Tribological and Acoustic Performance of *Luffa acutangula* Fiber and Sal Wood Sawdust Reinforced Epoxy Composites: An Experimental Study

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Hybrid epoxy composites reinforced with *Luffa acutangula* fiber (LAF) and Sal wood sawdust (SWD) were examined for their tribological and acoustic properties. A consistent 20 wt% LAF was employed throughout all composites, with the SWD content adjusted to 0%, 5%, 15%, and 25%. The engineered composites underwent assessment for wear loss, coefficient of friction (CoF), sound absorption coefficient, and noise reduction coefficient. The results demonstrated a notable reduction in wear loss with the addition of SWD up to 15 wt%, with the 20FL/15SWD sample exhibiting the lowest wear at 0.32%. In a similar manner, the CoF decreased to 0.26 for the identical composition, indicating an ideal equilibrium between filler dispersion and fiber-matrix interaction. The enhancement of sound absorption and noise reduction coefficients was observed with increased SWD content, reaching peaks of 0.23 and 0.13, respectively for the 20FL/15SWD composite. The enhancements observed can be linked to the superior void-filling capacity and interfacial bonding facilitated by the SWD particles. Nonetheless, a high concentration of SWD (25 wt%) led to a minor decrease in performance attributed to particle agglomeration. The findings indicate that the 20FL/15SWD composite demonstrates enhanced tribo-acoustic performance, positioning it as a strong contender for applications requiring noise insulation and wear resistance.

DOI: 10.15376/biores.20.3.6360-6379

Keywords: Acoustic performance; Epoxy composites; Friction loss; Luffa acutangula; Salwood saw dust; Tribological properties

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INTRODUCTION

The rising global demand for sustainable materials has prompted a significant transition towards natural fiber-reinforced polymer composites, commonly known as bio-composites (Wadgave *et al*. 2024). These materials are attracting significant interest in both scholarly studies and commercial uses because of their environmental benefits, accessibility, lightweight nature, and affordability. Unlike synthetic fiber-reinforced composites that typically require significant energy consumption, generate toxic by-products, and lack biodegradability, natural fiber composites offer a promising alternative that supports global sustainability objectives (Rao *et al*. 2023). These materials originate from renewable sources, exhibit reduced carbon footprints, and frequently provide comparable, and at times enhanced, mechanical performance for non-critical applications (Bhuvaneswari *et al*. 2022).

Natural fibers including jute, sisal, flax, kenaf, banana, hemp, and coir have undergone significant investigation in composite formulations. Nonetheless, the localized presence and distinct morphological and chemical properties of certain fibers render them particularly appropriate for specific applications (Schio *et al*. 2022). A notable natural reinforcement is *Luffa acutangula* fiber (LAF), derived from the ridge gourd plant. LAF is a lignocellulosic fiber that has garnered interest because of its moderate mechanical strength, lightweight nature, and distinctive structural characteristics. The surface texture is coarse yet rough, which improves interfacial adhesion with polymer matrices. Furthermore, it is widely found in tropical and subtropical areas and necessitates little processing, positioning it as a compelling option for the advancement of sustainable materials (Fragassa *et al*. 2024).

The incorporation of particulate fillers can greatly improve the functional performance of composites, complementing the inherent strength and structure provided by natural fibers. In this context, Sal wood sawdust (SWD), a by-product of the timber and furniture industries, presents a valuable resource (Manickaraj *et al*. 2024a). Sal wood (*Shorea robusta*), which is indigenous to the Indian subcontinent, is a hardwood recognized for its exceptional durability and strength. The sawdust, frequently overlooked or utilized as a low-value fuel, possesses a significant amount of cellulose and lignin, demonstrating remarkable compatibility with thermosetting resins such as epoxy (Ramachandran *et al*. 2022). SWD serves as a micro-filler that enhances load distribution and crack resistance, while also addressing voids within the matrix, thereby reducing porosity and improving the overall homogeneity of the material (Suriani *et al*. 2021).

The collaboration between LAF and SWD within a polymer matrix, especially epoxy resin, offers an innovative and highly promising path for the creation of hybrid composites with customized multifunctional characteristics (Sekar *et al*. 2025). Epoxy resin, a commonly utilized thermosetting polymer, is recognized for its remarkable mechanical strength, dimensional stability, chemical resistance, and robust bonding properties. Nonetheless, the material's natural brittleness and limited impact strength can be improved through the incorporation of natural fibers and fillers, which enhances its potential for various applications (Vignesh *et al*. 2021; Palaniappan 2025a).

The mechanical performance of natural fiber composites has been thoroughly examined, covering aspects such as tensile, flexural, impact, and hardness properties (Karuppusamy *et al*. 2025). However, there has been a noticeable lack of focus on their tribological and acoustic behavior, especially in hybrid systems such as LAF-SWD epoxy composites. The characteristics of tribology, including wear resistance and the coefficient of friction (CoF), play a vital role in scenarios that involve continuous sliding contact or dynamic loading (da Costa *et al*. 2020). Materials utilized in automotive interiors, sliding panels, and rotating machine components need to demonstrate exceptional wear resistance and consistent frictional characteristics to guarantee enduring performance and dependability (Manickaraj *et al*. 2025). Conventional synthetic fillers such as carbon black, glass microspheres, and aramid powders exhibit commendable wear characteristics; however, they pose challenges to sustainability and recyclability. Utilizing biodegradable fillers such as SWD presents a more environmentally friendly alternative while maintaining performance standards (Ighalo *et al*. 2021).

