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Experimental Investigation of the Mechanical and Tribological Properties of Jute Fiber Composites with Nano-Sized Al_2O_3 Ceramic Particle Reinforcement †

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Abstract: Jute fiber, a sustainable and abundant material, has garnered attention as a potential reinforcement in composites. This study focuses on enhancing the jute fiber composite strength through the inclusion of Al_2O_3 nanoparticles at varying levels. Mechanical properties were rigorously examined to evaluate their suitability for high-stress applications. This research encompassed assessments of hardness, flexural strength, tensile strength, and impact resistance. The results indicate that the incorporation of Al_2O_3 nanoparticles significantly improves the composite mechanical properties. Increasing the Al_2O_3 content elevates hardness, enhancing resistance to indentation. Flexural strength tests highlight the increased stiffness and deformation resistance, rendering the composites suitable for structural use. Additionally, tensile tests reveal an enhanced load-bearing capacity under tension with higher Al_2O_3 percentages. An improved impact resistance confirms the durability and the ability to withstand sudden shocks. These findings present promising opportunities for utilizing Al_2O_3-reinforced jute fiber composites in industries requiring high-strength materials, such as the automotive, aerospace, construction, and sports equipment manufacturing industries, combining sustainability with enhanced mechanical properties.

Keywords: mechanical properties; characterization; SEM; jute fiber; nanoparticles

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1. Introduction

Jute fiber, sourced from jute plant stems, offers cost efficiency, biodegradability, and eco-friendliness. It has garnered interest for its potential use in composites, competing with traditional synthetic fibers [1,2]. Composite materials span diverse industries, serving in the aerospace industry in lightweight, robust aircraft parts, in automobiles for fuel efficiency and safety, in marine applications due to their water and corrosion resistance, and in construction for structural strength. They also excel in sports equipment, renewable energy, and more. However, unlocking the full potential of jute fiber composites requires enhancing their mechanical properties, primarily their strength [3,4].

Jute fiber composites have applications in the automotive industry for lightweight interior components, in construction for eco-friendly and cost-saving solutions, in packaging as a sustainable alternative, and in textiles for various products [5,6]. The core challenge in jute fiber composite use lies in meeting the strength demands of various applications. Improvements to properties like the stretchable strength, flexural strength, and Izod resistance are essential to expand their use. Jute fiber composites tend to have a lower strength compared to carbon or glass fibers, necessitating a focus on enhancing their strength.

To strengthen jute fiber composites, researchers have investigated techniques like incorporating fillers or nanoparticles into the composite matrix. Materials like nanoclay, carbon nanotubes, graphene, and alumina (Al_2O_3) nanoparticles are used to enhance the mechanical properties [7]. These fillers improve the bond between jute fibers and the matrix, enhancing the load-carrying capacity. Achieving a uniform dispersion and alignment of fillers within the matrix is crucial for the overall mechanical performance. The choice of matrix material also plays a vital role in influencing the composite strength [8,9]. Different polymers, including epoxy, polyester, polypropylene, and bio-based polymers, affect the mechanical properties, processing characteristics, and compatibility with jute fibers. The bond between jute fibers and the matrix is vital for stress transfer and load distribution.

The processing technique used to create jute fiber composites is crucial in determining their mechanical properties. Common methods include hand layup, compression molding, vacuum infusion, filament winding, and injection molding. Each technique has its advantages and limitations in terms of cost, complexity, fiber orientation control, and void elimination. Optimizing the processing parameters, such as the curing temperature, pressure, and fiber arrangement, is essential to achieve a uniform fiber distribution, minimize the void content, and enhance interfacial bonding, ultimately improving the composite strength [10,11]. Various parameters, such as the fiber content, fiber aspect ratio, fiber treatment, filler loading, filler size, and curing conditions, impact the jute fiber strength. A higher fiber content and longer fibers generally result in improved mechanical properties. Surface treatments of jute fibers, such as chemical treatments, plasma treatment, and silane coupling agents, enhance interfacial adhesion and compatibility with the matrix. The loading and size of fillers, as well as their dispersion and agglomeration behavior, can influence the mechanical properties. Curing conditions, including the temperature and time, play a vital role in achieving optimum cross-linking and matrix–fiber bonding, ultimately affecting the composite strength.

