



RESEARCH ARTICLE

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AN INVESTIGATION ON MECHANICAL BEHAVIOUR OF PINEAPPLE AND ALOE VERA NATURAL FIBRE STACKING HYBRID COMPOSITE

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ABSTRACT

This study investigates the mechanical performance, fracture behaviour, and water absorption properties of hybrid epoxy composites reinforced with pineapple leaf fibre (PALF) and aloe vera fibre (AVF) arranged in different stacking sequences. The aim is to analyse how fibre layer positioning influences tensile, flexural, and impact properties, and to identify optimal configurations for enhanced composite performance. Hybrid biocomposite laminates were fabricated using a hand lay-up method followed by compression moulding, with eight different stacking sequences of woven PALF–AVF mats. Mechanical testing was conducted in accordance with ASTM standards, while fracture surface morphology was examined using optical microscopy to identify failure modes such as fibre pull-out and matrix cracking. Water absorption tests were also performed to evaluate the influence of stacking arrangement on moisture uptake and long-term durability. The results revealed that certain PALF–AVF stacking sequences significantly improved mechanical strengths while reducing water absorption, highlighting the potential of these natural fibre hybrids in lightweight, semi-structural, and environmentally sustainable applications in the automotive, construction, and consumer goods industries.



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I. INTRODUCTION

Because of their extraordinary mix of qualities, including lightweight, corrosion resistance, and ease of production, polymer composites have become a class of materials with a wide range of applications. Several industries, including electronics, automotive, aerospace, and construction, can benefit from these materials. Fibre-reinforced polymer (FRP) composites are increasingly used across industries due to their lightweight nature and tunable mechanical properties, such as load-bearing capacity and fracture toughness. Unlike metals, their properties can be tailored by controlling fibre type, fiber stacking, and orientation, making them ideal for applications in construction, automotive, aviation, and energy sectors [1-3]. New materials have developed an improved opportunity for hybrid composites to be used for specialized applications. The increased demand for environmentally sustainable materials and high-performance materials have driven the rapid growth of hybrid polymer composites with natural fibres.

Commonly used natural fibres such as pineapple, banana, flax, jute, kenaf and hemp, have adequate properties of low cost, a degree of biodegradability, and reasonable strength-to-weight ratios. Natural fibres have less abrasivity, are environmentally friendly, and offer good vibro-acoustic properties, mechanical, dielectric, and damping over synthetic composites such as glass or Kevlar fibers. Natural fibre composites are emerging in new applications such as semi-structural automotive parts, sports equipment, packaging, and consumer goods [4-6]. According to [7] studied the alkali, silane, and combined treatments improved the mechanical, thermal, and moisture resistance properties of jute fibre-reinforced epoxy composites, finding that treated fibres enhanced adhesion, reduced water absorption, and improved durability. For authors [8] introduced and evaluated novel polyester resin composites reinforced with Rambans (Agave) fibres by varying the amount of fibre.

The composites were analysed for physical and mechanical properties, hardness, tensile, flexural and impact strength. The highest performing composite exhibited a tensile strength of 95.27 MPa, with an impact strength of 4.7 J/m². The fracture surfaces examined by Scanning Electron Microscopy (SEM) confirmed adequate fibre–matrix bonding. The authors concluded that the mechanical performance of Rambans fibre composites is superior and can be a sustainable alternative to conventional natural fibre composites in structural applications. In [9] studied hybrid epoxy composites reinforced with untreated and alkali-treated *Prosopis juliflora* bark (PJB), banana fibre (Bf), and coconut fibre (Cf), keeping Bf constant. Increasing Cf content improved tensile, flexural, and compression strength in untreated composites due to better fibre–matrix bonding, while impact strength peaked at 25 wt% loading. However, higher Cf content reduced hardness. Water absorption is a major issue affecting the adhesion between natural fibres and the epoxy matrix, often leading to poor interfacial bonding and reduced mechanical properties. However, this drawback can be mitigated through effective chemical treatments such as NaOH, silane, KOH, and acid treatments, which modify the fibre surface by removing impurities, reducing hydrophilicity, and enhancing natural fibre–thermo set matrix compatibility [10-12].

