Acoustic and Tribological Performance Evaluation of Hybrid Polymer Composites for Noise and Wear-Resistant Applications

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This study investigates the acoustic, tribological, and microstructural behavior of hybrid epoxy composites reinforced with *Calotropis* powder, milkweed fiber, and banana stem fiber. Six composite formulations (S1–S6) were fabricated by maintaining a constant epoxy content of 60 wt% while varying the proportions of *Calotropis* powder, milkweed fiber, and banana stem fiber. The optimized samples, S4 and S5, contained 10 wt% *Calotropis* powder with different fiber proportions. The acoustic performance was evaluated through sound absorption coefficient and noise reduction coefficient (NRC), while tribological behavior was assessed using dry sliding wear rate and coefficient of friction (COF). Scanning electron microscopy (SEM) was employed to examine the fracture surfaces and wear mechanisms of the developed composites. The results showed that the presence of *Calotropis* powder improved interfacial interaction and internal porosity, which enhanced the acoustic performance of the composites. Sample S4 (10 wt% *Calotropis* powder, 15 wt% milkweed fiber, and 15 wt% banana stem fiber) exhibited the highest sound absorption coefficient (0.45) and NRC (0.41). In contrast, tribological performance improved with higher banana stem fiber content, with sample S5 (10 wt% *Calotropis* powder, 10 wt% milkweed fiber, and 20 wt% banana stem fiber) showing the lowest wear rate (2.7×10^{-6} $mm^3/N \cdot m$) and COF (0.47). SEM observations confirmed good fiber dispersion and improved interfacial bonding in the optimized composites, indicating their suitability for acoustic damping and wear-resistant applications.

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INTRODUCTION

The increasing emphasis on environmental sustainability, resource efficiency, and functional performance has intensified research interest in eco-friendly and multifunctional engineering materials (Panin *et al*. 2022). Among various material classes, natural fiber–reinforced polymer composites have emerged as promising alternatives to conventional synthetic composites because of their renewable nature, low density, reduced carbon footprint, and favorable performance characteristics (Techawinyutham *et al.* 2025). These materials are increasingly being explored for applications that demand a combination of mechanical durability, acoustic comfort, and resistance to surface degradation, particularly in automotive interiors, building panels, industrial enclosures, and machinery housings (Song *et al*. 2024).

In modern engineering applications, noise pollution and friction-induced wear represent two critical challenges that significantly affect operational efficiency, user comfort, and service life of components (Manickaraj *et al*. 2025b). Excessive noise generated by mechanical systems and structural vibrations not only leads to environmental pollution but also causes discomfort and health issues. At the same time, friction and wear at contacting surfaces result in material loss, increased energy consumption, and premature failure of components. Therefore, the development of materials capable of simultaneously providing effective noise attenuation and resistance to frictional wear is of significant technological importance (Zhang *et al*. 2025).

Polymer composites reinforced with natural fibers have gained widespread attention as potential solutions to these challenges. Natural fibers exhibit inherent characteristics such as cellular structure, surface roughness, and anisotropy, which contribute to enhanced energy dissipation and interfacial friction within composite systems (Ghosh *et al*. 2020). These features are particularly advantageous for acoustic applications, where sound waves are attenuated through mechanisms such as viscous damping, internal friction, scattering, and multiple reflections within the composite microstructure. Additionally, natural fibers contribute to improved mechanical integrity and wear resistance when properly bonded with polymer matrices (Mahesh *et al*. 2023).

Milkweed fiber is one such natural fiber that has attracted attention due to its unique hollow and porous structure. The presence of internal voids and thin-walled cellular morphology enables efficient absorption and dissipation of acoustic energy by increasing airflow resistance and internal friction (Jason *et al.* 2020). When incorporated into polymer matrices, milkweed fiber promotes sound wave trapping and attenuation, making it particularly suitable for noise-control applications. Moreover, its low density contributes to the development of lightweight composite materials, which is a critical requirement in transportation and building sectors (Mahesh and Mahesh 2022).

Banana stem fiber, derived from agricultural waste generated during banana cultivation, offers a different set of advantageous properties. It possesses relatively higher stiffness, tensile strength, and load-bearing capacity compared to many other natural fibers (Prem Kumar *et al*. 2023). These characteristics make banana stem fiber suitable for applications requiring enhanced structural stability and resistance to deformation under mechanical and tribological loading. When used as reinforcement in polymer composites, banana stem fiber improves resistance to surface damage, reduces plastic deformation, and enhances the overall durability of the composite under sliding and abrasive conditions (Ganvir *et al*. 2021).

The hybridization of different natural fibers within a single polymer matrix has emerged as an effective strategy to tailor composite properties by combining the advantages of individual reinforcements. By integrating milkweed fiber and banana stem fiber in appropriate proportions, it is possible to achieve a synergistic balance between acoustic damping and tribological performance (Ganvir *et al*. 2021). While milkweed fiber contributes significantly to sound absorption due to its porous structure, banana stem fiber enhances stiffness, load transfer, and resistance to wear. Such hybrid reinforcement systems enable the design of multifunctional composites that meet diverse application requirements (Basavaraju *et al*. 2024).

In addition to fibrous reinforcements, the incorporation of particulate fillers plays a crucial role in improving the functional performance of polymer composites. *Calotropis* powder, obtained from *Calotropis* plant biomass, has gained attention as a natural particulate filler due to its availability, low cost, and surface characteristics (Reghunathan *et al.* 2025). When dispersed within an epoxy matrix, *Calotropis* powder increases micro-roughness and interfacial friction, thereby enhancing energy dissipation during sound wave propagation. Furthermore, the presence of particulate fillers improves stress distribution and restricts localized matrix deformation, contributing to improved wear resistance (Deng *et al*. 2025).

The combined use of natural fibers and particulate fillers introduces complex interactions at the fiber–matrix and filler–matrix interfaces. These interactions significantly influence the microstructural integrity, acoustic behavior, and tribological response of the composite. Improved interfacial bonding promotes efficient load transfer and reduces fiber pull-out during sliding, while controlled micro-porosity enhances sound absorption (Muhammed *et al.* 2023). However, excessive filler or fiber content can lead to agglomeration, void formation, and weak interfacial regions, which adversely affect composite performance. Therefore, systematic optimization of reinforcement composition is essential to achieve the desired multifunctional properties (Gokul *et al*. 2024).

