

Effect of Sal Wood and Babool Sawdust Fillers on the Mechanical Properties of Snake Grass Fiber-Reinforced Polyester Composites

Giridharan Ravichandran,^a Karuppasamy Ramasamy,^{a,*} Karuppusamy Manickaraj ^b,
Sathish Kalidas,^c Manivannan Jayamani ^d, Kuwar Mausam ^e,
Sivasubramanian Palanisamy ^{f,*} Quanjin Ma ^g, and Saleh A Al-Farraj ^h

The mechanical, moisture absorption, and chemical bonding properties were studied for hybrid polyester composites reinforced with snake grass (SG) fiber and Sal wood (S) and Babool (B) sawdust fillers. Composites were fabricated via compression molding with 60% polyester resin and varying filler-fiber ratios. Mechanical tests showed tensile strength increasing from 38 MPa (S1) to 56 MPa (S4), flexural strength peaking at 85 MPa (S4), and maximum hardness of 84 Shore D (S4). Impact strength reached 6.98 J (S4). Water absorption decreased with higher filler content, with S4 absorbing only 21%. Scanning Electron Microscopy (SEM) revealed improved interfacial bonding in S3 and S4, while S1 showed voids and fiber pull-out. Fourier-transform infrared spectroscopy (FTIR) analysis confirmed enhanced chemical interactions in samples with optimized filler-fiber ratios, particularly in S4, contributing to its superior performance. The filler-fiber composition was optimized to maximize mechanical strength, moisture resistance, and chemical bonding, demonstrating the potential of these sustainable composites for durable, eco-friendly applications.

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Contact information: a: Department of Mechanical Engineering, Karpagam Academy of Higher Education, Pollachi Main Road, Eachanari Post, Coimbatore - 641021, Tamil Nadu, India; b: Department of Mechanical Engineering, CMS College of Engineering and Technology, Coimbatore - 641032, Tamil Nadu, India; c: Department of Mechanical Engineering, Sri Eshwar College of Engineering, Kondampatti [Post], Vadasithur (via), Coimbatore - 641202, Tamil Nadu, India; d: Department of Mechanical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil-626126, Tamil Nadu, India; e: Department of Mechanical Engineering, GLA University, Mathura, India; f: Department of Mechanical Engineering, PTR College of Engineering and Technology, Austinpatti, Madurai - Tirumangalam Road, Madurai - 625008, Tamil Nadu, India; g: School of Automation and Intelligent Manufacturing, Southern University of Science and Technology, Shenzhen 518055, China; h: Department of Zoology, College of Science, King Saud University, P.O. Box 2455, Riyadh, Saudi Arabia;

* Corresponding Authors: sivaresearch948@gmail.com; s.r.karuppasamy@gmail.com

INTRODUCTION

Natural fiber-reinforced polymer composites have gained significant interest due to their sustainability, biodegradability, and superior strength-to-weight ratio. These materials are increasingly used in automotive, aerospace, and construction industries as eco-friendly alternatives to synthetic composites (Kumar *et al.* 2022). Among various natural fibers, snake grass (*Sansevieria cylindrica*) fiber has emerged as a promising reinforcement

material due to its high tensile strength and flexibility. Additionally, incorporating wood sawdust fillers, such as sal wood (*Shorea robusta*) and babool (*Acacia nilotica*), can further enhance the composite's mechanical properties, reduce water absorption, and improve its durability (Sri *et al.* 2023).

This study is novel in its combined utilization of snake grass fiber with two different wood sawdust fillers, sal wood and babool, to fabricate polyester-based hybrid composites with systematically varied filler-fiber proportions (Pachiappan and Santhanam 2023). The primary objective is to investigate how different filler and fiber contents influence the mechanical performance, water absorption behavior, and microstructural characteristics of these composites. By doing so, the study aims to optimize the composite formulation to achieve an ideal balance of tensile and flexural strength, impact resistance, hardness, and moisture resistance, addressing a critical need for sustainable, high-performance materials in structural applications (Chandramohan *et al.* 2024).

Sal wood, a tropical hardwood native to India, Nepal, and Southeast Asia, is well known for its exceptional durability, high density, and mechanical strength, making it an excellent reinforcement in composite materials (Rajamanickam *et al.* 2023). The sawdust from sal wood consists of fine granular particles with high cellulose (40 to 45%) and lignin (30 to 35%) content, contributing to improved stiffness, hardness, and impact resistance when integrated into a polymer matrix (Parthasarathy *et al.* 2024; Vijayakumar *et al.* 2021). When incorporated into polyester resin, sal wood sawdust significantly increases surface hardness, wear resistance, and ensures prolonged durability and structural integrity of the composite material (Jenish *et al.* 2025). Similarly, babool, a dense hardwood commonly found in India and Africa, serves as a reinforcing filler due to its high lignin content (35 to 40%), fine particle size, and natural tannins, which provide antimicrobial and antifungal properties (Gökdağ and Borazan 2016). Its fine particle size allows better dispersion in the polymer matrix, reducing porosity and improving mechanical interlocking between the matrix and reinforcement (Gurusamy *et al.* 2024).