Of the new natural fibres, pineapple leaf fibre (PALF) and aloe vera fibre (AVF) have significantly improved their structural properties as reinforcements in both thermoset and thermoplastics. PALF and AVF reinforcement, effectively improve the mechanical performance of composites by improving tensile strength, stiffness, and interfacial bonding. Recently, PALF and AVF are useful as natural alternatives to synthetic reinforcements for engineering applications that are lightweight and sustainable [13-15]. According to [15] investigated the mechanical, vibration, and wear characteristics of laminated composites made from aloe vera, flax, hemp, wire mesh, and BaSO₄. The findings revealed that BaSO₄ reinforcement increases the composite's natural frequency. The filler enhances the beam's natural frequencies by increasing the specific stiffness of the beam. For authors [16] investigated the mechanical properties of woven aloe vera, sisal, and kenaf fibres and hybrid composites. They produced many varieties of woven aloe vera and kenaf, sisal and kenaf, and aloe vera, sisal, and kenaf fibre (ASK) epoxy composites. The results showed that the hybrid composite performed better in flexural properties, while the ASK hybrid composite had the best impact strength. According to [17] studied the mechanical properties of aloe vera fibre reinforced polymer composite.

The performance of aloe vera fibre-reinforced composites with different fibre orientations were characterized by tensile, flexural, impact, and water absorption testing, while the fracture surface morphology of tensile-tested specimens were examined using Field Emission Scanning Electron Microscopy (FE-SEM). The data showed that the 0°/90° fibre orientation produced the highest mechanical properties whilst the 45° orientation gave the lowest strength and stiffness, which emphasizes the significance of fibre orientation on composite performance. The arrangement of the stacking of fibres is important in enhancing the performance properties of polymer composites. The order of the fibre layers and where each fibre layer is located in the build-up is important in the mechanical performance properties (tensile, flexural and impact properties) in a part made from a hybrid composite with fibres. The sequence of placing high strength fibres on the outer layers in conjunction with a more flexible fibre in the core of a hybrid composite provided a balance of a more rigid structure, as well as providing energy dissipation and structural integrity in the composite. Understanding the possibilities of stacking or changing the stacking direction of fibres, provides ways to tailor composites to have the behaviour required for the specified loading [18-21].

While traditional synthetic fibre composites are regarded as being physically strong, plastic pollution presents challenges in non-biodegradability, high cost of manufacture, and poor sustainability. Alternatively, natural fibres such as woven pineapple leaf fibre (PALF) and aloe vera fibre (AVF) have been gaining momentum over the last few years as environmentally friendly options which are renewable, biodegradable, and have desirable mechanical properties. This study represents a novel investigation of the impact of PALF and AVF fibre stacking patterns on the mechanical, fracture behaviour and water absorption properties of epoxy-based hybrid composites. The study reveals optimal designs to enhance tensile, flexural, and impact strength by varying the fibre layer stacking sequence and orientation. Furthermore, the investigation incorporates characterisation of fracture surfaces with microscopy and provides insight into the fibre pull-out, matrix crack, and delamination failure mechanisms based on the number of layers and stacking sequences. Absorption experiments using the ASTM standard methods are also performed to clarify the fibre composition and stacking and orientation of the layers affects moisture absorption. The combined investigation of mechanical performance, fracture behaviour, and water resistance ultimately offers a holistic understanding to develop environmentally friendly, sustainable, and mechanically reliable natural fibre hybrid composites used in automotive, construction, and packaging industries.

II. MATERIALS AND METHODS

II.1 RAW MATERIALS USED FOR DEVELOPING THE AVF/PALF POLYMER COMPOSITE

PALF and AVF woven fibres are purchased from GoGreen Industry in Chennai, Tamil Nadu, India. The chemical treatment of both fibers is immersed in a NaOH solution for 4 hours. After, PALF and AVF woven fibres are cleaned with water and placed in a hot oven at 70 °C. The research utilised epoxy as a thermoset matrix. Sakthi fibers enterprises is provided the matrix and hardener.

