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# Study on tribological behavior of *Phyllostachys bambusoides* bamboo fiber reinforced epoxy composites from Arunachal Pradesh, India

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**Abstract:** This research explores the mechanical and tribological properties of bamboo fiber-reinforced epoxy composites, focusing on *Phyllostachys bambusoides*, a bamboo species known locally as "Bije bamboo," sourced from the Apatani plateau, Arunachal Pradesh, India. The composites are fabricated by incorporating bamboo powder into an epoxy–hardener blend at 5 %, 15 %, and 25 % weight fractions using a manual molding process under sustained pressure for 24 h. The composites underwent a comprehensive tribological assessment, varying key parameters such as load (2 N, 5 N, 7 N), speed (50, 100, 150 cm $s^{-1}$), and bamboo fiber content. A ball-on-disc tribometer was used to simulate wear behavior under these conditions. Profilometry, 3D surface morphology analysis, and optical microscopy are employed to assess wear depth and surface morphology. Notably, the composite containing 15 % bamboo fiber (BFC15) demonstrated superior tribological performance, achieving a low coefficient of friction (*COF*) of 0.087 at 5 N load and 50 cm $s^{-1}$ speed. Additionally, it exhibited a remarkable 53 % improvement in wear resistance compared to the composite with 5 % bamboo fiber (BFC5). Surface roughness was observed to increase with higher bamboo fiber content, with BFC25 recording a maximum roughness of 17.57 µm, indicating delamination wear at higher speeds. The study confirms that the 15 % bamboo fiber composition strikes an optimal balance between mechanical strength, wear resistance, and frictional stability. These findings position bamboo-based biocomposites as a viable, sustainable alternative for industries requiring efficient wear management, particularly in automotive and aerospace applications.

**Keywords:** bamboo fiber-reinforced composites; tribological performance; *Phyllostachys bambusoides*; epoxy-based biocomposites; wear resistance; coefficient of friction

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## Abbreviations

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| BF | Bamboo fiber |
| BFC5 | Matrix with 5 % BF content |
| BFC15 | Matrix with 15 % BF content |
| BFC25 | Matrix with 25 % BF content |
| *COF* | Coefficient of friction |
| FDM | Fused deposition modelling |
| FE-SEM | Field emission scanning electron microscopy |
| HDPE | High density polyethylene |
| $R_t$ | Maximum height of the surface roughness profile |
| $R_a$ | Average surface roughness |
| TEM | Transmission electron microscopy |
| XRD | X-ray diffraction |

## 1 Introduction

The growing demand for environmentally friendly materials in engineering and construction has reignited interest in natural fibers, particularly bamboo, as a viable reinforcement in polymer composites. Bamboo fibers (BFs) possess exceptional mechanical properties, making them attractive for various applications in composite materials. The potential of BF-reinforced epoxy composites to replace conventional synthetic fibers, which often have a greater environmental impact, has gained significant attention. The mechanical and tribological characteristics of BF reinforced epoxy composites are of great interest because it has the potential to substitute conventional synthetic fibers, which frequently have a greater environmental impact. Bamboo, an easily replenishable resource, has distinct structural properties that enhance its mechanical durability. Studies have shown that BFs have a remarkable tensile strength of up to 400 MPa and a modulus of elasticity of approximately

30 GPa, which put it in the same category as certain artificial fibers.[1] The intrinsic characteristics of BFs, such as their low crystallite structure, which is predicted to be between 24 and 26 Å, result in decreased water absorption and chemical reactivity when used in composites.[1] This property is especially beneficial in improving the strength and lifespan of BF reinforced composites in different environmental situations. Extensive research has been conducted on the mechanical properties of epoxy composites reinforced with BFs, demonstrating that the inclusion of BFs greatly improves the tensile and flexural strength of the composites. According to Manalo et al.[2] and Mohanty and Nayak,[3] it was noted that the tensile strength of BF reinforced high density polyethylene (HDPE) composites increased as the amount of BF grew from 10 % to 30 %. The maximum tensile strength reached roughly 50 MPa before a decrease was noticed at higher BF levels. Studies have demonstrated that BF reinforced epoxy composites display enhanced flexural strength, with values reaching as high as 80 MPa. The specific strength depends on the amount of BF used and the treatment procedures applied.[1,4–6]

