, weather resistance, and some waterproof qualities. They can also be chemically modified. These fibers possess excellent elongation at break, allowing them to stretch beyond their elastic limit without breaking [13]. Research has extensively explored coir fibers' structural, morphological, mechanical, and thermal properties. However, its variability in terms of these characteristics because of its biological nature is a disadvantage. Coir is used in various applications, such as composite boards, building construction, car parts, and even as fillers in helmets. Studies have investigated combining coir fibers with other materials like kenaf, bamboo, rice straws, and glass fibers to enhance the composite's properties. While there is considerable research on various fiber composites, there has been relatively less focus on coir fiber composites alone. Coir can be treated with alkali to enhance its strength and surface characteristics by reducing the impurities and lignin content [14]. Several researchers have also demonstrated better adhesion to matrices through SEM analysis [15]. Chemical treatments to natural fiber enhance the tensile and flexural strengths of composites.

Venkateshappa et al. [16] performed an evaluation of the flexural and physical characteristics of composites manufactured from areca fibers that were randomly distributed. Compared to untreated fiber, the flexural strength of composites reinforced with treated areca fiber shows significant improvement. Dixit et al. [17] prepared hybrid epoxy composites using alkali-treated date palm fiber and native coir fiber at varying weight fractions. The results indicate that alkali treatment significantly enhanced the hybrid composites' mechanical, hydrophobic, and thermal properties. The hybrid composite with 50 wt% coir fiber and 50 wt% treated date palm fiber exhibits superior structural properties, with 76.51 MPa tensile strength values and a 2.77% elongation limit. Rong et al. [18] investigated the effects of treatment on the properties of epoxy composites reinforced with unidirectionally oriented sisal fibers. Post-treatment, the interaction between the fibers and the epoxy matrix is enhanced, improving the interface adhesion and resistance to fiber pullout.

Qiao et al. [19] explored the enhancement of lap shear behavior in adhesively bonded metal–carbon fiber-reinforced thermoplastic polymer composite (CFRTP) dissimilar joints, specifically focusing on the AA6061 carbon–fiber-reinforced polyphthalamide (CFRPPA) combination. Plasma treatment of adherend and adhesive tape surfaces increases the hydroxyl groups, promoting covalent bonding and forming a denser cross-linked network. This led to a 200% improvement in the single-lap shear strength compared to non-treated counterparts. Lim et al. [20] investigated the impact of laser surface treatment on carbon fiber-reinforced polymer composites (CFRP) and CFRTP surfaces to enhance the adhesive bonding strength. For CFRP, a 92% increase in shear strength (up to 37.5 MPa) is observed after 11.25 W laser treatment, attributed to the improved wettability and increased surface free energy. In the case of CFRTP, a 150% increase in shear strength (up to 25.5 MPa) results from the enhancement of hydrogen bonding.

Luz et al. [21] conducted pullout tests to contrast coir and pineapple leaf (PALF) fibers' interfacial adherence with epoxy resin despite their vastly differing properties. The results show a critical length for the coir fiber that was 70% more than for the PALF and an interfacial strength that is 3.5 times lower, indicating that the PALF adhered to the epoxy resin more firmly. Karthikeyan et al. [22] explain the effects of the fiber length and NaOH treatment on the impact behavior of coir fiber composites. Coir fibers are placed in the NaOH solution with different wt% for ten days. The fiber lengths for each batch of coir are 10, 20, and 30 mm. The impact strength of the treated specimens increases by 15% compared to untreated fiber.

When added to composites, these natural fibers can increase the strength and stiffness of the material. To address this, natural fibers are incorporated into polymer matrices. These fibers, readily available from plants, enhance the physical and mechanical properties of the resulting composite materials [23].

1.2. Nanoclay-Reinforced Polymer Composites

The addition of organomodified montmorillonite (MMT) to reinforce polymer-based composites has gained attention for its ability to substantially enhance the mechanical properties [24]. However, the interaction between nanoclay and the surrounding matrix is often overlooked, which can impact the homogeneity and performance of the composites. Factors like agglomeration, nanoclay clusters, and uncured resin can result from the improper addition of nanoclay [25]. Adjusting the resin's viscosity and sonication time is crucial to producing desirable composites with moderate strength and ductility. Excess energy during sonication can lead to premature resin curing, making the composites brittle. Nanoclay, as described, is a specialized material with a layered structure that consists of very fine, crystalline sheets [26]. These sheets are typically stacked on top of each other, similar to the pages of a book. The unique characteristics of nanoclay, such as its ease of use, environmental compatibility, and well-understood chemistry, make it a valuable component in various applications.

