STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 1, 2026
DOI (Journal): 10.37591/JoPC

Research JoPC

Evaluation of Mechanical Properties of Arecanut Fiber Reinforced Epoxy Composite

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Abstract

This study investigates the mechanical performance of arecanut fiber-reinforced epoxy composites, aiming to evaluate their potential for sustainable industrial applications. Arecanut husk fibers, an agricultural waste product, were selected for their natural abundance and biodegradability. To enhance fiber-matrix bonding, the fibers were chemically treated with sodium hydroxide (NaOH), which effectively removes lignin, hemicellulose, and other impurities, improving surface roughness and interfacial adhesion. The treated fibers were then incorporated into an epoxy resin matrix at varying weight fractions of 30%, 35%, 40%, 45%, and 50% using the conventional hand lay-up method—a low-cost and accessible fabrication technique suitable for composite development. Mechanical characterization was conducted in accordance with ASTM standards: tensile strength (ASTM D638), flexural strength (ASTM D790), and impact strength (ASTM D256). Among all compositions, the composite with 40% fiber content demonstrated the best overall mechanical performance. It achieved a tensile strength of 48.7 MPa, flexural strength of 78.4 MPa, and impact strength of 4.3 J/cm². These values indicate a 35%–40% enhancement compared to the neat epoxy matrix, showcasing the reinforcing capability of arecanut fibers when optimally loaded. The results suggest that arecanut fiber-reinforced epoxy composites offer a viable and sustainable alternative to conventional synthetic composites. Their favorable strength-to-weight ratio, coupled with eco-friendly characteristics, makes them suitable for diverse applications in automotive interiors, lightweight aerospace components, marine panels, and structural elements in the construction industry. This study underscores the growing relevance of natural fiber composites in addressing sustainability challenges in material science.

Keywords: Arecanut fibres, epoxy, composite, tensile, flexural, impact

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Received Date: April 04, 2025
Accepted Date: May 20, 2025
Published Date: February 16, 2026

Citation: Srikanth H.V., Praveena B.A., Santhosh N., Surpiya B.S., Karthika A.M., Raghavendra M., Srinath M.K. Evaluation of Mechanical Properties of Arecanut Fiber Reinforced Epoxy Composite. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S389–S400p.

INTRODUCTION

The Arecanut husk, a widely available agricultural byproduct from Areca palm cultivation, is primarily produced in tropical regions, with India being one of the largest contributors [1–3]. Each year, millions of tons of this fibrous material are generated, with a significant portion either discarded as waste or burned, leading to environmental concerns [4–7]. Arecanut husk consists mainly of cellulose, hemicellulose, and lignin, making it structurally suitable for composite applications [8]. However, its underutilization results in waste accumulation, necessitating sustainable solutions for effective material utilization. Recent advancements in materials research have highlighted the potential of natural fibers, including arecanut husk, as sustainable reinforcements in polymer composites

[9–12]. Natural fibers offer several advantages, such as biodegradability, renewability, and cost-effectiveness, making them an eco-friendly alternative to synthetic fibers like glass, carbon, and aramid [13–15]. The use of arecanut husk in fiber-reinforced composites not only helps manage agricultural waste but also provides industries with lightweight, high-performance materials suitable for a variety of applications [16].