2. Material Preparation

In this study, we investigate the impact of varying Al_2O_3 nanoparticles of 70 nm in size with concentrations of 2%, 4%, and 6% on the mechanical properties of jute fiber composites. Epoxy resin served as the matrix material. To optimize workability, the epoxy resin was heated to 60 °C to lower its viscosity, facilitating improved impregnation of jute fibers. Simultaneously, Al_2O_3 nanoparticles were heated to 250 °C for efficient dispersion within the epoxy resin. These heated nanoparticles were gradually mixed into the resin with continuous stirring over 30 min, ensuring a uniform distribution. The hand layup technique was employed to integrate jute fibers into the composites. Diaminodiphenyl sulfone hardener was used for crosslinking.

The curing process was accelerated with the addition of a hardener, leading to the formation of solid composites. The resulting composites underwent comprehensive mechanical testing, including Vickers hardness, flexural strength, impact resistance, and tensile strength evaluations. The Vickers hardness test measures the material's hardness using a specific load and depth of indentation. Flexural tests assess the material's ability to withstand bending forces. Impact tests measure the energy absorption and resistance to sudden impacts, while tensile tests determine the tensile strength and elongation properties. Figure 1 illustrates the methodology of the proposed research.

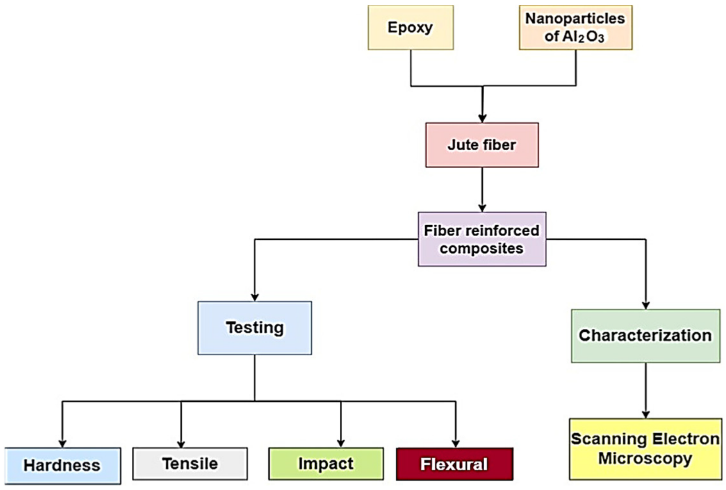

Figure 1. Material preparation.

3. Result and Discussion

3.1. Vickers Hardness

In this research, Vickers hardness testing, following ASTM standards, determined the hardness values of the three composite compositions. Figure 2 depicts the Vickers hardness test setup, adhering to ASTM guidelines. The Vickers hardness values are as follows: the 2% composition shows a hardness value of 84 MPa, the 4% composition has an 88 MPa hardness, and the 6% composition has the highest hardness value at 95 MPa. These results demonstrate a direct relationship between the percentage of reinforcement and material hardness. The Vickers hardness test, a well-established method in material assessment, including composites, involves applying a known load with a diamond indenter and measuring the resulting indentation diagonals. The hardness value is computed based on the load and indentation area. Higher hardness values signify a greater resistance to indentation and deformation, reflecting an increased material strength.

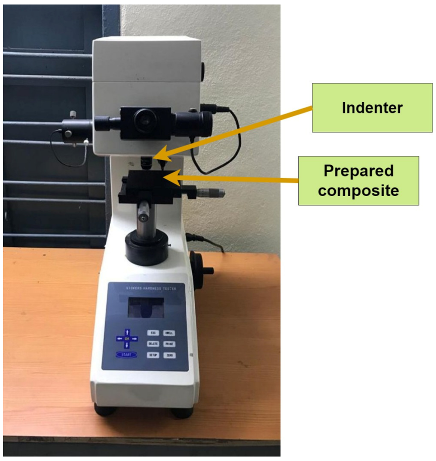

Figure 2. Vickers hardness.