It must be compatible with organic polymers to utilize nanoclay in composite materials effectively. This is achieved by modifying the surface of the nanoclay with organic compounds like ammonium or phosphonium ions. The resulting modified nanoclay is often referred to as "organically modified nanoclays" or "organoclays". When nanoclays are added to composite materials, they significantly enhance various properties. For example, even a small amount, such as 1% by weight, of nanoclay can act as a toughening agent when used in epoxy composites. Additionally, adding 3–5 wt% nanoclay has been found to improve the mechanical properties of FRP composites [27]. One of the most commonly used nanoclays is MMT, which is extracted from bentonite. MMT is favored for its availability, eco-friendliness, and well-documented chemistry. It is often modified to make its surface organophilic, enhancing its compatibility with polymer matrices. Other types of nanoclays, such as kaolinite, smectite, chlorite, kenyaite, ilerite, zeolite, and more, are also used for various applications [28].

The existing literature shows that natural fibers have several disadvantages that can be eliminated or reduced through alkaline treatment of the fiber and adding fillers. The literature also suggests that nanoclay can be used as filler with polymer resin to enhance the composites' properties by influencing the resin's structural properties. There is no thorough research regarding the synergistic effects of incorporating coir fiber and nanoclay on the mechanical properties of epoxy-based composites. The present study endeavors to expose the influence of alkaline treatment on coir fibers and nanoclay addition on the properties of epoxy-based composites. Furthermore, this investigation thoroughly examines the impact of varying weight percentages of coir fiber on both the tensile and flexural properties. Additionally, the study delves into the consequences of introducing nanoclay on the properties of coir fiber-reinforced epoxy composites. Moreover, an in-depth analysis of the fractured surfaces of the tensile test specimens is conducted using scanning electron microscopy (SEM) to understand the causes of specimen failure under tensile loading.

2. Materials and Methods

2.1. Materials

Epoxy resin is a widely available and universally esteemed matrix material, renowned for its exceptional physical properties, cost-effectiveness, and user-friendly handling compared to other polymers. The epoxy resin employed in the present work is Lapox L12, in combination with the K6 hardener, sourced from Atul Polymers, Gujarat, India. For this study, coir fiber harvested from local farms in Udupi, India, is used as the natural reinforcement. Coir fiber has been selected due to its abundant availability and its frequent classification as a byproduct. Furthermore, it offers a viable fiber extraction process compared to alternative fiber sources [29]. In addition, 15–35 wt% octadecyl amine and 0.5–5 wt% aminopropyltriethoxysilane surface-treated MMT nanoclay is used as filler material and purchased from Sigma Aldrich.

2.2. Alkaline Treatment

The alkaline treatment considerably impacts the characteristics of the coir fibers, particularly regarding their surface texture and ability to form strong interfacial bonds [22]. The coir fibers are acquired and subsequently immersed in a 5% sodium hydroxide (NaOH) [30] solution for a duration of 8 h. Following this treatment, the processed coir fibers are carefully rinsed with distilled water to remove any impurities. The fibers are then dried in a hot air oven set at 80 °C to eliminate any remaining surface moisture effectively.

2.3. Specimen Preparation

The composites for this study are fabricated using 20, 30, and 40 wt% alkaline-treated coir fiber and 0, 2, and 4 wt% of nanoclay, with each wt% of coir fiber with epoxy resin as the matrix material, and each composite is designated as illustrated in Tables 1 and 2, respectively. Further combinations of 50 wt% of coir fiber and 6 wt% of nano clay have been tried and failed to fabricate sound and healthy composites due to a resin shortage for mixing and the agglomeration of nanoclay in the resin. Moreover, 20 wt% untreated coir fiber epoxy composite is also prepared to study the effect of alkaline treatment. All the composites are carefully fabricated through the open molding process, also known as the general casting technique. This process is simple, efficient, and accessible, with low tooling complexity, eliminating the need for extensive machinery. The nanoclay is blended with epoxy before mixing the shortened coir fibers. A different wt% of nanoclay is mixed with epoxy using a magnetic stirrer at 300 rpm for 15 min and then exposed to a sonicator (35% amplitude, 10 s on/off cycle) for 15 min to agitate the nanoclay particles into epoxy resin. After being treated with an alkaline solution, the fibers are finely chopped to a length of less than 5 mm using scissors. The alkaline-treated and untreated chopped fibers, are measured with a digital weighing scale and then mixed with epoxy resin reinforced with varying wt% of nanoclay and subjected to stirring using a mechanical stirrer at 500 rpm for 10 min. After rigorous stirring, the K6 hardener is introduced into the mix (resin and hardener in the ratio of 10:1). The mixture is then poured into the mold. The molds are then allowed to cure at room temperature for 24 h without any external pressure application, which is attributed to the effectiveness of the composite preparation technique. The composite fabrication process is shown in Figure 1.

The mold for the tensile and flexural specimens is prepared beforehand according to ASTM D638 (type I for reinforced plastics) and ASTM D7264 as per the standard dimensions. After curing, the mold is coated with wax to remove the specimens easily. The well-mixed mixture of the resin with hardener is poured into the mold. The mold is then allowed to cure for 24 h.

Table 1. Composition of the coir fiber-reinforced epoxy composite.