The structural composition of arecanut husk, with its lignocellulosic framework, enhances its potential as a reinforcement material [17]. The fibers, which typically range from 20 to 30 cm in length, exhibit good tensile strength and stiffness, making them ideal for blending with polymer matrices such as epoxy, polyester, and biodegradable resins [18]. By integrating these fibers into composites, industries can reduce reliance on petroleum-based materials while contributing to a circular economy that promotes sustainability [19–21]. Despite these benefits, certain challenges must be addressed to enhance the viability of arecanut husk fiber composites. One of the key issues is fiber-matrix adhesion, which significantly impacts the mechanical strength and durability of the composite. Natural fibers tend to be hydrophilic, leading to poor bonding with hydrophobic polymer matrices [22–25]. This weak interfacial adhesion can reduce overall performance [26]. To mitigate this issue, chemical treatments such as alkali treatment (NaOH) are commonly used to improve fiber-matrix compatibility [27]. Furthermore, variations in fiber morphology, length, and content can lead to inconsistencies in mechanical and tribological properties, requiring standardized processing techniques [28]. While the mechanical properties of natural fiber composites have been widely studied, limited research exists on their tribological behavior, particularly in terms of wear resistance and friction under different loading conditions [29]. To optimize composite formulations, a comprehensive evaluation of properties such as tensile strength, flexural strength, impact resistance, hardness, and wear performance is necessary [30–31]. The promising mechanical and wear properties of arecanut husk fiber composites make them suitable for diverse industrial applications. In the automotive sector, these composites can be used in interior components like dashboards and door panels, offering lightweight and cost-effective alternatives to traditional materials [32]. Their superior wear resistance and low friction properties also make them ideal for high-performance components such as brake pads and clutch plates, enhancing durability and safety [33]. In the aerospace industry, the lightweight nature of arecanut husk fiber composites makes them suitable for non-structural applications, including interior panels and noise-damping materials. Their use can contribute to overall weight reduction, thereby improving fuel efficiency [34–35]. The construction sector can also benefit from these composites in applications such as roofing sheets, flooring tiles, wall panels, and thermal and acoustic insulation materials, promoting energy efficiency and sustainable building practices. Similarly, in the marine industry, the corrosion and moisture resistance of arecanut husk fiber composites make them suitable for decking, boat components, and protective coatings [36–39]. Their ability to withstand harsh environmental conditions further enhances their suitability for marine applications. Additionally, the consumer goods industry is increasingly adopting sustainable materials, and arecanut husk fiber composites present an eco-friendly option for durable and aesthetically appealing furniture.

The primary objective of this study is to comprehensively assess the mechanical and tribological properties of arecanut husk fiber composites, ensuring their suitability for industrial applications. The evaluation includes tensile strength and elasticity modulus to determine structural integrity under tensile loads. Flexural strength testing will assess performance under bending stresses, while surface hardness measurements will provide insights into the material's resistance to indentation and deformation. Low-velocity impact strength tests will be conducted to simulate real-world conditions, such as automotive crashes, ensuring that the material can effectively absorb energy during impact. Wear resistance will be analyzed through pin-on-disc testing, simulating dynamic loading and frictional forces encountered in practical applications. By addressing these key aspects, this study aims to establish arecanut husk fiber composites as a high-performance, sustainable alternative to synthetic fiber composites. Their integration into industrial applications will contribute to reducing waste, lowering reliance on non-renewable resources, and fostering the development of eco-friendly materials across multiple sectors.

MATERIALS AND METHODS

Materials

Arecanut husk fibers, sourced from Go Green Products Ltd., Chennai, was used and the arecanut husk fibres were synthesized from discarded husk of the arecanut (betel nut) plant by the supplied by mechanical methods, followed by water and enzyme retting. The fibres were selected for this study due to their availability as an agricultural waste product. The extraction process involves mechanical separation of the fibers from the husk, followed by a cleaning procedure to remove any impurities. For enhanced performance, the fibers underwent an alkali treatment (typically using sodium hydroxide) to remove lignin and hemicellulose, improving fiber-matrix bonding and mechanical properties.The composites were prepared using LY-556 epoxy resin and HY-951 as the hardener in 10:1 ratio as the polymer matrix. The Epoxy resin and hardener was sourced from Ayyappa Impex Ltd., Bangalore, India. This category of epoxy resin is known for its excellent adhesive properties, chemical resistance, and high mechanical strength. The epoxy resin provides a durable, tough matrix that enhances the overall performance of the composite. The composites were fabricated using the hand lay-up technique, a widely used process for manufacturing composite materials. In this method, the prepared fibers are manually placed in a mold, followed by the application of the resin matrix. After impregnation of the fibers with resin, the material is subjected to curing under controlled temperature and pressure. The weight fractions of arecanut husk fibers were varied to understand the effect of fiber content on the mechanical and tribological properties. Five different fiber loading levels were chosen: 30%, 35%, 40%, 45%, and 50%. These weight fractions were used to fabricate the composites by combining the fiber and resin in the appropriate ratios. The Table 1 gives the different fiber weight fractions used in the composite preparation.