II.1.2 Fabrication of Avf/Palf Polymer Composite

Figure 1 demonstrates the composite stacking structures for fabricating the AVF/PALF polymer composite. Table 1 shows the composite types and wt.% of reinforcement and fiber. The PALF–AVF hybrid composite laminates were fabricated using the hand lay-up technique followed by compression moulding. Pineapple leaf fibre (PALF) and aloe vera fibre (AVF) were first cleaned, washed, and sun-dried, then subjected to alkaline treatment using a 5% NaOH solution to enhance fibre–matrix adhesion. After treatment, the fibres were rinsed thoroughly and oven-dried at 60 °C for 24 hours. An epoxy resin (LY556) and hardener (HY951) were mixed in a 10:1 weight ratio to serve as the polymer matrix. Fibre mats were arranged in various stacking sequences and placed layer by layer inside a mould coated with a release agent.

Each layer was manually impregnated with the epoxy mixture using a roller to ensure uniform resin distribution and air bubble removal. The mould was then closed and placed in a hydraulic press, where the laminate was compressed at a pressure of 20–30 MPa at room temperature for 24 hours. After curing, the laminate was removed, post-cured in an oven at 60 °C for 2 hours, and cut into standard-sized specimens for mechanical and water absorption testing as per ASTM standards.

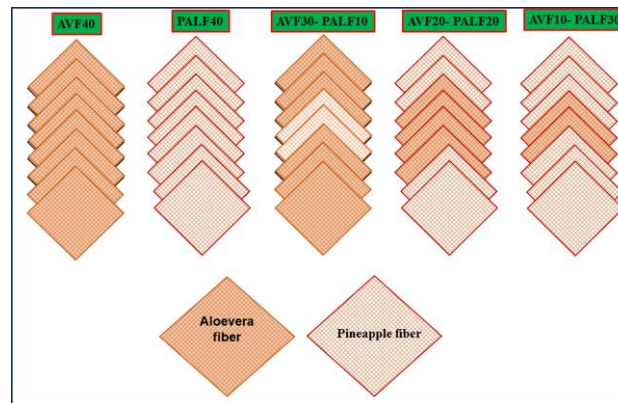


Figure 1: PALF and AVF woven fibers composite stacking structure.

Source: Authors, (2026).

Table 1: Composite types and wt.% of reinforcement and fiber.

Composite types	AVF (wt.%)	PALF (wt.%)	Epoxy (wt.%)
AVF40	40	-	60
PALF40	-	40	60
AVF30- PALF10	30	10	60
AVF20- PALF20	20	20	60
AVF10- PALF30	10	30	60

Source: Authors, (2026).

II.1.3 Mechanical Behaviours of Avf/Palf Polymer Composites

Tensile strength of specimens was calculated according to ASTM D 3039 international standard using Universal Testing Machine (Bluehill INSTRON 5567). The test was carried out with a load capacity of 50 kN with a cross head speed at 3 mm/min. Average of three test samples were considered for maximum stress. The impact strength of fabricated composite specimens was determined by Charpy impact testing machine. The fabricated specimens for test were according to ASTM D 256. The average results of 5 specimens are reported. Scanning electron microscope (SEM) is employed to assess the failure characteristics of the tensile fractured samples. All the images are taken in the transverse section of the composite after their failure under flexural load at a magnification of 100x.

II.1.4. Water Absorption

Water absorption behaviour of the pineapple and aloe vera natural fibre hybrid composites was evaluated in accordance with ASTM D570. Specimens of dimensions 76.2 mm × 25.4 mm × 4 mm were oven-dried at 60 °C for 24 hours, then cooled in a desiccator to attain a constant weight (W_1). The samples were then fully immersed in distilled water at room temperature (23 ± 2 °C). At predetermined intervals of 24, 48, 72, and 168 hours, the specimens were removed, surface-dried using a clean cloth, and weighed (W_2). The percentage of water absorbed was calculated using the equation 1.

$$\text{Water Absorption} = ((W_2 - W_1) / W_1) * 100 \quad (1)$$

III. RESULTS AND DISCUSSIONS

III.1 MECHANICAL BEHAVIOUR

III.1.1 Hardness

Shore D hardness values also varied with fibre arrangement. Laminates with PALF layers at the surface exhibited higher surface hardness due to PALF's rigidity and fibre density. In contrast, those with AVF on the outermost layers showed comparatively lower hardness, as AVF fibres are softer and more moisture-sensitive. The results suggest that incorporating PALF in the outer layers enhances resistance to surface indentation and wear, which is critical for load-bearing and abrasive environments.