In a similar vein, the acoustic characteristics of composites are gaining significance in sectors that require effective sound insulation and vibration damping. Sound absorption and noise reduction are essential design considerations in various products, including automotive components, building panels, packaging materials, and consumer electronics (Chithra *et al*. 2024). The porous structure and inherent damping capacity of natural fibers contribute to their favorable acoustic properties. The incorporation of micro-sized fillers like SWD can affect the characteristics of sound transmission and reflection, possibly improving the composite's capacity to absorb and dissipate sound energy (Manickaraj *et al*. 2024b). Nonetheless, these effects are significantly influenced by the content of fillers, the quality of dispersion, the interaction between fibers and the matrix, and the overall structural integrity (Gurusamy *et al*. 2025; Palaniappan 2025b).

In light of this context, the current investigation seeks to create and assess hybrid epoxy composites that incorporate a fixed proportion of *Luffa acutangula* fiber (LAF) alongside differing amounts of Sal wood sawdust (SWD) filler (Gokul *et al*. 2024). The main aim is to examine the impact of these compositions on tribological and acoustic properties, which have not been thoroughly studied for this particular fiber-filler system (Velmurugan *et al*. 2022).

The methodology consists of fabricating composite laminates through the hand lay-up technique, followed by a thorough evaluation of essential performance indicators to determine the material's functional capabilities (Gurusamy *et al*. 2024). Wear loss is quantified using standardized dry sliding wear tests to assess material degradation resulting from mechanical abrasion. The coefficient of friction (CoF) is assessed to ascertain the frictional stability of the composite when subjected to repeated loading conditions (Sasan Narkesabad *et al*. 2023). The assessment of acoustic performance is conducted through impedance tube techniques, which measure the sound absorption coefficient (SAC) over a spectrum of frequencies. This measurement reflects the material's capacity to absorb incident sound waves. The noise reduction coefficient (NRC) is calculated as a scalar average of sound absorption coefficient (SAC) values across critical octave bands. This coefficient is utilized to assess the material's overall effectiveness in reducing sound transmission (Aruchamy *et al*. 2025).

The incorporation of *Luffa acutangula* fiber (LAF) and Sal wood sawdust (SWD) in composite materials offers significant environmental benefits. LAF is a renewable and biodegradable resource derived from the sponge gourd plant, which requires minimal inputs for cultivation and leaves a low carbon footprint (Aruchamy *et al*. 2025). Its natural decomposition at the end of life reduces environmental pollution and waste accumulation. SWD, a byproduct of the wood processing industry, represents an opportunity to valorize industrial waste that might otherwise contribute to landfill build-up or be incinerated, releasing greenhouse gases (Thangavel *et al.* 2024). Utilizing SWD in composites promotes a circular economy by transforming waste into valuable resources while reducing the reliance on synthetic fillers derived from non-renewable petrochemicals. Together, LAF and SWD reduce environmental impact by minimizing carbon emissions, decreasing dependency on fossil-based materials, and offering biodegradable and recyclable options for advanced composite applications (Manickaraj *et al.* 2025; Palaniappan 2024).

This study sought to systematically analyze these parameters to reveal trends and establish correlations between SWD filler content and the multifunctional performance of the composites. The hypothesis suggests that moderate filler levels will improve wear resistance and sound absorption, attributed to enhanced particle dispersion and better interaction between the matrix and particles (Supriya *et al*. 2024). On the other hand, an overabundance of filler content can result in clumping and ineffective stress transfer, ultimately diminishing overall performance. The results of this study are anticipated to enhance the understanding of bio-composite development, providing valuable insights for material designers and engineers focused on creating lightweight, sustainable, and high-performance composite materials (Shetty *et al*. 2024). Possible uses encompass automotive interior parts, construction panels, furniture components, and packaging systems that necessitate mechanical strength, durability, and sound-dampening properties all at once (Thirupathi *et al*. 2024). Furthermore, by enhancing the value of agricultural and industrial waste such as LAF and SWD, this study advances the principles of a circular economy and contributes to the overarching goal of sustainable material innovation (Zamora-Mendoza *et al*. 2023).

This work enables the realization of a new class of multifunctional bio-composites, providing environmental compatibility while maintaining functional performance (Al-Mamun *et al.* 2023). In summary, this study delves into an innovative fiber-filler-polymer system while also tackling essential property areas that hold practical importance across various industrial applications.

EXPERIMENTAL

Materials and Methods

Materials matrix

The polymer matrix utilized in this study was a thermosetting epoxy resin system, specifically comprising LY556 epoxy resin in conjunction with HY951 hardener. These materials are frequently utilized in composite manufacturing because of their superior mechanical strength, chemical resistance, and adhesion characteristics (da Cunha *et al*. 2021). The resin and hardener were combined in a stoichiometric ratio of 10:1 by weight, in accordance with the manufacturer's specifications. The specified ratio facilitates optimal crosslinking throughout the curing process, which is critical for attaining the desired structural and functional characteristics in the composite (Prabhudass *et al*. 2022).