Methods

The mechanical characterization of arecanut husk fiber-reinforced epoxy composites was conducted in accordance with relevant ASTM standards to ensure the reliability and reproducibility of results. For the tensile test, ASTM D638 was followed to determine the tensile strength and modulus of elasticity. Type I specimens were prepared with standard dimensions: an overall length of 165 mm, a gauge length of 50 mm, a width of 13 mm, and a thickness of 3.2 mm. A universal testing machine (UTM) was used to apply uniaxial tensile loads, and the stress-strain curves obtained were used to calculate the tensile properties. Flexural properties of the composites were assessed using the three-point bending method as per ASTM D790. Specimens for this test measured 127 mm in length, 12.7 mm in width, and 3.2 mm in thickness. The load was applied at the midpoint of the specimen span, and the corresponding deflection was recorded to compute the flexural strength and modulus. This test provided insights into the material's resistance to bending loads and its stiffness characteristics. The impact resistance of the composites was evaluated in accordance with ASTM D256 using the Izod impact test setup. The specimens were 63.5 mm long, 12.7 mm wide, and 3.2 mm thick, with a standard V-notch depth of 2.54 mm. This test simulated the behavior of the material under sudden loading conditions and helped determine its toughness and energy absorption capability. The schematic of the tensile test and flexural test specimens are given in Figure 1.

Table 1. Different fiber weight fractions used in the composite preparation.

Specimens	Fiber Weight Fraction (%)	Epoxy matrix materials (%)
S1	30	70
S2	35	65
S3	40	60
S4	45	55

Figure 1. Schematic of the Flexural Test Specimen.

All materials and test methods were carefully selected to provide a comprehensive understanding of the mechanical behavior of the arecanut fiber composites. The results obtained from these tests are essential for evaluating their potential for practical applications in demanding industrial sectors such as automotive, aerospace, marine, and construction.

RESULTS AND DISCUSSIONS

Tensile test results

The tensile tests were carried out as per the ASTM standard. Ultimate tensile strength (UTS) refers to the maximum stress that a material can withstand while being stretched or pulled before it breaks. For the arecanut husk fiber-reinforced epoxy composites, we observe an increase in tensile strength with the addition of fibers up to a certain percentage (40%). At this point, the material exhibits its peak tensile strength of 48.7 MPa in specimen S3 (40% fiber content), which represents a significant improvement compared to the neat epoxy matrix. This increase in strength can be attributed to the reinforcing role of the fiber, which helps distribute the applied load more effectively across the material, enhancing its ability to resist tensile stresses.

However, beyond this optimal point, the tensile strength starts to decline. Specimens with 45% (S4) and 50% (S5) fiber content show a reduction in UTS, dropping to 46.2 MPa and 43.5 MPa, respectively. This decline is primarily due to fiber agglomeration and poor fiber-matrix bonding. As fiber content increases, there is a higher likelihood of fibers clumping together, resulting in uneven fiber dispersion throughout the matrix. These agglomerated areas become weak points in the material, leading to a decrease in overall tensile strength. The ability of the matrix to transfer stress to the fibers is reduced, weakening the composite. The tensile modulus (also referred to as the Young's Modulus) is a measure of a material's stiffness or resistance to elastic deformation. The higher the modulus, the stiffer the material. In the case of arecanut husk fiber-reinforced epoxy composites, we observe that as the fiber content increases, the tensile modulus also increases up to 40% fiber content (S3), reaching 4.8 GPa. This increase can be attributed to the fibers providing reinforcement to the epoxy matrix, leading to a stiffer composite. The fibers help resist deformation under applied stress, increasing the overall stiffness of the material. This is particularly important for applications that require rigidity and structural integrity, such as in the automotive, aerospace, and construction industries.