Despite extensive research on natural fiber–reinforced polymer composites, most existing studies focus primarily on mechanical performance or acoustic behavior in isolation. Investigations that simultaneously address acoustic damping, tribological characteristics, and microstructural features within a single composite system remain limited (Velmurugan *et al.* 2025). In particular, studies involving the hybridization of milkweed fiber and banana stem fiber in the presence of a natural particulate filler such as *Calotropis* powder are scarce (Wang *et al*. 2025). A comprehensive understanding of how fiber hybridization and filler incorporation influence sound absorption, noise reduction capability, wear resistance, and frictional behavior is still lacking.

Microstructural analysis using advanced characterization techniques such as scanning electron microscopy (SEM) plays a crucial role in establishing structure–property relationships in composite materials (Marian and Tremmel 2021). Examination of worn surfaces and fracture morphologies provides valuable insights into failure mechanisms, reinforcement dispersion, interfacial bonding, crack initiation, and transfer layer formation. Such microstructural observations are essential for correlating experimental acoustic and tribological results with underlying material behavior and for guiding the design of optimized composite formulations (Selvaraj *et al*. 2021).

In this context, the present study aims to systematically investigate the acoustic, tribological, and microstructural performance of epoxy composites reinforced with milkweed fiber, banana stem fiber, and *Calotropis* powder (Karuppusamy et al, 2025). By maintaining a constant epoxy content and *Calotropis* powder loading while varying the proportions of milkweed fiber and banana stem fiber, the study seeks to identify optimal hybrid compositions that provide enhanced sound absorption, improved noise reduction capability, reduced wear rate, and lower coefficient of friction (Fragassa *et al*. 2025; Kafaltiya *et al.* 2025). The integration of acoustic testing, tribological evaluation, and scanning electron microscopy enables a comprehensive assessment of multifunctional performance and structure–property relationships (Manickaraj *et al*. 2024c).

The novelty of the present study lies in the development of hybrid natural fiber composites reinforced with the incorporation of *Calotropis* powder as a secondary filler, which has not been widely explored in previous hybrid composite research. Unlike earlier studies that mainly focus on mechanical performance alone, this work provides a comprehensive evaluation of mechanical, tribological, and acoustic properties within a single experimental framework. This integrated approach helps to understand the multifunctional behavior of the developed composites for potential engineering applications. Furthermore, the study identifies optimized composite formulations (S4 and S5) with improved performance characteristics, demonstrating the effectiveness of *Calotropis* powder in enhancing the overall properties of hybrid natural fiber composites.

The outcomes of this research are expected to contribute valuable insights into the development of sustainable, high-performance polymer composites for noise-control and wear-resistant applications. The findings may support the replacement of conventional synthetic materials with eco-friendly alternatives in automotive interior components, building acoustics, industrial enclosures, and other engineering systems where noise reduction and durability are critical requirements (Raghunathan *et al.* 2025a).

EXPERIMENTAL

Materials

Epoxy resin was used as the primary matrix material for the fabrication of the composite specimens. The epoxy system was selected due to its excellent adhesion characteristics, good mechanical strength, low shrinkage during curing, and suitability for structural and functional composite applications (Arasu and Manickaraj 2025). The corresponding hardener compatible with the epoxy resin was used in the manufacturer-recommended ratio to ensure proper crosslinking and curing.

Milkweed fiber and banana stem fiber were employed as natural fibrous reinforcements. Milkweed fiber was chosen because of its hollow, porous, and lightweight structure, which is highly beneficial for acoustic energy dissipation (Chauhan *et al*. 2022). Banana stem fiber, obtained from agricultural residue, was selected for its comparatively higher stiffness, tensile strength, and load-bearing capability, making it suitable for improving tribological performance and structural stability. Both fibers were used in chopped form to facilitate uniform dispersion within the epoxy matrix (Ganapathy *et al*. 2025). Figure 1 shows the plants and its fibers used in the study. In this study, Milkweed and Banana stem fibers were used without any surface treatment and were only cleaned and dried before fabrication. However, treatments such as alkali (NaOH) or silane treatment can improve fiber–matrix bonding, reduce moisture absorption, and enhance composite performance (Shah *et al.* 2025). The effect of such treatments will be investigated in future work.

Fig. 1. (a) Milkweed plant; (b) Milkweed fiber; (c) Banana tree; and (d) Banana fiber

Calotropis powder was used as a natural particulate filler in the composite system. The filler was prepared by collecting dried *Calotropis* plant residues, which were cleaned, sun-dried, and mechanically ground to obtain fine powder. The ground material was then sieved to obtain particles within an approximate size range of 75–150 µm. The *Calotropis* powder particles exhibit irregular morphology and rough surface texture, which can enhance mechanical interlocking and interfacial bonding with the epoxy matrix (Subramanian *et al.* 2026). The incorporation of *Calotropis* powder (Fig. 2) contributes to improved load transfer between the matrix and reinforcing fibers, while also increasing surface roughness and interfacial friction within the composite structure. In addition, the presence of the particulate filler can promote energy dissipation during sound wave propagation and help restrict localized matrix deformation under sliding conditions (Lakshmaiya *et al.* 2025).

Fig. 2. *Calotropis* powder

All raw materials, including epoxy resin, hardener, milkweed fiber, banana stem fiber, and *Calotropis* powder, were procured from the local market in Coimbatore, Tamil Nadu, India. The use of locally available materials highlights the economic feasibility and sustainability of the developed hybrid composites (Lakshmaiya *et al.* 2025).

Fiber and Filler Preparation

Milkweed fiber and banana stem fiber were initially cleaned thoroughly with distilled water to remove surface impurities, dust, and adhering organic matter. The fibers were then air-dried followed by oven drying at 60 °C for 24 h to eliminate moisture content, which is critical for improving fiber–matrix adhesion and reducing void formation during composite fabrication (Marković *et al*. 2023). After drying, the fibers were chopped to a uniform length suitable for composite processing. The chopped fibers were then sieved to ensure size consistency and stored in airtight containers until further use. *Calotropis* powder was dried for 24 h to remove residual moisture. The dried powder was sieved using a standard mesh to obtain uniformly sized particles, ensuring homogeneous dispersion within the epoxy matrix (Nayak and Satapathy 2022).

Composite Formulation and Fabrication

Six composite formulations were prepared by maintaining a constant epoxy resin content of 60 wt% while varying the proportions of milkweed fiber and banana stem fiber. *Calotropis* powder was incorporated at a fixed loading of 10 wt% for all filler-reinforced samples. One control sample without *Calotropis* powder was also prepared for comparison (Thangavel *et al*. 2024). Table 1 shows the sample compositions.