Fig. 1a. Luffa acutangula**; 1b.** LAF; **1c.** LAF fiber mat

Reinforcement – *Luffa acutangula* Fiber

The primary reinforcement utilized in this application is derived from fibers of *Luffa acutangula*. The fibers derived from the dried ridge gourd plant exhibit a moderately high strength-to-weight ratio and possess natural porosity, which can improve matrix bonding (Jawaid *et al*. 2022). The LAF fiber was purchased from Amman Impex, Pollachi. Figure 1 shows the LAF, its fiber and fiber mat.

Filler – Sal Wood Sawdust

Sal wood sawdust (SWD), a by-product generated from timber processing, served as a particulate filler utilized in different proportions. The raw sawdust underwent a drying process to remove moisture content that could potentially affect the curing and mechanical properties of the composite (Birniwa *et al*. 2021). The SWD powder was purchased from Amman timber, Pollachi area, Coimbatore. The small particle size facilitates superior dispersion within the matrix and enhances the interaction of the filler with the epoxy resin, leading to improvements in mechanical, tribological, and acoustic properties (Balaji *et al*. 2021). Figure 2 shows the Sal wood and its dust powder.

Fig. 2a. Sal wood; **2b.** Sal wood dust powder

Chemical Treatment

The fibers were subjected to an alkali treatment using a 5% sodium hydroxide (NaOH) solution before use. The chemical treatment effectively eliminates impurities including lignin, hemicellulose, waxes, and oils from the fiber surface (Maguteeswaran *et al*. 2024). This process enhances surface roughness and promotes better fiber-matrix adhesion. The fibers were immersed in the NaOH solution for a duration of several hours. Following this, they were meticulously rinsed with distilled water until a neutral pH was attained, and subsequently dried at ambient temperature (Dev *et al*. 2024).

Fabrication Process

The fabrication of the composite laminates was executed using the hand lay-up technique followed by compression molding, a widely adopted method in natural fiber composite manufacturing due to its simplicity, cost-effectiveness, and suitability for small to medium-scale production. Initially, the epoxy resin (LY556) and hardener (HY951) were measured in a 10:1 weight ratio and thoroughly mixed using a mechanical stirrer for

5 min to ensure uniform distribution and eliminate unreacted pockets (Kumar *et al*. 2022). The LAF were incorporated at a constant level of 20 wt%, while SWD filler was added at varying weight percentages of 0%, 5%, 15%, and 25%. The fibers and fillers were gradually introduced into the epoxy mixture under continuous stirring to achieve homogeneous dispersion and avoid agglomeration (Sahoo *et al*. 2022). The resulting mixture was poured into a stainless-steel mold pre-coated with polyvinyl alcohol (PVA) as a release agent. The filled mold was closed and subjected to a hydraulic press at 5 MPa to remove trapped air and ensure compactness. Initial curing was conducted at room temperature (~ 27 °C) for 24 h, followed by post-curing in a hot-air oven at 80 °C for 3 h to enhance cross-linking and improve the thermal and mechanical integrity of the composite. The cured laminates were then trimmed and cut into standard test specimens in accordance with ASTM guidelines (Krishnadas *et al*. 2024). Table 1 shows the different sample designations used in this study.

Table 1. Composite Formulations

No.	LAF Layer (wt%)	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

Testing and Characterization

Wear test

The wear behavior of the hybrid composites was assessed using a Pin-on-Disc tribometer in accordance with ASTM G99 standards (Velmurugan *et al*. 2022). This test simulates the real-time frictional contact that materials endure in service conditions. A cylindrical pin (specimen) was brought into contact with a rotating steel disc under a specified load and speed. The setup evaluates the resistance of the material to wear by measuring the volume or percentage loss of the composite due to mechanical abrasion (Beemkumar *et al*. 2025). The weight of the specimen was measured before and after testing using a high-precision balance, and the percentage wear loss was calculated. This analysis is crucial in determining the suitability of the composite for applications involving continuous mechanical interactions, such as in automotive or structural components (Hosseini *et al*. 2023).

Coefficient of friction

The coefficient of friction (CoF) was evaluated to understand the frictional response of the composites during contact-based movement. Testing was conducted using a tribometer following ASTM D1894, which quantifies the static (initial) and dynamic (steady-state) coefficients of friction between the composite surface and a standard reference material under controlled conditions (Sathish Gandhi *et al*. 2025). The static CoF represents the resistance to the start of motion, while the dynamic CoF measures the resistance once the motion has commenced. These values are critical for determining how the material will behave in real-life applications where sliding contact occurs, such as brake pads, bearings, or machine parts (Biswas and Satapathy 2010).

Sound absorption test

The sound absorption capacity of the composite specimens was assessed using the impedance tube method as per ASTM E1050. This test involves placing a circular sample at one end of an impedance tube and subjecting it to plane sound waves generated by a loudspeaker at the other end (Krishnamoorthy *et al*. 2024). Microphones positioned at different points inside the tube measure the incident and reflected sound waves, enabling the calculation of the sound absorption coefficient (SAC) at various frequencies. SAC indicates the material's ability to absorb sound energy instead of reflecting it. This parameter is especially important for acoustic applications such as interior automotive panels, building insulation, and soundproofing systems (Fouly *et al*. 2021).

