Enhanced Properties of Eco-Friendly Epoxy Composites with *Luffa acutangula* and Sawdust Reinforcement

Srinivas Tadepalli [a,*] and Thulasi Mani Murugesan [b,*]

Hybrid epoxy composites were reinforced with a constant 20 wt% of *Luffa acutangula* fiber (LAF) and varying Sal wood sawdust (SWD) content ranging from 0 to 25 wt%. The evaluation covered mechanical properties including tensile, flexural, impact strengths, hardness, and water absorption behavior. Results indicated a notable enhancement in all mechanical properties up to 15 wt% SWD, with a slight reduction observed beyond this point. The composite with 20LAF/15SWD exhibited superior performance, achieving tensile, flexural, and impact strengths of 46 MPa, 66 MPa, and 3.12 J, respectively. Shore D hardness and water absorption tests confirmed increased material rigidity and decreased moisture affinity up to the 15 wt% SWD level. Scanning electron microscopy revealed improved fiber–matrix bonding and homogeneous filler distribution at the optimal formulation. These findings highlight the potential of combining *Luffa acutangula* fiber and sawdust as sustainable reinforcements for high-performance biocomposites.

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INTRODUCTION

Natural fiber-reinforced polymer composites have attracted considerable attention due to their environmental sustainability, lightweight properties, and cost-effectiveness. *Luffa acutangula* fiber (LAF) is recognized for its moderate strength, porous surface that improves adhesion, and local availability (Sharath *et al.* 2024). Sawdust (SWD), a byproduct of woodworking industries, has a high surface area and cellulose content, making it a promising candidate for particulate reinforcement (Arul *et al.* 2024). Hybrid composites incorporating short fibers and particles aim to enhance strength, stiffness, and toughness. This study explores the combined impact of incorporating LAF and SWD with epoxy resin to enhance the performance of composites. This investigation explored mechanical behavior, hardness, water absorption, and microstructural characteristics to evaluate the effectiveness of reinforcement (Fathima *et al.* 2024). The rising global demand for sustainable and eco-friendly materials has established natural fiber-reinforced polymer composites (NFRPCs) as a central focus in the field of materials research and engineering applications (Alhijazi *et al.* 2020). This shift is driven by ecological factors and the need to reduce reliance on synthetic materials derived from petroleum, which are not biodegradable and generally demand considerable energy for their production (Mina 2018). Natural fibers derived from renewable materials offer notable benefits, such as biodegradability, low density, high specific strength, accessibility, and cost-effectiveness. Their characteristics make them ideal for enhancing polymer matrices, especially concerning the reduction of carbon footprints and the promotion of circular economy principles (Saada *et al.* 2024). The application of natural fiber composites is increasingly prevalent in various engineering fields, including automotive, aerospace, marine, civil infrastructure, sports equipment, and packaging (Motaung *et al.* 2017). Their decreased weight, simplicity in processing, and sufficient mechanical properties make them suitable for semi-structural and functional components (Antor *et al.* 2025). Recent developments in surface treatment technologies, fiber hybridization, and the inclusion of particulate fillers have significantly improved the performance characteristics of these materials, making them comparable to synthetic alternatives in multiple areas (Fragassa *et al.* 2024).

In this study, the simultaneous use of *Luffa acutangula* fiber (LAF) and sawdust (SWD) was intentionally designed to leverage their complementary characteristics, rather than adding redundant complexity. LAF, a short natural fiber with a porous surface and vascular structure, primarily functions as a load-bearing reinforcement, enhancing tensile and flexural strength through efficient stress transfer and interlocking with the epoxy matrix. SWD, on the other hand, acts as a particulate filler, filling microvoids, improving fiber–matrix wetting, and enhancing dimensional stability while reducing water absorption (Sikhosana *et al.* 2025). Its high surface area and cellulose content contribute to improved toughness and reduced crack propagation under mechanical stress. The choice of LAF and SWD is strategic—their distinct morphology (fiber *vs.* particle) and reinforcement mechanisms enable synergistic improvements in composite performance without direct interference. Additionally, both are locally available, low-cost bio-wastes, aligning with sustainability and circular economy goals (Islam *et al.* 2024). This dual-reinforcement approach allows for enhanced mechanical properties and environmental resistance, addressing the limitations of single-fiber composites and making the material suitable for broader engineering applications (Manickaraj *et al.* 2025).

Natural fibers are primarily composed of cellulose, hemicellulose, lignin, and pectin, which collectively contribute to their mechanical integrity (Bhagwat and Jaspal 2022). Cellulose acts as the main element that enhances tensile strength and stiffness, while hemicellulose and lignin influence water absorption properties and thermal characteristics (Paula *et al.* 2024). The unique microstructure of natural fibers, defined by their hollow lumen, fibrillar orientation, and surface roughness, facilitates mechanical interlocking with polymer matrices, enhancing interfacial bonding and load transfer efficiency (Bhuvaneswari *et al.* 2022). Over the years, various plant-based fibers, such as flax, jute, hemp, kenaf, sisal, coir, and banana, have been extensively examined for their ability to enhance thermoplastic and thermoset resins. Newly developed fibers such as *Luffa acutangula*, commonly known as ridge gourd or sponge gourd, have garnered interest because of their distinctive characteristics, availability, and minimal processing expenses (Schio *et al.* 2022). *Luffa acutangula* fiber (LAF), obtained from the mature fruits of the ridge gourd plant, offers several benefits over conventional natural fibers (Fragassa *et al.* 2024). The material exhibits a lightweight structure, impressive tensile strength, a porous surface morphology, and advantageous thermal stability. The configuration of fibrous vascular bundles in LAF creates a network that enhances mechanical interlocking with resins, making it particularly suitable for composite reinforcement (Manickaraj *et al.* 2024a). LAF demonstrates biodegradability, is easily obtainable in tropical and subtropical regions, and can be cultivated with a low environmental footprint. However, akin to many lignocellulosic fibers, its inherent hydrophilicity due to hydroxyl groups leads to insufficient compatibility with hydrophobic polymer matrices (Giri *et al.* 2024). Alkali treatment using NaOH is commonly employed to remove surface impurities such as waxes, as well as possibly decreasing the amounts of lignin and hemicellulose. The chemical modification improves surface roughness and boosts the availability of hydroxyl sites, thereby promoting better fiber–matrix adhesion (Jagadeesh *et al.* 2022; Palaniappan *et al.* 2025).

Epoxy resin stands out as a key matrix material in the realm of composite fabrication within thermosetting polymers, recognized for its remarkable mechanical strength, chemical resistance, dimensional stability, and excellent adhesion properties (Iwuozor *et al.* 2024). Epoxy shows negligible shrinkage during the curing process, exhibits resistance to moisture and fatigue, and is compatible with various reinforcements, making it an appropriate choice for structural applications (Thangavel *et al.* 2024).

