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Study of Mechanical and Thermal Properties of Hybrid Jute Sisal Nano-Filler Reinforced Polymer Composites

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Abstract: Natural fiber composites provide eco-friendly alternatives to synthetic fiber composites but suffer from lower strength and thermal resistance. Hybrid reinforcement using jute–sisal fibers combined with nano-fillers significantly improves mechanical, thermal, and microstructural performance. This review analyzes fabrication techniques, mechanical/thermal behavior, microstructural evolution, and industrial applicability of hybrid jute–sisal nano-composites,
Keywords: Natural fiber composites provide eco-friendly alternatives to synthetic fiber composites but suffer from lower strength and thermal resistance.

I. INTRODUCTION

Natural fiber composites have gained significant global interest due to their biodegradability, low density, low cost, and ease of processing. They are increasingly utilized in automotive components (door trims, dashboards, interior panels), construction materials (partition boards, roofing sheets), packaging solutions, furniture, sports equipment, and household products**.** Despite these advantages, natural fibers inherently suffer from limitations such as high moisture absorption, which causes swelling and dimensional instability; weak interfacial bonding with hydrophobic polymer matrices due to their hydrophilic nature; and limited thermal stability, which restricts their applicability in high-temperature or load-bearing environments. These drawbacks necessitate material innovations to enhance the performance of natural fiber composites for broader industrial adoption.

Hybridization—combining two or more natural fibers in a single composite—has emerged as an effective method to overcome individual fiber limitations and achieve a synergistic balance of properties. Among various natural fibers, jute and sisal stand out due to their mechanical strength, availability, and cost-effectiveness. Jute fibers are known for their high tensile strength, stiffness, and good acoustic properties, making them suitable for semi-structural applications. In contrast, sisal fibers possess higher toughness, elongation at break, and excellent impact resistance**,** which enhances energy absorption and reduces sudden brittle failure. When combined, jute provides the structural rigidity, while sisal contributes ductility and toughness, resulting in a composite with improved mechanical stability and balanced performance. The incorporation of nano-fillers such as nano-clay, SiO_2, Al_2O_3, carbon nanotubes (CNTs), and graphene further enhances the composite's functionality. Nano-fillers act as nucleating agents, improving polymer crystallinity and increasing the matrix stiffness. They also create a tortuous pathway that slows down heat transfer and volatile degradation, thereby improving thermal resistance and thermal stability**.** At the microstructural level, nano-fillers fill voids and micro-gaps between the fibers and the matrix, resulting in better load-transfer efficiency, reduced crack propagation, and improved interfacial bonding. Their extremely high surface area enables enhanced stress distribution, which significantly increases tensile, flexural, and impact properties. As a result of these combined mechanisms, hybrid jute–sisal–nano-filler reinforced composites demonstrate superior mechanical and thermal properties compared to single-fiber or non-hybrid composites. This makes them suitable for use in load-bearing, thermally stressed, and long-life applications, offering an eco-friendly alternative to synthetic fiber composites like glass or carbon fiber, especially in moderate-performance engineering sectors.

II. MATERIALS AND METHODS

A. Fibers

Jute and sisal fibers are among the most widely studied natural reinforcements for hybrid polymer composites because of their complementary mechanical and physical characteristics. Jute fibers possess a high cellulose content, which contributes to their good tensile strength, rigidity, and biodegradability.

These attributes make jute a suitable reinforcement for applications requiring stiffness and dimensional stability. In contrast, sisal fibers contain a comparatively higher lignin content, giving them superior toughness, impact resistance, and moderate thermal stability. When combined in a hybrid configuration, the properties of both fibers complement each other, resulting in improved tensile, flexural, and thermal behavior. The primary aim of hybridization is to achieve a synergistic enhancement, where jute provides stiffness and tensile strength while sisal contributes ductility and impact resistance, ultimately producing a balanced and high-performance composite.

B. Nano-Fillers

The incorporation of nano-fillers further enhances the effectiveness of hybrid jute–sisal composites. Common nano-fillers include nano-clay, SiO_2 nanoparticles, Al_2O_3 nanoparticles, carbon nanotubes (CNTs), graphene or graphene oxide, and nano-$CaCO_3$. These nano-scale reinforcements significantly improve the composite's mechanical, thermal, and microstructural characteristics due to their high surface area and strong interfacial interactions with the polymer matrix. Their presence enhances matrix stiffness, promotes controlled crystallization, increases interfacial adhesion, and contributes to improved thermal resistance. Nano-fillers also act as microstructural modifiers by reducing voids and restricting polymer chain mobility, which results in enhanced load transfer and better overall composite performance.

C. PolymerMatrices

Both thermosetting and thermoplastic polymers are used as matrices in natural fiber hybrid composites. Thermosetting matrices such as epoxy, polyester, and vinyl ester are commonly preferred for structural applications due to their high strength, dimensional stability, and strong interfacial bonding with natural fibers. Thermoplastic matrices, including polypropylene (PP), polylactic acid (PLA), and high-density polyethylene (HDPE), offer recyclability and good impact resistance but often require additional treatments for improved fiber adhesion. Among these options, epoxy resin is the most widely used matrix because of its excellent wetting characteristics, superior bonding with natural fibers, and ability to uniformly encapsulate nano-fillers, resulting in mechanically robust and thermally stable composites.

