Development of Sustainable Silane-Treated Hemp Fiber and *Lansium parasiticum* Shell Bio-Filler-Reinforced Polyester Composite

Kannapiran Karuppasamy,[a,*] Prabu Ram Ganesamoorthy,[b] Saravanan Pandiaraj,[c,d] and Satheesh Rajendran [a]

Natural fibre composites are globally recognized for their sustainability and functionality, yet challenges such as poor interfacial bonding and high moisture absorption limit their performance. This study developed and characterized a polyester-based hybrid composite reinforced with silane-treated hemp fibres and *Lansium parasiticum* shell powder—an underutilized agricultural byproduct. The effects of reinforcement loading on mechanical, wear, dynamic mechanical, hydrophobic, and flammability behaviours were systematically investigated. The 3 vol% filler (T3) formulation exhibited maximum tensile and flexural strength, while 5 vol% enhanced hardness and wear resistance. Excess filler loading led to agglomeration and property deterioration. Silane treatment significantly improved fibre–matrix adhesion, thermal stability, and water repellence, as evidenced by increased contact angle and dynamic mechanical analysis results. Overall, the study demonstrated that silane-treated hybrid bio composites offer superior mechanical integrity, reduced moisture uptake, and improved thermal resistance. These findings highlight their potential for sustainable applications in automotive components, building panels, prosthetic sockets, and orthotic supports, contributing to lightweight and eco-friendly material development. This sustainable silane-treated hemp and bio-filler composite demonstrates potential as a next-generation material for lightweight biomedical support and rehabilitation applications in disability research.

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Keywords: Composite; Polyester resin; Hemp fibre; Lansium parasiticum shell powder; Mechanical properties; Sustainable materials

*Contact information: a: Department of Industrial Engineering, College of Engineering Guindy, Anna University, Chennai 600025, India; b: Department of Mechanical Engineering, Ramco Institute of Technology, Rajapalayam 626117, India; c: Department of Self-Development Skills, King Saud University, Riyadh, Saudi Arabia; d: King Salman Center for Disability Research, 11614 Riyadh, Saudi Arabia; *Corresponding author: srikanna.piran@gmail.com*

INTRODUCTION

In recent years there is an increased interest in the development of sustainable materials and high-performance composites, motivated by the necessity for materials that demonstrate exceptional properties while also conforming to environmental standards (Sri *et al.* 2023). Natural fiber and bio filler reinforced polymer composites have attracted increasing attention as partially sustainable alternatives to conventional synthetic composites. These materials offer significant benefits, including biodegradability,

renewability, and a reduced environmental footprint, making them highly appealing for various industrial applications (Andrew and Dhakal 2022; Das *et al.* 2024).

Enhancing the mechanical properties of polymer matrices to create high-toughness composites has historically depended on synthetic additives, such as fibres, fillers, and ceramic particles (Cristaldi *et al.* 2010). However, natural plant fibres have recently gained attention as an effective alternative to glass fibres in organic matrix composites, offering ecological benefits including lower density, improved specific properties, and reduced wear during use. Their incorporation into polymer matrices has led to notable improvements in mechanical behaviours, thermal stability, and overall composite performance (Elfaleh *et al.* 2023). Furthermore, the use of naturally derived fillers can significantly boost the biocompatibility and overall performance of these composites. Various agricultural and industrial by-products, such as fruit shells, seed husks, and biomass residues, have been identified as viable fillers (Maluin 2024). The utilization of these materials not only improves mechanical properties but also adheres to the values of the circular economy by transforming waste into valuable resources (Biagi *et al.* 2024).

Natural fibres are frequently employed to enhance the rigidity and strength of composites. When incorporated into matrix systems, these fibres can be meticulously chosen and combined to fulfil specific performance criteria across various applications, thereby improving the overall efficacy of the composite (Song *et al.* 2024). Recent studies have explored various combinations of natural fibres and matrix polymers to optimize composite properties. The hand lay-up method, which allows for versatile configurations, such as chopped or continuous strands, has been particularly effective in producing cost-efficient and high-performing composites. This method is widely used in hand lay-up processes, conventional laminating, and certain closed molding techniques, offering manufacturers a cost-effective route to effective composite materials (Amarnath *et al.* 2024). Incorporating natural fibres into thermoset polymers significantly enhances mechanical behaviours such as strength, impact toughness, and stiffness. This results in lightweight yet durable materials that are particularly suited for the automotive and construction industries (Spyridonos and Dahy 2025). Hemp fibre exhibits remarkable material strength and low weight, making it particularly advantageous for reinforcing composites; its integration improves durability and decreases overall weight, positioning it as a suitable component for sustainable, high-performance products (Gioffrè and Pepi 2024).

Untreated natural fibre–reinforced biocomposites serve as environmentally sustainable substitutes for synthetic materials; yet, they encounter difficulties including inadequate interfacial adhesion with the matrix, elevated moisture absorbance, and inconsistent mechanical characteristics. These issues arise from the hydrophilic nature of natural fibres, which results in weak adhesion and reduced durability. To overcome these limitations, surface treatment techniques, such as alkali modification, silane coupling, and plasma treatment, are employed to improve fibre–matrix bonding, reduce moisture uptake, and enhance mechanical properties. Surface-treated fibre biocomposites thus offer improved strength, durability, and overall performance (Motaleb *et al.* 2024; Naik *et al.* 2024; Sanfilippo *et al.* 2024). The silane treatment process is widely recognized for its ability to enhance the properties of natural fibres by removing undesirable components such as hemicellulose and lignin. This process not only cleans the fibre surface but also facilitates improved adhesion between the fibre and matrix. The presence of amine groups in silane compounds plays a pivotal role in forming strong interfacial bonds and providing

a protective barrier against chemical degradation of the fibres. Leveraging these advantages, Narayanan and Muthukumaran (2024) studied the strength and wear characteristics of silane-treated corn husk fibre epoxy composites. Their findings demonstrated that treating corn husk fibres with 3 wt% 3-aminopropyltriethoxysilane significantly improved the material strength and wear life of the composites—highlighting silane's value for optimizing fibre–matrix interactions.