The combination of sal wood and babool sawdust fillers ensures a well-balanced composite with enhanced hardness, flexural strength, and reduced water absorption, making it a suitable alternative for structural applications requiring durability and strength. While wood-based fillers improve various properties, the inclusion of snake grass fiber plays a crucial role in enhancing mechanical performance, particularly tensile and flexural strength. Snake grass, commonly known as African Spear Plant, is a natural fiber characterized by its long, slender structure, high tensile strength (400 to 600 MPa), and low density, contributing to its high strength-to-weight ratio and lightweight structure (Ramadoss *et al.* 2024; Sathish *et al.* 2024; Sathishkumar *et al.* 2022). Wood-based fillers such as sal wood and babool sawdust particles are increasingly explored for their sustainability and ability to enhance mechanical, thermal, and moisture-resistant properties of composites (Repon *et al.* 2024; Mohammed *et al.* 2023; Arpitha *et al.* 2017; Kaewpruk *et al.* 2021). Babool's natural tannins provide resistance to termites and fungi, while its biodegradability makes it a more eco-friendly alternative to synthetic fillers (Ramesh *et al.* 2022). Sal wood's high density, moisture resistance, and thermal stability make it suitable for applications in humid and fluctuating temperature environments (Chowdhury *et al.* 2025; Ganapathy *et al.* 2024; Mohan Kumar *et al.* 2023).

Wood's high strength-to-weight ratio makes it an attractive option for lightweight yet durable composite materials used in furniture, automotive interiors, and sustainable building components. Both babool and sal wood sawdust particles provide sustainable, cost-effective, and mechanically advantageous alternatives to conventional fillers in

polymer composites (Manickaraj *et al.* 2024a). While babool sawdust enhances strength, hardness, and termite resistance, sal wood dust contributes to moisture resistance, toughness, and dimensional stability. Their incorporation into biocomposites not only improves material properties but also supports environmentally responsible manufacturing, making them valuable resources for a greener future (Islam *et al.* 2025).

Additionally, chemical treatments, such as alkali treatment (NaOH) or silane coupling agents, can be applied to snake grass fibers to further enhance fiber-matrix adhesion and mechanical stability (Azad *et al.* 2022). The development of modified resin formulations with improved moisture resistance and thermal stability can also be explored to expand the use of these composites in high-performance applications (Thandavamoorthy *et al.* 2024). The use of natural fiber and filler-based composites aligns with global sustainability goals by reducing reliance on non-renewable synthetic materials while offering superior mechanical properties. The successful integration of snake grass fiber, sal wood sawdust, and babool sawdust into polyester resin composites presents a viable alternative for eco-friendly and durable materials, paving the way for future advancements in sustainable composite technology (Ahmed *et al.* 2024).

EXPERIMENTAL

Materials Used

The composite materials in this study consisted of reinforcement fibers, fillers, a polymer matrix, and a curing agent. Each of these components plays a crucial role in defining the final properties of the hybrid composite.

Reinforcement Fiber

Snake grass (*Sansevieria cylindrica*) fiber was used as the primary reinforcement due to its high tensile strength, lightweight nature, and biodegradability (Vignesh *et al.* 2021; Aredla *et al.* 2024). Fibers were washed, dried, and cut to approximately 10 mm length before composite fabrication. Figure 1 shows the snake grass plant and its fibers.



Fig. 1. A. Snake grass plant; B. Snake grass fibers

Fillers

Sal wood (*Shorea robusta*) sawdust and babool (*Acacia nilotica*) sawdust were used as fillers to enhance mechanical properties and reduce water absorption. Sawdusts were sieved through 100-mesh and oven-dried at 100 °C for 12 h prior to use (Sathishkumar 2014; Khalil *et al.* 2006; Lette *et al.* 2018; Manickaraj *et al.* 2025). Figure 2 shows the sawdust powders.



Fig. 2. A. Sal wood sawdust; B. Babool wood sawdust

The addition of these natural fillers improves the mechanical performance of the composite by acting as load-bearing elements, preventing crack propagation, and increasing resistance to deformation. Additionally, they reduce the overall cost of the composite material by replacing a portion of the polymer resin (Manickaraj *et al.* 2025).

Unsaturated Polyester Resin

Unsaturated polyester resin constituted 60% of the composite formulation. The resin was mixed with 1 to 2% Methyl Ethyl Ketone Peroxide (MEKP) as catalyst and 0.5 to 1% cobalt naphthenate as accelerator for curing (Sombatsompop and Wimolmala 2006; Osuya and Mohammed 2017; Hossain *et al.* 2014). Figure 3 shows the polyester resin and its catalyst.



Fig. 3. Polyester resin and its catalyst

Composite Designations

Five composite formulations (S1 to S5) were prepared with constant polyester resin (60%) and snake grass fiber content (25%), varying filler proportions totaling 15% between sal wood sawdust (S) and babool sawdust (B) (Periasamy *et al.* 2024). The filler ratio shifts from S1 (2.5% S + 12.5% B) to S5 (12.5% S + 2.5% B) (Chithra *et al.* 2024). Details are summarized in Table 1.

Table 1. Composite Designation

Sample No	Filler Content (%)		Fiber Content (%)	Polyester Resin (%)	Composite Designation
	Sal wood sawdust (S)	Babool wood sawdust (B)	Snake Grass (SG)		
1	2.5	12.5	25	60	S1
2	5	10	25	60	S2
3	7.5	7.5	25	60	S3
4	10	5	25	60	S4
5	12.5	2.5	25	60	S5

Composite Fabrication Process

The composites were fabricated by compression molding (Periasamy *et al.* 2024). The pre-treated snake grass fibers and sawdust fillers were mechanically stirred into the polyester resin with MEKP and cobalt accelerator at 500 rpm for 10 to 15 minutes to ensure uniform dispersion (Kartal and Karagöz 2024). The mixture was poured into a steel mold coated with silicone release agent, then compressed at 5 MPa and 120 °C for 2 hours. Post-curing was performed at room temperature for 24 hours to complete cross-linking (Srinivasababu 2019). Figure 4 shows the composite specimen as per ASTM standards.