Designation	Composition
ER	100 wt% Pure epoxy resin
20UC	20 wt% Untreated coir fiber + 80 wt% Epoxy
20C	20 wt% Alkaline treated coir fiber + 80 wt% Epoxy
30C	30 wt% Alkaline treated coir fiber + 70 wt% Epoxy
40C	40 wt% Alkaline treated coir fiber + 60 wt% Epoxy

Table 2. Composition of the coir fiber and nanoclay-reinforced epoxy composite.

Designation	Composition
20C2N	20 wt% Alkaline treated coir fiber + 2 wt% Nanoclay + 78 wt% Epoxy
20C4N	20 wt% Alkaline treated coir fiber + 4 wt% Nanoclay + 76 wt% Epoxy
30C2N	30 wt% Alkaline treated coir fiber + 2 wt% Nanoclay + 68 wt% Epoxy
30C4N	30 wt% Alkaline treated coir fiber + 4 wt% Nanoclay + 66 wt% Epoxy
40C2N	40 wt% Alkaline treated coir fiber + 2 wt% Nanoclay + 58 wt% Epoxy
40C4N	40 wt% Alkaline treated coir fiber + 4 wt% Nanoclay + 56 wt% Epoxy

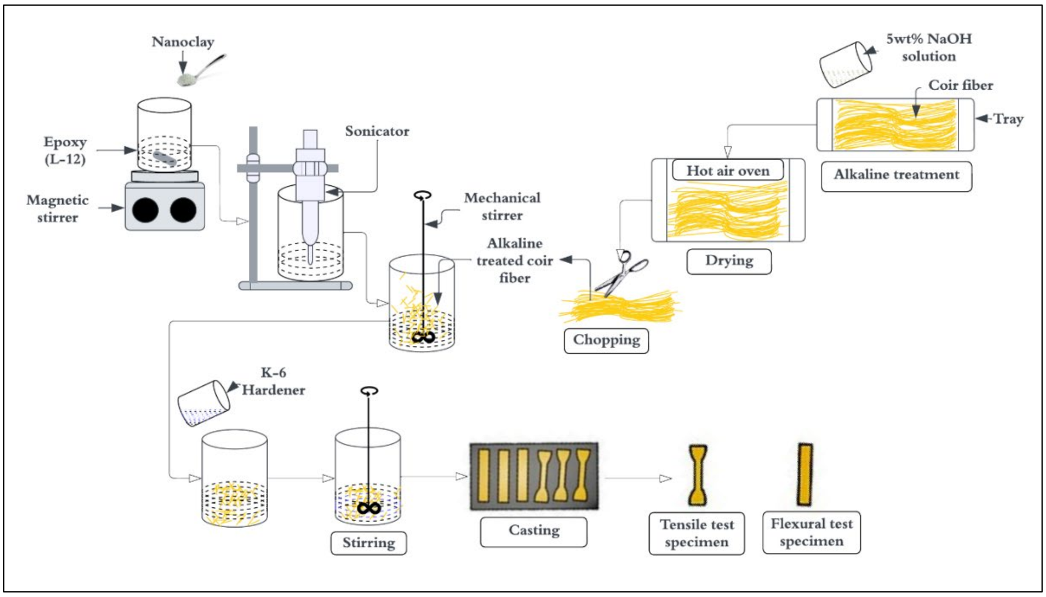


Figure 1. Schematic of the composite preparation technique.

2.4. Testing

2.4.1. Mechanical Properties

The tensile and flexural properties are considered significant in deciding a material's mechanical properties. The tensile test is performed to determine the mechanical behavior of a material when subjected to a uniaxial pulling force. The test involves applying an increasing axial load to a standardized test specimen until it fractures. The flexural test, also referred to as a bending test or a three-point bend test, is used to evaluate a material's flexural strength and modulus. It measures how a material resists bending or deformation under a bending moment. The tensile and flexural tests are conducted on 5 samples of each composite in a Universal Testing Machine (UTM) with a load cell limit of 50 kN, keeping the testing speed at 2 mm/min as per the ASTM D638 and D7264 standards, respectively.

2.4.2. SEM Analysis

The fractured samples from the tensile test are subjected to fractographic analysis using a ZEISS EV018 scanning electron microscope with 15 kV acceleration voltage for all the samples and a working distance varying from 7 to 11 mm. The fractured specimens are cut according to the sample holder of the microscope. Sputtering of the gold–palladium (80:20) layer is performed on the Quorum sputtering unit using a 10 mA current for 10 min. The fine layer coated on the surface promotes secondary electrons, aiding the imaging process.