The use of polyester resin as a matrix in composites has significantly enhanced mechanical properties and stability. Polyester resin is favoured for its excellent chemical resistance, ease of processing, and cost-effectiveness. However, the inherent brittleness cured polyester resin can facilitate the initiation of micro-cracks and interfacial voids under mechanical stress, which may adversely affect the durability of the composite (Baghloul *et al.* 2024; Shahid *et al.* 2024). Appropriately selected and well-dispersed fillers may contribute to improved structural integrity by modifying the microstructure of the composite and limiting void growth. Moreover, with the growing emphasis on sustainability, the use of eco-friendly fillers derived from natural or renewable sources has gained considerable attention, aligning with current priorities in environmentally responsible material development (Kumar and Bhowmik 2023). Fillers sourced from natural origins, including organic matter, by-products from the food industry, and household waste, have attracted considerable interest in composite fabrication. (Goutham *et al.* 2023). Agricultural waste—such as fruit shells, peel waste, and outer seed cores offers a sustainable and cost-effective solution for reinforcing composites (Palanisamy *et al.* 2022). Among these, certain fruit shells, which are characterised by a hard endocarp, serve a dual purpose as both consumable components and effective filler materials in composites. Although promising, there is a paucity of research on the application of such fruit shells to improve the strength of composite materials. An example of such a filler is the shell of *Lansium parasiticum*, a species from the mahogany family (Meliaceae). Known for its hardness, this fruit shell originates from Southeast Asia and is primarily cultivated in humid tropical regions; it is widely recognized for its edible fruit and the agricultural residue it produces, making it a promising candidate for sustainable composite reinforcement (Karuppasamy and Ranganathan 2023).

Despite significant advances in natural-based composite materials, a research gap remains in innovative routes to optimize performance while maintaining environmental sustainability. The main objective of this study was to evaluate the effect of silane-treated hemp fibres and *Lansium parasiticum* shell powder on the mechanical, tribological, thermal, and flammability properties of polyester-based bio composites. The specific objectives were:

- To enhance fibre–matrix adhesion through silane surface treatment.
- To investigate the influence of varying filler content on composite performance.
- To assess the suitability of the developed composites for structural and industrial applications.

Based on these objectives, it was hypothesized that silane treatment and optimal filler loading will synergistically improve the mechanical strength, wear resistance, hydrophobicity, and thermal stability of the bio composites.

To guide this investigation, the following research question is posed: How does the incorporation of silane-treated hemp fibres and *Lansium parasiticum* shell powder influence the mechanical, tribological, thermal, and flammability properties of polyester-

based composites? This question frames the study's contribution to sustainable material development by linking microstructural modifications to functional performance.

EXPERIMENTAL

Materials

Unsaturated polyester resin, exhibiting a density of 1.12 g/cm³, was obtained from Huntsman India Ltd. It functioned as the matrix material. The curing agent, Methyl Ethyl Ketone Peroxide (density: 1.17 g/cm³), was procured from Herenba Instruments & Engineers. Cobalt naphthenate, supplied by Herenba Instruments & Engineers and possessing a density of 0.95 g/cm³, was employed as a promoter to enhance the polymerization process. Hemp fibres, used as reinforcement, were sourced from the M.C.R. D, Chennai. These fibres had a density of 1.45 g/cm³ and a length of 50 mm. Finely powdered *Lansium parasiticum* fruit shell was used as a bio-filler. The particles had an average size of approximately 3 μm and a density of 0.8 g/cm³. The powder was obtained by mechanical grinding followed by sieving to ensure uniform particle distribution.

Table 1. Composite Fabrication

Sl. No	Composite Designation	Polyester Resin (Vol%)	Hemp Fibre (50 mm) (Vol%)	*Lansium parasiticum* Shell Powder (Vol%)
1	P	100	–	–
2	TF	60	40	–
3	T1	59	40	1
4	T3	57	40	3
5	T5	55	40	5

Notes: P – polyester resin; TF – treated fibre without filler; T – silane treated; numerals denote Lansium parasiticum shell filler vol%

Silane Treatment

Silane treatment was applied on both chopped hemp fibres and *Lansium parasiticum* shell powder. 3- aminopropyl triethoxysilane (APTES) was chosen because its amine group enhances hydrogen bonding with ester groups of polyester, while the silane group forms Si–O–Si linkages with hydroxyl groups on the fibre surface, thereby improving interfacial adhesion. A 2 wt% silane solution was formulated with APTES in a 95:5 ethanol-to-water mixture. The solution underwent ultrasonication for 15 min to achieve adequate dispersion. The fibres and particles were immersed in the silane solution and stirred for 10 min. The excess solution was eliminated *via* decantation, and the treated materials were subjected to oven drying in a silica crucible at 120 °C for 1 h to promote the formation of siloxane (Si–O–Si) bonds and ensure the removal of moisture. This treatment enhances fibre–matrix adhesion through the modification of the hydrophilic surface and the promotion of chemical bonding (Alshahrani and Vr 2022).

Methodology

The unsaturated polyester resin was meticulously combined with the necessary amounts of MEKP (Methyl Ethyl Ketone Peroxide) and cobalt naphthenate to form a uniform matrix. The curing agent and promoter were included with continuous agitation to guarantee homogeneous polymerisation. Hemp fibres and particles were pretreated to

improve interfacial adhesion and eliminate surface contaminants (Varma and Chandran 2025). The modified fibres and *Lansium parasiticum* shell powder were uniformly dispersed in the resin mixture. A conventional lay-up methodology was adopted for composite fabrication. The resin composite, augmented with hemp fibres and filler, was meticulously poured in layers into a pre-cleaned mould coated with a release agent. (Palaniappan *et al.* 2024). The homogeneity of the resin-reinforcement mixture was ensured by continuous mechanical stirring at 500 rpm for 10 min. Visual inspection confirmed the absence of agglomerates, and density checks across specimens verified uniform distribution. After the layers were applied, the composite was allowed to cure at ambient temperature under air pressure. The curing process was conducted for 24 to 48 h to ensure complete cross-linking of the resin matrix. Upon curing, the composite samples were demolded and sectioned into standardised configurations for evaluation. The prepared samples underwent evaluations of mechanical, thermal, and physical properties, encompassing tensile, flexural, and compressive strength tests, Izod impact resistance, wear resistance, flammability, water absorbance, and dynamic mechanical analysis (DMA). All tests were performed in accordance with ASTM standards to guarantee trustworthy and precise results.