Noise reduction coefficient

The Noise Reduction Coefficient (NRC) provides a single-number rating that represents the average sound absorption performance of a material across mid-frequency bands (typically 250 to 2000 Hz). NRC was determined based on ASTM C423 standard methods, which involve either reverberation room measurements or calculations derived from impedance tube test data (Hegde *et al*. 2021). It is a scalar value ranging from 0 (no sound absorption) to 1 (perfect absorption), offering a simplified metric for comparing different materials. A higher NRC indicates better acoustic damping, making the composite more effective for use in environments where noise control is critical, such as offices, theaters, and transport interiors (Bobby and Samad 2017).

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 were subjected to gold coating before analysis to improve surface conductivity (Gangwar and Pathak 2021). The SEM analysis yielded significant insights into the microstructural properties of the composites, emphasizing elements such as fiber-matrix interfacial bonding, the pull-out behavior of LAF, and the distribution and dispersion uniformity of SWD particles. The SEM micrographs displayed the presence of microvoids, cracks, and delamination zones, which underscored the variations in mechanical performance across the various composite formulations (Natarajan *et al*. 2023).

RESULTS AND DISCUSSION

Wear Loss

The wear resistance of the fabricated hybrid epoxy composites was evaluated through a pin-on-disc test under standardized conditions (ASTM G99), and the results demonstrated a clear dependency on SWD filler content. The control sample, 20FL/0SWD, exhibited the highest wear loss of 0.0045 g (0.45%), indicating limited resistance to surface degradation under sliding conditions. This can be attributed to the relatively unfilled matrix structure, where load concentration on the fiber-matrix interface likely initiated micro-cracks and debris generation due to poor load transfer and interfacial shear strength. Upon the addition of 5 wt% SWD, wear loss decreased to 0.0042 g (0.42%), signifying an improvement in wear performance. The filler particles acted as micro-reinforcements and stress distributors within the epoxy matrix, thereby reducing localized deformation. A further reduction in wear loss was observed with 15 wt% SWD (0.0032 g, or 0.32%), which is indicative of an optimal filler content where the SWD particles are uniformly dispersed and filled microvoids, enhancing surface hardness and forming a more compact microstructure. The embedded SWD particles likely prevented excessive matrix removal by forming a tribo-protective layer during sliding, thus minimizing material loss (Bhargav and Babu 2021). However, when the filler content was increased to 25 wt% (20FL/25SWD), a slight increase in wear loss to 0.0038 g (0.38%) was noted. This marginal deterioration in wear resistance can be associated with the tendency of filler agglomeration at higher loadings, which introduces heterogeneities and weak zones in the composite. These agglomerates can act as abrasive third bodies or stress risers under mechanical sliding, leading to increased material detachment and surface damage (Sureshkumar and Uvaraja 2018). Overall, the results suggest that the incorporation of SWD up to 15 wt% was beneficial in enhancing the wear resistance of LAF-reinforced epoxy composites. The observed improvements are primarily attributed to better stress distribution, enhanced interfacial bonding, and reduced porosity—the key factors governing wear behavior in particulate-filled polymer systems. Figure 3 shows the wear loss.

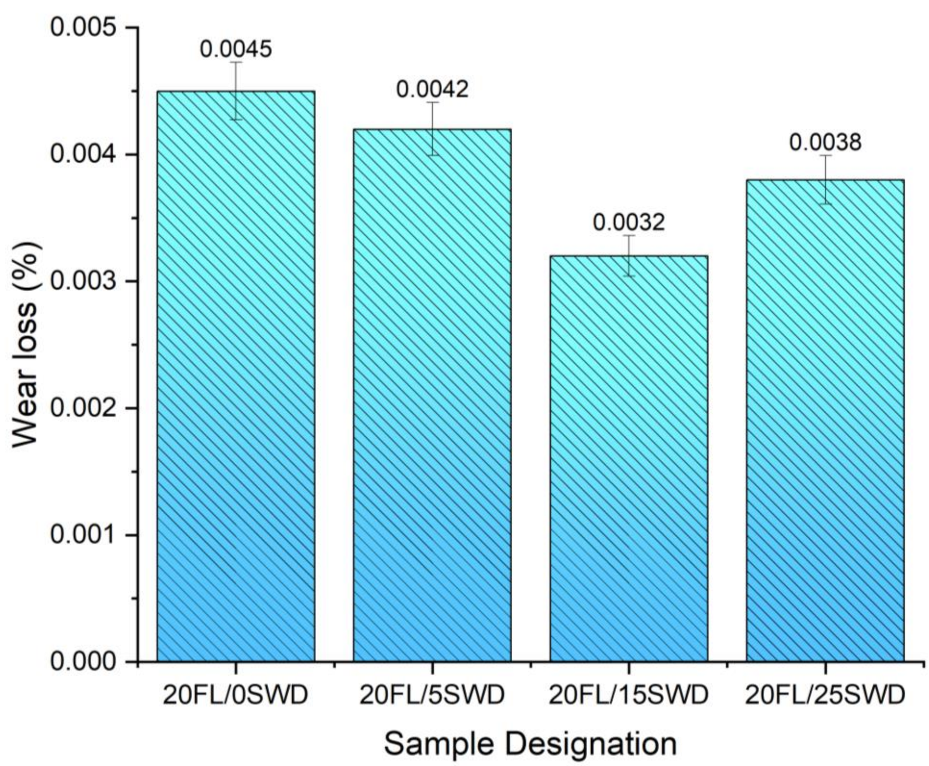

Fig. 3. Wear loss of hybrid epoxy composites

Coefficient of Friction

The CoF values for the hybrid epoxy composites with LAF containing various levels of SWD filler contents were determined using the ASTM D1894 standard, employing a tribometer to measure both static and dynamic friction.