The friction and wear characteristics of epoxy composites reinforced with BFs are crucial for their application in tribologically demanding environments. Recent research has shown that adding BFs to epoxy matrix greatly decreases the rate at which the composites wear down. Researchers found a notable decrease in wear rate of about 30 % by incorporating BFs into epoxy composites, demonstrating improved wear resistance.[7–9] Scanning electron microscopy analysis showed that the inclusion of BFs in the composites leads to the development of a protective layer on the surface. This layer helps reduce wear and prolong the lifespan of the materials.[8] Moreover, BF reinforced epoxy composites have demonstrated a higher impact toughness compared to conventional synthetic fiber composites. The study by Venkatesh et al.[10] discovered that the impact toughness of BF reinforced composites achieved a remarkable value of 560.78 $J\,m^{-1}$, surpassing that of other synthetic fiber composites. The increased durability of bamboo composites is due to the inherent ability of BFs to absorb energy, enabling them to tolerate higher levels of stress without breaking. The use of BF as reinforcement in epoxy composites has several advantages for the environment in addition to its mechanical and tribological qualities. Bamboo, being a biodegradable substance, is well-suited for use in composite manufacturing due to its alignment with the concepts of sustainability and environmental conservation. Studies have examined the durability of BF reinforced composites over extended periods of time and in different weather situations. These studies have shown that these composites retain their mechanical strength over time, even when exposed to UV radiation and moisture.[4–6,11] This durability further strengthens the argument for using BFs as a sustainable substitute for synthetic reinforcements.