D. Fabrication Processes

Several fabrication techniques are used to manufacture hybrid jute–sisal composites with nano-fillers. The hand lay-up technique remains the most common due to its simplicity, low cost, and suitability for natural fiber reinforcement. Compression molding is another frequently used method that provides better consolidation and reduced void content. More advanced processes such as vacuum bagging and resin transfer molding (RTM) allow improved fiber wetting, controlled fiber alignment, and enhanced mechanical properties. Regardless of the fabrication technique, achieving uniform dispersion of nano-fillers is critical. Techniques such as ultrasonication, mechanical stirring, and high-shear mixing are commonly employed to prevent agglomeration of nano-particles and ensure homogeneous distribution within the polymer matrix.

III. MECHANICAL PROPERTIES OF HYBRID COMPOSITES

A. Tensile Strength and Modulus

The tensile behavior of hybrid jute–sisal composites is significantly enhanced due to the complementary mechanical characteristics of the two fibers. Jute provides the stiffness and tensile rigidity, whereas sisal contributes ductility and resistance to sudden failure. When nano-fillers are added, the tensile properties further improve as a result of increased stress transfer efficiency and enhanced fiber–matrix interfacial bonding. Nano-fillers refine the composite microstructure by filling gaps and preventing micro-crack formation. Studies commonly report a 10–30% increase in tensile strength with the addition of nano-clay or SiO_2, demonstrating the effectiveness of nano-reinforcement in boosting load-bearing performance.

B. Flexural

Hybrid jute–sisal composites exhibit superior flexural properties due to the structural compatibility between the two fibers. The alternating fiber arrangement helps distribute bending stresses effectively. Nano-fillers further enhance flexural strength and modulus by increasing matrix stiffness and restricting crack initiation under bending loads. The presence of nano-clay at optimal loading levels (2–3 wt%) significantly improves flexural rigidity and reduces failure propagation, leading to more durable and damage-tolerant composite structures.

C. Impact Strength
Sisal fibers contribute significantly to the impact performance of hybrid composites due to their high toughness and ability to absorb energy during fracture. When nano-fillers such as CNTs or graphene are introduced, the impact resistance increases even further. Nano-fillers restrict crack propagation and create energy-dissipation pathways, resulting in composites that are better suited for dynamic or shock-loading applications.

D. Hardness
The addition of nano-fillers enhances the surface hardness of hybrid composites by improving polymer crystallinity and creating a stiffer microstructure. This results in increased wear resistance and better performance under abrasive conditions, making the composites suitable for applications where surface durability is essential.

IV. THERMAL PROPERTIES OF HYBRID JUTE–SISAL–NANO COMPOSITES

A. Thermal Proporties
The thermal stability of hybrid composites improves significantly with the incorporation of nano-fillers. Thermogravimetric analysis (TGA) and differential thermogravimetric analysis (DTG) reveal increases in onset degradation temperature, maximum decomposition temperature, and char residue formation. Nano-fillers act as thermal barriers that slow heat transfer and restrict polymer chain mobility, thereby improving the resistance of the composite to high-temperature degradation.

B. Heat Deflection Temperature (HDT)
Hybrid jute–sisal composites exhibit higher heat deflection temperatures when reinforced with nano-particles. This improvement results from enhanced matrix rigidity and increased cross-linking, both of which contribute to greater thermal resistance under applied loads. Nano-fillers create a more thermally stable network within the polymer, enabling the composite to sustain higher temperatures before deformation occurs.

C. Thermal Conductivity
Natural fibers inherently offer low thermal conductivity, making them suitable for thermal insulation applications. However, the introduction of highly conductive nano-fillers such as graphene or CNTs increases the composite’s thermal conductivity. The choice of nano-filler type and loading level depends on application requirements—whether the composite is intended for insulation or heat-dissipation purposes.

D. Differential Scanning Calorimetry (DSC)
DSC studies reveal that nano-fillers act as nucleating agents, promoting increased crystallinity within the polymer matrix. This leads to improved thermal stability and enhanced structural rigidity. Additionally, the incorporation of nano-fillers causes a noticeable shift in the glass transition temperature (Tg), indicating restricted polymer chain mobility and enhanced thermal performance of the hybrid composite.

V. RESULTS AND DISCUSSION
Hybrid jute–sisal natural fiber composites reinforced with nano-fillers exhibit remarkable enhancements in mechanical, thermal, and microstructural properties, making them highly attractive for next-generation sustainable engineering materials. The synergistic interaction between jute and sisal fibers contributes to a balanced combination of stiffness, toughness, and energy absorption, while the integration of nano-fillers—such as nano-clay, SiO_2, Al_2O_3, CNTs, or graphene—provides substantial improvements in matrix rigidity, interfacial bonding, and resistance to crack propagation. Optimized nano-filler loading (typically 2–3 wt%) has been shown to offer the most effective balance between improved strength, dispersion quality, and viscosity control during processing.