Table 2. ASTM-Compliant Samples and Instruments

Experiment	ASTM	Instrument
Fourier Transform IR Spectroscopy (FTIR)	E1252-98 (2021)	Spectrum Two FT-IR, PerkinElmer (USA)
Tensile	D3039/D3039M-17 (2017)	Universal Testing Machine (FIE 1600-TS)
Flexural	D790-17 (2017)	Universal Testing Machine
Compression	D695-23 (2023)	Universal Testing Machine
Izod Impact	D256-24 (2024)	Micro Impact, Kristal India Pvt. Ltd. (India)
Wear	G99-23 (2023)	Pin-on-disc (Novus Tribo Solution)
Flammability	D635-22 (2022)	Horizontal/Vertical Bunsen Burner
Contact Angle	D5946-24 (2024)	HO-IAD-CAM-01 (Holmarch, India)
DMA	D4065-20 (2020)	DMS 6100 (Inkarp Japan)

Methods

Tensile test

Tensile testing was conducted on surface-treated hemp fibre, alongside *Lansium parasiticum* shell powder-reinforced hybrid polyester composites, following the ASTM D3039/D3039M-17 (2017) standard. The specimens, with a uniform thickness of 3 mm, were assessed using a 5-ton capacity Universal Testing Machine (UTM), model FIE 1600-TS, manufactured by Fuel Instrument Engineers (FIE) in Pune, India, at a crosshead speed of 2.5 mm/s. Both pure polyester and hybrid composites were thoroughly examined to uncover their tensile characteristics.

Flexural test

The flexural properties of a hybrid composite comprising surface-treated hemp fibre-reinforced *Lansium parasiticum* shell powder particles incorporated into polyester resin were evaluated using a three-point bend test utilizing a universal testing machine (FIE 1600-TS) in accordance with ASTM D790-17 (2017). All samples maintained a uniform thickness of 3 mm for the test specimens.

$$\sigma_x = 3FL/(2bd\text{^}2) \quad (1)$$

where σ_x is the flexural stress, F is the maximum load (N), L is the span length (mm), b is the width (mm), and d is the thickness (mm).

Impact test

The impact testing was conducted utilising a micro impact machine from Kristal India Pvt. Ltd. The specimens were meticulously prepared following the guidelines set forth by ASTM D256-24 (2024). A 'V' groove was created in the centre of the specimens. All samples were consistently kept at a thickness of 3 mm.

Hardness test

In accordance with the requirements established by ASTM D2240-15 (2021), the hardness test was performed with the assistance of a Shore durometer (Blue Steel brand). An indenter with a conical shape and an angle of 35º ± 1º was utilised for the measurements.

Hydrophobicity

The contact angle test technique was employed to verify the water absorption characteristics of the polyester hybrid composites. This technique involved placing a little amount of water on the test sample and capturing an image of it using an opto-electronic device called HOLMERC, specifically the HO-IAD-CAM-01 model. The angle relative to the ground was subsequently determined using the image. The device features a CMOS sensor that enables video capture at a resolution of 2592 × 1944 pixels. The lighting option selected in this situation was a fused lighting system utilizing LEDs. The contact angle was employed to determine the surface tension of each sample. When the contact angle is increased, the absorption of water decreases, and conversely, when the contact angle is decreased, the absorption of water increases.

Fatigue

The fatigue characteristics were evaluated using a tension-tension fatigue tester, equipped with hydraulically operated mechanical grippers to firmly attach the test specimens. Five identical dumbbell-shaped specimens underwent cyclic loading, adhering to the testing technique specified in ASTM D3479/D3479M-19 (2023). The specimens were subjected to controlled loading conditions, and the number of loading cycles until failure was documented to ascertain the material's average fatigue life. This approach facilitated a thorough comprehension of the material's behaviour under cyclic tensile stress, offering insights into its durability and resistance to fatigue failure.

Wear

The wear characteristics were assessed utilising a pin-on-disc apparatus (Novus Tribo solution). The wear disc measured 165 mm in diameter, operating within a speed range of 100 to 2000 rpm and a normal load range of 5 to 200 N. The parameters for testing comprised a weight of 20 N, a sliding velocity of 500 rpm, and a test duration of 10 min. The samples, measuring 3 mm in thickness and 5 mm in width, were used to assess the wear resistance of the hybrid bio composite material,

$$W = \Delta V/(F\ X\ D) \quad (2)$$

where ΔV is the volume loss (mm³), F is the applied load (N), and D is the sliding distance (m).

Flammability

The flammability characteristics of the hybrid composites were tested in accordance with ASTM D635-22 (2022). The Horizontal Bunsen Burner (UL-94 HB) test is a standardized procedure for assessing the flammability of plastic materials positioned horizontally. Specimens measuring 125 mm x 13 mm x 3 mm were positioned horizontally during the horizontal burning test. The Bunsen Burner flame was utilized for a specified duration, after which the distance or time it traversed was calculated.

Dynamic mechanical analysis

The DMA was employed to evaluate viscoelastic properties, including the storage modulus and loss factor. Following the guidelines of ASTM D4065-20 (2020), the analysis was conducted using a dual cantilever-mounted DMA system operating in sweep mode. A temperature interval of 30 to 260 °C was employed for the test, with a regulated heating rate of 5 °C per minute, while maintaining a constant frequency of 1 kHz throughout the experiment.