*Phyllostachys bambusoides* (Bije bamboo), a monopodial male bamboo species found in the Apatani Plateau of Arunachal Pradesh, India, has been highlighted in several studies for its exceptional properties. This species is known for its durability, exhibiting strength greater than mild steel, and possessing significant antibacterial properties. In the Apatani Plateau, *P. bambusoides* is a primary material for crafting and structural products.[12–14] Tribology, the study of friction, wear, and lubrication, plays a crucial role in determining the performance and durability of materials in various engineering applications. Addressing this gap is essential for comprehensively evaluating the suitability of bamboo composites in tribologically demanding environments. This introduction sets the stage for a focused investigation into the tribological behavior of epoxy-based bamboo composites. Several recent studies have explored various aspects of bamboo-based composites, shedding light on their mechanical, morphological, and tribological properties. Hasan et al.[15] explored the current status and future prospects of sustainable BF reinforced polymeric composites (BFRCs). Bamboo's rapid growth, renewability, and minimal environmental impact position as a promising alternative to meet the growing demand for eco-friendly materials. The article provides an overview of production methods, mechanical properties, and applications of BFRCs. Additionally, it addresses challenges and opportunities associated with BFRC development that impact their performance in various industrial applications. Escalating global energy demand and carbon dioxide emissions from fossil fuels necessitate urgent exploration of alternative energy sources. Amidst the 0.5 % rise in carbon dioxide emissions and 1.3 % increase in primary energy consumption reported in the 2019 global energy review, biofuels emerge as a promising solution.[16–18] Derived from renewable biomass, biofuels offer low carbon dioxide emissions, reduced pollution, and potential mitigation of climate change impacts.[19,20] Santhosh et al.[21] synthesized BF-reinforced polyester composites through hand lay-up techniques. These bio-composites undergo rigorous mechanical and morphological characterization. Elevated fiber weight content enhances flexural, tensile, and impact strength while improving damping characteristics. Microstructural analysis confirms uniform fiber distribution within the resin matrix. Fracture analysis highlights matrix cracks as the primary failure mechanism, underscoring the effective reinforcement mechanism facilitated by BFs in polyester composites. Pulikkalparambil et al.[22] investigates the impact of graphite nanoparticles on woven BF hybrid composites, focusing on thermal, mechanical, physical, and fatigue properties. Through the incorporation of varying graphite nanoparticle fractions into the epoxy matrix via hand layup, three-layered BF/graphite composites are produced and extensively characterized. Results reveal enhanced properties in hybrid composites, including increased tensile strength, flexural strength, and impact resistance by up to 32.78 %, 27.37 %, and 172.4 %, respectively, with graphite nanoparticle addition. Moreover, thermal analysis demonstrate improved thermal stability, while water contact angle studies indicate heightened hydrophilicity. Fatigue testing underscores the long-term durability of these composites under cyclic loading, affirming their potential for multifaceted applications. Hu et al.[23] explores the influence of scrimmed bamboo bundle morphology and product density on the properties of Wood-Based Scrimber (WBS). Optimal strength properties and minimal thickness swelling are achieved with three or four fiberization passes, promoting higher resin absorption. The included, 1–2 fiberization passes and a panel density of 0.9–1.0 g $cm^{-3}$ makes its performance cost-effective. Comparative analysis with other bamboo composites highlights the variability in properties due to manufacturing processes and element treatments. Atmakuri et al.[24] explores the fabrication and characterization of five composite materials using hemp, flax fibers, and epoxy resin based on a hybridization rule. Contact angle measurement, flexural test, and interlaminar shear test, are conducted following American Society for Testing and Materials (ASTM) standards. Results indicate improved properties in hybrid composites compared to pure composites, particularly in flexural strength and interlaminar shear strength. The research underscores the efficacy of hybridization strategies in enhancing the mechanical properties of composite materials, offering insights into the development of high-performance structural materials. Ashrith et al.[25] examines the fabrication and mechanical characterization of fibrous composites for engineering applications. It delves into fabrication methods, such as hand lay-up and resin transfer molding, and discusses mechanical properties like strength and stiffness. The review highlights the influence of fiber reinforcement on mechanical characteristics and the potential for tailoring properties through factors such as fiber orientation and volume fraction. Despite offering advantages, challenges such as high manufacturing costs and limited design guidelines hinder widespread adoption. Liu et al.[26] investigates frictional behavior between a steel ball and 40CrMnMo, focusing on maximum friction force, fluctuating time, and vibration concerning initial lubricant temperature. Findings reveal friction force reaching a peak followed by oscillations before stabilization. Low viscosity lubricant (LO) significantly reduces maximum friction force, fluctuating time, and vibration at cold start compared to high viscosity lubricant (HO), promoting low and stable friction coefficients and wear loss over long-term testing. LO's fluidity enables rapid lubricant distribution, forming a robust lubricating film. Meanwhile, high temperature decreases HO viscosity, resulting in friction reduction. Sahoo et al.[27] study the novel method for incorporating graphite particles into aluminium (Al-1100) surfaces to create surface composites via electrical resistance heating-assisted pressing. By coating the aluminium surface with graphite and locally heating the interface, mechanical pressure facilitates incorporation. Adjusting process parameters regulates aluminium softening. Microstructural analysis via field emission scanning electron microscopy (FE-SEM), transmission electron microscopy (TEM), Raman spectroscopy, and X-ray diffraction (XRD) reveals significant improvements in surface mechanical properties, with over 200 % enhancement in hardness and 150 % increase in reduced Young's modulus. Tribological studies demonstrate wear resistance and *COF* improvements exceeding 50 %, supported by microstructural changes observed through Raman spectroscopy and XRD, offering insights into enhanced performance. Sarmin et al.[28] investigates the mechanical performance of olive waste/BF hybrid composites compared to pure olive and BF-reinforced epoxy. Utilizing olive residues from various parts of the plant, three hybrid composites are produced with enhanced mechanical properties, including tensile strength, flexural strength, and impact strength. Among them, the OTB/B hybrid demonstrates superior mechanical and impact properties, making it suitable for load-bearing applications including floor panels and automotive interiors. Morphological analysis reveals stronger fiber-matrix adhesion in bamboo composites, resulting in fewer voids and microcracks. Ahmad et al.[29] review delves into the realm of additive manufacturing (AM) with a focus on fused deposition modeling (FDM) and its integration with natural fibers to produce eco-friendly components. It highlights the burgeoning interest in employing natural fibers as bio-filters in conjunction with thermoplastics, fostering environmentally sustainable manufacturing practices. The paper meticulously examines the fabrication, characterization, and challenges associated with developing natural fiber composite filaments for FDM. Through mechanical testing, dimensional stability analysis, morphological study, and surface quality assessment, it provides valuable insights into the properties of these filaments. More et al. [30] used radioactive materials necessitating advanced shielding materials for radiation protection. Polymers stand out for their versatile properties, including mechanical, electrical, and thermal characteristics. Incorporating high atomic number fillers into polymer matrices offers lightweight, flexible, and easily processable shielding materials. This review examines the synthesis of polymer-based radiation shielding materials, emphasizing the role of nanofillers. It evaluates the efficacy of polymers in absorbing fast neutrons and explores recycling polymers for composite production. By harnessing the potential of polymers and nanotechnology, innovative solutions for radiation protection can be developed, addressing the growing concerns of radioactive pollution. Anusha et al.[31] investigates the wear behavior of Al 7178-based composites reinforced with boron carbide, titanium dioxide, and fly ash. Utilizing the stir casting method, composites with a fixed reinforcement content of 3 % are prepared. Wear tests are conducted on a pin-on-disc apparatus with varying levels of load, sliding speed, and sliding distance, following a central composite design. Results reveal that the maximum wear rate occurs at specific parameter combinations, while analysis of variance highlights the significant influence of load and its interaction with sliding distance on wear rate. Oliver et al.[7] investigated the tribological properties of bamboo fiber-reinforced epoxy composites. They performed sliding wear study under various lubrication, load, speed, temperature and fiber orientation conditions using a linear reciprocating tribometer. According to preliminary results, wear rate is dependent on temperature and load, and lubrication has a major impact on wear and friction. Further, scanning electron microcopy was used to analyze the wear mechanism.