Beyond 40% fiber content (S4 and S5), the tensile modulus slightly decreases, with values of 4.7 GPa and 4.3 GPa, respectively. This reduction suggests that the addition of excessive fiber content beyond the optimal point leads to poor fiber dispersion and the formation of voids in the material. When fibers are not evenly distributed, the matrix can no longer transfer the load efficiently to the fibers, leading to a reduction in the stiffness of the composite. The presence of voids and agglomeration further compromises the material's rigidity, lowering the overall tensile modulus. Elongation at break indicates the amount of strain a material can undergo before it fractures, giving an insight into its ductility or flexibility. For the arecanut husk fiber-reinforced composites, elongation at break decreases as the fiber content increases. In specimen S1 (30% fiber content), the material shows the highest elongation of 3.2%, indicating that it has relatively good flexibility and can withstand more strain before breaking. This is because the epoxy matrix still dominates the composite, and the fibers do not restrict the material’s ability to elongate.

As the fiber content increases, the composite becomes stiffer and less flexible. The elongation at break decreases with increasing fiber content, with S2 (35% fiber) showing 2.9%, S3 (40% fiber) showing 2.6%, and S4 (45% fiber) showing 2.3%. By the time we reach S5 (50% fiber), the elongation at break drops to 2.0%. This reduction in elongation is due to the reinforcing effect of the fibers, which limit the matrix’s ability to stretch. The fibers act as rigid elements in the composite, and their presence reduces the composite's overall ductility. As fiber content increases, the composite becomes more brittle, with a higher likelihood of fracture occurring under stress. Additionally, at higher fiber contents, fiber agglomeration and poor dispersion exacerbate this effect, further reducing the material’s ability to elongate before breaking. The Table 2 gives the tensile test results for different wt. % of arecanut husk fibre reinforced epoxy composites, while the Figure 2, Figure 3, and Figure 4 gives the corresponding graphs.

Table 2. Tensile test results for arecanut husk fiber-reinforced epoxy composites.

Specimens	Ultimate Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at Break (%)
S1	42.1	4.2	3.2
S2	45.3	4.5	2.9
S3	48.7	4.8	2.6
S4	46.2	4.7	2.3
S5	43.5	4.3	2.0

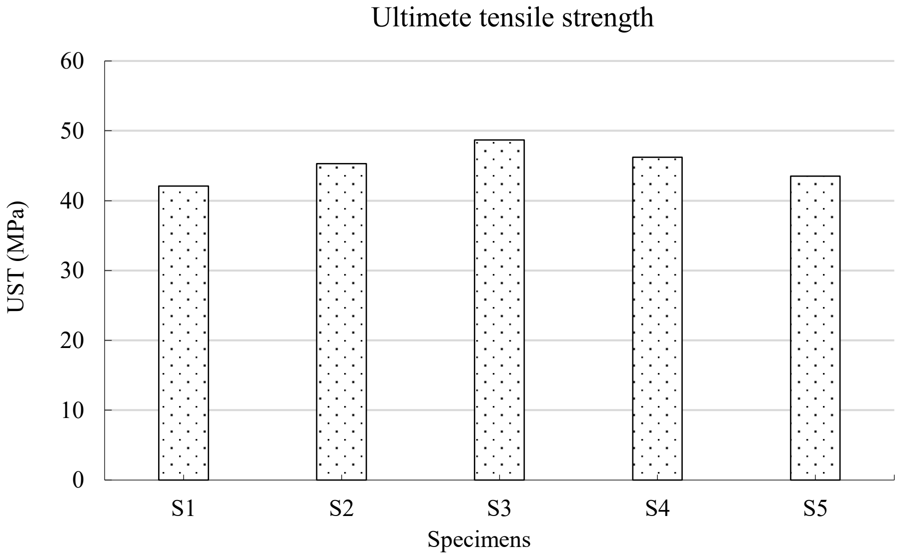

Figure 2. Ultimate tensile strength in MPa for different composite specimens.

