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Hybrid Epoxy Composites with Areca and Abaca Fibers: Effect of Nano-SiO₂ on Mechanical Properties

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Abstract

This study explores the fabrication and mechanical evaluation of sustainable epoxy-based hybrid composites reinforced with Areca fiber (ARF), Abaca fiber (ABF), and nano-silica (SiO_2). The composites were made using a hand layup process, maked five variants (S1–S5) with ARF content ranging from 0–40 wt% and nano-silica content from 0–8 wt%, while maintaining ABF as the primary reinforcement. Mechanical performance was assessed through tensile strength (TS), flexural strength (FS), and impact strength (IS) tests under both longitudinal and transverse loading conditions.The optimized formulation, containing 76% ABF, 20% ARF, and 4% nano-SiO_2, exhibited the highest overall mechanical properties, achieving superior strength and toughness compared to other compositions. This enhancement is accredited to enhanced fiber–matrix bonding, uniform filler dispersion, and efficient stress transfer between reinforcement phases. In contrast, higher nano-silica content (6–8 wt%) caused minor reductions in performance due to filler agglomeration and diminished effective fiber volume. This study presents the first systematic investigation of a novel ternary hybrid system combining Abaca fiber (ARF), Areca fiber (ABF), and nano-silica (SiO_2) in epoxy composites, advancing sustainable composite technology through agricultural waste valorization The results authorize that incorporating moderate levels of nano-silica into natural fiber hybrids significantly enhances their structural integrity while retaining lightweight and eco-friendly characteristics. The developed Areca–Abaca/nano-silica epoxy composites offer promising potential for sustainable engineering applications, particularly in automotive panels, construction elements, and protective packaging, where high mechanical strength and ecofriendly which are essential. This research underlines the viability of integrating agricultural waste fibers with nano-scale fillers to create high-performance, renewable composite materials.

Keywords: Areca fiber (ARF), abaca fiber (ABF), and nano-silica (SiO_2), hand layup process

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INTRODUCTION

Man-made fibers derived since petrochemical sources are non-recyclable, contribute to microplastic pollution, and require significant energy for production, resulting in long-term environmental impacts. In contrast, natural fibers are recyclable, renewable, and typically require less energy to process. However, their cultivation may impact water resources and soil quality if not managed sustainably. Unlike synthetic fibers, which persist in the environment, natural fibers decompose naturally and do not contribute to microplastic contamination, making them a more environmentally responsible choice. Currently, natural fibers are drawing increasing interest from both academic and industrial researchers due to their ecological benefits, wide availability, and sustainable lifecycle. Plant-based fibers such as jute, areca, banana, flax, hemp, coir, and kenaf have been extensively studied over the ancient two decades and are increasingly preferred over synthetic alternatives [1]. Composite materials often require intricate structural designs to balance performance with cost. Hence, early-stage trade-off analysis and thoughtful material selection are critical. Novel fiber systems – particularly natural fibers – are promising for cost-effective applications that demand moderate stiffness [2]. In sectors like construction and automotive manufacturing, natural fiber-reinforced composites (NFRCs) have become valuable due to their lightweight properties, which enhance fuel efficiency and reduce emissions. Leading automotive manufacturers now incorporate NFRCs in vehicle components to improve performance and sustainability [3].

Plant-based fibers from stems, leaves, bast, and fruits continue to find growing use in applications such as packaging, automotive parts, and even aerospace components Hybrid fiber and bio-ceramic reinforced polyester composites have been explored for structural uses due to their enhanced mechanical strength, fatigue resistance, and creep behavior[4].Studies on hybrid carbon/kenaf composites showed that the C/C/K/C/C stacking sequence offered 170 MPa tensile strength, with carbon providing superior strength and kenaf contributing sustainability and cost-effectiveness [5].Similarly, carbon/flax hybrids displayed excellent tensile and flexural properties and improved water resistance due to fiber synergy.

Areca-carbon hybrids enhanced both mechanical and thermal properties, making them suitable for semi-structural uses despite increased water uptake due to synthetic fibers. Epoxy composites reinforced with areca, carbon, and basalt fibers showed that carbon-areca combinations perform best under medium loads. Abaca fiber, valued for its strength and flexibility, has potential in automotive and industrial composites. Surface treatments like alkali and silane have improved its compatibility and performance [6]. In textiles, incorporating Manila hemp yarn has improved air permeability and thermal conductivity, though issues like stiffness and poor handle ability persist. Areca fiber-based bio composites with nano-silica and neem oil show promise for antibacterial applications in medical and food sectors [7].