The significance of testing under a variety of situations to maximize material performance has been highlighted by many researchers that have examined tribological systems with different characteristics, reported in past few decades. The existing literature highlights a significant gap in the understanding of the tribological behavior of epoxy-based bamboo composites. The present research aims to address this gap by systematically investigating the mechanical & frictional characteristics and wear resistance, and lubrication effects of these composites. A more thorough grasp of wear mechanisms and frictional behavior in practical application circumstances, for example, could be obtained by using a linear reciprocating tribometer with pin-on-disc arrangement. These alternative strategies have the potential to advance the use of BF composites in difficult tribological conditions. The present study focusses in the development of epoxy-based composites reinforced with bamboo fibers (*P. bambusoides*) from Arunachal Pradesh, and examine the wear mechanism. The findings are expected to contribute to the fundamental understanding of these materials and support the development of more sustainable and durable solutions for engineering applications.

## 2 Materials and methods

In this study, *Phyllostachys bambusoides* bamboo of Arunachal Pradesh, India was considered, and the mechanical and frictional behavior of epoxy-based bamboo composites was thoroughly investigated. The study focused on understanding how varying the bamboo fine particle content (5 %, 15 %, and 25 % by weight) within the epoxy matrix affects the composite's mechanical properties and surface roughness. Additionally, the frictional characteristics, including wear resistance, were examined to assess the material's suitability for real-world applications. By systematically analyzing these aspects, the research aims to provide comprehensive insights into the performance of epoxy-based bamboo composites, contributing to the development of more sustainable and durable materials for various engineering purposes.

### 2.1 Preparation of EPOXY-based bamboo composites

Figure 1 shows optical microscopic and FE-SEM images of bamboo culm, where Figure 1a shows the vertical growth pattern and the jointed structure of bamboo comprising of nodes and internodes, Figure 1b and c shows the cross-section of bamboo culm in different magnifications of 25 × and 90 × respectively under optical microscopic view. It reveals a circular arrangement of vascular bundles. Figure 1d and e shows the vascular bundles and enlarged view of BF bundle under FE-SEM showcasing the presence of protoxylem, metaxylem, phloem, sieve elements and elementary BFs aligned having tube-like cells. The basic flowchart of epoxy-based matrix preparation with BF content is shown in Figure 2. The epoxy resin and the hardener were combined in a 2:1 wt. ratio. To achieve good homogeneity, the mixture was stirred with a stirrer at low speed for 3 min. Composites of different wt.% viz. 5 %, 15 % and 25 % were named as BFC5, BFC15 and BFC25 respectively. The mixture underwent a 13-min degassing process at 150 rpm in room temperature of 30 °C to remove air bubbles, using a vacuum pump and a glass desiccator maintaining a vacuum pressure of $7 \times 10^{-2}$ bar. After degassing, the mixture was put into a mold made of brass of dimensions 55 mm diameter. The counter-mold bolts were tightened to eliminate air bubbles and ensure a consistent thickness of the composite plate, ensuring compression. The inner surface of the mold was coated with adhesive tape to prevent the composite plate from sticking. The composite plates were left in the mold for 18–20 h at room temperature. After curing, the unidirectional composite specimens were removed from the mold. The specimens were stored for 20 days. The composites were then dried in an oven at 70 °C for 4 h. The dried composite plates were inspected for any defects such as voids, delamination, or uneven thickness. The specimens were then cut into the required dimensions for further mechanical testing and analysis.