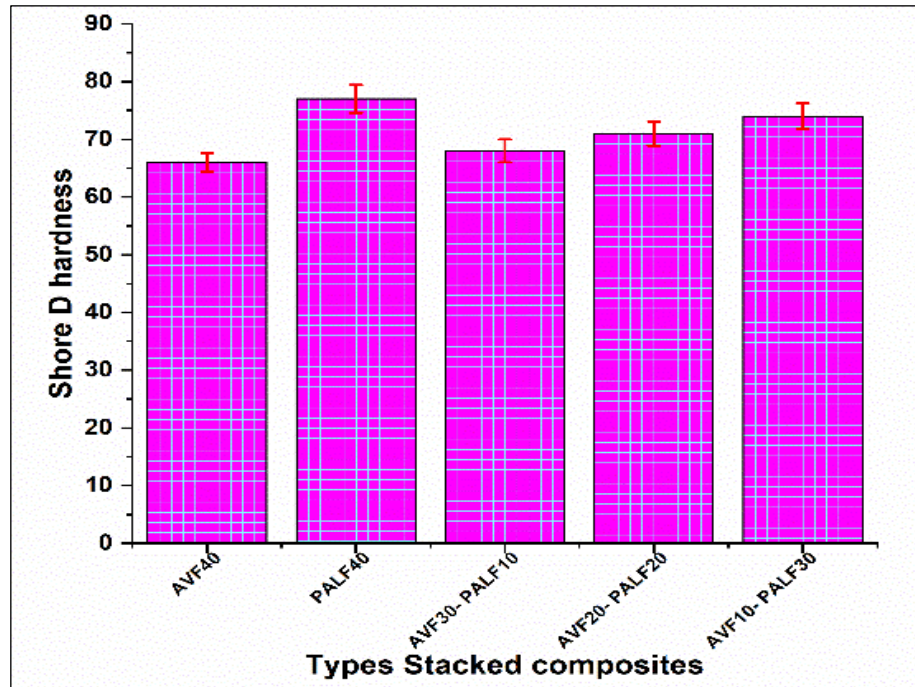


Figure 2: Hardness of AVF/PALF polymer composites.
Source: Authors, (2026).

III 1.2 Tensile Strength and Modulus

The tensile strength of the PALF–AVF hybrid composites was found to be highly dependent on the stacking sequence of the fibre layers. Composites with PALF layers on the outer surfaces and AVF in the core exhibited the highest tensile strength. This is attributed to PALF's higher stiffness and load-bearing capacity, which effectively resisted axial loads. Conversely, samples with AVF layers on the exterior showed lower tensile strength due to AVF's relatively lower tensile modulus and less efficient stress transfer. The variation in tensile performance highlights the importance of optimised fibre positioning in hybrid laminates.