3. Results and Discussion

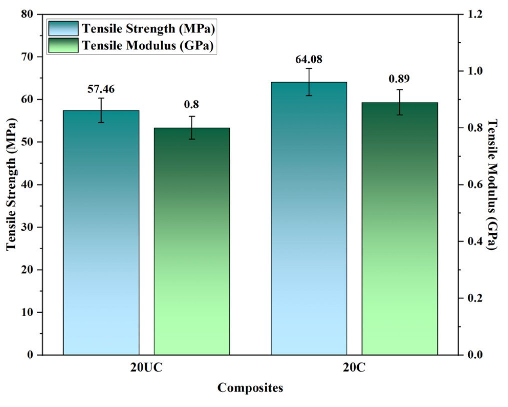
3.1. Effect of Alkaline Treatment

The treated coir fiber seems to have turned to a darker brown color than the untreated coir fiber, as shown in Figure 2. This change in the shade of color might be the visible confirmation of removing the dirt and lignin content from the surface of the coir fiber [31,32]. No other physical differences could be observed using the naked eye.

Figure 2. Chopped alkaline-treated and untreated coir fibers.

3.1.1. Mechanical Properties

The tensile and flexural properties of the alkaline-treated and untreated coir fiber-reinforced epoxy composites are shown in Figure 3a,b. The average tensile strength and modulus of the alkaline-treated coir fiber-reinforced epoxy composite (20C) are 64.08 MPa and 0.895 GPa, respectively. And the same for the untreated composite (20UC) are 57.46 MPa and 0.81 GPa, respectively. This indicates a 12 and 10% increase in the tensile properties in the 20C epoxy composites. Likewise, the average flexural strength and modulus of the 20C epoxy composite are 122.3 MPa and 2.42 GPa, which are 7 and 9% greater than those of the 20UC epoxy composite with 114.39 MPa and 2.21 GPa. The increase in strength is due to the betterment of the surface of the coir fiber after treatment that removes the dirt and lignin content present on the surface of the fiber, which makes the surface of the fiber rougher [33], which in turn enhances the interfacial bonding ability between the fiber and the matrix [34]. With this inference, further composites are prepared using alkaline-treated coir fibers.



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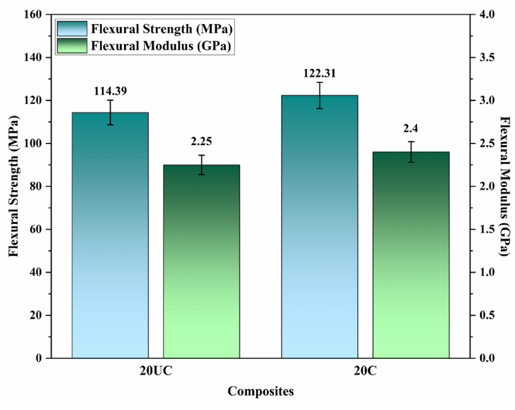
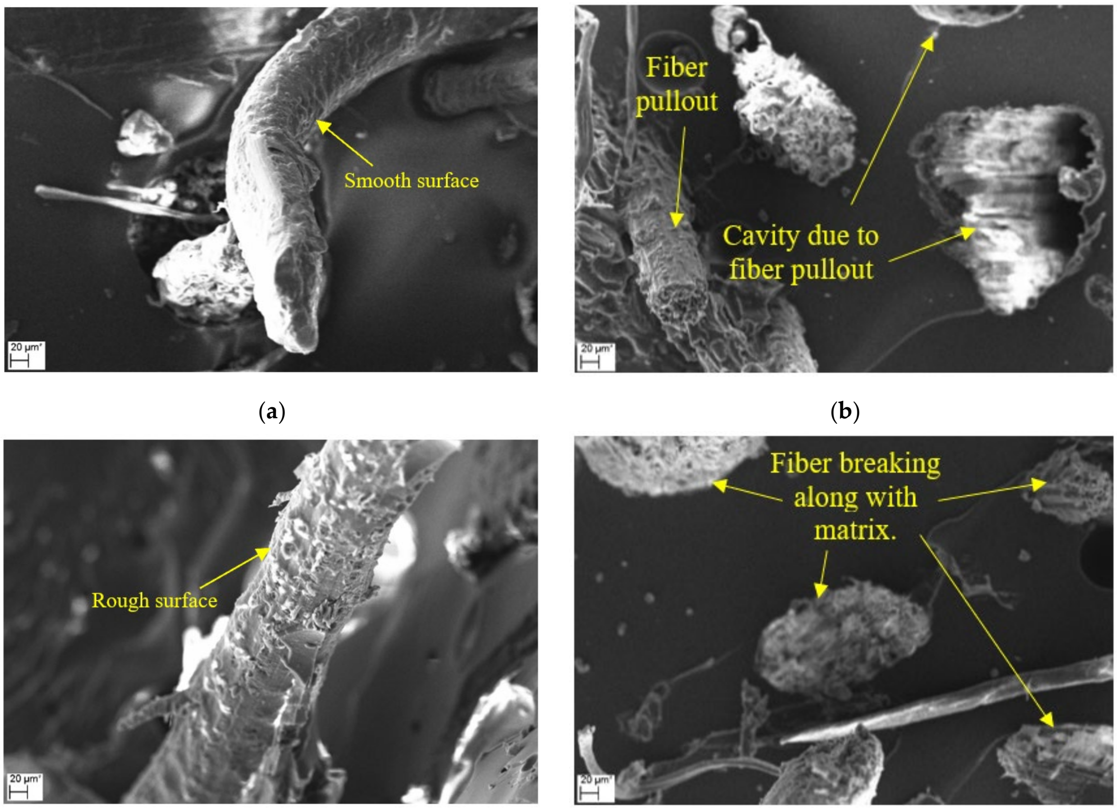


(**b**)

Figure 3. (**a**) Tensile and (**b**) flexural properties of the 20UC and 20C composites.