## 2.2 Tribology and surface profile tests

The surface of prepared matrix samples was characterized beforehand and after the tribology test with a 3D non-contact type surface profiler (3D NSP, Model: S-neox, Make: Sensofar). Roughness parameters of area and line profile were taken as per ISO 4287 and ISO 25178, respectively. The tribology test was performed in a high temperature tribometer (Model: THT 1,000 °C, make: Anton Paar, Germany), shown in Figure 3, with a rotating ball on disc configuration. All tribology tests were performed for a fixed travel distance of 1,000 m at room temperature condition. Normal load of 2, 5, and 7 N was maintained between the steel ball and epoxy-based bamboo composite disc. For these loads sliding speed was also varied for 50, 100 and 150 cm $s^{-1}$ at dry conditions.

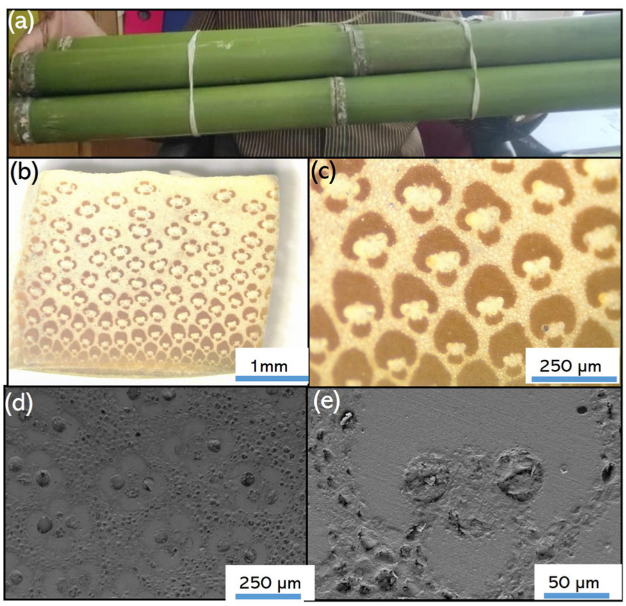


**Figure 1:** Microstructural Analysis of Bamboo Fibers. (a) Bamboo culm, (b) cross-section of bamboo culm, (c), (d) vascular bundle of the BF under optical microscope and FE-SEM, and (e) elementary BFs and vascular bundle under FE-SEM.