Epoxy composites find applications across multiple sectors, such as aerospace, marine, electronics, and sports equipment. Unmodified epoxy resins exhibit brittleness and have limited resistance to crack propagation (Aravindh *et al.* 2022). Efforts are currently underway to improve the toughness and durability of epoxy composites through the integration of fibers and fillers. Recent studies underscore the importance of bio-based particulate fillers, such as rice husk ash, wheat husk, coconut shell powder, and sawdust, in improving the performance of polymer composites (Satankar *et al.* 2023). The inclusion of these fillers leads to a decrease in costs while simultaneously improving mechanical strength, stiffness, and wear resistance, thanks to their high lignin and cellulose content. Sawdust (SWD) is a common byproduct of timber processing; it is often discarded or burned, leading to environmental pollution (Aigbodion *et al.* 2019). Sawdust functions as a highly efficient filler material, presenting considerable opportunities for waste valorization. The fibrous structure and increased surface area associated with sawing promote better dispersion within the polymer matrix, leading to enhanced stress distribution and reduced void formation in composites (Akhil *et al.* 2023). Furthermore, its relatively low density contributes to the overall lightweight characteristics of the composite (Manickaraj *et al.* 2024b). Sawdust, when mixed with continuous or short natural fibers, acts as a secondary reinforcement by filling the gaps in the matrix, reducing shrinkage, improving fiber wetting, and helping to stop cracks during impact or fatigue loading. This combined method has the potential to improve mechanical properties while maintaining environmental sustainability (Gurusamy *et al.* 2025). Determining the ideal filler loading is crucial for achieving the desired performance results. Insufficient filler content may not effectively alter matrix behavior, while an excess of filler can lead to particle agglomeration, poor dispersion, and reduced interfacial adhesion, ultimately undermining the properties of the composite (Sasi Kumar *et al.* 2023). A thorough examination of different SWD content is crucial to determine the best formulation. The main drawback of natural fiber composites is their susceptibility to moisture absorption, which affects dimensional stability, interfacial adhesion, and long-term performance (Ramachandran *et al.* 2022). The diffusion of water molecules through the matrix leads to their accumulation at the fiber–matrix interface, which causes swelling, microcracking, and ultimately debonding. This not only reduces the mechanical properties but also accelerates degradation under cyclic environmental conditions (Suriani *et al.* 2021). Fillers such as SWD effectively minimize water absorption by filling voids and acting as a barrier to water diffusion. Furthermore, the chemical treatment of fibers and fillers reduces the number of available hydroxyl groups, which in turn enhances hydrophobicity. The anticipated hybridization with SWD is likely to improve mechanical properties and reduce water absorption, which would consequently enhance the durability of the composite for outdoor applications (Sekar *et al.* 2025).

This study is guided by the hypothesis that the unique morphology of *Luffa acutangula* fibers (LAF)—characterized by their vascular bundles, high aspect ratio, and porous structure—can contribute to a bulky and lightweight composite, potentially introducing internal air pockets that reduce density and enhance energy absorption, similar to a solid foam structure. Simultaneously, the small particle size and irregular geometry of sawdust (SWD) are hypothesized to synergistically enhance the composite's performance by filling voids around the fibrous reinforcement, improving matrix packing, reducing porosity, and impeding crack propagation under load. This hypothesis is supported by literature indicating that porous and low-density natural fibers such as LAF improve interfacial bonding and reduce composite density while contributing to better mechanical interlocking (Daniel-Mkpume *et al.* 2019; Masud and Mubashar 2024). Meanwhile, studies on particulate fillers such as SWD demonstrate their ability to occupy microvoids, enhance dimensional stability, and act as crack-arresters due to their lignocellulosic composition and high surface area (Mohapatra *et al.* 2024; Arul *et al.* 2025; Sikhosana *et al.* 2025). The size and shape disparity between fibrous LAF and granular SWD may thus facilitate multi-scale reinforcement, leading to enhanced mechanical properties and reduced moisture uptake. This study seeks to validate this hypothesis by systematically varying SWD content and evaluating its interactive effect with constant LAF reinforcement (Ramakrishnan *et al.* 2024; Karuppusamy *et al.* 2025).

This study aimed to contribute to the current body of knowledge regarding the development of sustainable composites using agricultural and industrial bio-waste (Vignesh *et al.* 2021; Sali *et al.* 2025). This work employed locally sourced, renewable reinforcements and explored their synergistic effects, presenting an environmentally sustainable and economically viable solution for engineering applications that demand moderate mechanical performance and environmental compatibility (Kuan *et al.* 2021).

EXPERIMENTAL

Materials

Epoxy resin (matrix)

The matrix employed in this investigation was a commercially available bisphenol-A-based epoxy resin (LY556) mixed with an amine-based hardener (HY951). The ratio of resin to hardener was consistently upheld at 10:1 by weight, in accordance with the specifications provided by the manufacturer (Mahesh *et al.* 2025).

Salwood Sawdust (SWD)

The sawdust used in this study was specifically sourced from sal wood (*Shorea robusta*), a common hardwood species processed by nearby timber mills. The material, distinguished by high levels of lignin and cellulose, underwent a sieving process to obtain a uniform particle size and was then dried at room temperature for 24 h to eliminate moisture as shown in Fig. 1(a) and 1(b). (da Costa *et al.* 2020).

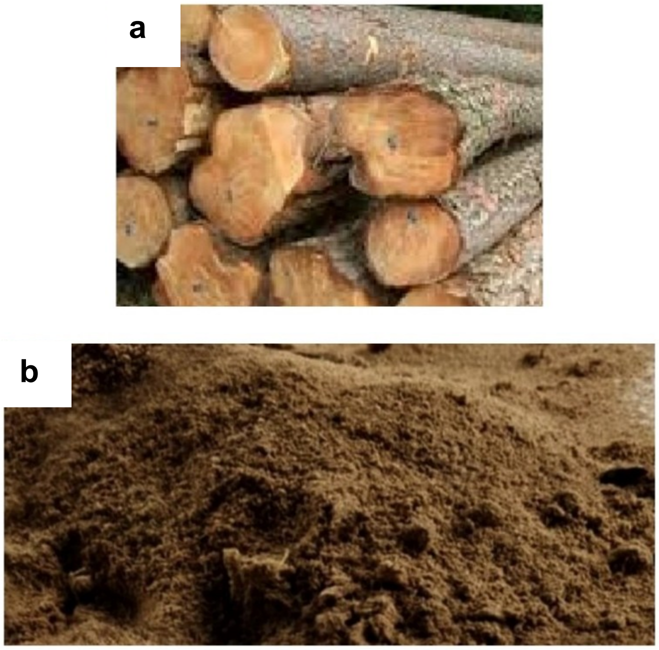

Fig. 1a. Sal wood tree; **1b.** Salwood saw dust

Fig. 2a. *Luffa acutangula*; **2b.** *Luffa acutangula* fiber

Luffa acutangula Fiber (LAF)

The fiber was sourced locally from fully matured ridge gourd plants. The fibrous network underwent extraction, followed by thorough washing, and was then dried Fig. 2(a) and 2(b). The fibers were then cut into short lengths of about 20 mm and subjected to chemical treatment (Karuppusamy *et al.* 2025).