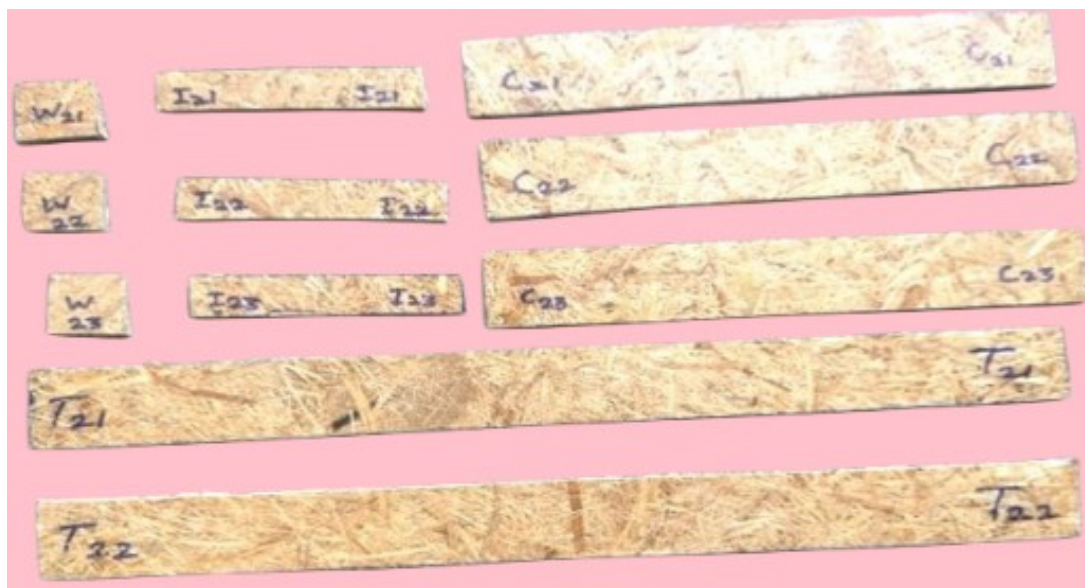


Fig. 4. Composite specimens

TESTING

After the curing process, the composite sheets were carefully removed from the mold and cut into standardized test specimens according to ASTM specifications to ensure uniformity and reliability in mechanical testing. (Saravanakumar and Reddy 2022).

Tensile Strength

Tensile tests were performed according to ASTM D638-14 (2022) using a universal testing machine. Specimens underwent uniaxial loading until failure, and tensile strength and modulus were calculated from the recorded maximum load and elongation. Composites with an optimal balance of fiber and filler exhibited enhanced tensile properties due to effective load transfer and reinforcement by the snake grass fibers (Rafi *et al.* 2024).

Flexural Strength

Flexural properties were assessed using the three-point bending test in accordance with ASTM D790 (2017). Samples were supported at two points while a load was applied centrally until fracture. Composites with a well-proportioned filler content demonstrated superior flexural strength, reflecting improved resistance to bending stresses. However, excessive filler loading slightly diminished flexural performance due to stress concentration and interrupted fiber continuity (Rafi *et al.* 2024).

Impact Strength

Impact resistance was measured *via* the Charpy impact test as per ASTM D256 (2023). Notched specimens were subjected to a pendulum hammer strike, and the energy absorbed prior to failure was recorded. The highest impact strength was observed in composites with balanced fiber-to-filler ratios, where strong interfacial bonding facilitated efficient energy dissipation. Elevated filler content led to localized weak zones, reducing impact resistance (Sasi Kumar *et al.* 2023).

Hardness

Surface hardness was determined by the Shore D durometer method following ASTM D2240 (2021). Incorporation of wood sawdust fillers increased hardness by producing a denser and more rigid surface layer. Slight reductions in hardness at higher filler loadings were attributed to filler agglomeration and the presence of micro-voids (Maguteeswaran *et al.* 2024).

Water Absorption Test

Water absorption behavior was evaluated according to ASTM D570 (2022) by immersing specimens in water and measuring weight gain over a fixed duration. Composites containing higher filler contents exhibited reduced water uptake owing to the hydrophobic properties of sal wood and babool sawdust, which limited moisture ingress. Conversely, composites with lower filler content showed increased water absorption due to higher porosity and exposed fiber surfaces (Gurusamy *et al.* 2025).

Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR analysis was conducted to investigate the chemical interactions between the snake grass fibers, fillers, and polyester matrix. Spectra were recorded using an FTIR

spectrometer over the range of 4000 to 400 cm^{-1} . The analysis identified characteristic functional groups and confirmed the presence of key chemical bonds, indicating good interfacial compatibility and possible chemical bonding between the reinforcement and matrix (Manickaraj *et al.* 2025). Changes in peak intensities and positions provided insight into the degree of interaction and the effectiveness of the composite formulation.

SEM Analysis

Scanning electron microscopy (SEM) was conducted using a Carl Zeiss AG (Carl Zeiss AG, Oberkochen, Germany) instrument to examine fracture surfaces for fiber-matrix interactions, filler distribution, and failure characteristics. Composites with balanced fiber and filler proportions displayed strong interfacial adhesion with minimal fiber pull-out and void formation, correlating with improved mechanical performance. In contrast, samples with lower fiber content revealed more voids and weak bonding, resulting in compromised strength and durability (Raja and Devarajan 2025).

RESULTS AND DISCUSSION

Tensile Strength

The tensile strength of the hybrid composites exhibited a progressive increase from S1 to S4, peaking at 56 MPa in S4 before slightly decreasing to 50 MPa in S5. This trend is primarily influenced by the balance between fiber reinforcement, filler-matrix interaction, and fiber-matrix adhesion (Sekar *et al.* 2025).