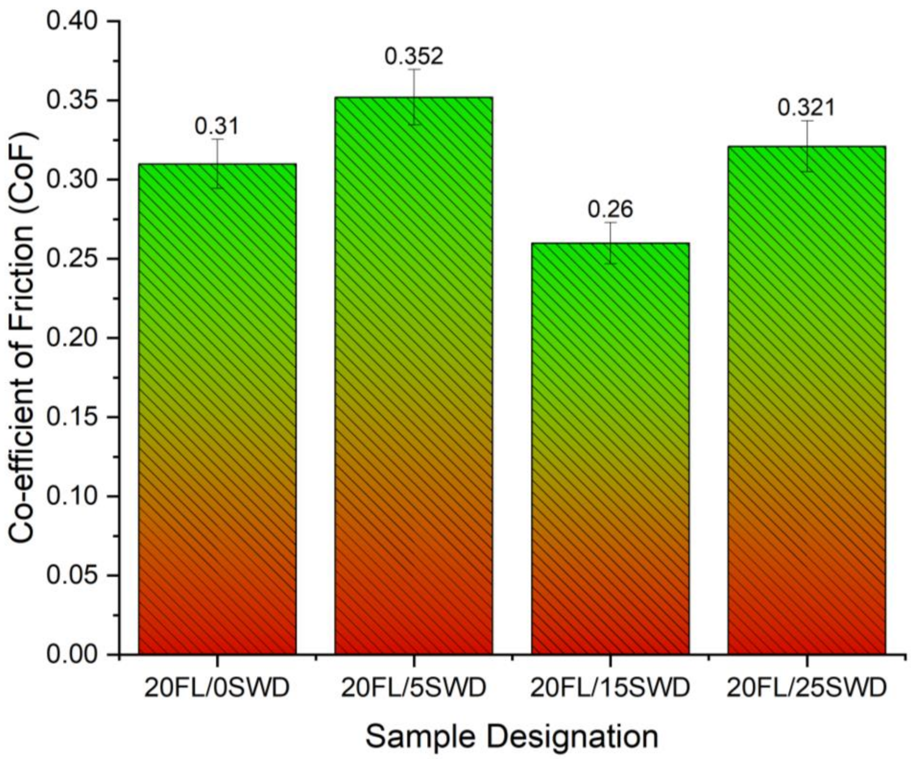

Fig. 4. CoF values of various hybrid epoxy composites

The CoF values exhibited a distinct trend with respect to SWD content, indicating changes in the frictional behavior of the composites. The composite without SWD filler, 20FL/0SWD, exhibited a CoF of 0.31, which can be attributed to the basic fiber-matrix interaction with limited surface modification or reinforcement. The fibers, though providing reinforcement, may not have sufficiently enhanced the frictional stability, leading to moderate friction values. With the addition of 5 wt% SWD, the CoF increased slightly to 0.352. This increase can be explained by the introduction of the SWD filler particles, which likely increased the roughness of the composite surface. The particles could create more surface contact points with the counter material during sliding, thus raising the frictional resistance. This suggests that while SWD particles were dispersed within the matrix, they did not yet optimize the composite's smoothness or wear resistance at this concentration. At 15 wt% SWD, the CoF dropped to 0.26, the lowest of all formulations. The significant decrease in CoF is indicative of an optimal balance between reinforcement and filler content (Teli *et al*. 2023). The SWD particles, in this optimal range, likely contributed to the formation of a smoother sliding surface by filling voids and improving interfacial bonding between the fibers and matrix. This minimized frictional contact and allowed for more stable sliding behavior. The increased matrix densification due to the filler also helped reduce the micro-roughness, lowering friction during dynamic loading. However, at 25 wt% SWD, the CoF increased again to 0.321, a value slightly higher than the control sample. This increase can be attributed to excessive SWD content leading to particle agglomeration and non-uniform dispersion within the matrix. The agglomerates may have introduced localized roughness or frictional hot spots, which resulted in higher frictional resistance during sliding (Sahu *et al*. 2023). Overall, the CoF values indicate that 15 wt% SWD provided the best balance between filler content and frictional stability, optimizing both the interfacial interactions and surface smoothness, while higher filler contents (25 wt%) compromised frictional behavior due to agglomeration. Figure 4 shows the CoF values.

Sound Absorption Coefficient

Sound Absorption Coefficient (SAC) values for the hybrid epoxy composites with LAF and varying SWD filler contents were measured using the impedance tube method, as per ASTM E1050. SAC is a key indicator of the material's ability to absorb sound across different frequencies, and it is crucial for applications requiring noise control and acoustic insulation.