Figure 3 displays the experimental Vickers hardness test results for the prepared composites. The graph illustrates hardness values for each composition, emphasizing the progressive increase in hardness with higher reinforcement percentages. This trend underscores the positive impact of Al_2O_3 nanoparticle reinforcement on the jute fiber composite's hardness. The findings suggest that adding Al_2O_3 nanoparticles enhances the material's hardness, reinforcing the matrix material and improving its resistance to indentation and deformation. The heightened hardness makes the composites more suitable for applications requiring an increased durability.

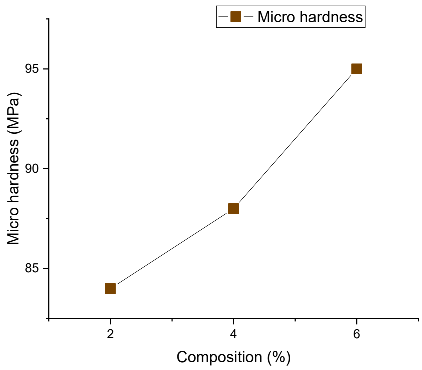

Figure 3. Hardness result.

3.2. Flexural Properties

Figure 4 depicts the flexural strength test in this study. The composites were tested for their ability to withstand bending forces, as shown in Figure 5. The composite with 6% Al_2O_3 reinforcement displayed the highest flexural strength at 117 MPa, followed by the 4% Al_2O_3 reinforcement composite at 98 MPa and the 2% Al_2O_3 reinforcement composite at 84 MPa. This shows that an increased percentage of Al_2O_3 reinforcement directly enhances the flexural strength of the composite. The improved flexural strength indicates greater resistance to deformation and bending, underscoring the effectiveness of Al_2O_3 reinforcement in enhancing the composite's mechanical properties. These results provide valuable insights for designing high-flexural-strength composite structures, especially in industries like thee construction, automotive, and aerospace industries.

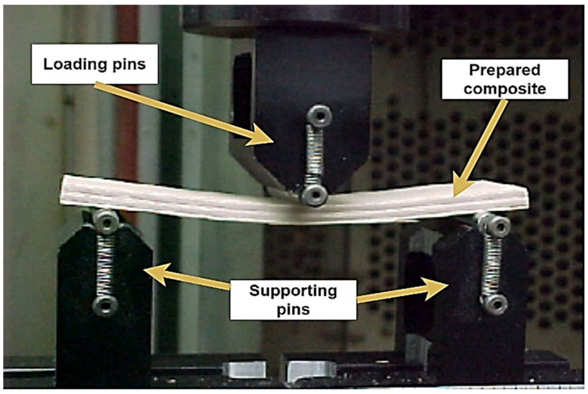

Figure 4. Flexural test of the composite.

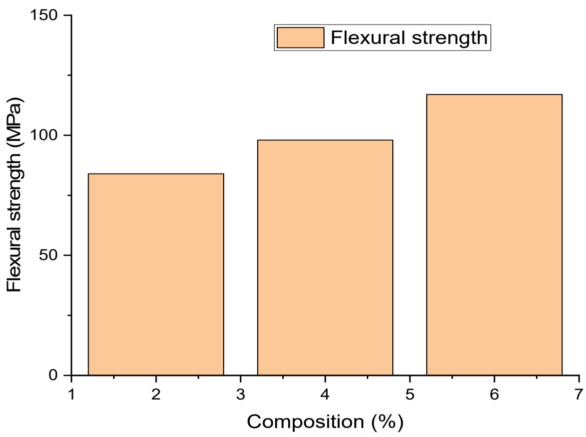

Figure 5. Result of flexural strength.

3.3. Tensile Test

In this research, tensile testing (Figure 6) assessed the composite materials' strength. Tensile testing measures a material's response to an applied tensile force, offering vital mechanical insights. The procedure involves gradually applying force to the samples along their longitudinal axis until they fracture.

Figure 6. Tensile test of the composite.