3.1.2. Fractographic Study

The surface of the untreated coir fiber is smoother than the treated coir fiber [34,35], as it is distinguishably visible in Figure 4a,c. This is because the alkaline treatment removes content like lignin, pectin, and other impurities from the fiber's surface, which is responsible for the cell wall rigidity of the fiber, which is responsible for the smoother surface [15]. The irregularities formed on the surface due to the removal of such content make the surface rougher and facilitate bonding between the matrix and the fiber [22]. The 20UC composites exhibit maximum fiber pullouts, and cavities are created on the fractured surface, as shown in Figure 4b. In contrast, the 20C composites exhibit better bonding between the fiber and the matrix, where the fiber breaks along with the matrix, as seen in Figure 4d. This may be the reason for the enhanced strength of the composite reinforced with alkaline-treated coir fiber in which the interfacial bonding between the fiber and matrix is stronger due to a rougher surface, which enhances the surface area of the fiber.



(**a**) (**b**) (**c**) (**d**)

Figure 4. SEM images of the fractured surface of the (**a**,**b**) 20UC and (**c**,**d**) 20C composites.

3.2. Mechanical Properties of the Composites

3.2.1. Tensile Properties

Figure 5 shows that the average tensile strength and modulus of ER are found to be 54.03 MPa and 0.74 GPa. The 20C composite displayed an 18.6 and 20.9% improvement in the average tensile strength (64.08 MPa) and modulus (0.895 GPa). As the wt% of coir fiber increases, the average tensile properties gradually increase. The average tensile strength of the 30C and 40C epoxy composites are found to be 69.61 MPa and 77.99 MPa, which are 8.6 and 21.7% greater than those of the 20C epoxy composites, respectively. Similarly, the average tensile modulus of the 40C (1.085 GPa) is 12.2% greater than the 30C (0.967 GPa), which is 9% greater than the 20C composites. Since each fiber has its own strength, adding fibers into epoxy enhances the cumulative strength of the composites, so the fibers in the composite are termed load-bearing members. The load applied to the composite is distributed throughout the fibers, thus enhancing the load-bearing capacity of the composite. Hence, the higher the wt% of coir fiber, the greater its average tensile strength [36].

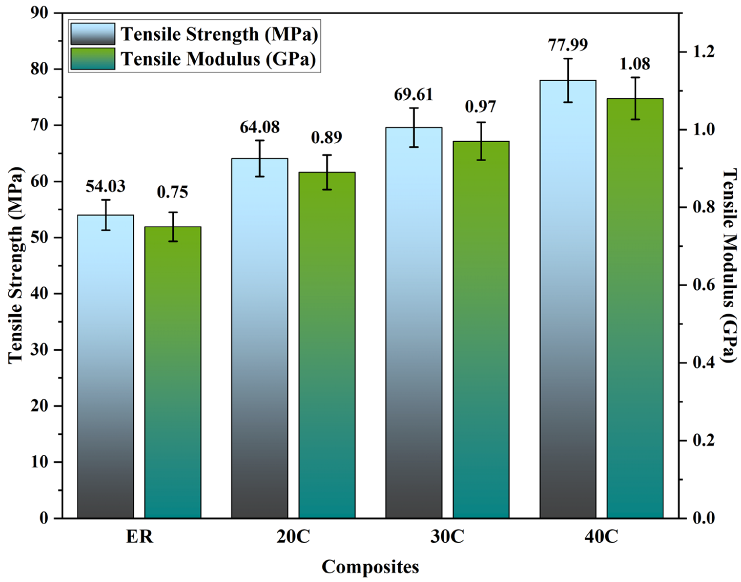


Figure 5. Tensile properties of the coir fiber-reinforced epoxy composites.

The addition of nanoclay has improved the average tensile properties of the composites, as illustrated in Figure 6, which is similar to the trend shown by Prabhu et al. [37]. The 20C4N, 30C4N, and 40C4N composites have 15.38, 11.4, and 7.4% greater average tensile strength and 14.7, 10.2, and 11.6% greater average tensile modulus than the 20C2N, 30C2N, and 40C2N composites, respectively. The 40C4N composite exhibits a maximum average tensile strength and modulus of 96.47 MPa and 1.34 GPa, respectively, compared to all the other compositions. Also, the effect of the addition of nanoclay is more when the fiber composition is higher, which indicates that the nanoclay enhances the interfacial bonding between the epoxy and coir fibers [38]. The multilayered structure of nanoclay provides enhanced surface area for the matrix to bond with the fiber, and the tensile load is distributed along the fiber–matrix interface, reducing the brittle nature of epoxy [27].