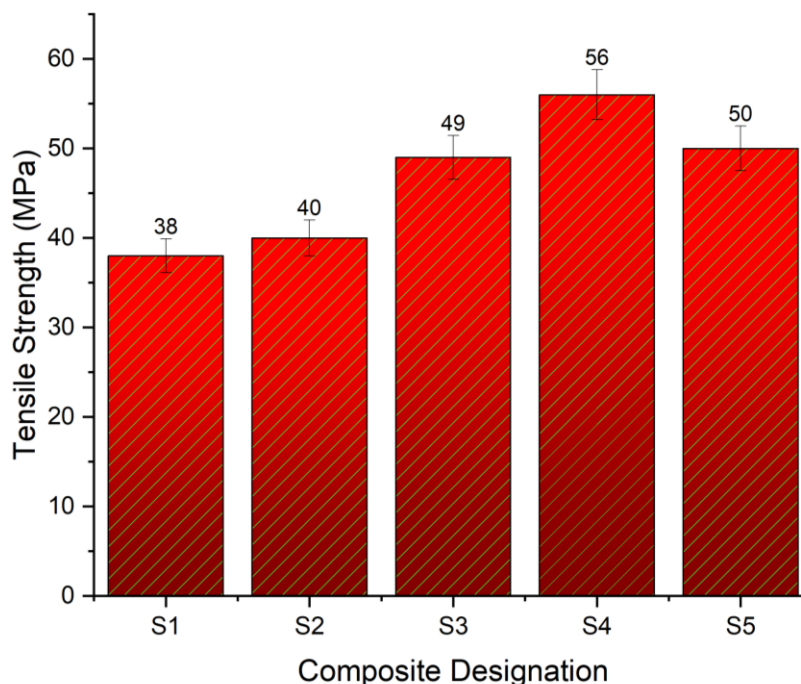


Fig. 5. Tensile strength vs. comosite designation

Snake grass fiber, known for its high tensile strength, enhances load-bearing capacity as its content increases, effectively transferring stress from the matrix to the fibers. However, excessive fiber content can lead to poor wetting and agglomeration, causing

stress concentration points that reduce strength, as seen in S5 (Thangavel *et al.* 2024). The addition of sal wood and babool sawdust fillers initially improved mechanical interlocking and matrix stiffness, contributing to the strength observed in S3 and S4. In contrast, lower filler content in S1 and S2 resulted in a polymer-dominated structure with weaker mechanical performance. At higher filler content in S5, excessive particles disrupt fiber alignment, weaken interfacial adhesion, and introduce micro voids, reducing tensile strength (Sukhija *et al.* 2024). The SEM analysis would likely show strong fiber-matrix bonding in S3 and S4, whereas S1 and S2 may exhibit fiber pull-out and voids, diminishing load transfer efficiency. In S5, excess fillers contribute to matrix discontinuity and defects, further explaining the slight decline in strength. The results confirm that an optimal combination of fiber and filler content is critical for maximizing the tensile performance of hybrid composites, with S4 demonstrating the best balance of reinforcement and structural integrity (Heckadka *et al.* 2018). Figure 5 shows the tensile strength of the composite specimens.

Flexural Strength

The flexural strength of the hybrid composites demonstrated a progressive increase from S1 to S4, peaking at 85 MPa in S4, before slightly decreasing to 82 MPa in S5. Specifically, the flexural strength values were recorded as 74 MPa for S1, 77 MPa for S2, 81 MPa for S3, 85 MPa for S4, and 82 MPa for S5. This trend suggests that the increasing presence of snake grass fiber and controlled incorporation of sal wood and babool sawdust fillers contribute to improved load distribution, better stress transfer, and enhanced fiber-matrix interaction (Prosper and Uguru 2018).

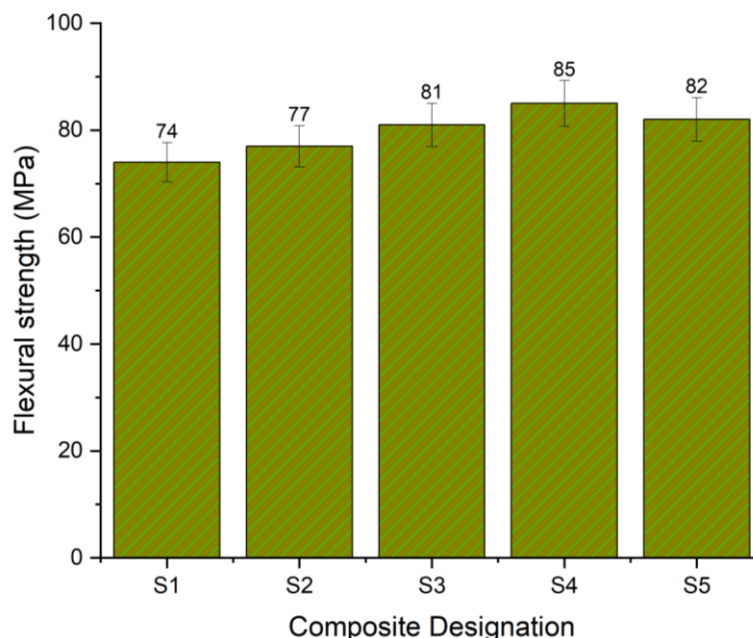


Fig. 6. Flexural strength vs. composite designation

The initial increase from S1 to S4 is attributed to the reinforcing effect of snake grass fibers, which provides structural integrity and prevents material failure under bending loads. The presence of wood sawdust fillers further enhances matrix stiffness, reducing

localized deformation and contributing to improved resistance against flexural stress. The peak value in S4 (85 MPa) indicates that this composition achieves an optimal balance between fiber and filler content, maximizing reinforcement efficiency and ensuring superior mechanical performance (Balakrishnan *et al.* 2022). However, in S5, where the filler content was at its highest, the flexural strength declined slightly to 82 MPa. This reduction is likely due to excessive filler content, which can lead to filler agglomeration, poor fiber dispersion, poor bonding within the clusters, and reduced fiber-matrix adhesion. High concentrations of filler particles can also create microvoids and stress concentration points, which weaken the overall structural integrity of the composite. The SEM analysis would likely reveal strong interfacial bonding and minimal voids in S3 and S4, while S5 may exhibit filler clustering, increased void formation, and weaker fiber alignment, negatively affecting stress transfer and load-bearing capability (Balakrishnan *et al.* 2022; Ramesh *et al.* 2023). These results highlight the necessity of optimizing fiber and filler content to achieve the best possible flexural performance, ensuring a balance between mechanical strength, filler reinforcement, and composite integrity. Figure 6 shows the flexural strengths.