Table 1. Composite Formulations

Sample Code	Epoxy (wt%)	*Calotropis* Powder (wt%)	Milkweed Fiber (wt%)	Banana Fiber (wt%)
S1	60	0	20	20
S2	60	10	25	5
S3	60	10	20	10
S4	60	10	15	15
S5	60	10	10	20
S6	60	10	5	25

The required quantities of epoxy resin and hardener were measured accurately and mixed thoroughly to obtain a homogeneous matrix system. *Calotropis* powder was gradually added to the epoxy resin and stirred mechanically to ensure uniform dispersion and to prevent agglomeration (Sreenivasa *et al*. 2024). Subsequently, the pre-weighed milkweed fiber and banana stem fiber were introduced into the resin–filler mixture and mixed until a uniform fiber distribution was achieved.

The prepared mixture was poured into a mold coated with a suitable release agent. The composite laminates were fabricated using a conventional hand lay-up technique followed by compression molding to minimize void formation and improve laminate consolidation. During the compression stage, a uniform pressure of approximately 5 MPa was applied using a compression molding machine to enhance fiber wetting and interfacial bonding between the reinforcement and the epoxy matrix (Zhu *et al.* 2025). The laminates were initially cured at room temperature for 24 h under constant pressure. Subsequently, post-curing was carried out in a hot air oven at 80 °C for 2 h to ensure complete crosslinking and stabilization of the epoxy matrix network. After curing, the composite laminates were carefully removed from the mold and allowed to stabilize at ambient conditions before specimen preparation for further testing (Manickaraj *et al.* 2025a). Figure 3 shows the final composite plate of Sample S5**.**

Fig. 3. Fabricated composite plate

Methods

Each mechanical, tribological, and acoustic test was conducted using five specimens for each composite sample to ensure repeatability and reliability of the experimental results. The average value of the five trials was reported for all measurements

Acoustic testing

The acoustic performance of the composite specimens was evaluated by measuring the sound absorption coefficient using an impedance tube method in accordance with ASTM E1050 (Novak *et al.* 2011). This standard method determines the normal incidence sound absorption characteristics of materials using the two-microphone transfer function technique (Gairola *et al.* 2022). Circular specimens were fabricated to match the internal diameter of the impedance tube and were positioned at the rigid termination end of the tube during testing. Broadband acoustic signals were generated using a loudspeaker, and the incident and reflected sound waves were captured by two microphones mounted at fixed locations along the tube. The sound absorption coefficient (α) was calculated from the measured transfer functions over a frequency range of 100 to 4000 Hz, which covers the typical audible range relevant for noise control applications. The noise reduction coefficient (NRC) was determined as a single-number rating by calculating the arithmetic average of the sound absorption coefficients measured at standard octave band center frequencies (250, 500, 1000, and 2000 Hz), as prescribed in ASTM C423 (Sorenson 2012). The NRC value provides an overall indication of the broadband sound absorption capability of the developed composite materials (Manickaraj *et al.* 2025c).

Tribological testing

Dry sliding wear tests were conducted in accordance with ASTM G99 (Muray 2013), which specifies the pin-on-disc method for evaluating the wear and friction characteristics of materials. Composite specimens were machined into pin geometry with flat contact surfaces, while a hardened steel disc served as the counterface (Sathish *et al*. 2024). The experiments were performed under a normal load of 30 N, sliding speed of 1 m s^{-1}, and total sliding distance of 1500 m to ensure consistent and repeatable test conditions. During testing, the composite pin was pressed against the rotating steel disc, and material removal occurred due to frictional interaction at the contact interface. The wear rate was determined from the volumetric material loss, which was calculated by measuring the mass loss of the specimen before and after testing and converting it into volume loss using the composite density. The wear rate was expressed as the volume loss per unit load and sliding distance ($mm^3/N \cdot m$) (Manickaraj *et al*. 2024a). The coefficient of friction was continuously monitored throughout the experiment using the tribometer data acquisition system. The steady-state coefficient of friction was obtained by averaging the friction values recorded during the stable sliding region of the test (Manickaraj *et al.* 2024b).

Scanning Electron Microscopy Analysis

Scanning electron microscopy was employed to examine the worn surfaces of the composite specimens after tribological testing, as well as selected fracture surfaces, to understand the underlying wear and failure mechanisms (Krishnadas *et al*. 2024). Prior to examination, the specimens were coated with a thin conductive layer to minimize charging effects. The SEM analysis focused on identifying microstructural features such as fiber pull-out, matrix deformation, filler dispersion, void content, crack initiation and propagation, debris formation, and transfer layer development. These observations were used to correlate microstructural characteristics with the experimentally observed acoustic and tribological behavior of the composites (Vijayan *et al*. 2025).

RESULTS AND DISCUSSION

Sound Absorption Behaviour

The sound absorption coefficients of the developed epoxy composites reinforced with milkweed fiber, banana stem fiber, and *Calotropis* powder are presented in Fig. 4. The results reveal a clear dependence of acoustic performance on reinforcement composition, indicating that the hybridization of fibers and the presence of particulate filler significantly influence the mechanisms governing acoustic energy dissipation within the composite structure. Sound absorption in porous and fibrous composites primarily occurs through viscous friction, thermal losses, and scattering of incident sound waves within internal pores and heterogeneous interfaces. Therefore, variations in fiber morphology, filler distribution, and matrix–reinforcement interaction can substantially alter the acoustic response of the material.

The control sample S1, which contains equal proportions of milkweed fiber and banana stem fiber but no *Calotropis* powder, exhibited the lowest sound absorption coefficient of 0.32. This relatively low value indicates limited acoustic damping capability due to the absence of additional microstructural heterogeneity introduced by particulate fillers. In this configuration, the epoxy matrix dominates the structural continuity, and the fiber–matrix interfaces alone are insufficient to generate significant frictional and viscous losses during sound wave propagation. As a result, a considerable portion of the incident acoustic energy is reflected rather than dissipated within the composite. Similar observations have been reported in natural fiber composites lacking particulate fillers, where reduced internal friction and limited pore connectivity restrict acoustic attenuation mechanisms.

The incorporation of *Calotropis* powder in the subsequent formulations (S2–S6) resulted in a noticeable improvement in sound absorption behavior. Sample S2 exhibited an absorption coefficient of 0.35, representing a moderate increase compared with the control sample. This improvement can be attributed to the combined influence of milkweed fiber morphology and the micro-scale surface roughness introduced by the *Calotropis* powder particles. Milkweed fibers possess a naturally hollow and porous structure, which increases airflow resistivity and promotes viscous damping as sound waves penetrate the composite. Furthermore, the filler particles act as micro-scale scattering centers that disrupt the propagation path of acoustic waves, thereby increasing internal reflections and energy dissipation (Pandiarajan *et al*. 2025).