FTIR and SEM analysis

Fourier Transform Infrared (FTIR) spectroscopy was conducted using a PerkinElmer Spectrum Two spectrometer to identify functional groups and assess the effectiveness of silane treatment on hemp fibres and composite interfaces. The spectra were recorded in the range of 4000 to 500 cm^{-1} with a resolution of 4 cm^{-1} using the KBr pellet technique. The characteristic absorbance peaks were analyzed to confirm the formation of Si–O–Si and other surface functional groups, validating enhanced interfacial bonding between fibre and matrix.

The surface morphology of the fractured composite specimens was examined using a Carl Zeiss Sigma 300 Field Emission Scanning Electron Microscope (FE-SEM). Prior to imaging, the samples were sputter-coated with a thin layer of gold to prevent charging. SEM micrographs were used to evaluate fibre–matrix adhesion, filler dispersion, void formation, and failure mechanisms under mechanical loading

RESULTS AND DISCUSSION

FTIR Analysis

Figure 1 shows the FTIR spectra of silane-treated bio filler particles. The FTIR analysis identified evident functional groups and structural changes on the surfaces of fibres and particles following acid hydrolysis and silane treatment. The absorbance peaks observed at 3697.2 cm^{-1} and 3349.2 cm^{-1} were attributed to the NH_2 functional group, confirming the formation of amino acid silane during the treatment process. Furthermore, minor peaks observed between 1721.0 and 1493.0 cm^{-1} indicated the presence of C-H bonds, as demonstrated by the elongation and deflection of IR waves. The silane modification process was validated by peaks at 1038.3 cm^{-1} and 874.4 cm^{-1}, confirming the formation of the Si-O-Si silane structure during oven drying (Jayabalakrishnan *et al.* 2022). The modifications improved surface adhesion, which is essential for enhancing interfacial bonding in bio-composites. The FTIR analysis indicates effective surface

functionalization, which is crucial for enhancing the mechanical and bonding properties of the composite.

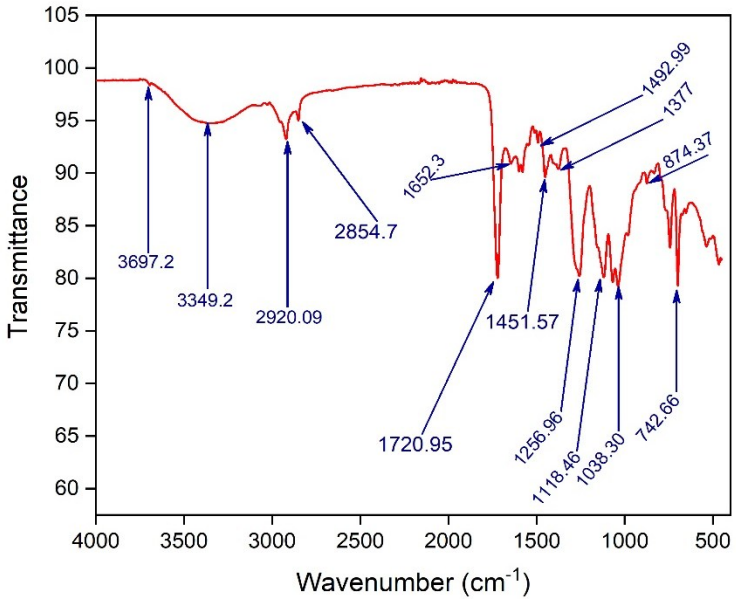

Fig. 1. FTIR spectral graphs of surface-treated composite

Mechanical Properties

Figure 2 displays the tensile, flexural, and compressive strength values for the P, TF, T1, T3, and T5 composite specimens. Figure 3 shows the corresponding stress-strain curves. The findings indicate that an increase in filler content from P to T3 correlated with consistent improvements in tensile, flexural, and compressive strengths, with T3 demonstrating the highest values in all assessments. The observed enhancement can be attributed to the improved load transfer efficiency, stronger interfacial bonding between the filler and matrix, and the uniform dispersion of filler particles.