Alkali Treatment of LAF

The process entailed subjecting the fiber to a 5% NaOH solution for 4 h to enhance the adhesion between the fiber and matrix. The procedure successfully removed lignin, hemicellulose, and surface contaminants. The fibers were subjected to several washes with distilled water to remove alkali residues and were then dried in an oven at 60 °C for a duration of 48 h (Sahu and Gupta 2022).

Composite Fabrication

The composite laminates were fabricated using the hand lay-up technique, which was then followed by compression molding. The content of *Luffa acutangula* fiber (LAF) was consistently held at 20 wt% in all formulations, whereas the sal wood sawdust (SWD) content was varied at 0, 5, 15, and 25 wt%. The remaining portion was made up of epoxy resin and hardener mixed in a 10:1 weight ratio (Palanisamy *et al.* 2023b; Thirupathi *et al.* 2024). The composite formulations are detailed in Table 1.

Table 1. Composite Formulations

Sl No	*Luffa Acutangula* Fiber (LAF) Layer (wt%)	Salwood dust (SWD) Particles (wt%)	Epoxy Resin (wt%)	Sample Designation
1	20	25	55	20FL/25SWD
2	20	15	65	20FL/15SWD
3	20	5	75	20FL/5SWD
4	20	0	80	20FL/0SWD

Fabrication Process

The epoxy resin was combined with the hardener in a precise 10:1 ratio. Following this, *Luffa acutangula* fiber and salwood sawdust were incrementally incorporated into the resin while maintaining continuous stirring to ensure uniform dispersion and minimize air entrapment. A stainless-steel mold underwent a cleaning process and was subsequently treated with a releasing agent to prevent adhesion during the curing phase. The mixture was introduced into the mold, distributed evenly, and gently pressed with a metal plate to eliminate any trapped air bubbles (Manickaraj *et al.* 2025). The mold was subsequently sealed and underwent compression with a hydraulic press, applying a pressure of 5 MPa. The curing process took place at room temperature for 24 h under pressure, subsequently followed by post-curing to ensure complete polymer crosslinking and improved dimensional stability (Ighalo *et al.* 2021). The cured composite laminates were then precisely cut into standard test specimen dimensions using a diamond saw, adhering to the relevant ASTM standards (Chithra *et al.* 2024).

Testing and Characterization

Composite samples were subjected to a comprehensive series of tests in accordance with ASTM standards to evaluate their mechanical, physical, and morphological characteristics.

Tensile Testing (ASTM D638-14 2022)

Tensile testing was conducted following ASTM D638-14 (2022) standards using Type I specimens. The experiments were carried out utilizing a Universal Testing Machine (UTM) with a crosshead speed set at 5 mm/min. The objective of the test was to assess the tensile strength of the composites and to examine the efficacy of fiber-matrix bonding when subjected to axial loading conditions (Okonkwo *et al.* 2020).

Flexural Properties (ASTM D790-17 2017)

The flexural properties were evaluated in accordance with ASTM D790-17 (2017) through the application of the three-point bending method. The span-to-depth ratio was consistently maintained at 16:1. This test aimed to evaluate the flexural strength and stiffness of composite laminates, which are crucial for structural applications (Arumugam *et al.* 2022).

Evaluation of Impact Strength (ASTM D256 2023)

The evaluation of the impact strength of the composites was conducted using the Izod impact test, in accordance with ASTM D256 (2023) standards. Specimens featuring notches were meticulously prepared in accordance with established dimensions. This test provided valuable insights into the energy absorption capacity of the composites under sudden impacts, highlighting their toughness (Manikandan *et al.* 2024).

Evaluation of Hardness (ASTM D2240-15 2021)

Measurements of Shore D hardness were performed in accordance with ASTM D2240-15 (2021) standards. The evaluation measured the surface resistance of the composite samples to indentation, illustrating their ability to endure surface deformation and wear (Pugazhenthi and Anand 2023).

Evaluation of Water Absorption (ASTM D570-22 2022)

The analysis of water absorption behavior was conducted in accordance with ASTM D570-22 (2022). Composite samples were immersed in distilled water for a period of 24 h. The percentage of water absorption was calculated by evaluating the weight difference before and after immersion (Adeniyi *et al.* 2021). The assessment focused on the moisture resistance and long-term durability of the composites when exposed to humid or wet conditions.

Scanning Electron Microscopy

Fractured surfaces of tensile-tested samples were examined using Scanning Electron Microscopy (SEM) with a JEOL scanning electron microscope (JEOL (Germany) GmbH Gute Änger 30 85356 Freising German) set to an accelerating voltage of 15 kV. All specimens underwent gold coating prior to analysis to enhance surface conductivity (Palanisamy *et al.* 2022; Hosseini *et al.* 2023; Gokul *et al.* 2024; Beemkumar *et al.* 2025). The use of SEM provided valuable insights into the microstructural characteristics of the composites, highlighting aspects such as fiber-matrix interfacial bonding, the pull-out behavior of *Luffa acutangula* fibers, and the distribution and dispersion uniformity of sal wood sawdust particles (Sasan Narkesabad *et al.* 2023; Gurusamy *et al.* 2024; Sathish Gandhi *et al.* 2025). The SEM micrographs revealed microvoids, cracks, and delamination zones, highlighting the differences in mechanical performance among the different composite formulations (Aruchamy *et al.* 2025).

RESULTS AND DISCUSSION

This section discusses and analyzes the experimental results concerning the mechanical, physical, and microstructural characteristics of epoxy composites enhanced with LAF and SWD. The influence of different SWD content on each property is examined.