Sample S3 demonstrated a further increase in sound absorption coefficient to 0.39 as the proportion of banana stem fiber was moderately increased while retaining a significant amount of milkweed fiber. This configuration provides an improved balance between structural rigidity and internal porosity. The increased banana stem fiber content enhances the mechanical stability of the composite, while the retained milkweed fiber maintains internal pore structures that facilitate acoustic attenuation. Additionally, the improved fiber–matrix interaction and more uniform dispersion of *Calotropis* powder enhance the formation of heterogeneous interfaces that contribute to increased frictional losses and multiple scattering events within the composite matrix.

The highest sound absorption coefficient of 0.45 was recorded for sample S4, which contains equal proportions of milkweed fiber and banana stem fiber along with *Calotropis* powder. This result suggests that S4 represents an optimal hybrid reinforcement configuration. The synergistic interaction between the porous milkweed fiber and the relatively stiff banana stem fiber creates a complex microstructure characterized by interconnected pore channels and heterogeneous interfacial regions. These microstructural features increase tortuosity and airflow resistance within the composite, thereby enhancing viscous and thermal losses during sound wave propagation. Moreover, the uniform dispersion of *Calotropis* powder increases micro-scale surface irregularities and interfacial friction, which further contributes to acoustic energy dissipation (Ravichandran *et al.* 2025).

However, a slight reduction in sound absorption performance was observed for samples S5 and S6, which exhibited absorption coefficients of 0.42 and 0.38, respectively.

These samples contain progressively higher proportions of banana stem fiber, which increases the overall stiffness and density of the composite. While higher stiffness is beneficial for structural and tribological performance, it tends to reduce internal pore connectivity and restrict sound wave penetration into the composite interior. Consequently, the dominant acoustic mechanism gradually shifts from internal dissipation to surface reflection, leading to a moderate decline in sound absorption efficiency. Similar behavior has been observed in dense natural fiber composites where excessive reinforcement reduces effective porosity and limits acoustic damping (Ayyappan *et al.* 2025).

Overall, the results clearly demonstrate that the acoustic performance of the developed composites is strongly influenced by the interplay between fiber porosity, filler-induced interfacial friction, and composite stiffness. Excessive milkweed fiber content may compromise mechanical stability, whereas excessive banana stem fiber content reduces the internal damping capacity. The superior acoustic performance of sample S4 highlights the importance of optimized hybrid reinforcement design for achieving enhanced sound absorption characteristics (Karuppusamy *et al*. 2025). Furthermore, the obtained absorption values are comparable with previously reported natural fiber-based acoustic materials used for noise control applications, suggesting that the developed composites possess promising potential for applications such as automotive interior panels, building acoustic boards, and industrial noise-control systems (Nanthakumar *et al.* 2025).

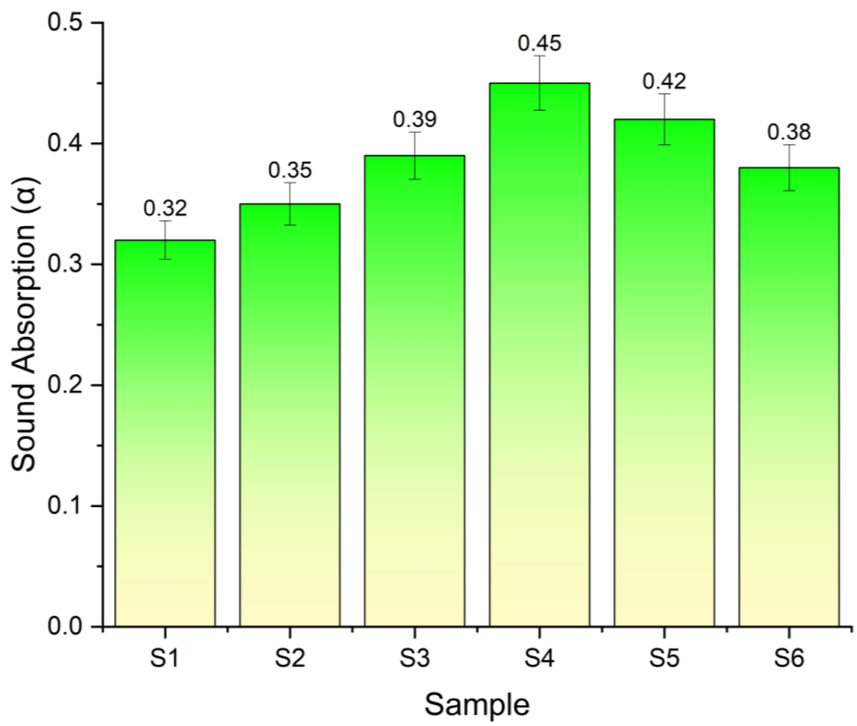

Fig. 4. Sound absorption coefficient of hybrid composites (S1–S6). Error bars represent ±SD

Noise Reduction Coefficient

The noise reduction coefficient (NRC) values of the epoxy composites reinforced with milkweed fiber, banana stem fiber, and *Calotropis* powder are presented in Fig. 5. The NRC is widely used as a simplified parameter for evaluating the broadband acoustic performance of materials because it represents the average sound absorption coefficient measured at selected octave band center frequencies. Although NRC does not capture the full frequency-dependent absorption behavior, it provides a practical single-number indicator for comparing materials used in noise control applications. The results indicate a clear variation in NRC values with changes in composite formulation, reflecting the influence of reinforcement architecture on broadband sound attenuation capability. The control sample S1 exhibited the lowest NRC value of 0.30, which can be attributed to the absence of *Calotropis* powder and the relatively homogeneous structure of the epoxy–fiber system. Without particulate filler, the composite contains fewer micro-scale interfaces capable of dissipating acoustic energy. Consequently, sound waves interacting with the surface of this material experience greater reflection and limited internal damping (Alrasheedi *et al.* 2026). With the incorporation of *Calotropis* powder and modification of fiber composition, a gradual increase in NRC values was observed for samples S2 through S4. Sample S2 recorded an NRC value of 0.33, which represents a noticeable improvement over the control formulation. The hollow structure of milkweed fiber plays an important role in this improvement by creating internal cavities that facilitate viscous airflow losses and multiple sound wave reflections. Simultaneously, the dispersed *Calotropis* powder particles increase microstructural complexity and interfacial friction, thereby enhancing acoustic energy dissipation mechanisms.