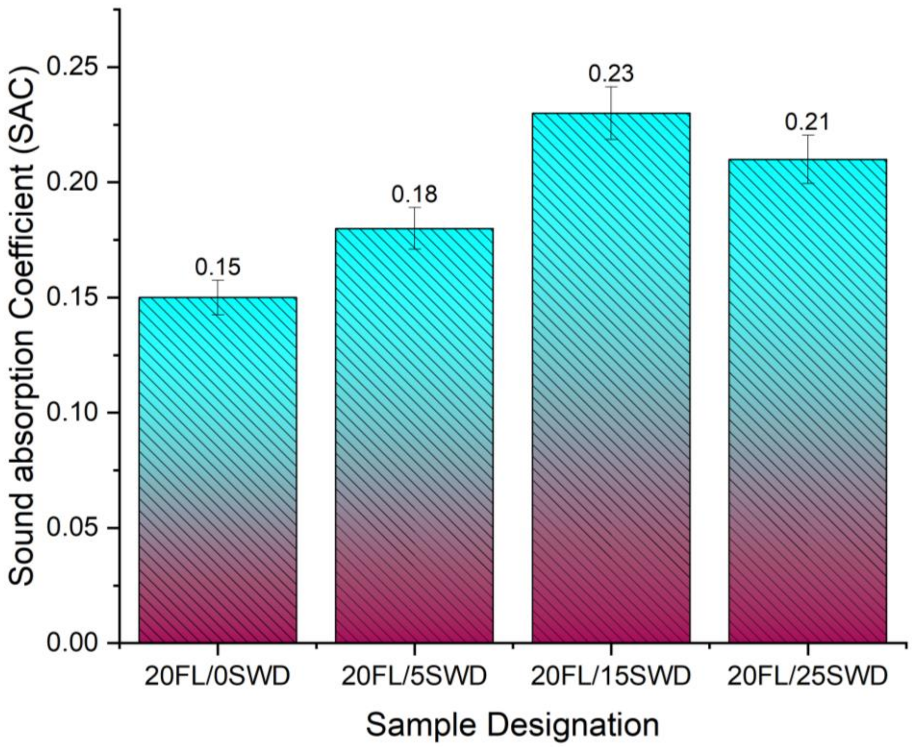

Fig. 5. SAC values of various hybrid epoxy composites

For the 20FL/0SWD composite, the SAC was 0.15, indicating a relatively low ability to absorb sound. This value is expected, as the unfilled composite primarily relied on the acoustic properties of LAF, which are limited in their ability to attenuate sound. The fiber structure, though providing mechanical reinforcement, does not contribute significantly to sound energy dissipation (Hoskins *et al*. 2011). As the SWD content increased to 5 wt% (20FL/5SWD), the SAC improved to 0.18. The inclusion of SWD fillers likely enhanced the composite's porosity and internal structure, promoting greater energy dissipation and frictional losses within the material. The finer particle size of the SWD likely helped create a more porous microstructure, increasing the material's capacity to trap and absorb sound waves. At 15 wt% SWD (20FL/15SWD), the SAC reached 0.23, which is the highest among the tested composites. This improvement can be attributed to an optimal filler content that increased the surface area and porosity of the material without compromising its structural integrity (Purohit *et al*. 2025). The SWD particles likely facilitated the creation of more voids and irregularities within the composite, which enhanced sound wave scattering and absorption. Additionally, the increased filler content likely helped in distributing the acoustic energy more effectively, allowing for more efficient sound dissipation. However, at 25 wt% SWD (20FL/25SWD), the SAC slightly decreased to 0.21, indicating a decline in sound absorption performance. This could be due to the over-saturation of the matrix with SWD, leading to reduced porosity and increased material density. At higher filler concentrations, the composite may have become more compact, resulting in less effective sound wave trapping and absorption. The excess filler particles could have also disrupted the formation of a porous network, leading to reduced overall acoustic performance (Banjare *et al*. 2014). Overall, the SAC values indicate that 15 wt% SWD provides the optimal combination of filler content and porosity, enhancing the composite's ability to absorb sound, which is crucial for noise insulation applications. At higher filler contents, the reduced porosity and increased density may limit sound absorption efficiency. Figure 5 shows the sound absorption coefficient.