Thermally, these hybrid nano-reinforced composites demonstrate superior thermal stability, elevated heat deflection temperatures (HDT), and increased char formation due to the barrier effect and restricted chain mobility imparted by nano-fillers. Enhanced crystallinity and shifts in glass transition temperature (Tg) indicate a more thermally robust polymer matrix, broadening the usability of these composites in temperature-sensitive applications.

Microstructural analyses (SEM, XRD, TEM) consistently reveal better fiber–matrix compatibility, reduced void content, and uniform filler dispersion when proper surface treatments and mixing techniques are employed. These improvements collectively translate into higher mechanical reliability, reduced degradation under load, and extended service life.

Given their lightweight nature, biodegradability, and high specific strength, hybrid jute–sisal nano-composites present strong potential for use in automotive components, construction materials, sports equipment, interior panels, packaging, and eco-friendly consumer products. Their ability to replace synthetic composites in many applications supports global initiatives for greener, cost-effective, and sustainable material development.

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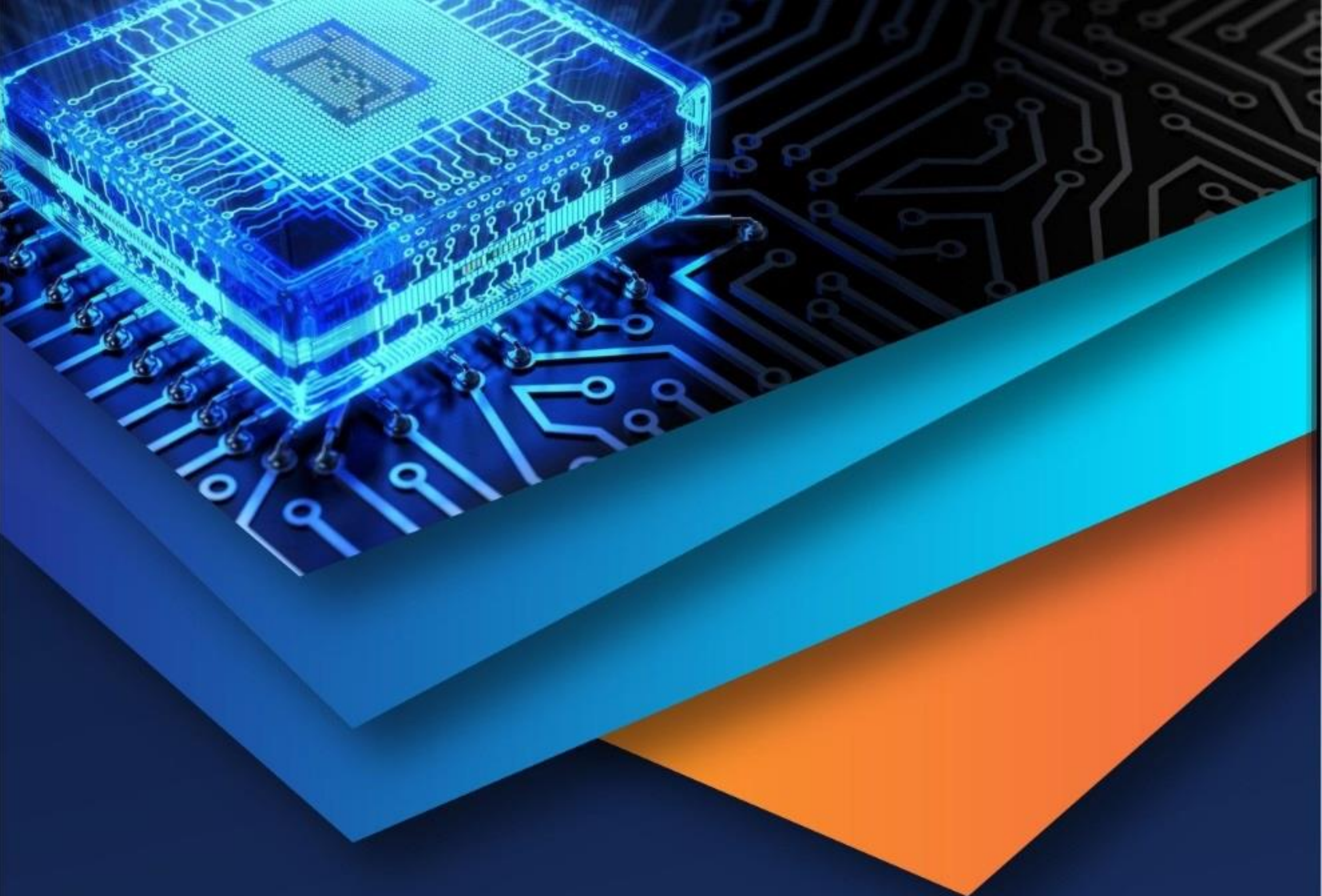

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