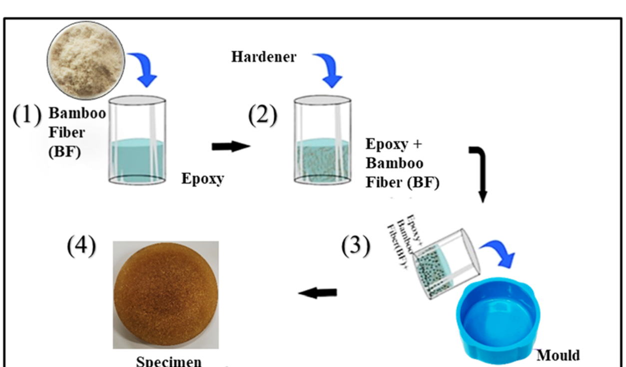


**Figure 2:** Flow chart of epoxy-based matrix preparation with BF content.

# 3 Results and discussion

## 3.1 Analysis of surface characteristics

3D surface profile images of matrix surfaces of BF composite with 5 %, 15 %, and 25 % (BFC5, BFC15, and BFC25) are presented in Figure 4. Along with the profile images the average surface roughness ($R_a$) and maximum height ($R_t$) of the line profile were also estimated in this study. It was observed that with increase of bamboo content in the matrix the roughness of surface increases. Surface profile graphs of the test path for tribology tests performed at 5 N load with 5 % (a), 15 % (b), and 25 % (c) BF content are presented in Figure 5. It can be seen from these graphs that the tribological behavior of BFC 15 samples is best suited for epoxy-based bamboo composites. Profiles of BFC15 show the lowest wear in 50, 100, and 150 cm $s^{-1}$ sliding speed. In BFC five samples, higher wear rate with increasing speed is observed with consistent pond-shaped wear, whereas the profile of BFC25 is irregular with higher peaks and valleys leading to three body wear mechanisms. Surface profile images of matrix surfaces (BFC5, BFC15, and BFC25) with test path in the end for tribology test performed at 7 N load and 150 cm $s^{-1}$ sliding speed are presented in Figure 6. The BFC15 showed a consistent path pattern with the lowest areas of surface roughness ($S_a$) corresponding to a low *COF* and abrasion type of wear. BFC5 showed higher adhesive behavior due to which eruption and breakage of material from surface is visible with *COF* reaching the maximum permissible limit before travelling 200 m. With the increase in travel distance, it may show a much higher eruption. The highest $S_a$ of 17.57 μm is obtained for the BFC25 sample due to delamination wear with unstable *COF* profile after 700 m of travel distance at 7 N load and 150 cm $s^{-1}$ of sliding speed.


**Figure 3:** Experimental setup for surface profiling, hardness tests and tribology tests.

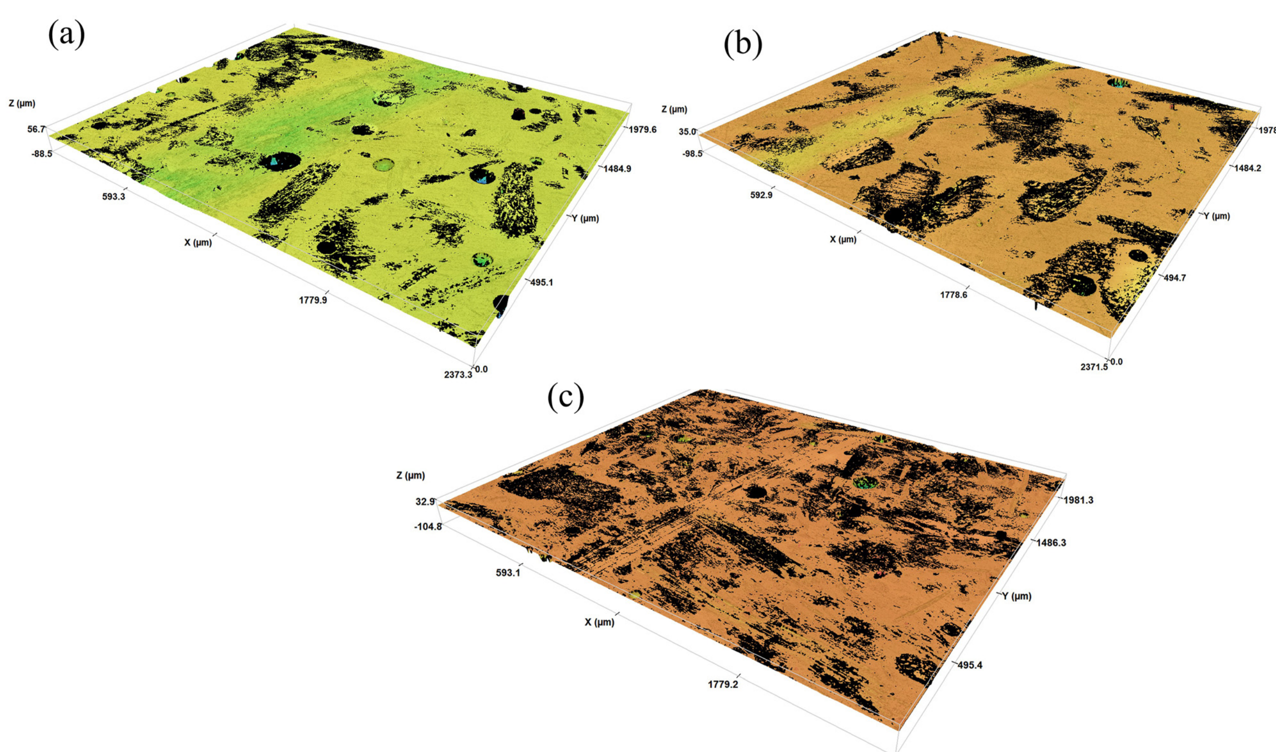


**Figure 4:** Surface profile images of the matrix with wt.% of (a) 5 % ($R_a$ = 0.15 µm, $R_t$ = 4.59 µm), (b) 15 % ($R_a$ = 0.35 µm, $R_t$ = 6.69 µm), and (c) 25 % ($R_a$ = 1.15 µm, $R_t$ = 11.5 µm) BF content.