Optimal strength was achieved with 2.5–7.5 wt% nano-Al_2O_3 and areca nutshell filler, offering a sustainable alternative to wood [8]. Basalt fiber composites exhibited fatigue-related stiffness loss due to transverse and longitudinal fiber breakage. Nonwoven fabric composites impregnated with latex showed increased transverse tensile strength at higher impregnation levels. Abaca/polyamide composites enhanced strength and permeability due to the inclusion of lower tex spacers. Lastly, auxetic fabrics in geopolymer composites improved energy dissipation and thermal stability, suitable for impact-resistant applications [9]. Non-crimp carbon textiles remain ideal for high-stiffness applications like wind blade spar caps. This study focuses on composites made from high-density polyethylene (HDPE) and abaca fiber. Chemically treated abaca/PP composites demonstrated improved mechanical and thermal properties, making them suitable for automotive applications. Areca fiber and biochar-reinforced polymer composite rebars showed enhanced strength, thermal stability, and low water absorption. Specifically, sample C exhibited high bending strength, while sample E had superior hardness and hydrophobicity [10].

Areca nuts coated with sodium alginate (SA) and xanthan gum (XG) showed improved gloss, water resistance, and mechanical strength – especially with a 50:50 SA-XG ratio, forming dense, effective edible films. Hybrid fibers combining Abaca's high tensile strength (980 MPa) with Areca's impact resistance offer a strong, tough, and lightweight alternative to synthetic composites. These bio-based hybrids also show better fiber-matrix bonding and reduced voids, outperforming single natural fiber composites in mechanical performance while remaining biodegradable and eco-friendly [11].

This study presents a novel hybrid composite using Abaca and Areca fibers with nano-silica in a polyester matrix, fabricated via hand layup. The objective is to enhance mechanical properties through fiber synergy and improved fiber–matrix bonding. Multiple compositions are tested for tensile, flexural, and impact performance, aiming to develop sustainable, lightweight materials for structural and automotive use. This study represents a significant advancement by demonstrating that strategically designed natural fiber hybrids with nano-reinforcement can achieve high-performance characteristics while maintaining complete biodegradability and sustainability, bridging the gap between environmental responsibility and engineering performance requirements. The systematic approach and comprehensive characterization provide a foundation for future bio-composite development and industrial implementation.

EXPERIMENTATION

Materials

Areca fiber (ARF) and Abaca fiber (ABF) mats were employed as reinforcements in the fabrication of epoxy-based hybrid composites, with nano-silica (SiO_2) incorporated as a filler and LY556 epoxy resin serving as the matrix. The ARF, featuring fiber diameters ranging from 100 to 300 µm, and the unidirectional ABF mat with a weight of 400 gsm, were procured from Go Green Enterprises, Chennai, India. To initiate and accelerate the curing process, Methyl Ethyl Ketone Peroxide was used as the catalyst and Cobalt Naphthenate as the accelerator [12].

The physical characteristics of the raw materials significantly influence composite behavior. Areca and Abaca fibers have densities of 1.0 g/cm^3 and 1.4 g/cm^3, respectively, while nano-SiO_2 and epoxy resin exhibit densities of 2.6 g/cm^3 and 1.3 g/cm^3. In terms of tensile strength, Areca fiber reaches 200 MPa, Abaca fiber 980 MPa, nano-SiO_2 40 MPa, and epoxy resin 85 MPa. Their elastic moduli also vary considerably, with Areca at 5 GPa, Abaca at 41 GPa, nano-SiO_2 at 75 GPa, and the epoxy matrix at 4 GPa. Stiffness values further highlight the reinforcement capabilities, with Areca and Abaca registering 2.5 kN/mm and 12 kN/mm, respectively, while nano-silica provides significantly high stiffness. Both natural fibers also exhibit notable hydrophilicity, with Areca absorbing up to 70% water and Abaca 65%, alongside apparent porosity values of 20% and 25%, respectively [13]. These characteristics underline the necessity for proper surface treatment and optimized hybridization to achieve desired mechanical performance in the final composite.

Composite preparation by Hand layup process

The hybrid epoxy-based composites were prepared using the conventional hand layup process, followed by compression molding to ensure uniform fiber–matrix compaction. Five different composite samples (S1 to S5) were fabricated by systematically varying the content of Areca fiber (ARF) and nano-silica (SiO_2), while maintaining Abaca fiber (ABF) at a constant weight percentage across all samples. The specific compositions were as follows: S1 – 100% ABF (no ARF or SiO_2), S2 – 80% ABF, 20% ARF (no SiO_2), S3 – 76% ABF, 20% ARF, 4% nano-SiO_2, S4 – 72% ABF, 20% ARF, 8% nano-SiO_2, and S5 – 60% ABF, 40% ARF (no SiO_2).