Impact Strength

The impact strength of the hybrid composites exhibited a progressive increase from S1 to S4, reaching a peak of 6.98 J in S4, before slightly decreasing to 6.51 J in S5. Specifically, the impact strength values were recorded as 5.56 J for S1, 5.98 J for S2, 6.12 J for S3, 6.98 J for S4, and 6.51 J for S5. This trend indicates that the combination of snake grass fiber with sal wood and babool sawdust fillers significantly influenced the energy absorption capability of the composite under sudden impact loads (Manickaraj *et al.* 2024b). The initial increase from S1 to S4 is attributed to the reinforcing effect of snake grass fibers, which enhanced energy dissipation and prevented brittle failure by creating an efficient load distribution network within the polymer matrix. Additionally, the presence of sal wood and babool sawdust fillers contributed to crack deflection and energy absorption, further improving impact resistance (Krishnadas *et al.* 2024). The highest value observed in S4 suggests an optimal fiber-to-filler ratio, allowing for enhanced fiber pull-out mechanisms and strong interfacial bonding, which effectively absorbs and dissipates impact energy. However, in S5, the impact strength decreased slightly to 6.51 J, which is likely due to excessive filler content leading to filler agglomeration and reduced fiber-matrix adhesion (Manickaraj *et al.* 2024a).

High filler concentrations may introduce microvoids and stress concentration points, reducing the composite's ability to absorb energy efficiently. The SEM analysis would likely reveal better interfacial bonding and fewer voids in S3 and S4, while S5 may show evidence of filler clustering, microcracks, and weak fiber adhesion, leading to lower impact resistance (Ogunleye *et al.* 2022). These results emphasize the importance of optimizing the filler-to-fiber ratio to achieve maximum impact strength, ensuring enhanced toughness and durability in hybrid polyester composites. Figure 7 shows the impact strength.

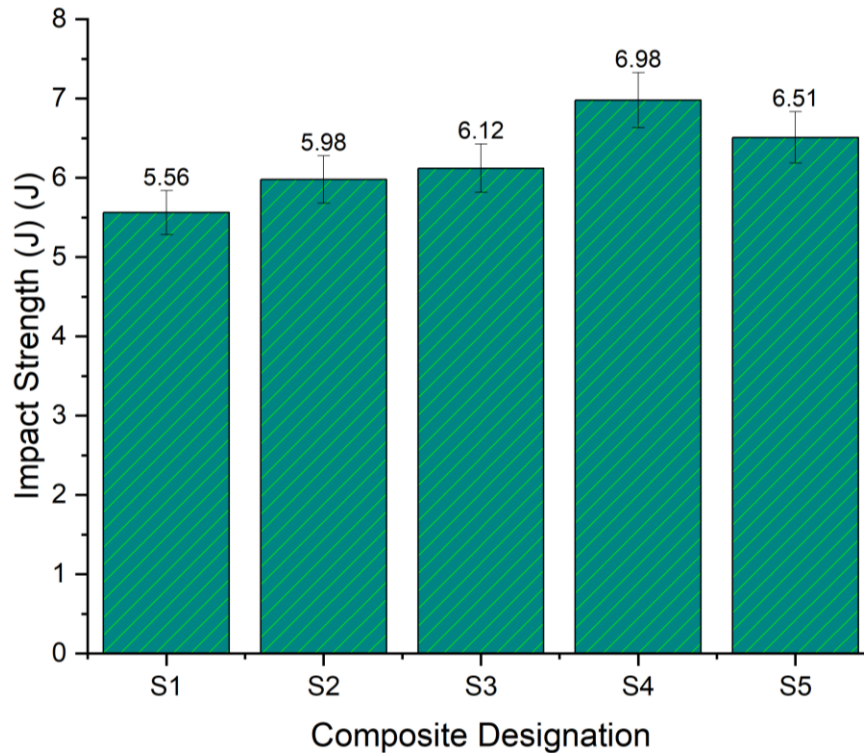


Fig. 7. Impact strength vs. composite designation

Hardness Test

The Shore D hardness values of the hybrid composites demonstrated a clear increasing trend from S1 to S4, with a peak value of 84 in S4, followed by a slight reduction to 80 in S5. Specifically, the hardness values recorded were 72 for S1, 76 for S2, 79 for S3, 84 for S4, and 80 for S5. This increasing trend up to S4 suggests that the inclusion of snake grass fiber, along with sal wood and babool sawdust fillers, enhanced the surface hardness of the composite. The improvement in hardness is primarily attributed to the reinforcement effect of the natural fibers and fillers, which contributed to increased stiffness, load-bearing capacity, and resistance to indentation (Sumesh *et al.* 2024). Sal wood and babool sawdust fillers, being lignocellulosic materials with a high lignin content, improved the compactness of the composite, reducing material deformability under localized pressure. The highest hardness value observed in S4 (84 Shore D) indicates that this particular fiber-filler ratio provided an optimal distribution of reinforcing elements within the polyester matrix, minimizing void formation and maximizing load transfer (Manalu *et al.* 2024). However, in S5, the hardness value slightly decreased to 80, which can be explained by excessive filler content leading to potential agglomeration and reduced fiber-matrix adhesion. Excessive filler concentration may create weak zones within the composite, affecting its overall density and indentation resistance. The SEM analysis of these samples would likely show improved surface uniformity and filler dispersion in S3 and S4, while S5 may exhibit microvoids and uneven filler clustering, leading to minor reductions in hardness (Sumesh and Kanthavel 2022; Prasad *et al.* 2023). These findings highlight the significance of balancing fiber and filler content to achieve optimal hardness, ensuring enhanced wear resistance and surface durability for potential applications in structural and load-bearing components. Figure 8 shows the hardness test results.