During a tensile test, force and elongation are continuously recorded, enabling the calculation of stress and strain, pivotal in assessing material properties. Figure 7 displays the tensile test results. The composite with 6% Al_2O_3 reinforcement demonstrates a tensile strength of 76.28 MPa, the 4% Al_2O_3 reinforcement composite exhibits a tensile strength of 56.33 MPa, and the 2% Al_2O_3 reinforcement composite shows a tensile strength of 32.23 MPa. These results highlight the positive impact of increased Al_2O_3 reinforcements on the tensile strength. The addition of Al_2O_3 nanoparticles enhances the material's ability to withstand tensile forces, resulting in an improved mechanical performance. This research yields valuable insights into the relationship between the Al_2O_3 reinforcement percentage and the composite tensile strength, with implications for automotive, aerospace, and construction industries, where a high tensile strength is crucial.

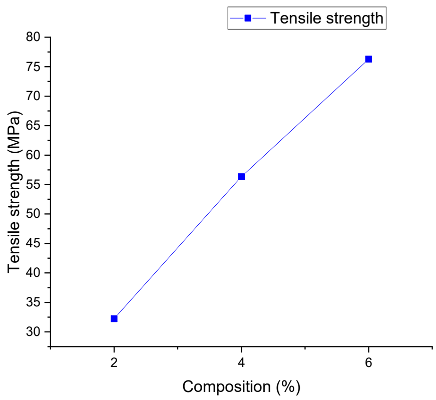

Figure 7. Experimental results—tensile strength.

3.4. Impact Test

In this study, an impact test assessed the impact strength of the composite materials. This test measures a material's ability to absorb energy under high-speed loading conditions, simulating sudden impact or shock scenarios. Impact tests were conducted on composites with varying Al_2O_3 reinforcement percentages. Figure 8 illustrates the impact test setup, involving a pendulum-type testing machine. The machine releases a pendulum that strikes and fractures the sample, measuring energy absorption. Figure 9 shows the impact strength results for each composite. The composite with 2% Al_2O_3 reinforcement exhibited an impact strength of 544.7 J/m, the 4% Al_2O_3 reinforcement composite had an impact strength of 520.23 J/m, and the 6% Al_2O_3 reinforcement composite demonstrated an impact strength of 570.34 J/m. These results reveal that the impact strength of the composites varies with Al_2O_3 reinforcement percentages, with the 4% reinforcement composite exhibiting the highest impact strength, followed by the 2% and 6% reinforcement composites, as shown in Figure 9. Al_2O_3 nanoparticles enhance the composite material's impact strength, improving energy dissipation and the resistance to sudden fractures. In summary, incorporating Al_2O_3 nanoparticles as a reinforcement in jute fiber composites significantly enhances their mechanical properties. The Vickers hardness test demonstrates an increased hardness with higher Al_2O_3 reinforcement percentages, boosting the resistance to indentation. The flexural strength test indicates that composites with higher Al_2O_3 reinforcement percentages exhibit a greater strength, rendering them suitable for structural applications requiring stiffness and deformation resistance.

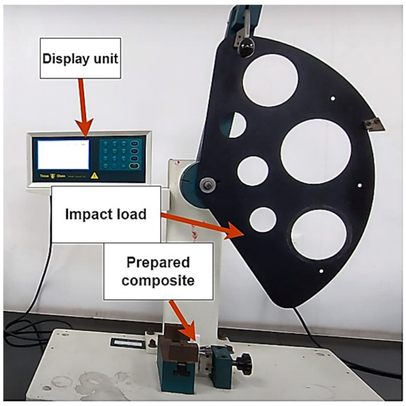

Figure 8. Impact test.

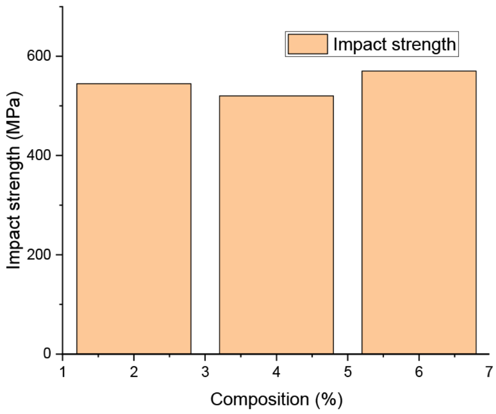

Figure 9. Result of the impact test.