For each composition, the required amount of polyester resin was mixed with nano-silica filler (where applicable), followed by the addition of 1% catalyst (methyl ethyl ketone peroxide) and 1.5% accelerator (cobalt naphthenate) to initiate curing. The fiber mats were pre-dried at 80°C for 24 hours to eliminate moisture and enhance fiber–matrix bonding. A flat mold was coated with a polyvinyl alcohol (PVA) release agent to facilitate easy removal of cured laminates. The mold was then layered alternately with ten layers of ABF and ARF mats, depending on the target composition, and impregnated with the resin–filler mixture. The layered assembly was subjected to compression molding using a hydraulic press to ensure uniform distribution of resin and eliminate air entrapment. No resin leakage was observed during pressing, confirming effective wetting [14].

The cured laminates were trimmed to the final dimensions of 30 × 30 cm with a thickness of 4 ± 0.02 mm, and edges were finished using a woodruff file. The fabrication was performed under controlled atmospheric conditions (30°C and 65% relative humidity). Volume fractions of each composite were calculated using the rule of mixtures based on the density and weight proportions of the resin, fibers, and nano-fillers [15]. The entire fabrication and preparation workflow is schematically represented in Figure 1.

MECHANICAL PROPERTIES

Tensile Strength Testing

Tensile strength was measured according to ASTM D638 using dog-bone specimens prepared by hand lay-up and compression molding. Tests were conducted on a Universal Testing Machine (F150 series) under constant strain rate, with specimens oriented longitudinally and transversely. Stress-strain data and elongation at break were recorded to study the effect of Areca fiber (ARF), Abaca fiber (ABF), and nano-SiO_2 on strength and ductility.

Flexural Strength Testing

Flexural properties were evaluated via three-point bending as per ASTM D790 using rectangular specimens on the same UTM. Load was applied at the midpoint between two supports, and flexural strength and modulus were calculated. Both orientations were tested, showing that optimal ARF–ABF–nano-SiO_2 combinations improved bending resistance through enhanced interfacial bonding [16].

Impact Strength Testing

Impact strength was tested following ASTM D6110 using notched specimens and a Charpy Impact Tester (Model KI-300). Energy absorbed during fracture was recorded for both orientations. Results indicated higher impact resistance in hybrids with suitable ARF, ABF, and nano-SiO_2 proportions, confirming improved toughness from fiber-filler synergy.

RESULTS AND DISCUSSION

Tensile Strength (TS)

Tensile strength (TS) is a fundamental mechanical property that reflects a composite material's ability to resist forces that attempt to pull it apart. It is particularly significant in evaluating the efficacy of fiber–matrix adhesion, the load-bearing capability of the reinforcing fibers, and the overall integrity of the composite under axial loading.. As illustrated in Figure 2, composites tested in the longitudinal fiber orientation consistently exhibited higher tensile strength compared to those in the transverse direction. This anisotropic behavior arises from the fact that in the longitudinal direction, the fibers are aligned parallel to the applied load, enabling efficient stress transfer from the matrix to the reinforcing fibers In contrast, the transverse specimens showed reduced TS due to limited fiber engagement and weaker interfacial bonding in the loading direction.

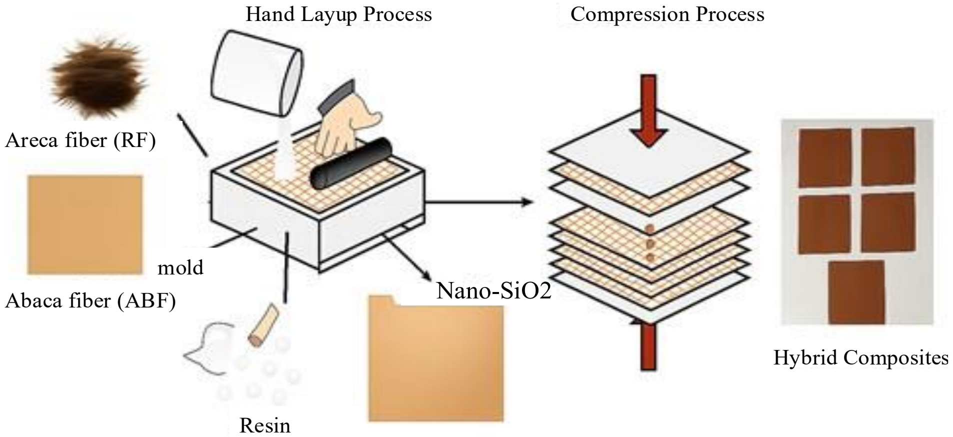

Figure 1. Work flow process.