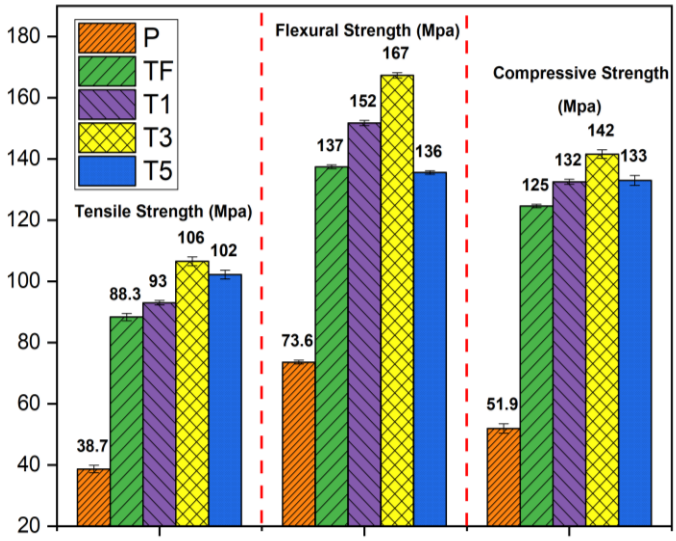

Fig. 2. Mechanical strength *vs* various composites

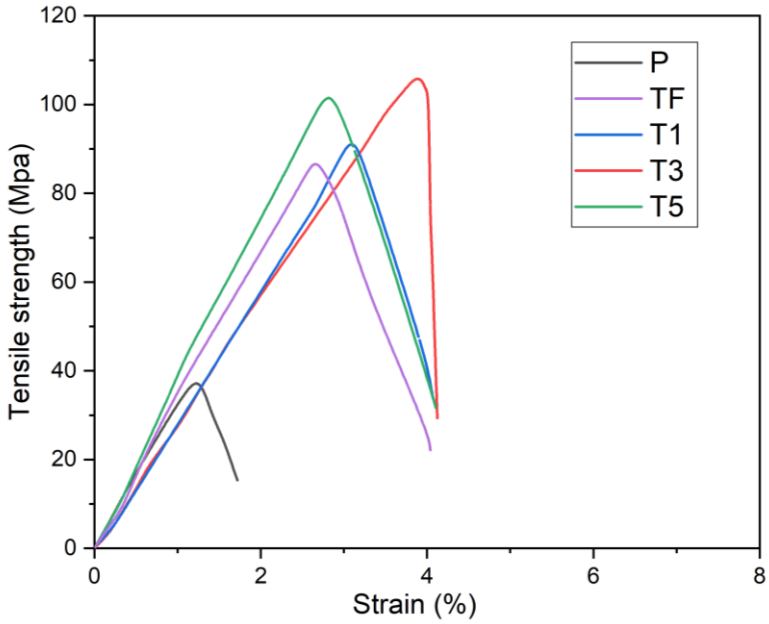

Fig. 3. Tensile stress–strain behavior

This suggests that an optimal filler content ensures effective stress transfer and matrix reinforcement without creating voids or weak zones. These factors synergistically contribute to reinforcing the composite, thereby increasing its resistance to externally applied stresses (Asyraf *et al.* 2022). This structural improvement results from the formation of a continuous stress-transfer network between the silane-treated hemp fibres and the polyester matrix, allowing better mechanical interlocking and minimizing voids. The enhanced fibre–matrix interface directly translates into higher strength values, confirming the critical role of microstructural uniformity in mechanical performance. Specimen T5 exhibits a decrease in all three mechanical strengths. The observed decline is likely attributable to excessive filler content, which results in particle agglomeration (Dhanasakkaravarthi *et al.* 2025). The agglomerated regions disrupt stress continuity and create weak points in the internal structure, demonstrating how filler dispersion strongly influences the structure–property relationship. Thus, maintaining uniform filler distribution is crucial to preserve mechanical integrity.

Hardness Test

Figure 4 presents the Shore D hardness values of the specimens P, TF, T1, T3, and T5. A gradual increase was observed from P (76) to T5 (86), with a minor plateau between TF and T3 (both at 83). The enhancement in hardness can be attributed to the uniform dispersion of fibres and improved interfacial bonding with the polyester matrix, which collectively increase resistance to surface deformation (Thanu *et al.* 2023). Structurally, the higher hardness suggests restricted polymer chain mobility near the well-bonded interfaces, confirming that interfacial integrity contributed to the composite's resistance against localized deformation. The maximum hardness observed in T5 is likely due to higher filler loading, contributing to increased rigidity; however, excessive filler may introduce drawbacks such as reduced toughness or localized stress concentrations.

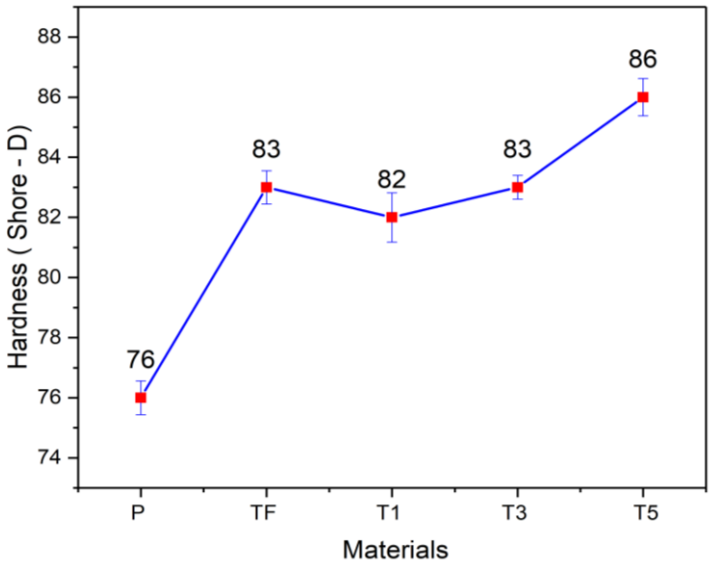

Fig. 4. Results of hardness Shore D of various composites

Impact Energy

Figure 5 illustrates the impact energy of the composites P, TF, T1, T3, and T5. A progressive increase was observed from P (0.32 J) to T3 (5.4 J), followed by a slight decline in T5 (5.0 J). The enhancement up to T3 is attributed to improved fibre–matrix adhesion and uniform fibre distribution, which facilitate effective energy absorption and hinder crack propagation. This demonstrates that a stronger interfacial structure allowed stress redistribution during sudden loading, preventing brittle fracture. The energy absorption mechanism was thus governed by the integrity and bonding at the interface. The marginal reduction in T5 was likely due to filler agglomeration at higher content, which impaired stress transfer and reduced fracture resistance (Sanjay *et al.* 2018).