Sample S3 exhibited a further increase in NRC to 0.37, indicating improved broadband acoustic attenuation. This improvement can be attributed to the balanced combination of milkweed fiber and banana stem fiber, which enhances structural integrity while maintaining sufficient internal porosity. The improved fiber–matrix interaction also contributes to a more stable microstructure that supports efficient sound energy dissipation across a wider frequency range. Additionally, the uniform dispersion of *Calotropis* powder increases micro-scale surface roughness and promotes scattering of sound waves within the composite interior (Manickaraj *et al.* 2025a). The highest NRC value of 0.41 was obtained for sample S4, which contains equal proportions of milkweed fiber and banana stem fiber along with *Calotropis* powder. This result indicates that S4 provides the most effective broadband noise attenuation among all formulations. The optimal hybridization of fibers produces a heterogeneous microstructure that enhances airflow resistivity and increases the number of acoustic scattering sites within the composite. The presence of *Calotropis* powder further amplifies these effects by increasing internal friction and promoting localized energy dissipation during sound wave propagation (Sureshbabu et al, 2024). A slight decrease in NRC values was observed for samples S5 and S6, which recorded values of 0.39 and 0.36, respectively. These compositions contain higher proportions of banana stem fiber, which increases the stiffness and density of the composite. While these characteristics may improve mechanical strength and wear resistance, they reduce the ability of sound waves to penetrate into the material interior. As a result, the acoustic attenuation mechanism shifts toward surface reflection rather than internal absorption, leading to a moderate reduction in broadband noise attenuation (Manickaraj *et al.* 2024a).

Overall, the NRC results closely follow the trends observed in the sound absorption coefficient data, confirming that optimized hybrid reinforcement is essential for achieving effective acoustic performance. The results suggest that neither excessively porous nor overly dense composite structures are ideal for broadband noise control applications. Instead, a balanced combination of fiber porosity, structural stiffness, and filler-induced interfacial friction is required to maximize acoustic energy dissipation. The developed composites, particularly sample S4, demonstrate promising NRC values comparable with previously reported natural fiber acoustic materials used in building insulation panels and automotive interior components (Dev *et al.* 2023).

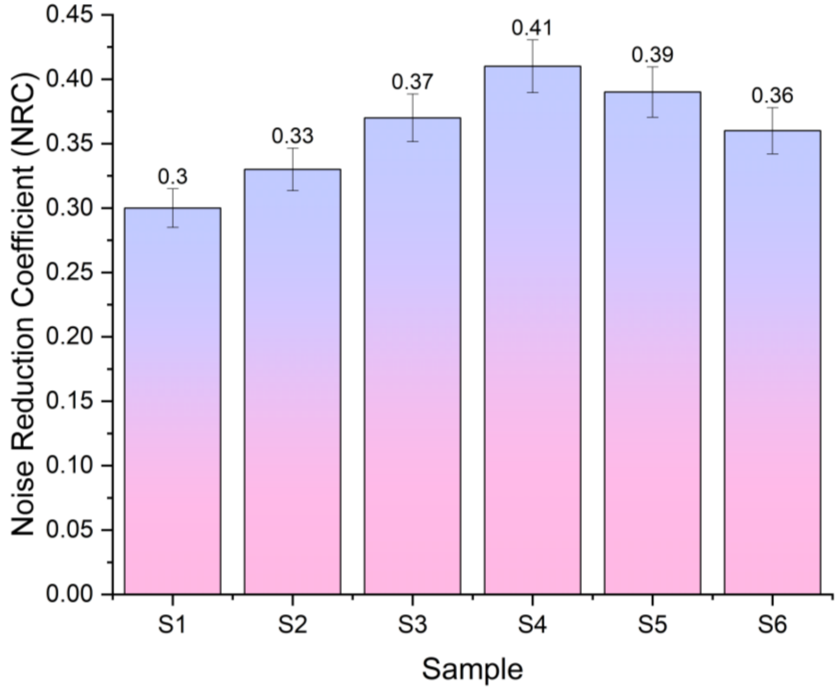

Fig. 5. Noise reduction analysis of hybrid composites (S1–S6). Error bars represent ±SD.

Wear Rate Analysis

Wear rate is one of the most important tribological parameters used to evaluate the durability and service life of composite materials under sliding conditions. It represents the rate at which material is removed from the surface due to frictional interaction with a counterface. The wear performance of polymer composites is influenced by several factors, including matrix properties, fiber reinforcement, filler content, interfacial bonding, and the formation of protective tribological layers during sliding. Figure 8 shows the variation in wear rate for the developed hybrid composites containing different percentages of *Calotropis* powder. The unfilled composite specimen exhibited relatively higher wear compared to the filled composites. In polymer composites without particulate fillers, the sliding interaction is mainly governed by the epoxy matrix and exposed fiber surfaces. During dry sliding, the polymer matrix tends to experience localized plastic deformation due to the applied load and frictional heating. This deformation weakens the matrix structure and leads to material removal in the form of micro-fragments. Additionally, weak fiber–matrix bonding may result in fiber pull-out, which further contributes to increased material loss during sliding.

The introduction of *Calotropis* powder into the composite significantly influences the wear resistance of the material. At lower filler concentrations, the particles are dispersed within the epoxy matrix and act as micro-reinforcing elements. These particles help to increase the hardness and stiffness of the composite surface, which improves resistance to abrasion and micro-cutting during sliding. As a result, the wear rate begins to decrease with the addition of the filler. Another important factor contributing to improved wear resistance is the enhancement of load transfer within the composite structure. *Calotropis* particles act as load-bearing elements that distribute the applied load more effectively across the sliding surface. This reduces localized stress concentration within the epoxy matrix and minimizes matrix cracking and fragmentation. The improved load distribution helps maintain the structural integrity of the composite during repeated sliding cycles.

As the filler content increases further, the wear resistance of the composite improves due to the formation of a more stable tribological layer on the sliding surface. During sliding, small fragments of polymer matrix, fibers, and filler particles accumulate at the interface between the composite and the counterface. These fragments may compact and form a protective tribo-layer that acts as a solid lubricant. The tribo-layer reduces direct contact between the composite surface and the steel disc, thereby decreasing material removal.

The presence of hybrid natural fibers also plays a crucial role in improving the wear performance of the composites. Milkweed fiber and banana stem fiber provide structural reinforcement to the epoxy matrix and increase the load-bearing capacity of the material. Strong fiber–matrix adhesion helps restrict fiber pull-out and improves resistance to crack propagation during sliding. The fibers also contribute to energy absorption and help dissipate frictional stresses generated at the interface. Furthermore, the incorporation of *Calotropis* powder enhances the surface hardness and roughness of the composite, which helps resist micro-ploughing and abrasive wear mechanisms. Hard filler particles can act as protective barriers that prevent severe penetration of the counterface into the softer polymer matrix. This reduces the depth of wear grooves formed during sliding and contributes to lower material loss.