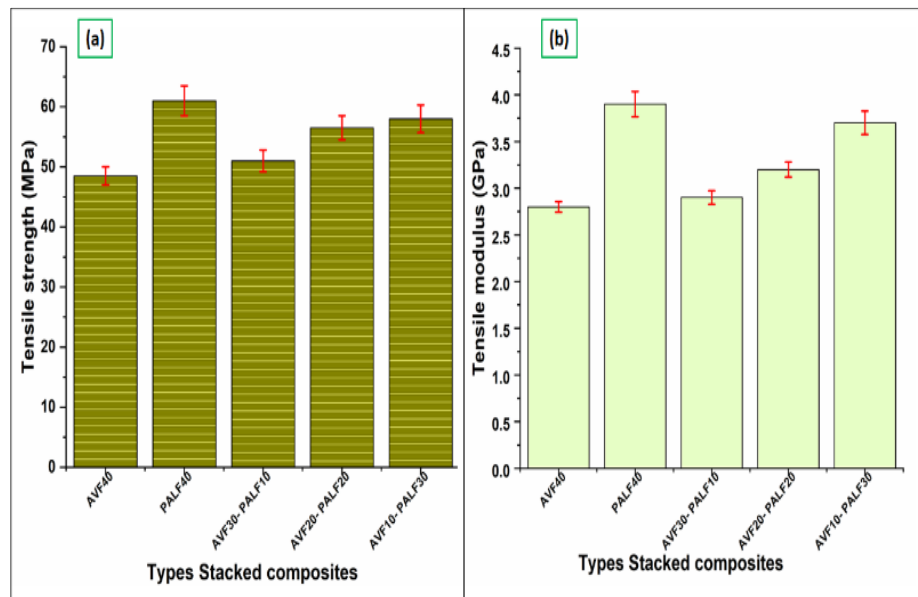


Figure 3: TS and TM of AVF/PALF polymer composites.
Source: Authors, (2026).

III 1.3 Impact Strength

Izod impact test results showed that composites with alternating PALF–AVF stacking (symmetric layering) demonstrated improved impact resistance compared to unidirectional or asymmetrically stacked laminates. The combination of stiff PALF and ductile AVF allowed for better energy absorption and crack propagation resistance during impact loading. Composites with AVF concentrated in the mid-layers offered better energy dissipation, resulting in higher impact values. This indicates that hybridisation not only strengthens the composite but also enhances its toughness when the stacking pattern is optimised.

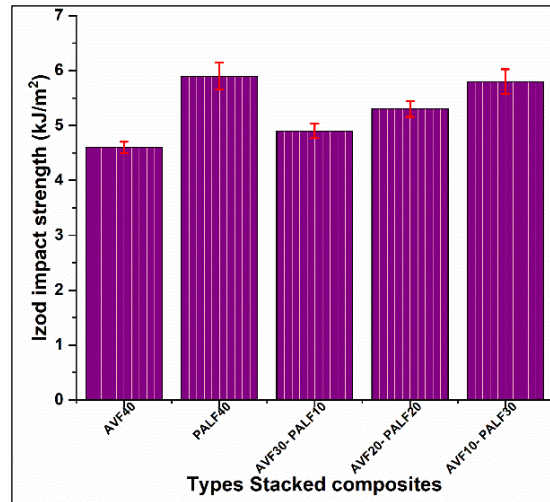


Figure 4: IIS of AVF/PALF polymer composites.
Source: Authors, (2026).

III.1.4 Fracture Surface Analysis

Scanning Electron Microscopes (SEM) were used to characterize the fracture surfaces of AVF/PALF hybrid epoxy composites in order to ascertain the failure mechanisms and the extent of fibre-matrix interaction as shown in Figure 5. SEM photographs of polymer composites revealed a quasi-continuous film of voids, fibre pull-outs, interfacial gaps and large voids which indicated poor bonding between the hydrophilic natural fibres and epoxy matrix. Poor contact will decrease stress transfer and result in early failure on mechanical loads. The SEM micrographs from the NaOH-treated composites indicated improved fibre-matrix adhesion with less voids and better fibre embedment, and there were indications of matrix deformation, along with fibre breaking suggesting that stress was effectively being transmitted from the matrix to the fibres. There were also SEM characterisation in hybrid stacking modes with PALF on the outer layers and AVF in the core, which indicated a much more even fracture arrangement with less delamination present and limited evidence of fibre pull-outs. This confirmed that we had achieved better bonding and therefore improved mechanical integrity through effective stacking design (specialised stacking) and surface treatment (alkali). Overall, the SEM did support some of the mechanical test results, in addition, it indicated that stacking sequence and fibre treatment would need to be addressed in order to control the fracture behaviour of AVF/PALF hybrid composites.