Tensile Test

The tensile strength of the developed epoxy composites exhibited a clear trend with different SWD content: it rose from 36 MPa for the 20FL/0SWD sample to a peak of 46 MPa for 20FL/15SWD, followed by a slight decline to 43 MPa for 20FL/25SWD. This trend can be elucidated by examining the fundamental material behavior and the mechanisms at the interfaces. The 20FL/0SWD composition consisted exclusively of 20 wt% LAF as the reinforcing agent, with no particulate filler included (Arul *et al.* 2024; Raghunathan *et al.* 2024; Sumesh *et al.* 2024a). While LAF enhances strength, the comparatively lower tensile value of 36 MPa indicates a restricted efficiency in stress transfer between the fiber and the matrix. The inherent characteristics of natural fibers include a rough, porous surface that can retain moisture, potentially impeding optimal interfacial adhesion with epoxy resin. Inadequate bonding results in fiber pull-out or debonding when subjected to axial loading, representing a prevalent failure mode in fiber-reinforced composites, thereby limiting the potential for tensile strength. The inclusion of 5 wt% SWD in the 20FL/5SWD sample resulted in an enhancement of tensile strength to 40 MPa (Karuppiah *et al.* 2020a; Kar *et al.* 2023; Palanisamy et al. 2024). This improvement can be attributed to the filler's function in enhancing load transfer and occupying microvoids within the matrix. SWD, with its high cellulose and lignin content, exhibits enhanced compatibility with the polymer matrix due to the presence of polar functional groups. The fine particles of SWD serve as secondary reinforcements, enhancing stress distribution by halting crack propagation and hindering matrix deformation (Fragassa *et al.* 2024; Varma *et al.* 2024). Furthermore, the presence of particulate matter enhances the interfacial bonding between the matrix and the fiber by augmenting frictional resistance and providing anchoring points along the load path The 20FL/15SWD sample exhibited the highest tensile strength at 46 MPa, suggesting an optimal effective interaction between LAF and SWD. At this level, SWD particles are adequately dispersed throughout the epoxy resin, improving matrix stiffness and enabling more uniform stress distribution across the composite. The integration of LAF's fibrous reinforcement with the microstructural attributes of the filler enhances the composite's ability to withstand tensile loading (Prasath *et al.* 2020; Palanisamy *et al.* 2023a). The matrix-fiber-filler interface establishes a well-structured balance, effectively utilizing the filler to diminish microcracks, enhance the interface's strength, and reduce the presence of weak zones. The effective distribution and bonding enhance the load-bearing ability of the composite, resulting in enhanced mechanical performance. Nevertheless, when the SWD content was increased to 25 wt% (20FL/25SWD), there was a slight decrease in tensile strength, which measured at 43 MPa. The observed decline can be attributed to the initiation of filler agglomeration. At elevated concentrations, the SWD particles exhibit a tendency to aggregate as a result of inadequate wetting within the viscous resin medium. The presence of these clusters leads to localized inhomogeneities, thereby enhancing the likelihood of voids and defects occurring within the matrix. Previous studies using Luffa fibers alone at various loadings (Mohanta and Acharya 2016; Daniel-Mkpume *et al.* 2019) have shown improvements in mechanical strength up to an optimal threshold, beyond which performance declines due to poor dispersion and fiber entanglement. In this study, a constant LAF content (20 wt%) was selected, and SWD was varied to improve matrix packing and interfacial bonding. The observed enhancement in tensile strength for the 20LAF/15SWD composite compared to LAF-only systems suggests that the introduction of SWD contributed positively by reducing voids and increasing stress transfer efficiency.

Furthermore, an excess of inflexible particles may compromise the matrix's integrity, reducing its ductility and leading to premature failure. In conclusion, the notable enhancement in tensile strength observed up to 15 wt% SWD highlights the advantageous reinforcement impact of effectively dispersed fillers when paired with LAF, leading to improved fiber-matrix adhesion and minimized voids (Mehdikhani *et al.* 2019; Keerthiveettil *et al.* 2025). Exceeding this optimal point leads to diminishing returns in tensile performance, mainly attributed to processing challenges, filler agglomeration, and structural discontinuities that counterbalance the benefits of increased filler content. Figure 3 illustrates the tensile strength.

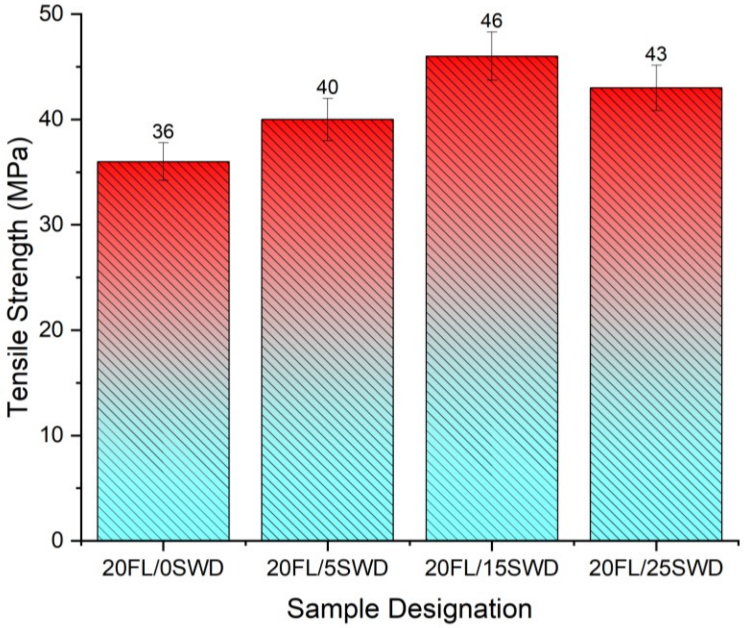

Fig. 3. Tensile strength

Flexural Strength

The flexural strength of the epoxy composites reinforced with *Luffa acutangula* fiber (LAF) and Sal wood sawdust (SWD) showed a steady enhancement as the SWD content increased to 15 wt%, after which there was a minor decrease at 25 wt%. At the outset, the 20FL/0SWD sample, which comprised solely 20 wt% LAF, exhibited a flexural strength of 56 MPa (Karuppiah *et al.* 2020b; Palaniappan *et al.* 2024b). This configuration allows the composite to leverage the unidirectional reinforcement provided by LAF, enhancing its ability to resist stress during bending. Nonetheless, the lack of particulate filler resulted in restricted support within the matrix regions between fibers, potentially facilitating early crack initiation and propagation under bending conditions. The incorporation of 5 wt% SWD into the 20FL/5SWD composite led to an enhancement in flexural strength, achieving a value of 60 MPa.