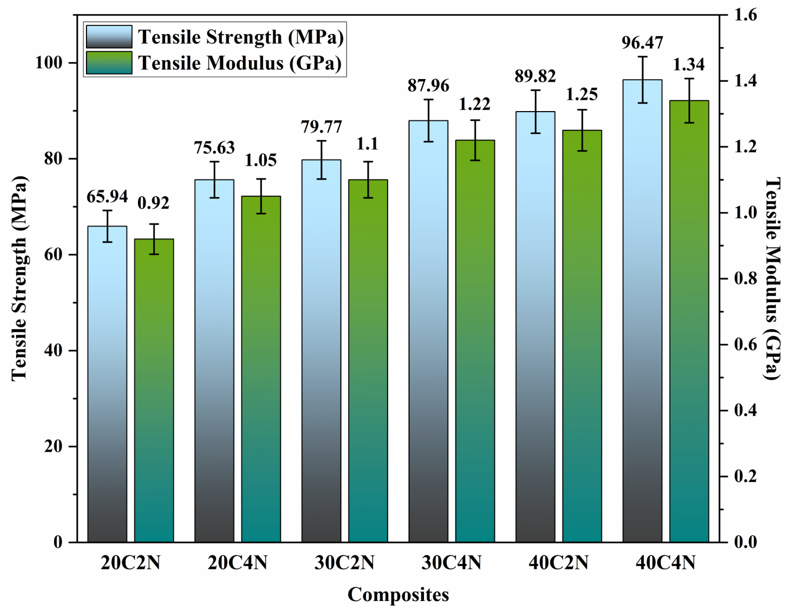
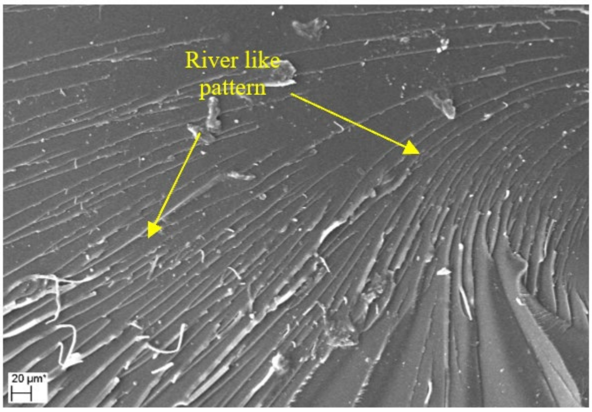


Figure 6. Tensile properties of the coir fiber and nanoclay-reinforced epoxy composites.

3.2.2. Fractographic Analysis

Figure 7 illustrates the effect of the addition of nanoclay on the fractured surface of the coir fiber-reinforced epoxy composites. The surface texture of ER displays smooth catastrophic failure, forming a river-like pattern while encountering brittle fracture [27], as shown in Figure 7a. In the coir fiber-reinforced epoxy composites, the fractured surface displayed poor interfacial bonding [39], displaying multiple fiber pullouts, as shown in Figure 7b. It is evident from Figure 7c that incorporating nanoclay into the matrix material improved the matrix flowability, which enabled the matrix distribution around the surface of the coir fiber [40], and the effect of fiber pullout was eliminated substantially. This change in the surface pattern is due to the multilayered property of nanoclay, which provides a larger surface area. When a tensile load is applied, the load is distributed on these layers, which creates a pulling effect in the breaking region and encounters ductile failure [41]. This might be the reason for the enhancement of the mechanical properties of the composites. Also, it is observed from Figure 7d that when nanoclay is introduced, the crack deviates from its original path as the nanoclay arrests the growing crack [27] and provides a deviated path, prolonging the failure of the material that increases the strength.



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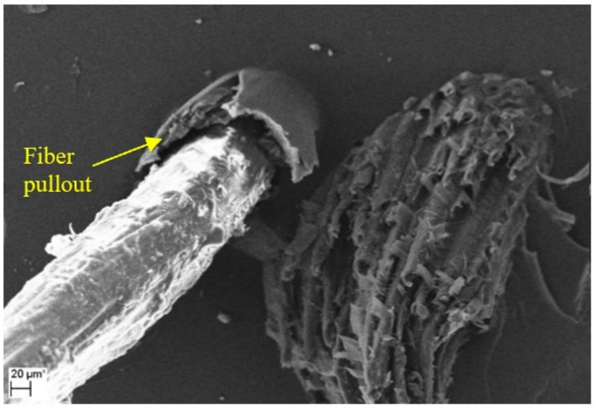