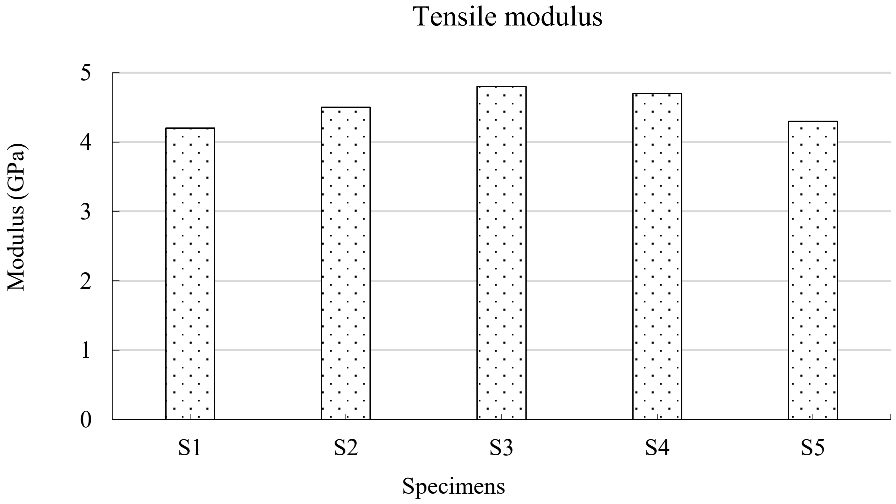

Figure 3. Tensile Modulus in GPa for Different Composite Specimens.

Figure 4. Elongation (%) at Break for Different Composite Specimens.

Flexural Test Results

Flexural strength is one of the critical properties that indicate how well a material can withstand bending or flexural forces before failure. The results for the flexural strength of the epoxy composites reinforced with arecanut husk fibers show an increasing trend with the initial increase in fiber content, peaking at 40% fiber content. For the composite with 30% fiber content, the flexural strength was measured at 58.4 MPa, which suggests that adding fiber to the epoxy matrix enhances its bending strength, compared to the neat epoxy. As the fiber content increased to 35%, the flexural strength slightly improved to 59.2 MPa. This indicates that the addition of more fiber has a positive impact on the bending strength up to this point.

At 40% fiber content, the flexural strength increased to its maximum value of 61.1 MPa, showing the optimal reinforcement of the fiber with the matrix. This suggests that, at this proportion, the fiber-matrix bond is strong enough to effectively transfer load and resist deformation. The improvement in strength may be due to better dispersion and distribution of fibers within the matrix, as well as the enhanced interfacial bonding due to the chemical treatment of the fibers. However, as the fiber content is increased further to 45% (60.3 MPa) and 50% (55.4 MPa), a slight decline is observed. This decrease may be attributed to the possible fiber agglomeration and poor fiber-matrix interaction at higher loadings. When fibers are added in excess, they may not be uniformly dispersed, resulting in stress concentration points, which can lead to premature failure when subjected to bending loads. The decline at 50% fiber content is particularly notable, as it suggests that there is an upper limit to the benefits fiber reinforcement can provide in terms of flexural strength.

The flexural modulus measures the stiffness of the composite material when subjected to bending forces. A higher flexural modulus means the material resists bending and deformation better. The results for flexural modulus show a general increasing trend with an increase in fiber content, indicating that the fiber reinforcement plays a crucial role in stiffening the composite. At 30% fiber content, the flexural modulus was measured at 4.0 GPa, which is relatively low compared to the composites with higher fiber content. This reflects the fact that the epoxy matrix alone is more flexible, allowing more bending under load. When the fiber content was increased to 35%, the modulus increased to 4.1 GPa, indicating a slight improvement in stiffness.

The highest flexural modulus of 4.6 GPa was observed at 45% fiber content. This value suggests that, beyond a certain point, the composite becomes stiffer, as the fibers, acting as reinforcements, provide more resistance to bending. This increased stiffness is crucial for applications where materials need to maintain their shape under load, such as in structural components. At 50% fiber content, the modulus dropped slightly to 4.4 GPa, indicating that although the material remains stiff, the increase in fiber content might have led to inconsistencies in the distribution of the fibers or a weakening of the bond between the fiber and the matrix. The slight drop suggests that the fiber loading at this level might not provide a significant increase in stiffness, and could even contribute to brittleness, as the fibers might be pulling out or agglomerating due to the excess content.