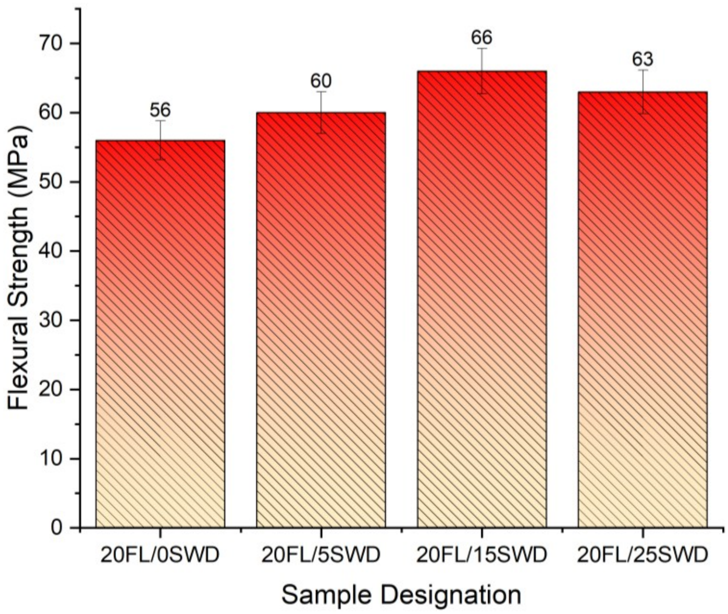

Fig. 4. Flexural strength

The observed increase can be attributed to the SWD particles functioning as micro-reinforcement elements, which improve stress transfer and impede matrix deformation (Vivek and Kanthavel 2019; Manalu *et al.* 2024; Ramakrishnan *et al.* 2025). The evenly distributed fillers fill the gaps between fibers and function as stress bridges, reinforcing the matrix during flexural loading scenarios. The inclusion of SWD enhances interfacial bonding by effectively filling microgaps and improving the mechanical interlocking between the fiber and matrix. The 20FL/15SWD sample demonstrated the highest flexural strength at 66 MPa, showcasing an optimal synergy between fiber and particulate reinforcements. In this formulation, the SWD content is adequate to establish a more rigid and crack-resistant matrix, while also ensuring effective dispersion and interfacial adhesion. The synergistic reinforcement effects of LAF and SWD significantly enhance stiffness and resistance to bending stresses, due to the well-balanced interactions among the matrix, filler, and fiber. The particles serve to strengthen the matrix while simultaneously inhibiting the initiation and spread of microcracks when subjected to flexural stresses. In the 20FL/25SWD sample, an increase in SWD content to 25 wt% resulted in a slight decrease in flexural strength, measuring 63 MPa. The observed reduction is linked to the excessive incorporation of fillers into the matrix, resulting in inadequate particle dispersion, agglomeration of fillers, and heightened porosity (Gopinath *et al.* 2022; Ramasubbu *et al.* 2024; Manickaraj *et al.* 2025). The presence of these defects undermines the structural integrity of the matrix, diminishes its continuity, and obstructs effective load transfer. Furthermore, an overabundance of fillers can interfere with the fiber wetting process and diminish the bonding area between the fiber and matrix, consequently adversely affecting the composite’s capacity to endure bending loads. In summary, the flexural strength behavior demonstrates that incorporating up to 15 wt% of SWD yields a positive reinforcing effect by enhancing interfacial bonding, improving load transfer, and increasing the rigidity of the matrix. In addition to this ideal filler content, the buildup of defects starts to negate the benefits, resulting in a minor decline in performance. Figure 4 illustrates the flexural strength.

Impact Strength

The impact strength of the epoxy composites reinforced with *Luffa acutangula* fiber (LAF) and Sal wood sawdust (SWD) showed a notable enhancement up to 15 wt% SWD, after which there was a minor decline at 25 wt%. The sample labeled 20FL/0SWD, comprising solely LAF, exhibited an impact strength of 1.52 J. In this configuration, the composite exhibited a relatively low capacity for energy absorption, as LAF, a natural fiber, generally possesses a limited capability to absorb sudden impact energy. The fibers, although they offer tensile reinforcement, are not capable of effectively dissipating impact loads because of their low fracture toughness and the absence of particulate reinforcement in the matrix (Ogunleye *et al.* 2022). The addition of 5 wt% SWD to the 20FL/5SWD sample resulted in an increase in impact strength to 2.43 J. The incorporation of SWD particles significantly enhanced the energy absorption capacity of the composite, probably because of the filler's role in improving the toughness of the matrix (Raju *et al.* 2021; Aramwit *et al.* 2023). The SWD particles, characterized by their elevated cellulose and lignin levels, functioned as micro-reinforcements that facilitated the dispersion of impact energy, thereby hindering the swift spread of cracks and enhancing the composite's ability to withstand sudden loads. The presence of these particles facilitated a more uniform distribution of impact force throughout the matrix, thereby minimizing localized failures and enhancing overall toughness. The 20FL/15SWD sample exhibited the highest impact strength at 3.12 J, suggesting that the optimal concentration of SWD particles (15 wt%) enhanced the composite's capacity to absorb impact energy effectively. Currently, the integration of LAF and SWD seems to offer the optimal equilibrium between stiffness and toughness. The fibers serve to enhance tensile strength, whereas the SWD particles contribute to the matrix's toughness by absorbing energy and inhibiting crack formation. The collaborative effect of LAF and SWD enhances the composite's ability to withstand impact failure, thereby increasing its durability when subjected to abrupt loading scenarios (Sathish *et al.* 2017; Sumesh *et al.* 2022; Ayrilmis *et al.* 2024). In the 20FL/25SWD composite, which had the highest SWD content at 25 wt%, the impact strength was observed to decrease to 2.71 J. The observed reduction can be linked to the surplus of SWD particles, which probably resulted in inadequate dispersion and agglomeration of the filler. The presence of these agglomerates could lead to the formation of localized weak points or voids within the composite, thereby diminishing the efficacy of the SWD particles in enhancing energy absorption. Furthermore, an overabundance of SWD content can modify the fiber-matrix interface, resulting in diminished interfacial bonding, which in turn impacts the composite's capacity to endure impact loading efficiently. The analysis indicates that the impact strength of the composites improved with the incorporation of SWD, reaching its peak at 15 wt%, which is identified as the optimal filler content (Srivastava and Mittal 2017; Palaniappan *et al.* 2024a). At this stage, an overabundance of SWD particles led to a decrease in impact strength, which can be attributed to inadequate filler dispersion, agglomeration, and diminished interfacial adhesion, ultimately undermining the composite's capacity to effectively absorb impact energy. Figure 5 illustrates the impact strength of the composites.