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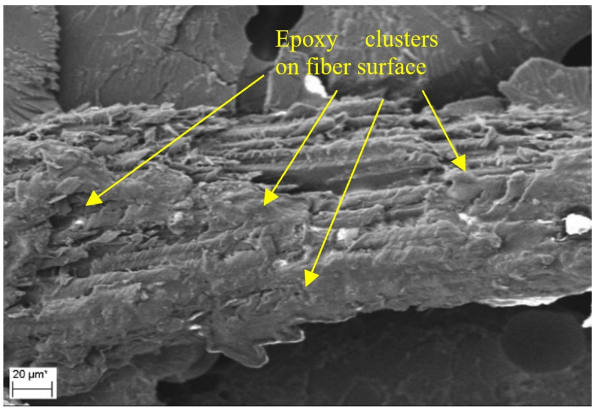

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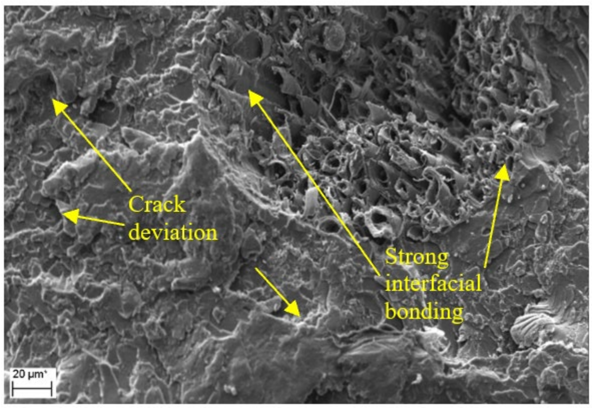

(**d**)

Figure 7. SEM images of the fractured surface of ER (**a**) coir fiber-reinforced epoxy composites without (**b**) and with nanoclay (**c**,**d**).

3.2.3. Flexural Properties

Figure 8 shows that ER has an average flexural strength of 110.19 MPa and a modulus of 2.16 GPa. The highest average flexural strength is achieved by the 40C composites with 136.15 MPa and a modulus of 2.67 GPa. The graph shows an increase in the flexural strength and modulus of around 23% in 40C over ER. It is evident from the graph that the flexural strength of the composites increases with an increasing fiber content [39]. This is because the fibers reinforce the matrix, making the composite stronger and more resistant to bending. The coir fibers present in the composite absorb the force applied on the composites and distribute it along the length. This increase in flexural strength with increasing fiber content is not linear. This is because the fibers do not contribute equally to the strength of the composite [34,42].

Composites reinforced with nanoclay have better average flexural properties than composites without nanoclay. The trend that can be seen in Figure 9 is that the average flexural strength of the 20C2N, 30C2N, and 40C2N composites, viz., 135, 158, and 179 MPa, is increased compared to the composites without nanoclay. A sudden drop is observed for the 20C4N, 30C4N, and 40C4N composites (127, 137, and 162 MPa) compared to their similar fiber wt% counterparts. A similar trend is observed for the average flexural modulus. The multilayered structure of nanoclay responsible for the enhancement of the tensile properties forms nanoclay clusters within the composite. Agglomeration of the stacked nanoclay layers in the composite might be one of the reasons for the reduction in flexural strength. As a result, the composite is more likely to fail catastrophically when subjected to bending loads [43,44]. However, it is important to note that all the composites with nanoclay have better flexural strengths, and the choice of composite will depend on the specific application requirements.

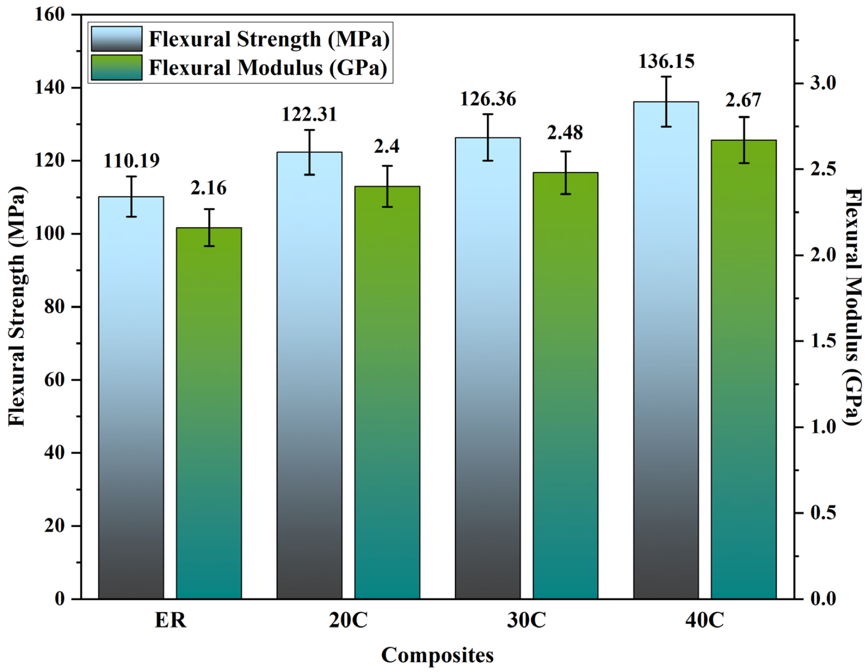

Figure 8. Flexural properties of the coir fiber-reinforced epoxy composites.