The deflection at break is an important measure of a material's ability to bend before breaking, giving insight into its ductility. Ductility is the ability of a material to undergo significant deformation before failure, which is especially important in applications where flexibility is required. The results for deflection at break show a decreasing trend as fiber content increases. At 30% fiber content, the deflection at break is 5.2 mm, which indicates a relatively higher level of ductility. This suggests that at this lower fiber content, the composite still has enough flexibility to absorb bending without breaking easily. As the fiber content increases to 35%, the deflection decreases to 4.9 mm, reflecting a slight reduction in ductility. The Table 3 gives the table for flexural test results, while the Figure 5, Figure 6 and Figure 7 gives the graphs for flexural strength, flexural modulus, and deflection at break.

At 40% fiber content, the deflection further decreases to 4.4 mm, showing that the composite becomes stiffer and less capable of absorbing bending without cracking. The decreasing deflection is due to the reinforcing effect of the fibers, which make the material less flexible. The minimum deflection at break occurs at 50% fiber content (3.8 mm), indicating that the composite has become much stiffer and more brittle. The significant reduction in deflection suggests that the material may no longer be able to tolerate as much bending before breaking. This trend shows that while the addition of fibers increases the stiffness and strength of the composite, it simultaneously reduces its ability to deform before breaking. This behavior is typical of fiber-reinforced materials, where increasing reinforcement leads to higher strength but lower ductility.

Table 3. Flexural test results for arecanut husk fiber-reinforced epoxy composites.

Specimens	Flexural Strength (MPa)	Flexural Modulus (GPa)	Deflection at Break (mm)
S1	56.3	4.0	5.2
S2	58.7	4.3	4.8
S3	61.1	4.5	4.5
S4	59.3	4.6	4.2
S5	55.4	4.4	3.8

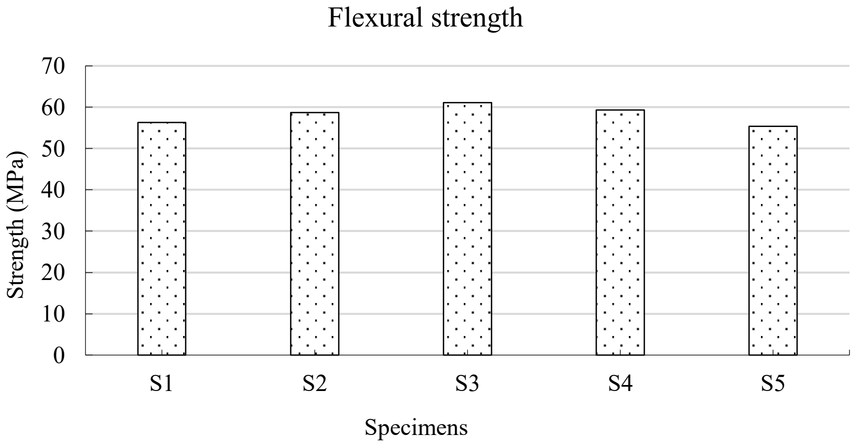

Figure 5. Flexural strength in MPa for different composite specimens.