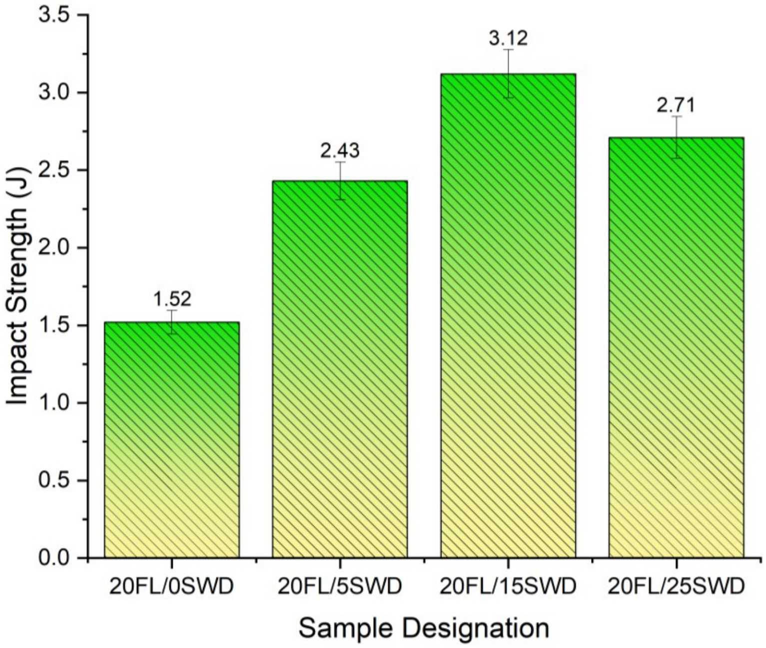

Fig. 5. Impact strength

Shore D Hardness

The hardness of the epoxy composites reinforced with LAF and SWD exhibited a distinct increasing trend with the incorporation of SWD up to 15 wt%, followed by a minor decline at 25 wt%. The sample with 20FL/0SWD, comprising solely 20 wt% LAF, exhibited a Shore D hardness value of 58. This composition features a matrix primarily composed of epoxy resin, which naturally exhibited a lower hardness in comparison to the fiber reinforcements (Palanisamy *et al.* 2021; Manalu *et al.* 2024). The LAF fibers, although providing strength and stiffness, did not substantially enhance the surface hardness due to their fiber morphology and the relatively weak interfacial bonding with the resin. The addition of 5 wt% SWD to the 20FL/5SWD composite resulted in a hardness increase to 65. The incorporation of SWD particles into the matrix significantly contributed to the improvement of surface hardness. The inclusion of particulate fillers enhanced the rigidity of the structure, thereby augmenting the composite's ability to resist indentation and surface deformation (Binoj *et al.* 2016; Sun *et al.* 2022). The SWD particles, characterized by their elevated cellulose content, enhanced the matrix by occupying voids and augmenting the overall stiffness of the composite. This resulted in enhanced hardness due to the filler particles forming a denser and less deformable structure. The 20FL/15SWD sample demonstrated the highest hardness value of 72, suggesting that the integration of LAF with an optimal quantity of SWD (15 wt%) markedly enhanced the surface hardness of the composite. In this composition, the particles were evenly distributed, and the interfacial bonding among the fiber, matrix, and filler was at its best, leading to a material that was both highly rigid and hard. The enhanced hardness arose from the synergistic interaction between LAF and SWD, where the filler contributed to the rigidity of the matrix, while the fibers impart tensile strength, leading to a composite that effectively resisted deformation when subjected to indentation or surface pressure. At 25 wt% SWD in the 20FL/25SWD composite, there was a slight decrease in hardness to 68. The observed decrease in hardness is likely due to the surplus of SWD, which could result in inadequate particle dispersion, agglomeration, or the creation of voids within the composite material.

These imperfections may lead to localized soft areas within the material, thereby diminishing its overall hardness. Moreover, an increased filler content could compromise the continuity of the matrix and its capacity to sustain a robust bond with the LAF fibers, which may further detrimentally influence the surface hardness. In conclusion, the hardness of the composites showed an increase with the incorporation of SWD up to 15 wt%, reaching its peak value at this optimal filler concentration (Sumesh *et al.* 2024; Bachtiar *et al.* 2025). Beyond this point, there was a slight decrease in hardness, which can be attributed to inadequate filler dispersion and the possible emergence of weak zones within the composite matrix. Consequently, the addition of SWD particles significantly improves the surface hardness of the composite; however, an overabundance of filler material may lead to negative consequences. Figure 6 illustrates the Shore D hardness of the composites.

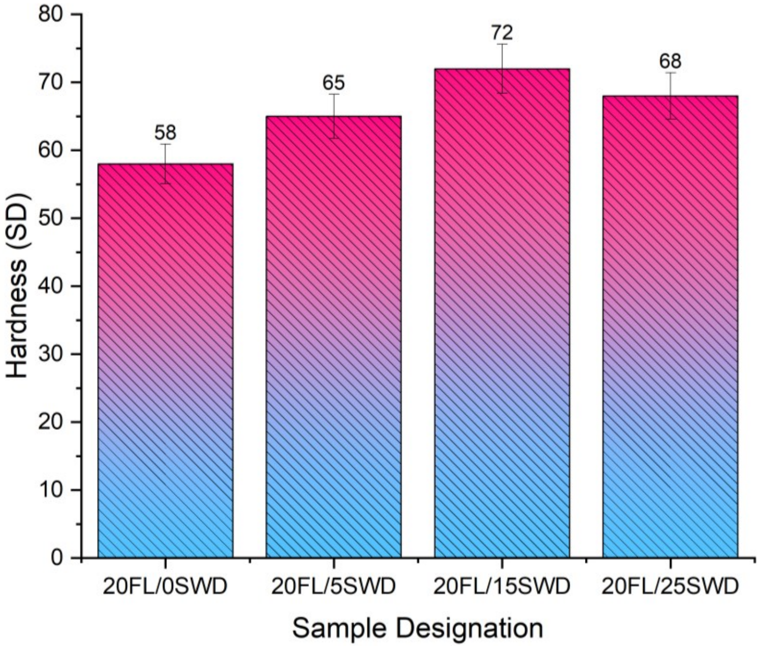

Fig. 6. Hardness of composites

Water Absorption

The water absorption behavior of the epoxy composites reinforced with LAF and SWD demonstrated a significant decrease in moisture uptake with the addition of SWD up to 15 wt%, followed by a minor increase at 25 wt%. The sample 20FL/0SWD, composed entirely of LAF, demonstrated the greatest water absorption at 18%. This phenomenon is common in natural fiber-reinforced composites, where fibers such as LAF possess hydroxyl groups that exhibit significant hydrophilicity. The presence of these groups allows the fibers to take in moisture, which may adversely affect the mechanical properties and dimensional stability of the composite, resulting in problems such as swelling and degradation (Prasad *et al.* 2023; Imran *et al.* 2024). The addition of 5 wt% SWD to the 20FL/5SWD composite resulted in a reduction of water absorption to 15%. The incorporation of SWD particles contributes to a decrease in the total water absorption of the composite. SWD, as a lignocellulosic material, possesses hydroxyl groups; however, its particulate form facilitates a more efficient distribution within the matrix, which can partially obstruct water from infiltrating the fiber-matrix interface. The outcome indicates a reduction in the composite's overall hydrophilicity, thereby enhancing its resistance to moisture absorption (Chaudhary *et al.* 2018; Ramesh *et al.* 2022; Aramwit *et al.* 2023).

The 20FL/15SWD sample exhibited the lowest water absorption, recorded at 10%. The ideal concentration of SWD (15 wt%) appeared to yield the most effective synergy of reinforcement from the fibers and the particles.