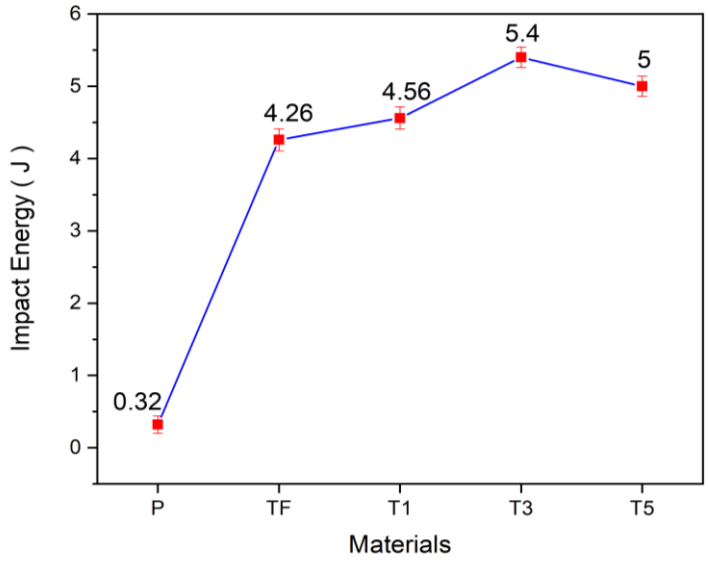

Fig. 5. Results of impact energy of various composites

Hydrophobicity Test

The hydrophobicity test outcomes, assessed using the water contact angle, revealed considerable disparity among the evaluated materials. Material TF demonstrated the highest contact angle of around 97°, signifying exceptional hydrophobic characteristics. Conversely, material T5 had the lowest contact angle of around 86°, indicating lower hydrophobicity. The intermediate materials, P, T1, and T3, exhibited contact angles lying between these extremes, indicating moderate hydrophobic properties. The results underscore the efficacy of various treatments in augmenting or reducing the hydrophobicity of natural fibre composites (Karthigairajan *et al.* 2021), with TF demonstrating the highest hydrophobicity among the materials evaluated. The investigation highlights the significance of surface treatment in altering hydrophobic characteristics. This improvement in water repellency confirmed the success of silane treatment in minimizing surface hydroxyl groups and enhancing composite durability.

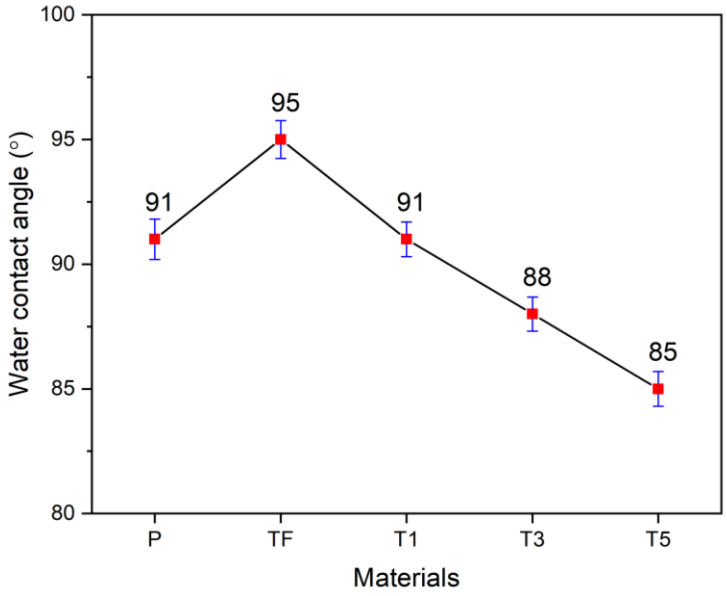

Fig. 6. Hydrophobicity of composites

Fatigue Test

The fatigue test results (Fig. 7) revealed considerable variation in fatigue life among the samples P, TF, T1, T3, and T5. The neat resin (P) exhibited the lowest fatigue life at 1890 cycles, indicating limited resistance to cyclic loading. Incorporation of fibres and filler significantly improved fatigue performance (Malakar *et al.* 2025) with TF achieving 3427 cycles, and T1 and T5 reaching 3894 and 4312 cycles, respectively. T3 exhibited the highest fatigue life of 4394 cycles, indicating an optimal combination of filler content and interfacial adhesion. Although T5 showed slightly lower fatigue life than T3, it still marked a substantial improvement over P.

The SEM analysis supports these findings. Figure 8(a) shows a brittle, planar fracture surface in the neat resin, consistent with poor fatigue resistance. In contrast, T1 (Fig. 8b) displays strong fibre–matrix adhesion, while T3 (Fig. 7c) reveals the absence of delamination, indicative of enhanced bonding and effective load transfer. The enhanced fatigue behaviour of the treated composites can be primarily ascribed to improved interfacial strength and a more uniform stress distribution, highlighting the role of surface

treatments in improving durability under cyclic loading. The uniform stress distribution achieved through fibre–matrix interaction plays a major role in delaying crack initiation and propagation, thereby extending fatigue life.