The maximum tensile strength of 193.77 MPa was recorded for the hybrid composite consisting of 76% Abaca fiber (ABF), 20% Areca fiber (ARF), and 4% nano-silica (SiO_2) in the longitudinal orientation. The high strength achieved in this configuration can be attributed to the synergistic interaction between ABF and ARF, where ABF provides high tensile stiffness and load transfer efficiency, while ARF contributes to toughness and energy absorption. Furthermore, the incorporation of nano-SiO_2 particles significantly contributed to the mechanical enhancement by improving interfacial adhesion between the fibers and the epoxy matrix [17].

These nanoparticles act as stress transfer bridges and micro-fillers, which help in dispersing applied loads more uniformly across the fiber–matrix interface. As a result, the hybrid composite demonstrated improved resistance to crack initiation and propagation, leading to enhanced tensile performance [18].

Flexural Strength (FS)

Flexural strength (FS) is a critical mechanical property that reflects a composite material's ability to withstand bending or flexural loads without failure. It combines both tensile and compressive behaviors within the material's cross-section and is a key factor in structural applications, especially in components subjected to bending, such as beams, panels, and enclosures. As presented in Figure 3, the flexural strength increased significantly with higher Abaca fiber (ABF) content, reaching a maximum value of 295.35 MPa in the longitudinal direction for composites reinforced with 100% ABF. This superior performance is primarily attributed to the high tensile modulus and stiffness of ABF, which provides excellent resistance against bending-induced deformation.

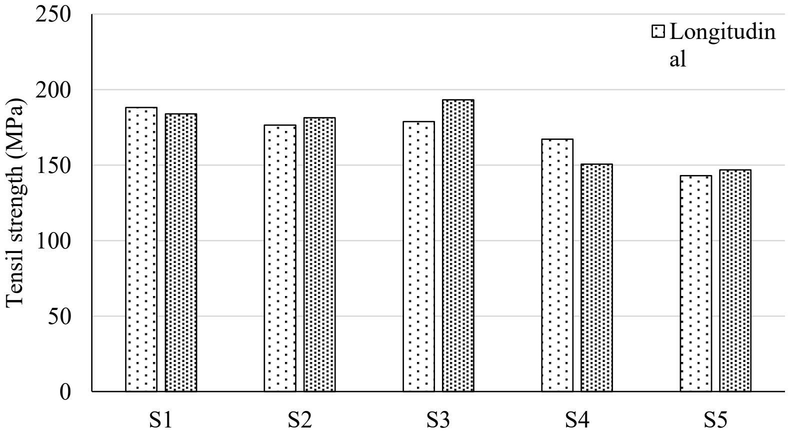

Figure 2. Tensile strength of hybrid composites in longitudinal and transverse directions.

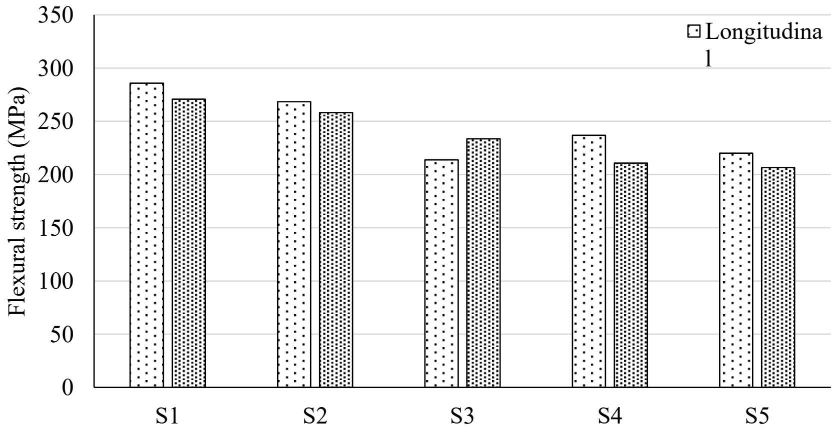

Figure 3. Flexural strength of various hybrid composites in both orientations.