Noise Reduction Coefficient

The Noise Reduction Coefficient (NRC) values for the hybrid epoxy composites with LAF and various SWD contents were calculated based on the average sound absorption performance in key mid-frequency bands (250 to 2000 Hz), as per ASTM C423. NRC is a widely used metric to assess the overall noise damping effectiveness of materials, especially for applications involving noise control and soundproofing. For the 20FL/0SWD composite, the NRC was 0.07, indicating a relatively low noise reduction capability. This low value suggests that the unfilled composite, despite the reinforcement from LAF, did not significantly dampen sound in the critical frequency range. The limited sound absorption properties of the matrix, coupled with the lack of filler, contributed to the low NRC value. With the addition of 5 wt% SWD (20FL/5SWD), the NRC increased to 0.1, showing a noticeable improvement in noise reduction. The inclusion of SWD particles enhances the material's internal structure, increasing porosity and surface area, which in turn aids in scattering and damping sound waves. The increase in NRC indicates that the SWD filler had begun to positively affect the acoustic properties of the composite, albeit to a moderate extent at this concentration. At 15 wt% SWD (20FL/15SWD), the NRC further improved to 0.13, representing the highest noise reduction capability among the samples tested (Shettar *et al*. 2020). This increase in NRC can be attributed to the optimal filler content, which likely optimized the composite's ability to absorb and dampen sound waves. The SWD filler, at this concentration, effectively enhanced the material's acoustic performance by improving both sound wave dissipation and internal energy absorption. This makes the composite more suitable for noise reduction applications, such as automotive interiors or soundproofing materials. However, at 25 wt% SWD (20FL/25SWD), the NRC slightly decreased to 0.11, indicating a slight reduction in noise reduction efficiency. This decrease could be due to the overloading of the matrix with SWD filler, which might have led to a denser structure with less porosity and fewer voids to trap and dissipate sound (Sardar *et al*. 2020). The filler at higher concentrations may have disrupted the optimal balance of the composite's porosity and matrix structure, resulting in a marginal decline in sound damping performance. Overall, the results suggest that the optimal 15 wt% SWD provided the best balance between noise reduction and material properties, improving the NRC and making the composite more effective for acoustic applications (kanchan Balasaheb and Abhang 2020). Higher SWD contents (25 wt%) appear to reduce the overall noise reduction efficiency due to changes in the material's microstructure. Figure 6 shows the NRC values of the composites.

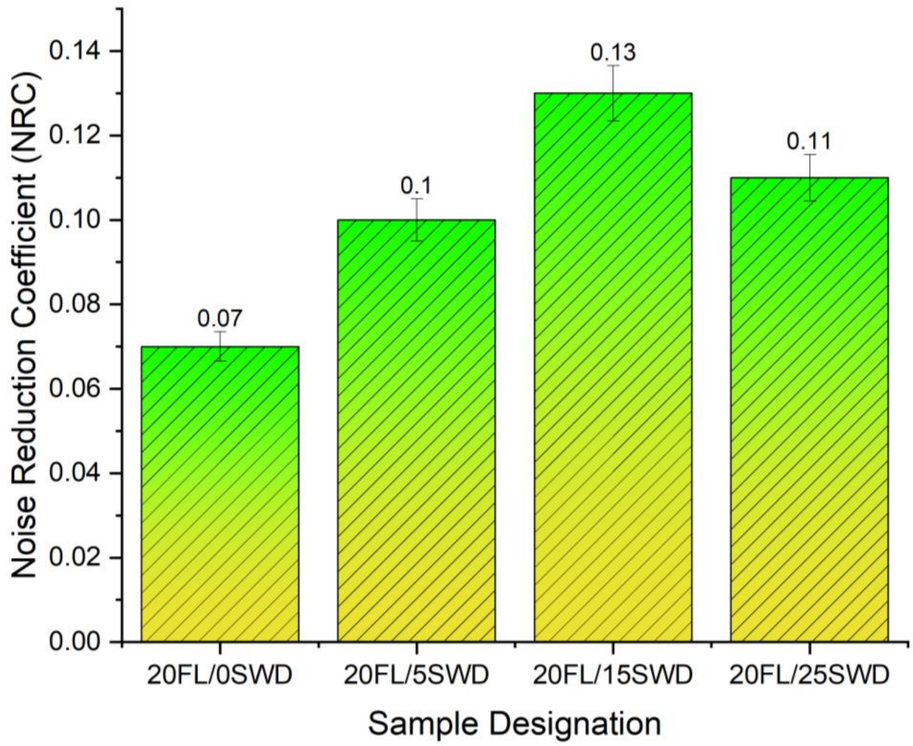

Fig. 6. NRC values of various hybrid epoxy composites

Scanning Electron Microscopic Analysis

The SEM analysis of the wear surfaces and frictional behavior of hybrid epoxy composites reinforced LAF and varying concentrations of SWD filler provided valuable insights into the wear mechanisms and frictional characteristics of the composites (Rao 2018). The introduction of SWD as a filler significantly impacted the wear resistance and frictional performance of the composites. At 15 wt% SWD, the composites demonstrated the most balanced and effective performance, characterized by a uniform surface morphology and optimal filler distribution. This concentration of SWD allowed for the effective filling of microvoids in the matrix, leading to a smooth and compacted wear surface with minimal fiber pull-out and matrix degradation, resulting in optimal wear resistance and frictional stability (Chen *et al*. 2007). The outcome suggests that 15 wt% SWD provided an ideal balance between reinforcement and filler content, effectively enhancing the mechanical and tribological properties of the composite.

However, at higher concentrations of SWD, specifically at 25 wt%, the composites exhibited agglomeration of SWD particles, which led to increased surface roughness and the formation of localized friction hotspots. These structural imperfections negatively impacted both wear resistance and frictional stability, highlighting the importance of carefully controlling the filler content to avoid negative effects such as agglomeration, which can undermine the composite's overall performance (Gbadeyan *et al*. 2018).

These findings underscore the critical role of optimizing filler content to achieve superior wear resistance and frictional stability in hybrid composites. The incorporation of an optimal amount of filler, in this case, 15 wt% SWD, enhanced the wear and frictional behavior by promoting uniform particle dispersion and reducing surface roughness. This research provides a deeper understanding of the tribological performance of natural fiber-reinforced composites and sets the foundation for further investigations into the development of sustainable, high-performance materials for various industrial applications, including automotive, structural, and sound insulation materials (Singh and Rajamurugan 2023). Furthermore, these insights can guide the development of other natural fiber composites, where the precise optimization of filler content is essential for achieving desired performance characteristics in real-world applications. Figure 7 shows the SEM analysis of frictional samples.