It is evident from the results obtained that the average strengths have shown a substantial increase in value. In contrast, the error bars indicate that the spread of values of some of the compositions overlaps with others. The randomly orientated coir fibers might be one of the reasons for this kind of trend, as it has already been proven that the orientation of fibers directly influences the strength of the composite [13,45]. Using smaller increments in the wt% of nanoclay might also be the reason for such a trend in the results, and the improvement is quite substantial for introducing such a small amount of nanoclay.

The obtained results are compared with the other findings related to short-coir FRP composites, as shown in Table 3. As observed from the table, the mechanical properties in the present study are competitive with the existing literature.

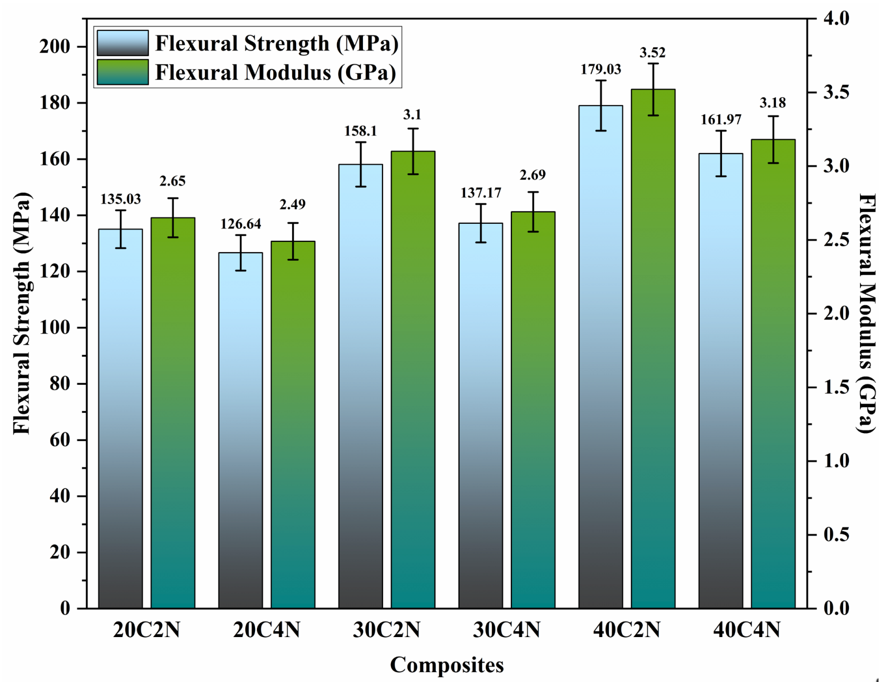

Figure 9. Flexural properties of the coir fiber nanoclay-reinforced epoxy composites.

Table 3. Comparison of the obtained results with the literature related to short-coir FRP composites.

Work/Literature	Matrix Material	Wt% of Coir Fiber	% Increase in Tensile Strength	% Increase in Tensile Modulus	% Increase in Flexural Strength	% Increase in Flexural Modulus
Current work	Epoxy	20 30 40	18.6 8.6 14.9	20.9 9.1 11.3	11 4 7	10 3.3 8
Samia et al. [46]	Polypropylene	10	11.7	-	16	20
Haque et al. [47]	Polypropylene	10 15 20 25 30	9.5 6.6 - - -	- 9 16 10 13	14.3 2 1.8 2.1 5	- 13 12 17 6
Hydar et al. [48]	Polypropylene	10 20 30 40	- 10.7 11.2 -	- 18.7 14.2 15.1	- - - -	- - - -
Mohit et al. [49]	Epoxy (DGEBA)	40	9.7	21.31	-	-

4. Conclusions

The following conclusions are drawn from the tensile and flexural tests conducted for the various composites of coir fiber-reinforced epoxy nanoclay composites.

- The alkaline treatment removes the dirt and lignin content from the fiber's surface, enhancing the fiber's bonding ability with the matrix and improving its mechanical properties.
- The maximum average tensile strength and modulus are displayed by the 40C4N composite, which are found to be 96.47 MPa and 1.34 GPa, respectively.
- The tensile strength increases with an increase in the wt% of both the fiber and nanoclay content.
- The average flexural strength and modulus of the 40C2N epoxy composite are found to be 179.03 MPa and 3.52 GPa, respectively, which is almost 32% greater than the 40C epoxy composites and drops by around 10% for the 40C4N epoxy composites.

- The average flexural strength increases with an increase in the fiber content. Also, the strength increases with the addition of 2 wt% nanoclay, whereas it decreases for 4 wt% nanoclay epoxy composites.
- SEM analysis confirms that nanoclay arrests the crack propagation by deviating its path during fracture and enhances the interfacial bonding between the fiber and matrix.
- Incorporating nanoclay improves the spreadability of the matrix material around the fiber, reducing the fiber pullout.

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