The unidirectional alignment of fibers in the longitudinal direction also ensured more effective stress transfer along the loading axis. However, as the proportion of Areca fiber (ARF) increased in the hybrid formulations, a gradual decrease in FS was observed. This decline is likely due to ARF's relatively lower stiffness and load-bearing capacity compared to ABF. Despite this, the hybrid composites still maintained good flexural performance, thanks to the toughening effect of ARF, which helped absorb energy and delay crack propagation under bending stresses. The optimized hybrid composition comprising 76% ABF, 20% ARF, and 4% nano-silica (SiO_2) demonstrated a well-balanced combination of strength and ductility [19]. While it did not reach the peak FS value of pure ABF composites, it showed enhanced damage tolerance and interfacial bonding, resulting from the nano-SiO_2's reinforcing action and fiber synergy. This optimized blend is particularly advantageous in applications where moderate stiffness is required along with improved impact and fatigue resistance.

Impact Strength (IS)

Impact strength (IS) is a critical parameter for evaluating a composite material's ability to absorb energy under sudden or dynamic loading conditions. This property becomes particularly important in applications subjected to shock, impact, or sudden forces. As shown in Figure 4, the impact strength of the hybrid epoxy-based composites improved noticeably with the incorporation of Areca fiber (ARF), especially in the longitudinal orientation.

The highest impact strength recorded was 26.90 J for the optimized composition comprising 76% Abaca fiber (ABF), 20% ARF, and 4% nano-silica (SiO_2). This enhancement is attributed to the synergistic effect between the high-tensile strength of ABF and the ductility and toughness of ARF [20]. Together, these fibers facilitated better energy absorption by promoting crack deflection, fiber bridging, and delamination resistance. In contrast, the transverse direction exhibited slightly lower impact strength values. This reduction is likely due to weaker interfacial bonding between the matrix and the fibers in the direction perpendicular to the primary reinforcement alignment, limiting the load transfer and energy dissipation mechanisms.

CONCLUSION

This study comprehensively investigated the mechanical behavior of epoxy-based hybrid composites reinforced with Areca fiber (ARF), Abaca fiber (ABF), and nano-silica (SiO_2). The experimental results confirmed that the strategic hybridization of natural fibers with nano-fillers leads to significant improvements in tensile, flexural, and impact strength, primarily due to enhanced fiber–matrix adhesion, effective stress distribution, and crack deflection mechanisms.

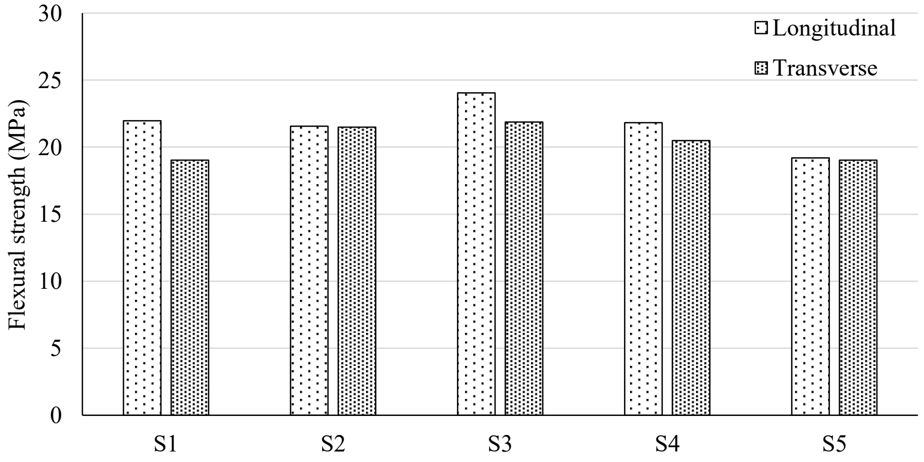

Figure 4. Impact strength comparison of hybrid composites in both directions.

- Among various formulations, the optimized blend of 76% ABF, 20% ARF, and 4% nano-SiO_2 consistently exhibited superior mechanical properties, especially in the longitudinal fiber orientation, which maximized load transfer efficiency.
- The synergistic effect of high-tensile ABF, tough ARF, and the reinforcing nano-silica contributed to improved toughness, ductility, and dimensional stability of the composites under different loading conditions.
- These enhancements make the hybrid composites mechanically robust and durable, suitable for semi-structural applications in fields such as automotive, construction, and consumer products.
- From a sustainability perspective, the use of biodegradable and renewable natural fibers offers a promising route to reduce dependency on synthetic, petroleum-based reinforcements, thereby minimizing environmental impact and supporting circular economy principles.

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