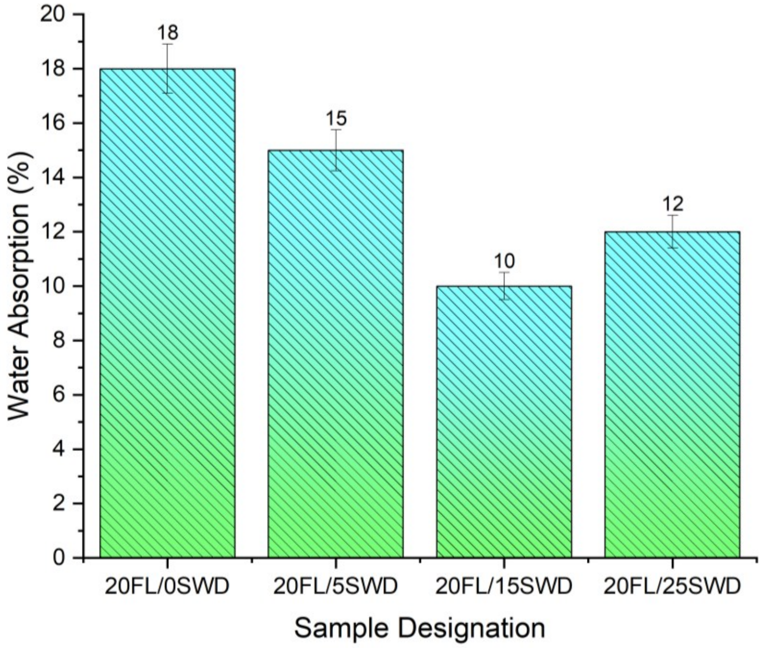

Fig. 7. Water absorption

The SWD particles occupied the spaces between the LAF fibers, effectively blocking water from penetrating the fiber-matrix interface and thereby lowering the total water absorption rate. Moreover, the increased SWD content probably contributed to enhanced dispersion and a more stable network structure within the matrix, which in turn further elevated the composite's resistance to moisture. In the 20FL/25SWD composite, which had the highest SWD content at 25 wt%, there was a slight increase in water absorption to 12%. The observed increase can be linked to the surplus of SWD particles, potentially leading to agglomeration or inadequate dispersion within the matrix. The formation of these agglomerates or clusters of SWD particles can result in localized areas where water may become trapped, consequently enhancing water absorption. Furthermore, an overabundance of filler content may compromise the consistency of the matrix, potentially elevating the overall porosity of the composite, which could subsequently allow for water penetration. In summary, the incorporation of SWD up to 15 wt% resulted in a reduction of water absorption in the composites, with the minimum absorption recorded at this optimal filler level (Adeniyi *et al.* 2021; Kavimani *et al.* 2022). Beyond this point, there was a slight increase in water absorption, which can be likely attributed to potential filler agglomeration and enhanced porosity within the composite. The integration of SWD particles effectively diminished water absorption, leading to enhanced moisture resistance and dimensional stability of the composite. Figure 7 illustrates the results of water absorption for the composites.

Scanning Electron Microscopy Analysis of the Composites

The microstructural characteristics of the fractured surfaces of the composite samples were investigated using SEM. The SEM images provide essential insights into the fiber-matrix interface, filler dispersion, and possible defects, clarifying the mechanical and physical properties observed. The SEM images of the 20FL/0SWD sample displayed a notably smooth fracture surface, featuring *Luffa acutangula* fibers integrated within the epoxy matrix. The interface between the fiber and matrix displayed weak properties, indicating a lack of strong adhesion between the fibers and the resin (Kurien *et al.* 2023; Palanisamy *et al.* 2023b; Pekhtasheva *et al.* 2023). The LAF fibers exhibited pull-out behavior, which can be linked to insufficient interfacial bonding between the fibers and the matrix. The matrix around the fibers showed signs of resin cracking and voids, which is typical of natural fiber composites that lack adequate interfacial adhesion. The presence of fiber pull-out and voids indicates a decrease in energy absorption capacity, which in turn leads to a reduction in the mechanical performance of the composite. SEM images demonstrated enhanced fiber-matrix adhesion in the 20FL/5SWD composite compared to the 20FL/0SWD sample. The SWD particles exhibited a uniform distribution throughout the matrix, efficiently filling the voids present between the LAF fibers. The improvement in interfacial adhesion between the fiber and matrix was evidenced by a reduction in fiber pull-out. The SWD particles exhibited significant adhesion to the epoxy resin, consequently enhancing the mechanical performance of the composite. Microcracks were noted, though in a restricted manner, indicating a moderate improvement in toughness and resistance to crack propagation. The composite with a ratio of 20FL to 15SWD displayed the most favorable microstructure in the SEM images (Kabir Ahmad *et al.* 2022; Nayak *et al.* 2022; Padmanabhan *et al.* 2024). The LAF fibers showed comprehensive embedding within the matrix, whereas the SWD particles displayed a consistent distribution throughout the composite. The interface between the fiber and matrix demonstrated strong adhesion, showing few instances of fiber pull-out or crack formation. The combination of SWD particles with the epoxy resin led to a more compact and uniform matrix, improving stiffness, toughness, and overall mechanical characteristics. The dispersion of SWD particles played a crucial role in preventing the formation of large voids and micro cracks, which was vital for enhancing the impact and tensile strength of the composite. The polished fracture surface indicates that the composite successfully absorbed impact energy, with the particles acting as energy dissipators. The SEM images of the 20FL/25SWD composite revealed noticeable agglomeration of the SWD particles, showing a less uniform distribution in comparison to the 20FL/15SWD sample. The excess of SWD led to a matrix that was more porous, with some SWD particles showing weak adhesion to the epoxy resin. The formation of agglomerates led to regions with insufficient interfacial bonding, which in turn heightened the matrix’s vulnerability to cracking when subjected to stress. The fracture surface displayed larger voids and fiber pull-out, indicating that the high filler content adversely affected the composite’s toughness and overall performance. The accumulation of SWD particles reduced the composite’s ability to endure impact and bending stresses, as the particles failed to serve as effective reinforcements within the matrix (Muthalagu *et al.* 2021). The SEM analysis indicated that incorporating SWD particles improved the adhesion between the fiber and matrix, as well as the distribution of the reinforcement within the composite. The 20FL/15SWD composite demonstrated the most consistent distribution of SWD particles and ideal fiber-matrix adhesion, resulting in enhanced mechanical properties. With the rise in SWD content, the consistency of the filler dispersion diminished, resulting in agglomeration and inadequate interfacial bonding, particularly observed in the 20FL/25SWD sample. The introduction of voids and weak spots adversely affected the composite’s performance, undermining its impact and tensile strength. The SEM analysis demonstrated that incorporating SWD up to 15 wt% positively influenced the mechanical properties. However, an excessive amount of filler resulted in diminished performance, attributed to inadequate filler dispersion and defects within the matrix. Figure 8 presents the SEM analysis conducted on all specimens.