However, at very high filler concentrations, excessive particle agglomeration may occur within the matrix. Agglomerated particles can act as stress concentration sites and may weaken the interfacial bonding between the filler and the matrix. This can lead to particle pull-out and micro-crack initiation under sliding conditions. Therefore, an optimal filler content is necessary to achieve the best wear resistance (Ramachandran *et al.* 2025; Gurusamy *et al.* 2025). Overall, the incorporation of *Calotropis* powder significantly improves the wear resistance of the hybrid natural fiber reinforced epoxy composites. The improved wear performance can be attributed to enhanced surface hardness, improved load distribution, formation of protective tribo-layers, and strong fiber–matrix interactions within the composite structure. These mechanisms collectively reduce material loss and enhance the durability of the composites under dry sliding conditions (Navin *et al.* 2025).

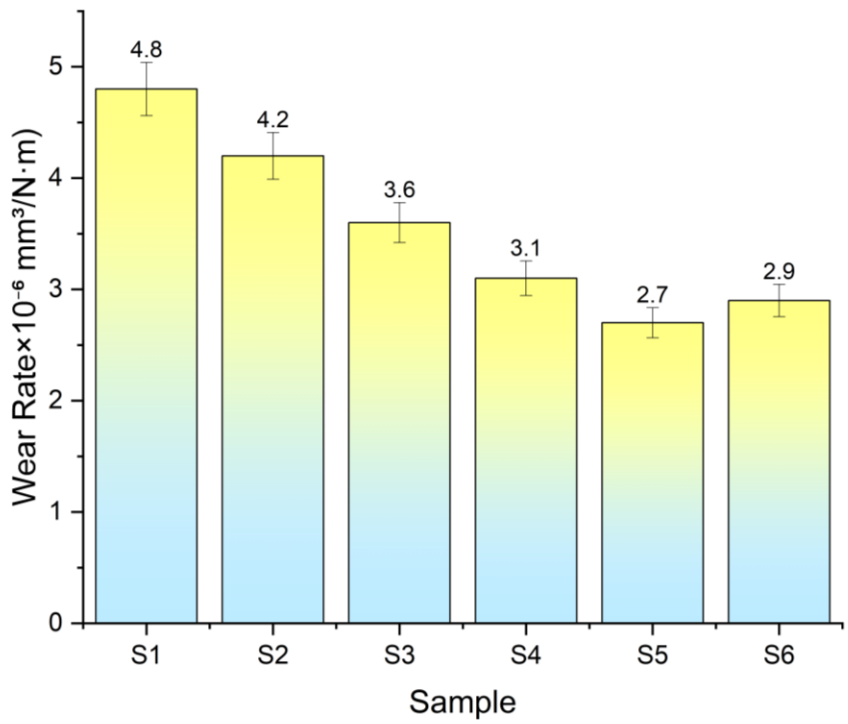

Fig. 6. Wear rate of hybrid composites (S1–S6). Error bars represent ±SD

Coefficient of Friction

The coefficient of friction (COF) is a key tribological parameter that represents the resistance to sliding between two contacting surfaces. It provides insight into the interfacial interactions occurring during sliding and is strongly influenced by the reinforcement characteristics, filler dispersion, matrix properties, and contact conditions. Figure 7 illustrates the variation in the coefficient of friction for the developed hybrid composites containing different concentrations of *Calotropis* powder. The unfilled composite sample exhibited a relatively moderate coefficient of friction during dry sliding conditions. In the absence of particulate fillers, the sliding interface is primarily governed by the epoxy matrix and the reinforcing natural fibers. The polymer matrix tends to soften slightly under frictional heating, which may lead to localized adhesion between the sliding surfaces. Such adhesive interactions generally increase friction and may also contribute to unstable sliding conditions. In addition, fiber exposure during wear can produce micro-asperities that increase mechanical interlocking between the contacting surfaces. With the introduction of *Calotropis* powder into the composite system, noticeable changes in frictional behavior were observed. The presence of hard particulate fillers modifies the surface characteristics of the composite and significantly influences the tribological response. At lower filler concentrations, the particles act as micro-asperities that increase the surface roughness of the sliding interface. This increased roughness promotes greater mechanical interlocking with the counterface, which can slightly increase the coefficient of friction during the initial stages of sliding. However, the presence of these particles also contributes to the formation of a stable tribo-layer on the sliding surface.

As the filler content increases, the frictional behavior becomes more stable due to the improved load-bearing capability of the composite. *Calotropis* powder particles act as micro-load carriers that help distribute the applied load more uniformly across the sliding interface. This reduces localized stress concentration within the polymer matrix and limits excessive deformation. The improved load distribution results in a more consistent sliding interaction between the composite and the counterface. Another important mechanism influencing friction behavior is the formation of a transfer film during sliding. Under repeated sliding contact, fragmented polymer debris and fine filler particles may accumulate at the interface, forming a thin tribological layer. This layer acts as a protective barrier that separates the contacting surfaces and reduces direct metal–polymer contact. The formation of such a transfer film contributes to the stabilization of the coefficient of friction over time (Ravichandran et al, 2025). At higher filler loadings, the *Calotropis* powder also contributes to improved thermal stability at the sliding interface. The particles can dissipate frictional heat more effectively than the polymer matrix alone, thereby limiting thermal softening of the epoxy. Reduced matrix softening helps maintain the structural integrity of the composite surface and prevents excessive adhesion during sliding. Furthermore, the hybrid fiber reinforcement used in the composite contributes to the frictional performance by providing structural rigidity to the material. The combination of milkweed fiber and banana stem fiber improves the load transfer capability of the composite and reduces excessive deformation under applied loads. This structural reinforcement works synergistically with the *Calotropis* filler to stabilize the sliding interface.

Overall, the incorporation of *Calotropis* powder influences the frictional characteristics of the hybrid composites through several mechanisms, including surface roughness modification, improved load distribution, formation of transfer films, and enhanced thermal stability at the sliding interface. These factors collectively contribute to a more stable and controlled coefficient of friction under dry sliding conditions (Pandiarajan *et al.* 2025). The observed frictional behavior indicates that the addition of natural particulate fillers can play a significant role in tailoring the tribological performance of hybrid natural fiber reinforced composites.