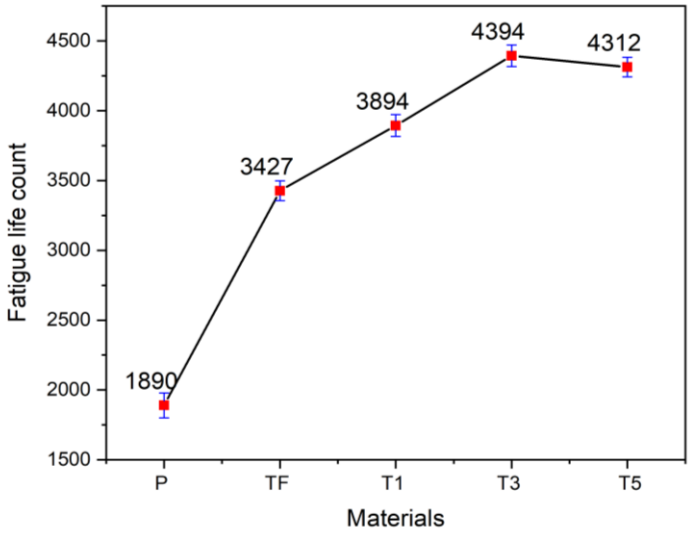

Fig. 7. Fatigue life cycles of surface treated composites

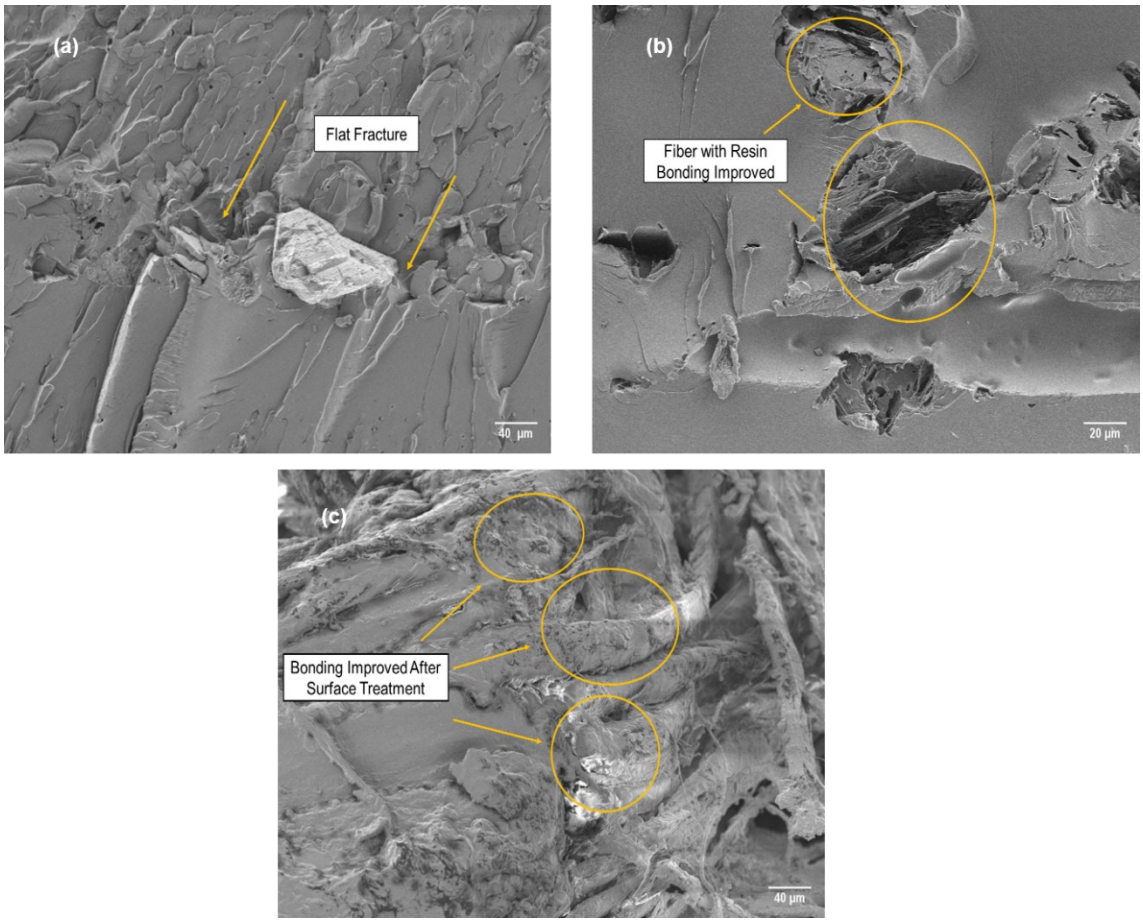

Fig. 8. SEM fractography for fatigue samples

Wear Test Results

The specific wear rate and associated coefficient of friction (COF) for P, TF, T1, T3, and T5 specimens are presented in Fig. 9. A consistent decline in both parameters was observed across the treated composites. The neat resin (P) recorded the highest COF (0.41) and specific wear rate (0.032 mm^3/Nm), indicating inferior wear resistance. In contrast, T5 exhibited the lowest COF (0.17) and wear rate (0.008 mm^3/Nm), reflecting enhanced tribological performance. This improvement is attributed to the surface treatments, which enhance fibre–matrix adhesion, reduce surface roughness, and increase hardness, thereby minimizing frictional forces and material loss (Pieniak *et al.* 2025). Additionally, the reduced friction coefficients may result from the presence of fine wear debris acting as micro-rollers between sliding surfaces, further lowering resistance. The results substantiate the role of the treatments in improving both wear resistance and frictional stability of the composites.

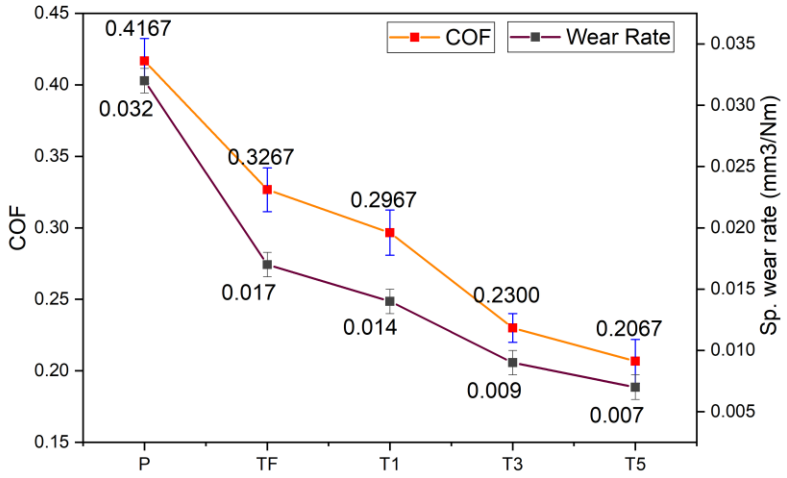

Fig. 9. The COF and sp. wear rate for different composite designations

Flammability Test

Flammability test results for the composite samples (P, TF, T1, T3, and T5), including flame propagation velocity, UL-94 ratings (horizontal and vertical), falling droplets, and cotton ignition, are summarized in Table 3. Sample P recorded the lowest burn rate of 10.26 mm/min and attained a V-0 classification in the UL-94 vertical test, demonstrating superior flame-retardant performance. This behaviour was attributed to the higher cross-link density, which promotes the development of a stable char layer serving as a thermal barrier during combustion (Bai *et al.* 2025). However, P received only an HB rating in the horizontal test. Samples TF and T1 showed increased flame propagation rates (17.3 and 20.2 mm/min, respectively), with V-1 vertical ratings and HB horizontal ratings, indicating moderate flame resistance. T3 and T5 exhibited the highest burn rates (23.2 mm/min and 25.6 mm/min, respectively), corresponding to V-2 ratings in the vertical test and reduced flame resistance. No falling droplets or cotton ignition were observed for any samples, suggesting acceptable flammability behavior overall. The slight decrease in flame resistance with filler addition may be linked to the organic nature of hemp and fruit shell particles, which tend to support charring at elevated temperatures.