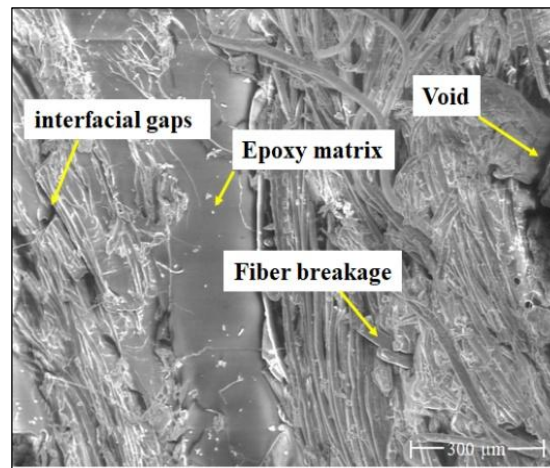


Figure 5: Fractured surface of AVF10- PALF30 tensile loaded polymer composites.
Source: Authors, (2026).

III.1.5 Fracture Surface Analysis

The results indicated that water absorption increased with immersion time and AV fibre content. Composites with higher AV natural fibre proportions showed greater water uptake due to the hydrophilic nature of lignocellulosic fibres and less cellulose content compared to pineapple fiber. Water absorption behaviour followed a trend consistent with the fibre hydrophilicity and layer exposure. Laminates with AVF layers on the outer surface absorbed more moisture due to AVF's higher affinity for water. In contrast, samples with PALF on the outer surfaces showed reduced water uptake, offering better dimensional stability and long-term durability. All samples showed a gradual increase in water absorption over time, but hybridisation and controlled stacking effectively reduced the moisture ingress rate. Chemical treatment and matrix encapsulation further aided in improving water resistance.

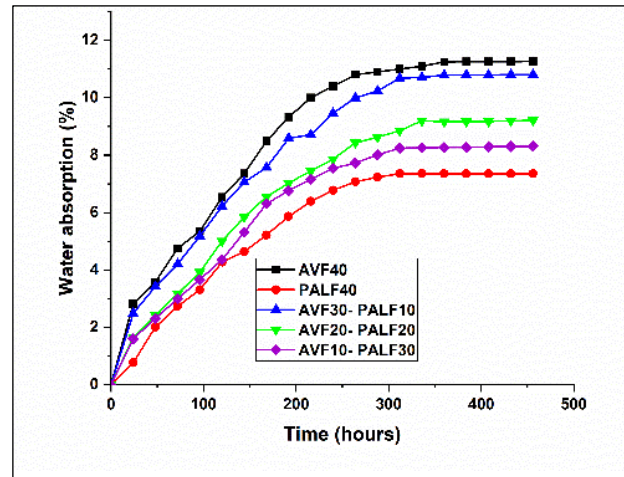


Figure 6: Water absorption of AVF/PALF polymer composites.
Source: Authors, (2026).

IV. CONCLUSIONS

1. The current study found that the stacking arrangement of pineapple leaf fibre (PALF) and aloe vera fibre (AVF) has a substantial influence on the mechanical behaviour, fracture characteristics, and water absorption capabilities of hybrid epoxy composites.
2. Certain stacking sequences evaluated showed increased tensile, flexural, and impact strength due to improved fibre dispersion and interfacial bonding. Fracture surface research identified critical failure mechanisms such fibre pull-out and matrix cracking, which were better controlled in improved stacking sequences.
3. Water absorption studies revealed that suitable fibre layering can effectively limit moisture uptake, enhancing composites' long-term durability.
4. Overall, PALF-AVF hybrid composites represent a viable, environmentally friendly option for semi-structural applications in the automotive, construction, and consumer industries. The study's findings help to develop sustainable material design by improving natural fibre stacking strategies for improved composite performance.

V. AUTHOR'S CONTRIBUTION

Conceptualization: J. Ekantha Moorthy and P. Loganathan.

Methodology: Ganeshkumar K V and Karthick. P.

Investigation: J. Ekantha Moorthy and P. Loganathan.

Discussion of results: J. Ekantha Moorthy and P. Loganathan.

Writing – Original Draft: J. Ekantha Moorthy and P. Loganathan.

Writing – Review and Editing: Ganeshkumar K V and Karthick. P.

Resources: J. Ekantha Moorthy, P. Loganathan, Ganeshkumar K V and Karthick. P.

Supervision: J. Ekantha Moorthy.

Approval of the final text: J. Ekantha Moorthy, P. Loganathan, Ganeshkumar K V and Karthick. P.

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