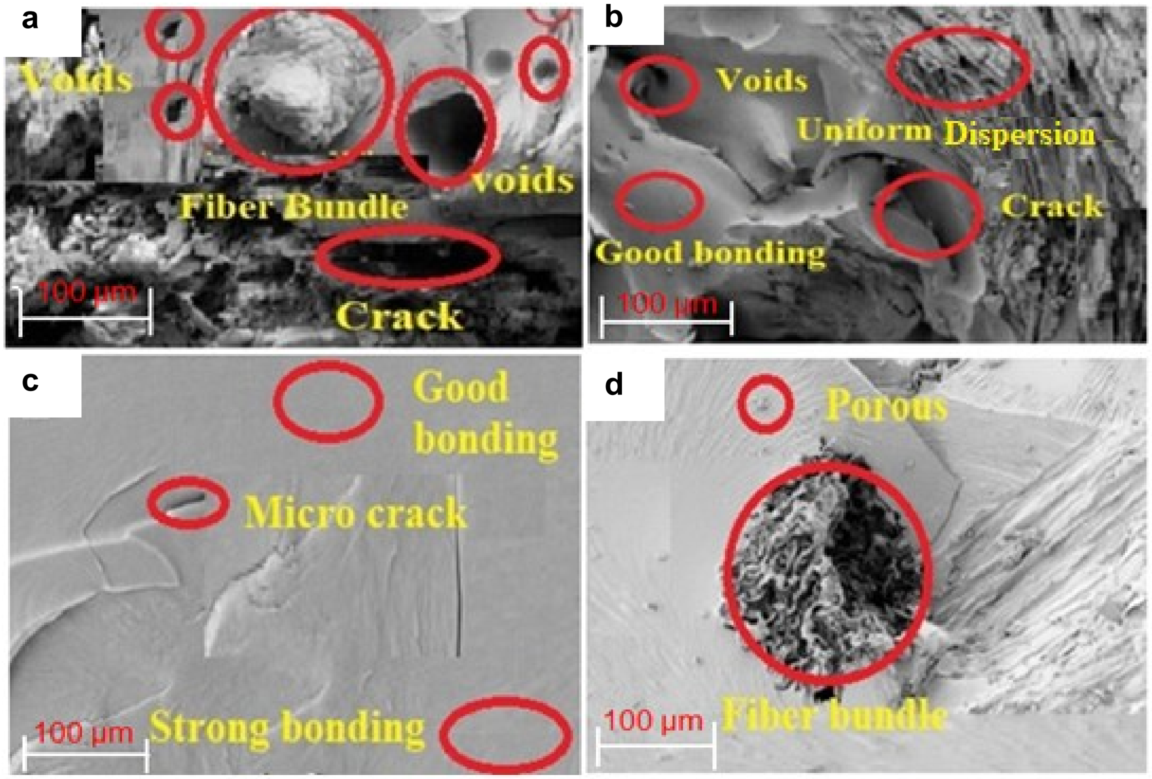

Fig. 8a. 20FL/0SWD; **8b.** 20FL/5SWD; **8c.** 20FL/10SWD; **8d.** 20FL/15SWD

CONCLUSIONS

This study on *Luffa acutangula* fiber (LAF) and sal wood sawdust (SWD) reinforced epoxy composites provides valuable insights into the mechanical and physical properties of these hybrid materials, as well as their microstructural characteristics. The findings from the experiments yield the subsequent conclusions:

1. The addition of SWD up to 15 wt% led to an enhancement in the tensile strength of the composites, reaching a peak of 46 MPa for the 20FL/15SWD sample. The noted enhancement arose from better adhesion between the fiber and matrix, along with a more effective distribution of the SWD particles, which served to reinforce the matrix efficiently. With an increased SWD content of 25 wt%, the tensile strength diminished to 43 MPa, probably because of insufficient filler dispersion and the agglomeration of SWD particles, which undermined the structural integrity of the composite.
2. The findings demonstrate that the flexural strength was enhanced with the addition of SWD up to 15 wt%, with the 20FL/15SWD composite showing the highest flexural strength of 66 MPa. The incorporation of SWD particles led to a decrease in voids and improved the overall stiffness of the composite. At 25 wt% SWD, the flexural strength showed a minor reduction (63 MPa), which can be linked to the clustering of SWD particles, leading to a less consistent structure and reduced mechanical performance.

3. The impact strength exhibited a similar trend, with the 20FL/15SWD composite achieving the highest impact strength at 3.12 J. The incorporation of SWD particles promoted energy dissipation upon impact, consequently improving the toughness of the composite. The 20FL/25SWD composite showed a reduction in impact strength (2.71 J), probably due to high filler content causing agglomeration and poor fiber-matrix bonding, which in turn weakened the composite's ability to withstand sudden impact forces.
4. The incorporation of SWD resulted in an increase in the Shore D hardness values of the composites. The 20FL/15SWD composite exhibited the highest hardness value of 72, indicating improved surface resistance to indentation. The incorporation of SWD particles improved the stiffness and hardness of the composite. At 25 wt% SWD, the hardness dropped to 68, probably because of insufficient filler dispersion, which affected the uniformity of the matrix and reduced its resistance to indentation.
5. The incorporation of SWD led to a decrease in the water absorption of the composites, demonstrating a reduction in moisture uptake with increasing filler content. The 20FL/15SWD composite demonstrated the lowest water absorption at 10%. This outcome can be attributed to the enhanced dispersion of SWD particles, which effectively filled the voids in the matrix and consequently reduced overall porosity. The 20FL/25SWD composite exhibited a higher water absorption rate of 12%, indicating that the elevated filler content led to agglomeration and enhanced porosity, thereby promoting increased moisture uptake.
6. The scanning electron microscope (SEM) analysis revealed that incorporating SWD particles improved fiber-matrix adhesion, particularly at 5 wt% and 15 wt% SWD concentrations. The 20FL/15SWD composite demonstrated excellent dispersion of fibers and fillers, marked by a reduction in fiber pull-out and cracking. This resulted in enhanced mechanical properties. At 25 wt% SWD, SEM images indicated the clustering of SWD particles, leading to weak points and voids within the matrix, which ultimately reduced the performance of the composite. The improved bonding and dispersion at lower SWD levels led to enhanced mechanical strength, impact resistance, and overall toughness.

The findings demonstrate that the addition of SWD at concentrations up to 15 wt% significantly improved the mechanical properties of LAF-reinforced epoxy composites, particularly in terms of tensile strength, flexural strength, impact resistance, and hardness. The SEM analysis supported these findings, demonstrating that the optimal dispersion of SWD particles enhanced fiber-matrix adhesion and reduced voids. As the SWD content exceeded 15 wt%, the performance of the composites declined due to insufficient filler dispersion and agglomeration. The 20FL/15SWD composite exhibits exceptional mechanical performance, making it suitable for applications that require a harmonious blend of strength, stiffness, and toughness.

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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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