Table 3. Evaluation of Flammability in Various Composite Combinations

Composite Type	Burn Rate (mm/min)	Horizontal Rating UL-94	Dripping Present	Ignition Observed	Vertical Rating UL-94
P	10.26	HB	NIL	NIL	V-0
TF	17.32	HB	NIL	NIL	V-1
T1	20.24	HB	NIL	NIL	V-1
T3	23.17	HB	NIL	NIL	V-2
T5	25.65	HB	NIL	NIL	V-2

DMA

Figure 10 presents the DMA results, showing the storage modulus and loss factor as functions of temperature for the samples P, TF, T1, T3, and T5. All samples exhibited a typical decline in storage modulus with increasing temperature, reflecting thermoplastic behaviour. Sample P showed the lowest modulus across the temperature range, while the inclusion of hemp fibres in the polyester matrix improved stiffness and reduced damping (loss factor) (Nikhil *et al.* 2025). Samples T1, T3, and T5 displayed higher initial moduli with evident drops around 90 °C, indicating the occurrence of glass transition.

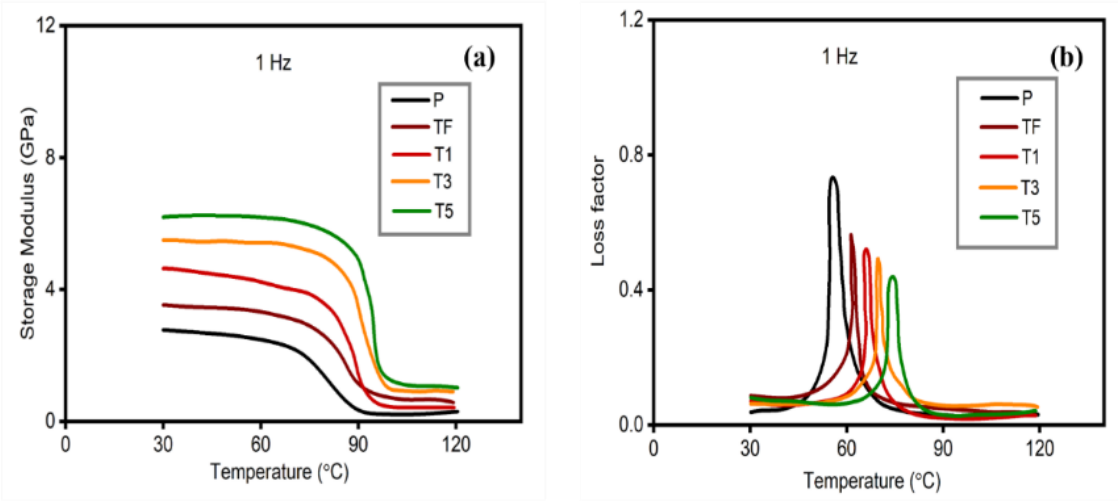

Fig. 10. Analysis of (a) storage modulus and (b) loss factors for different composite formulations

The loss factor curves revealed distinct damping behaviour, with sharp peaks near 60 °C for all samples. The TF exhibited the most prominent peak, indicating greater energy dissipation at that temperature. Variations in peak intensity and position suggest differences in viscoelastic properties among the samples, influenced by fibre–matrix interactions and compositional modifications. These findings confirm the role of natural fibre reinforcement and surface treatment in tuning the thermal-mechanical response of the composites. To quantify the glass transition temperature (T_g), the peak positions of the tan δ curves were analyzed. The neat polyester (P) exhibited a T_g of approximately 65 °C, while

the silane-treated fibre composite (TF) showed a T_g of ~72 °C. The hybrid composites demonstrated progressively higher T_g values with increasing reinforcement content: T1 (~78 °C), T3 (~85 °C), and T5 (~88 °C). This upward shift in T_g reflects restricted polymer chain mobility due to enhanced interfacial bonding and filler dispersion. These trends demonstrate that silane treatment and bio-filler incorporation not only improve stiffness and damping control but also delay the onset of glass transition, thereby enhancing the composites' load-bearing capacity at elevated temperatures. These trends demonstrate that silane treatment enhanced interfacial bonding. The enhanced bonding limited polymer chain mobility and improved load-bearing capacity at elevated temperatures.

CONCLUSIONS

This study investigated the effects of silane-treated hemp fibres and *Lansium parasiticum* shell powder on the mechanical, tribological, thermal, and flammability properties of polyester-based hybrid bio composites. The major findings are summarized below:

- **Surface modification confirmed:** Fourier transform infrared (FTIR) analysis validated successful silane treatment through the presence of amino and Si–O–Si functional groups, indicating enhanced fibre–matrix interfacial bonding.
- **Optimal mechanical performance:** The T3 composite exhibited superior tensile, flexural, and compressive strength, along with the highest fatigue life (4394 cycles), confirming its suitability for structural applications.
- **Tribological enhancement with filler loading:** T5 demonstrated the lowest wear rate (0.008 mm^3/Nm) and coefficient of friction (0.17), although excessive filler content led to agglomeration, negatively impacting strength and hydrophobicity.
- **Thermo-mechanical behavior:** Dynamic mechanical analysis (DMA) results revealed increased stiffness and delayed glass transition temperatures (~90 °C) in T1, T3, and T5. TF showed enhanced damping behavior (~60 °C), indicating efficient energy dissipation.
- **Flammability characteristics:** All composites were self-extinguishing. However, increased filler content slightly accelerated flame propagation, with T3 and T5 showing higher burn rates.

Significance of the Study

The significance of this study lies in transforming agricultural and fruit-shell waste into value-added reinforcements for polymer composites, aligning material performance enhancement with circular-economy principles. By effectively combining silane-treated hemp fibre and Lansium parasiticum shell powder, this work bridges environmental responsibility with engineering performance. The developed bio composites demonstrate a sustainable pathway for producing lightweight, durable, and cost-effective components, supporting the advancement of eco-friendly materials for structural and industrial applications.

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