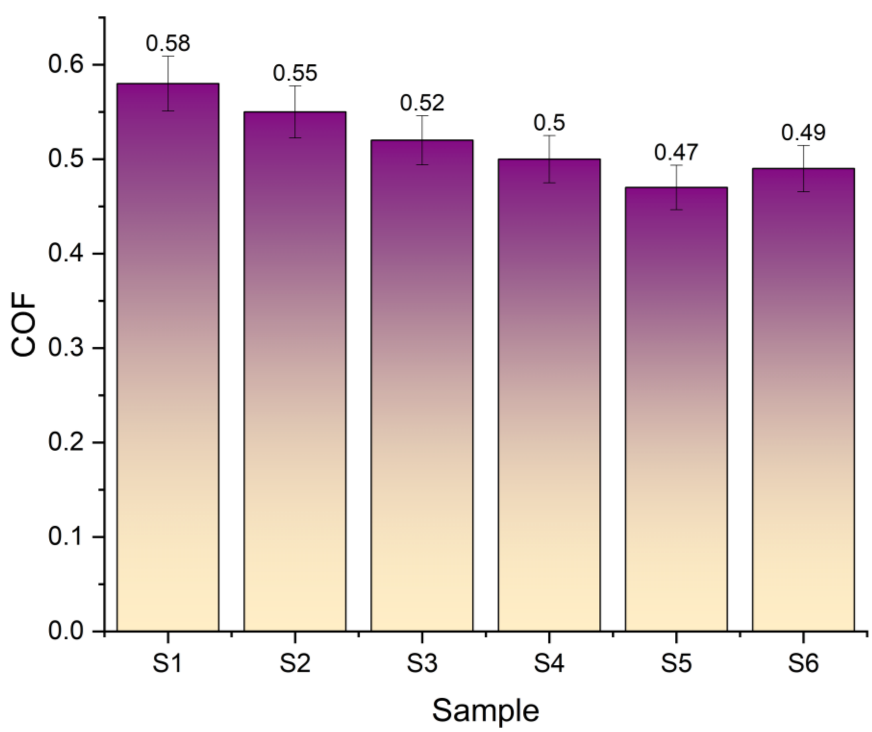

Fig. 7. Coefficient of friction of hybrid composites (S1–S6). Error bars represent ±SD

Scanning Electron Microscopy Analysis

Scanning Electron Microscopy (SEM) was employed to examine the worn and fractured surfaces of the developed epoxy composites in order to qualitatively interpret the microstructural mechanisms governing their acoustic absorption and tribological performance. The SEM observations focused primarily on features such as fiber–matrix interfacial adhesion, filler dispersion, fiber pull-out, matrix deformation, crack formation, and transfer layer development on the worn surfaces. The SEM micrograph of Sample S1, which contains no *Calotropis* powder, reveals extensive matrix smearing, fiber pull-out, and the presence of micro-voids. The exposed milkweed and banana stem fibers indicate relatively weak interfacial bonding with the epoxy matrix, resulting in inefficient load transfer during sliding (Mariamma and Nair 2022). The hollow structure of the milkweed fibers is clearly visible, with fractured cell walls contributing to debris formation. These microstructural features promote adhesive and abrasive wear mechanisms, which correspond to the higher coefficient of friction and wear rate observed for this sample. In addition, the absence of a stable transfer layer leads to direct and uncontrolled contact between the composite surface and the steel counterface.

In Samples S2 and S3, the incorporation of *Calotropis* powder leads to noticeable improvement in the overall microstructural integrity of the composites. The SEM images show better embedding of the fibers within the epoxy matrix and reduced interfacial gaps. The *Calotropis* powder particles appear to be relatively well distributed within the matrix, acting as reinforcing sites that help restrict fiber debonding and local matrix deformation. Compared to Sample S1, these samples exhibit reduced fiber pull-out and the presence of shallow ploughing marks, indicating a transition from severe adhesive wear to comparatively mild abrasive wear. These observations support the experimentally observed reduction in wear rate and coefficient of friction.

The SEM microstructure of Sample S4 shows a comparatively dense and compact surface morphology with fewer visible voids and improved distribution of fibers and filler. The hybrid reinforcement effect becomes more evident at this composition, where milkweed fibers contribute to energy dissipation while banana stem fibers provide structural support under applied load (Chairunnisa and Nurwidayati 2022). A relatively continuous transfer layer is visible on the worn surface, which helps reduce direct metal–composite contact during sliding. The limited presence of micro-cracks and reduced fiber fracture suggest improved stress transfer and stable sliding behavior, which contributes to the enhanced tribological and acoustic performance of this sample.

For Sample S5, which exhibited the lowest wear rate and coefficient of friction, the SEM images show a smoother worn surface with compacted wear debris and the formation of a stable transfer film. The higher proportion of banana stem fibers improves resistance to micro-cutting and reduces matrix ploughing during sliding. *Calotropis* powder particles are observed to be embedded within the worn surface and transfer layer, which may contribute to friction stabilization and wear resistance. The relatively strong fiber–matrix bonding limits extensive fiber pull-out, allowing more uniform stress distribution during sliding.

In contrast, Sample S6 shows signs of fiber clustering and localized interfacial debonding due to the higher banana stem fiber content. The SEM micrographs reveal fractured fibers, micro-cracks, and uneven transfer layer formation across the worn surface. Although the composite still maintains reasonable wear resistance, the irregular debris morphology and exposed fiber ends may contribute to the slight increase in friction observed compared with Sample S5 (Lee *et al.* 2023).

Overall, the SEM observations qualitatively indicate that the combined reinforcement of milkweed fiber, banana stem fiber, and *Calotropis* powder significantly influences the wear mechanisms and frictional behavior of the composites. Improved filler distribution, enhanced fiber–matrix adhesion, and the formation of a stable transfer layer are the key microstructural features associated with better tribological and acoustic performance. The optimized compositions, particularly Samples S4 and S5, exhibit relatively well-integrated microstructures that are favorable for applications requiring effective sound absorption, reduced friction, and improved wear resistance. Figure 8 presents the SEM images of the fractured and worn surfaces of the developed composite samples (Ari *et al.* 2023).