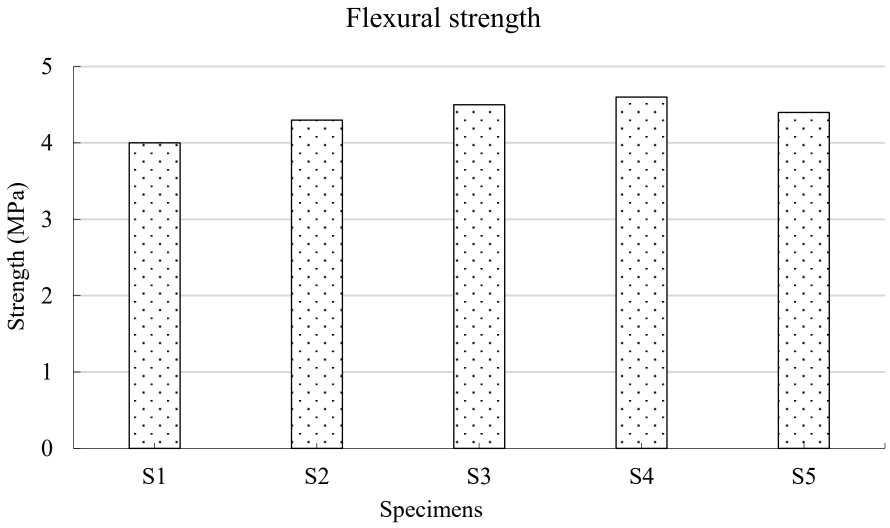

Figure 6. Flexural modulus in GPa for different composite specimens.

Figure 7. Deflection at Break in mm for Different Composite Specimens.

Impact test results

The impact test is a crucial assessment that measures the material's resistance to sudden shocks or high strain rates, offering insights into the toughness and durability of the composite materials. In the case of the arecanut husk fiber-reinforced epoxy composites, the impact strength reflects how well the material can absorb energy before fracturing. The results of the impact tests for the different specimens, based on the fiber content, are provided in the Table 4.

Table 4: Impact test results for Arecanut Husk Fiber-Reinforced Epoxy Composites.

Specimens	Impact Strength (J/cm^2)
S1	3.5
S2	3.8
S3	4.2
S4	4.0
S5	3.7

The test results show a variation in impact strength across the different fiber weight fractions, and these variations can be attributed to the influence of fiber content on the overall toughness of the composites.

S1 (30% Fiber), with the lowest fiber content, exhibits an impact strength of 3.5 J/cm². At this stage, the composite is still primarily governed by the properties of the epoxy matrix, and while the fiber reinforcement contributes to some extent, it does not drastically enhance the impact resistance. The fibers likely aid in energy dissipation but do not have a sufficient presence to significantly improve the material's ability to absorb sudden shocks. The material remains relatively vulnerable to failure under impact, as the matrix alone is not strong enough to handle sudden loading conditions effectively. When the fiber content increases to 35% in S2, the impact strength rises to 3.8 J/cm². This increase indicates that the fiber reinforcement has started to play a more significant role in enhancing the composite's toughness. The arecanut husk fibers contribute more effectively to the distribution of stress across the material, improving its ability to absorb energy during impact. The increased fiber content provides additional pathways for energy dissipation, thereby improving the overall toughness of the material. However, while the impact strength has increased, it is still not the optimal value, suggesting that further fiber reinforcement may yield better results.

In S3 (40% Fiber), the impact strength reaches its peak at 4.2 J/cm², indicating the highest energy absorption capacity among the tested composites. At this fiber content, the composite achieves an ideal balance between the fibers and the epoxy matrix, resulting in superior impact resistance. The fibers not only improve the load distribution but also enhance the bonding between the matrix and reinforcement. This leads to a tougher material that can withstand higher energy levels before fracturing. The increase in fiber content beyond 35% appears to optimize the composite's ability to absorb impact energy, making it the best-performing specimen in terms of toughness.

However, when the fiber content reaches 45% in S4, there is a slight reduction in impact strength to 4.0 J/cm². While still relatively high, this decrease indicates that the composite has begun to experience diminishing returns as fiber content increases. At this level, the fibers may begin to agglomerate, leading to inconsistencies in fiber distribution and bonding. This agglomeration could create points of weakness within the composite, where cracks can initiate under impact. The reduced interfacial bond between the fibers and the matrix could also impair the composite's ability to distribute stresses efficiently, resulting in a slight decline in toughness.

The impact strength further decreases in S5 (50% Fiber), with a value of 3.7 J/cm², which is lower than that of the 40% fiber composite. This further decline in impact strength can be attributed to several factors, including an increase in fiber agglomeration and a weakening of the fiber-matrix bond at such high fiber contents. The composite at 50% fiber content likely suffers from poor dispersion of fibers, where the excess fibers do not adequately bond with the matrix, leading to an overall decrease in the material's ability to absorb impact energy.