Tensile tests revealed that higher Al_2O_3 reinforcement percentages increased strength, making the composites more resistant to elongation and better suited for demanding applications. In impact tests, composites with 4% Al_2O_3 reinforcement displayed the highest impact strength, showing an improved energy absorption and shock resistance due to Al_2O_3 nanoparticles. This highlights the effectiveness of Al_2O_3 reinforcement in enhancing jute fiber composites, suitable for industries like automotive, construction, and aerospace industries which require high-performance materials. This study focused on specific Al_2O_3 reinforcement percentages (2%, 4%, and 6%). Future research can explore different reinforcement levels and assess the nanoparticle's size and distribution impacts on composite properties. SEM analysis shown in Figure 10 confirms that the uniform dispersion of nanoparticles in the 6% Al_2O_3 composite enhanced bonding with the jute fiber matrix, contributing to the strength increase. In contrast, the 2% Al_2O_3 composite exhibited a less uniform dispersion and some clustering, potentially affecting the observed lower strength. These findings stress the importance of a uniform nanoparticle dispersion to maximize reinforcement benefits. Future research can optimize dispersion techniques and explore surface modifications or coupling agents for enhanced nanoparticle–matrix bonding.

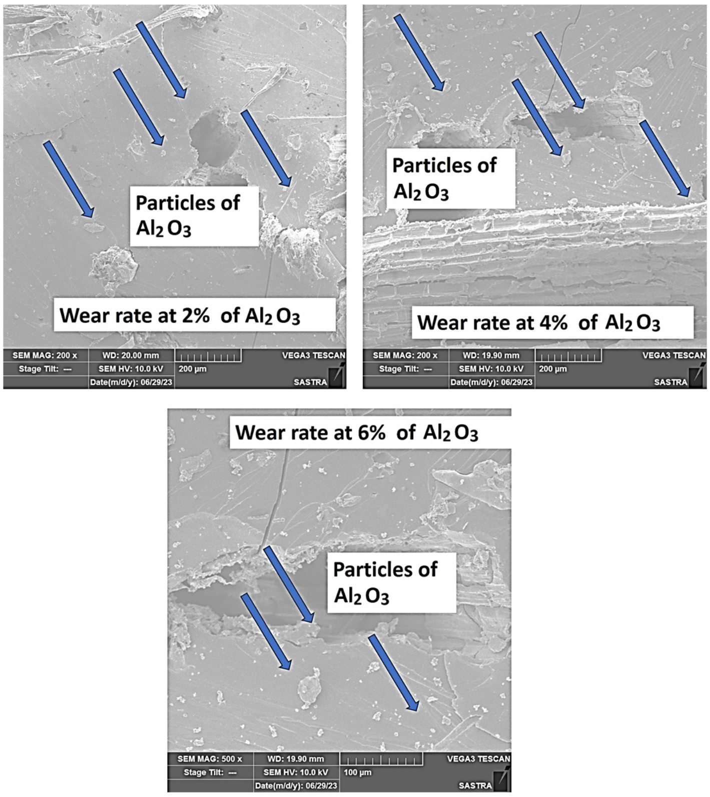

Figure 10. SEM analysis.

4. Conclusions

In this study, we investigated the mechanical properties and microstructure of jute fiber composites reinforced with varying Al_2O_3 nanoparticle percentages. SEM analysis highlighted the importance of a uniform nanoparticle dispersion, particularly in the 6% Al_2O_3 composite, enhancing mechanical properties through effective nanoparticle–jute fiber matrix bonding. The Vickers hardness test demonstrated the increased hardness with higher Al_2O_3 reinforcement percentages, indicating a better resistance to indentation. Flexural strength tests demonstrated an enhanced stiffness and deformation resistance for structural applications. Tensile tests revealed higher tensile strengths with increased Al_2O_3 reinforcements, enhancing the load-carrying capacity under tension. Impact tests confirmed the improved impact resistance. These findings provide valuable insights into the potential of Al_2O_3 reinforcements for enhancing the strength and performance of jute fiber composites.

Author Contributions: Authors M.T. and M.V. was involved in data collection, data analysis, manuscript writing. Authors T.S. and G.P. was involved in conceptualization, data validation, and critical review of manuscript. All authors have read and agreed to the published version of the manuscript.

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