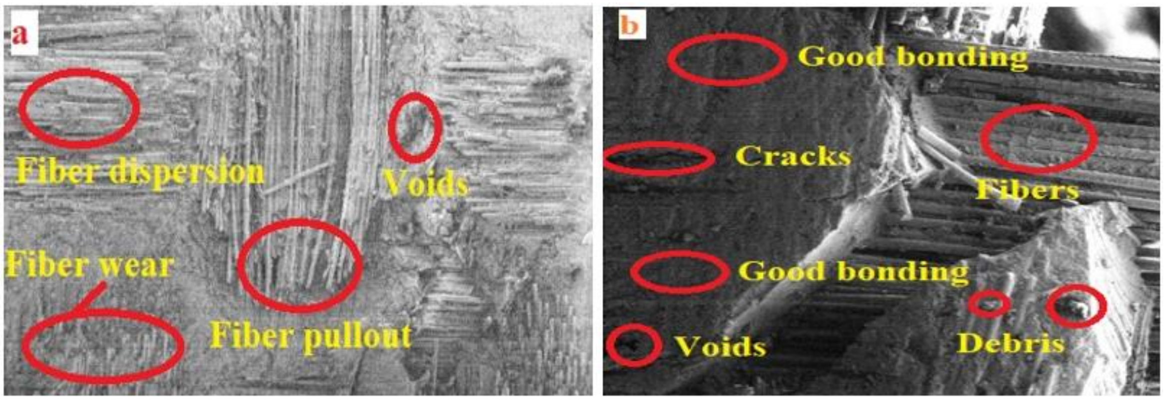

Fig. 7a. 20FL/25SWD; **7b.** 20FL/15SWD

CONCLUSIONS

This study on the hybrid epoxy composites reinforced with *Luffa aegyptiaca* fiber (LAF) and varying concentrations of Sal wood sawdust (SWD) filler has revealed valuable insights into their tribological and acoustic performance. Based on the results of wear loss, coefficient of friction (CoF), sound absorption coefficient (SAC), and noise reduction coefficient (NRC), the performance of these composites can be assessed in relation to their filler content.

1. The wear loss data indicated that the addition of SWD significantly affected the wear resistance of the composites. At 15 wt% SWD, the composite exhibited the lowest wear loss (0.32%), which reflects an optimized balance between filler and fiber content, improving the material's durability. The wear loss increased slightly at 5 wt% and 25 wt% SWD, with values of 0.42% and 0.38%, respectively, indicating that excess or insufficient filler content may not yield the best wear characteristics.
2. The CoF followed a similar trend. The 15 wt% SWD composites had the lowest CoF (0.26), showing the most efficient frictional behavior, while the control sample (0% SWD) exhibited a CoF of 0.31. The 5 wt% SWD composites showed a moderate CoF (0.352), and 25 wt% SWD exhibited an increased CoF of 0.321, suggesting that excessive filler can lead to higher frictional resistance, potentially affecting the composite's performance in dynamic applications.
3. In terms of acoustic properties, the SAC and NRC data demonstrated that the 15 wt% SWD composite also performed optimally, exhibiting the highest SAC (0.23) and NRC (0.13) values, indicating excellent sound damping properties. This suggests that the composite effectively absorbs sound waves, making it a promising candidate for noise insulation applications. The control sample (0% SWD) had a SAC of 0.15 and a NRC of 0.07, reflecting poorer acoustic performance. At 25 wt% SWD, the sound

absorption and noise reduction capabilities decreased, with values of 0.21 and 0.11, respectively, indicating that excessive filler content may hinder the material's ability to absorb sound.

4. The SEM analysis of the wear surfaces revealed further insights into the behavior of the composites. The SEM images of the 20FL/15SWD sample showed a smooth surface with minimal fiber pull-out and reduced matrix degradation, indicating effective filler distribution and improved wear resistance. In contrast, the 20FL/25SWD composite exhibited agglomeration of SWD particles, increased surface roughness, and localized friction hotspots, which correlated with the higher wear loss and CoF values observed. The SEM images also highlighted the presence of uniform filler dispersion in the 15 wt% SWD composites, which facilitated optimal wear and frictional behavior, while the 25 wt% SWD composites displayed disrupted surface structures due to excessive filler content.

In conclusion, the 15 wt% SWD hybrid composites demonstrated the best overall performance, balancing wear resistance, frictional stability, and acoustic properties. The findings emphasize the importance of optimizing SWD content to avoid negative effects such as agglomeration and excessive surface roughness. These results indicate that 15 wt% SWD provides the most effective reinforcement for hybrid composites, making them suitable for applications where both mechanical and acoustic properties are critical, such as in automotive interiors and noise insulation materials.

ACKNOWLEDGMENTS

This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-DDRSP2502).

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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Article submitted: May 6, 2025; Peer review completed: May 30, 2025; Revised version received: June 6, 2025; Accepted: June 8, 2025; Published: June 20, 2025.
DOI: 10.15376/biores.20.3.6360-6379