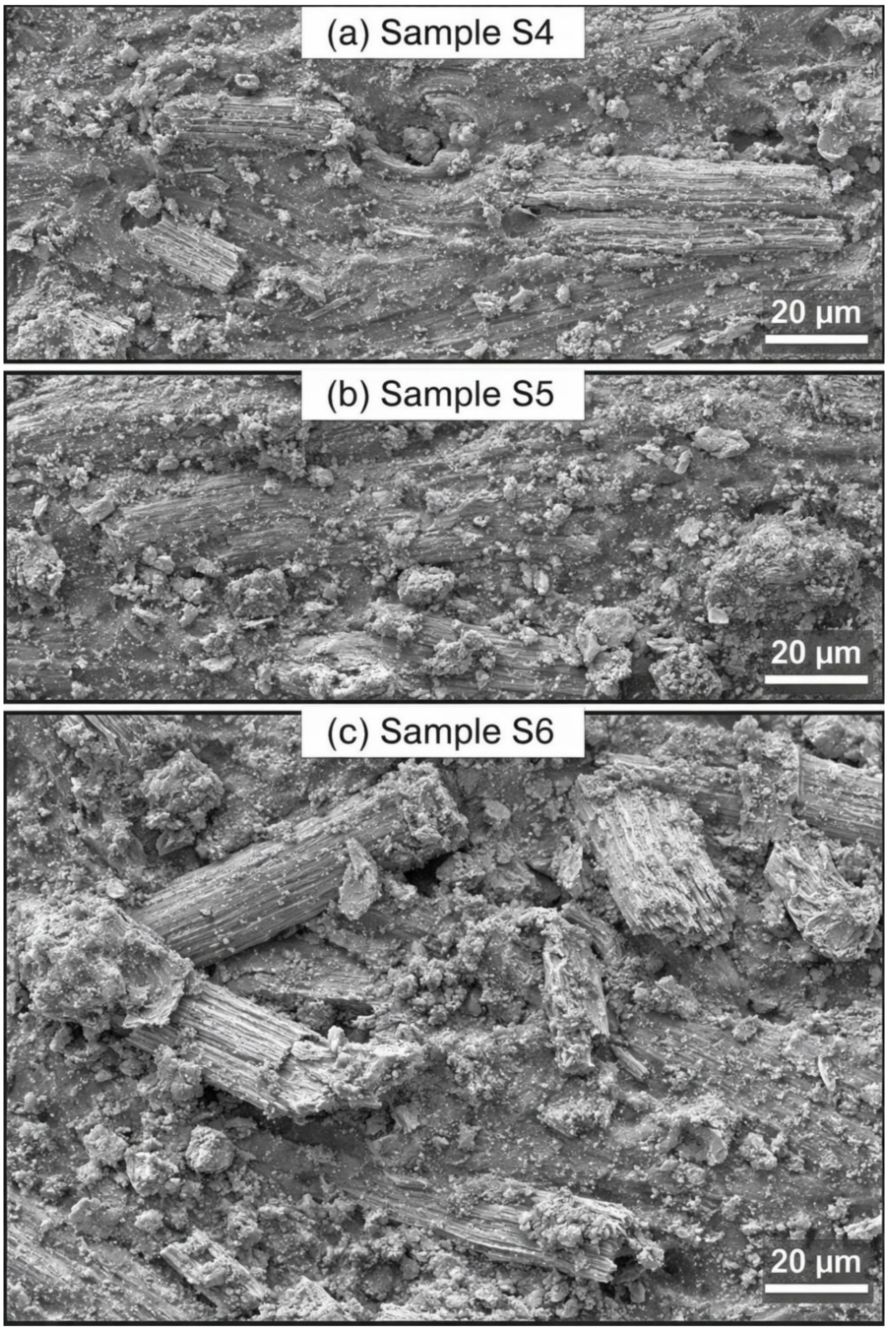

Fig. 8. SEM images of S4, S5, and S6

CONCLUSIONS

The present study systematically investigated the acoustic, tribological, and microstructural performance of hybrid epoxy composites reinforced with *Calotropis* powder, milkweed fiber, and banana stem fiber. Based on the experimental observations, the following conclusions and design insights can be drawn:

1. **Acoustic performance:**
   The incorporation of *Calotropis* powder improved the sound absorption behavior of the hybrid composites by increasing internal friction and promoting multiple reflections of sound waves within the composite structure. Among the developed formulations, the composite containing **15% milkweed fiber and 15% banana stem fiber** exhibited the highest sound absorption coefficient (0.45) and noise reduction coefficient (0.41). This indicates that balanced fiber hybridization creates a more favorable internal structure that enhances acoustic energy dissipation. From a design perspective, maintaining a balanced distribution of flexible and moderately stiff natural fibers can improve acoustic damping performance in hybrid polymer composites.
2. **Tribological behavior:**
   The tribological results revealed that the incorporation of banana stem fiber in combination with *Calotropis* powder improved wear resistance and stabilized the coefficient of friction during dry sliding conditions. The composite containing **20% banana stem fiber and 10% milkweed fiber** demonstrated the lowest wear rate (2.7×10^{-6} $mm^3/N \cdot m$) and coefficient of friction (0.47). This improvement can be attributed to the increased stiffness of banana stem fiber and the presence of *Calotropis* powder particles, which act as micro load-bearing elements and promote the formation of a stable transfer layer at the sliding interface. These findings suggest that optimizing fiber stiffness and filler distribution is essential for developing hybrid composites with improved tribological durability.
3. **Microstructural characteristics:**
   Scanning electron microscopy analysis provided important insights into the structure–property relationships within the developed composites. The optimized composite systems showed uniform fiber dispersion, strong interfacial bonding between fibers and the epoxy matrix, reduced void formation, and the presence of a stable tribological layer during sliding. These microstructural characteristics play a crucial role in enhancing load transfer efficiency and minimizing fiber pull-out and matrix cracking. Therefore, proper dispersion of fillers and effective fiber–matrix adhesion are key parameters in the structural design of high-performance hybrid composites.
4. **Synergistic hybridization effect:**
   The results demonstrate that the combined reinforcement of milkweed fiber, banana stem fiber, and *Calotropis* powder produces a synergistic effect that enhances both acoustic and tribological performance simultaneously. The hybridization approach enables the composite to utilize the flexibility and damping characteristics of milkweed fiber together with the stiffness and structural reinforcement provided by banana stem fiber. The presence of *Calotropis* powder further contributes by improving interfacial friction, surface roughness, and load distribution within the matrix.
5. **Design implications and potential applications:**
   The findings of this study provide useful guidelines for the design of

multifunctional natural fiber composites. Optimizing fiber hybridization ratios and incorporating suitable natural particulate fillers can significantly enhance acoustic absorption and wear resistance without increasing material complexity. The developed composites therefore show strong potential for applications in **automotive interior panels, sound insulation boards, lightweight industrial structures, and tribological components** where both noise attenuation and surface durability are required.

Overall, the study highlights the effectiveness of combining natural fibers and bio-based particulate fillers in designing sustainable hybrid composites with improved multifunctional performance.

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Data Availability Statement

Data are available on request from the authors.

Declaration of Conflicting Interests

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

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