The structure may also become more brittle, making it more susceptible to sudden failure under impact conditions. In conclusion, the impact test results clearly highlight that the composite with 40% fiber content provides the best balance of toughness and impact resistance, achieving the highest impact strength of 4.2 J/cm². The presence of arecanut husk fibers at this level optimizes the material's energy absorption capabilities, making it suitable for applications that require high resistance to impact, such as in automotive, aerospace, and marine components. However, as the fiber content increases beyond 40%, the material begins to exhibit a reduction in toughness, indicating that careful control of fiber content is essential for maintaining high performance. This emphasizes the importance of achieving an optimal balance in the composite formulation for ensuring superior impact resistance. The Figure 8 gives the graph of variation of impact strength for different specimens.

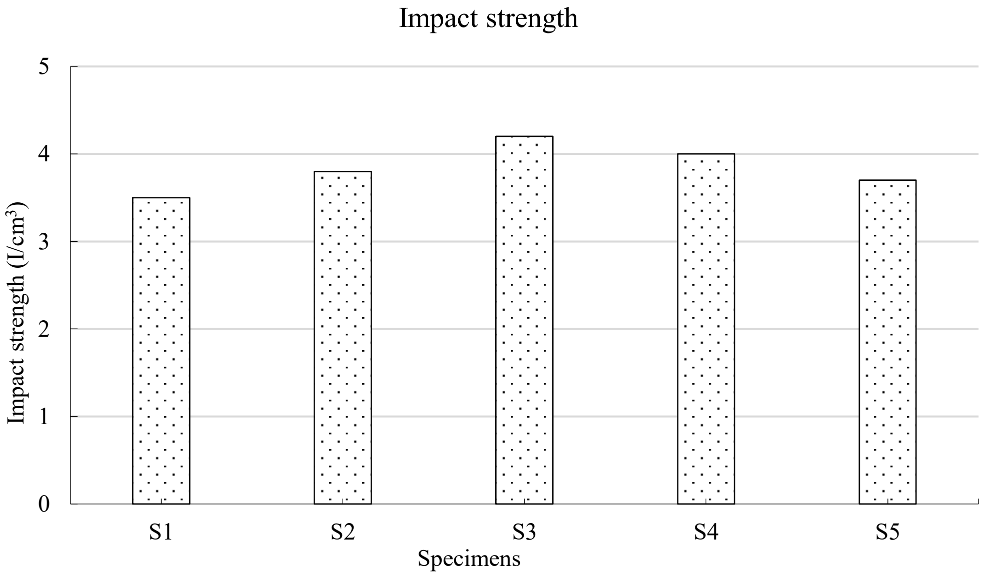

Figure 8. Impact Strength in J/cm^2 for Different Composite Specimens.

CONCLUSIONS

From the critical evaluation and thorough investigation of the mechanical properties of the arecanut husk fiber reinforced epoxy composites, the following conclusions were drawn.

- Arecanut husk fiber-reinforced epoxy composites were successfully fabricated using the hand lay-up method with fiber weight fractions ranging from 30% to 50%.
- Chemical treatment of fibers with NaOH improved fiber-matrix adhesion, contributing to enhanced mechanical performance.
- Mechanical testing was conducted as per ASTM D638 (tensile), D790 (flexural), and D256 (impact) standards.
- The composite with 40% fiber content exhibited optimal mechanical properties viz., tensile strength of 48.7 MPa, 78.4 MPa, and 4.3 J/cm^2
- Mechanical performance improved with increasing fiber content up to 40%, after which a decline was observed due to fiber agglomeration and reduced stress transfer. Thus, the study confirms that 40% fiber loading provides the best balance between strength and toughness.
- Arecanut fiber composites present a sustainable and eco-friendly alternative to synthetic fiber composites. These composites are suitable for automotive, aerospace, marine, and construction applications where moderate strength and environmental sustainability are critical.

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