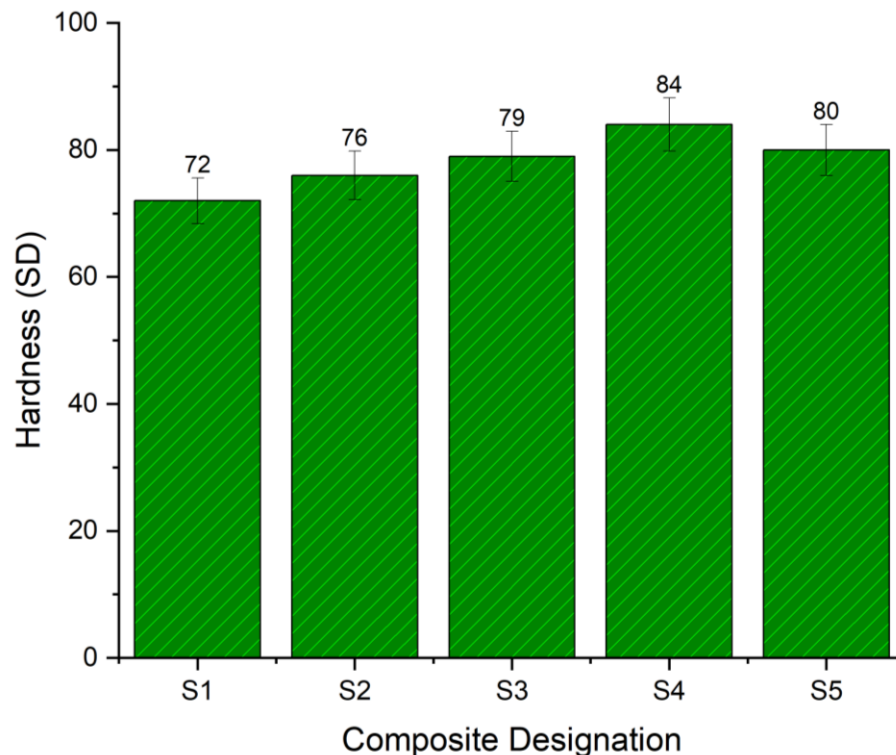


Fig. 8. Hardness vs. comosite designation

Water Absorption

The water absorption behavior of the hybrid polyester composites showed a decreasing trend from S1 to S4, with a slight increase in S5. The recorded values were 30% for S1, 27% for S2, 24% for S3, 21% for S4, and 23% for S5. This reduction in water absorption up to S4 indicates that increasing filler content enhanced the hydrophobic nature of the composite. The presence of sal wood and babool sawdust fillers played a crucial role in reducing the composite's water absorption by filling voids within the matrix, thereby limiting the pathways for moisture penetration (Abd El-baky and Attia 2019; Anjumol *et al.* 2023). The lowest water absorption, observed in S4 (21%), suggests that this composition provided the best filler dispersion and fiber-matrix bonding, effectively minimizing microvoids and surface porosity. However, in S5, the water absorption slightly increased to 23%, which could be attributed to excessive filler content leading to particle agglomeration, resulting in localized voids that facilitate moisture ingress. Additionally, the presence of snake grass fibers, which are naturally hydrophilic due to their cellulose content, can contribute to moisture absorption when fiber dispersion is not optimal (Balaji *et al.* 2022; Prasad *et al.* 2023). The SEM analysis of fractured surfaces would likely reveal fewer voids and better interfacial adhesion in S3 and S4, whereas S1 and S5 may show more porous structures and microcracks, explaining their higher water absorption tendencies. These findings indicate that an optimal balance between fiber and filler content is necessary to achieve a composite with reduced water absorption, improving its durability and resistance to environmental degradation, which is essential for applications in humid or aqueous environments (Sathish *et al.* 2017). Figure 9 shows the water absorption test values.

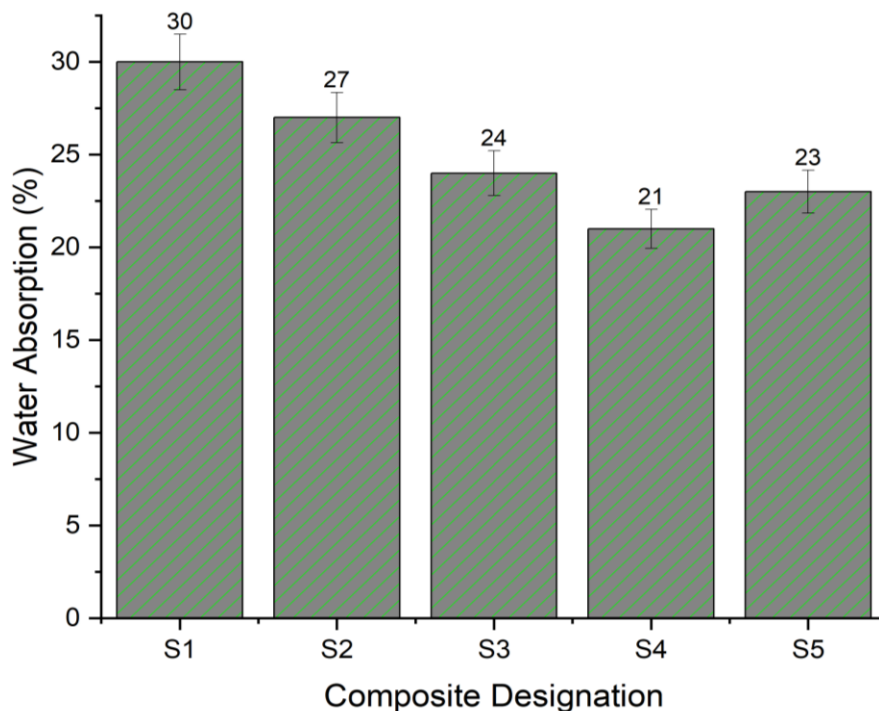


Fig. 9. Water absorption test vs. comosite designation

FTIR Spectra Test

The FTIR spectra of composites A–E show transmittance versus wavenumber (4000 to 400 cm^{-1}), highlighting chemical interactions between the matrix, snake grass fibers, and filler materials. Sample A (black) displayed minimal peaks, indicating low fiber/filler content, with broad features at 1000 to 1200 cm^{-1} (C-O) and 2900 cm^{-1} (C-H). Sample B (red) showed stronger peaks around 1000 to 1200 cm^{-1} (C-O-C) and 1700 cm^{-1} (C=O), indicating ester interactions (Karuppusamy *et al.* 2025). Samples C (blue) and D (green) revealed sharper peaks at 1020 cm^{-1} (C-O), 1500 to 1600 cm^{-1} (C=C), and a broad O-H band (3200 to 3500 cm^{-1}), suggesting hydrogen bonding and better matrix-fiber adhesion. Sample E (purple) had the most intense peaks, including O-H (3200 to 3500 cm^{-1}), C-H (2900 cm^{-1}), C=O (1700 cm^{-1}), and C-O (1000 to 1200 cm^{-1}), indicating strong chemical bonding and high filler incorporation (Aruchamy *et al.* 2025). Overall, increasing fiber/filler content from A to E enhanced chemical interactions and interfacial bonding, improving composite properties. However, excessive filler may cause peak broadening due to agglomeration and dispersion issues. FTIR findings align with mechanical test results, confirming the importance of chemical bonding in composite performance (Sathesh Babu *et al.* 2024). Figure 10 shows the FTIR test result of the various composite designations.

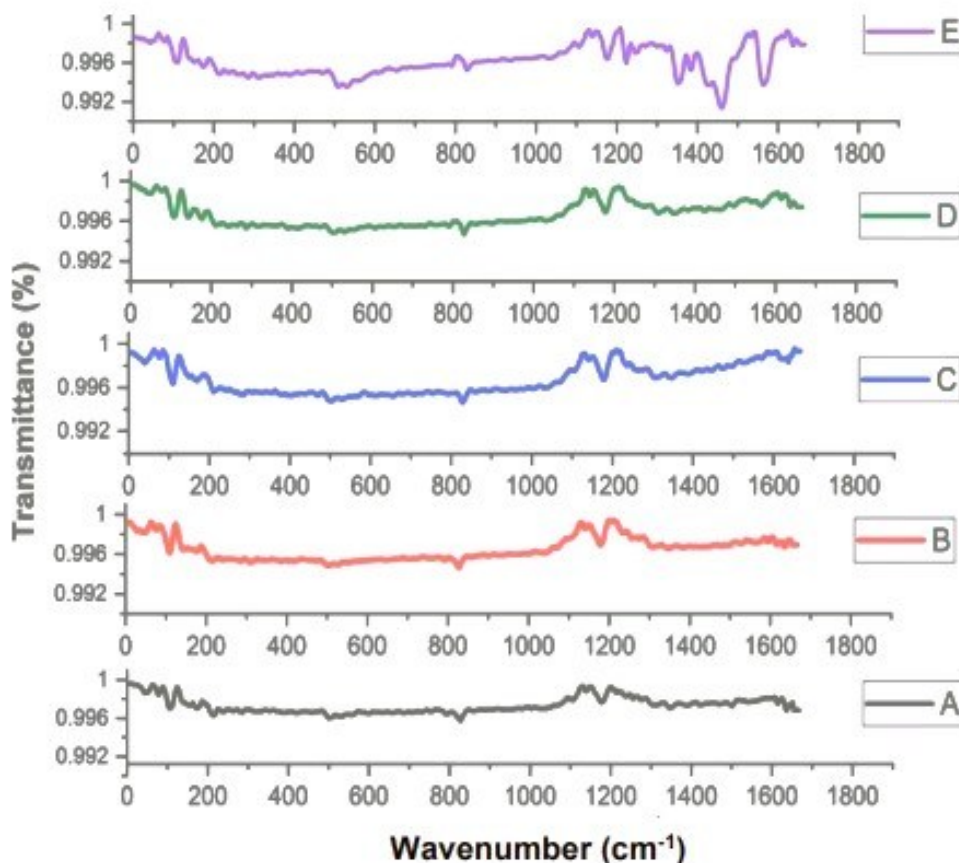


Fig. 10. FTIR Results. A.S1, B.S2, C.S3, D.S4, E.S5

Scanning Electron Microscopy

The SEM analysis was conducted to examine the microstructural characteristics of the hybrid polyester composites and to evaluate fiber-matrix adhesion, filler dispersion, and the presence of voids or cracks that influence mechanical and water absorption properties. The SEM images provide insights into the failure mechanisms and bonding quality between snake grass fibers, sawdust fillers (sal wood and babool), and the polyester resin. The SEM analysis of the composite fracture surfaces revealed distinct microstructural differences influencing mechanical behavior (Sari *et al.* 2017). In S1, numerous fiber pull-outs, cracks, and interfacial voids indicated poor fiber-matrix adhesion and weak bonding, leading to stress concentrations and a lower tensile strength of 38 MPa. In contrast, S4 showed good bonding with fewer voids, strong fiber presence, and minimal fiber pull-out, resulting in better stress transfer and the highest tensile strength of 56 MPa. The filler presence and dispersion also played a vital role; S2 and S3 exhibited uniform filler dispersion with reduced voids, enhancing their load-bearing capacity, while S5 showed filler agglomeration, uneven dispersion, and localized voids that slightly decreased its mechanical properties (Paramathma *et al.* 2022; Kar *et al.* 2024). Fracture morphology further confirmed that S1 and S2 underwent brittle failure with widespread cracks and fiber pull-out, whereas S4 displayed ductile fracture behavior with fibrillated fibers and limited cracking due to stronger bonding. Additionally, water absorption trends were influenced by surface porosity and voids; S1 had the highest absorption (30.00%) due to its porous structure and fiber pull-out, while S3 and S4, with better filler and fiber dispersion and fewer voids, showed lower absorption values of 24.00% and 21.00%, respectively. S5,

though having higher filler content, exhibited agglomeration and localized gaps that increased its water absorption slightly to 23% (Sumesh *et al.* 2022). Overall, the presence of well-bonded fibers, effective filler dispersion, and minimal voids in S4 contributed to superior mechanical and moisture-resistant performance. Figure 11 shows the SEM images of S5 and S4.

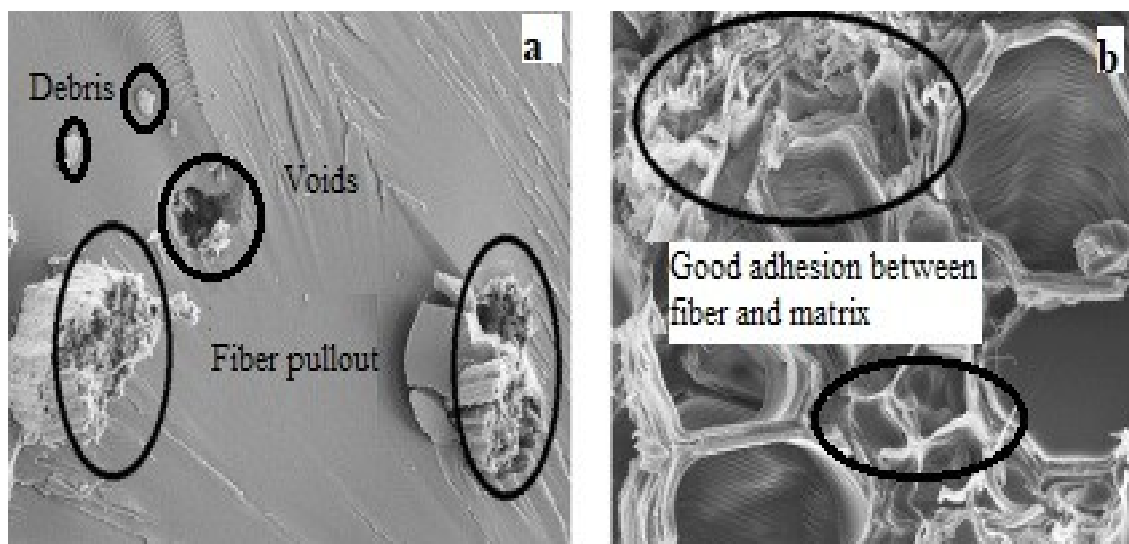


Fig. 11. SEM Images (A) S5; (B) S4

Overall, the study results exhibited the great potential of PPL and CSL fibers, combined with TSP filler, for developing high-performance hybrid composites. The results indicate that careful optimization of fiber and filler content is essential for maximizing the mechanical properties while minimizing water absorption, making these composites suitable for various applications in the fields of construction, automotive, and consumer products. Future work should focus on further refining the processing techniques to enhance fiber distribution and adhesion, ultimately improving the overall performance of these composite materials.

CONCLUSIONS

1. This study systematically evaluated the mechanical, water absorption, and microstructural properties of polyester-based hybrid composites reinforced with snake grass fibers and sal wood/babool sawdust fillers. The results demonstrated that composite performance was significantly influenced by fiber-matrix interaction, filler distribution, and microstructural integrity.
2. The hybrid composite designated as S4, containing an optimal balance of snake grass fibers and sawdust fillers, exhibited the highest tensile (56 MPa) and flexural (85 MPa) strengths, maximum impact resistance (6.98 J), and superior hardness (Shore D 84). These enhancements are attributed to efficient stress transfer, filler-induced stiffness, and effective fiber-matrix bonding. Conversely, excessive filler content (S5) led to agglomeration, stress concentration, and reduced performance.

3. Water absorption tests revealed that S4 had the lowest moisture uptake (21%), highlighting the role of filler packing and matrix hydrophobicity. SEM analysis confirmed improved microstructural uniformity and fewer defects in S4, compared to composites with lower filler content.
4. In conclusion, this study highlighted the critical role of optimizing the ratio of natural fibers and fillers to achieve superior mechanical performance, impact resistance, and moisture stability in polyester composites. These findings pave the way for developing eco-friendly composites for structural applications in automotive, aerospace, and construction industries. Future studies may focus on fiber and filler surface treatments to further enhance interfacial adhesion and overall composite performance.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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