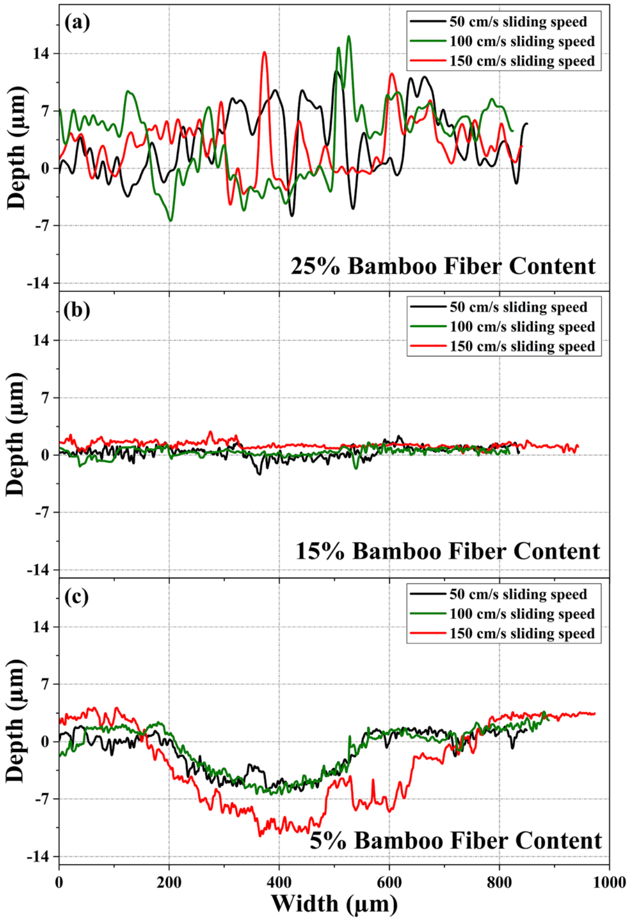


**Figure 5:** Surface profile graphs of test path for tribology tests performed at 5 N load with (a) 5 %, (b) 15 %, and (c) 25 % BF content.

Hardness values at 12 indentation points of matrix samples have been plotted in Figure 7. Compared to BFC5 and BFC15, BFC25 shows higher hardness due to higher bamboo reinforcement which eventually increases *COF* initially due to higher indentation energy. Higher hardness in the BFC25 also leads to changes in the *COF* profile as observed in *COF* profiles.

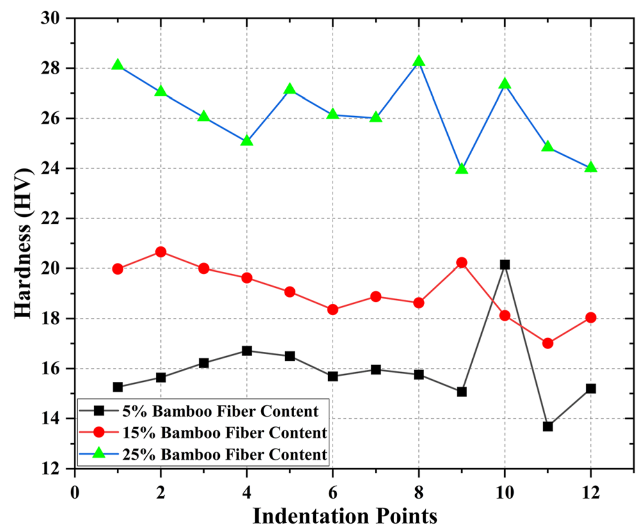


**Figure 7:** Hardness graphs of matrix surfaces with (a) 5 %, (b) 15 %, and (c) 25 % BF content.

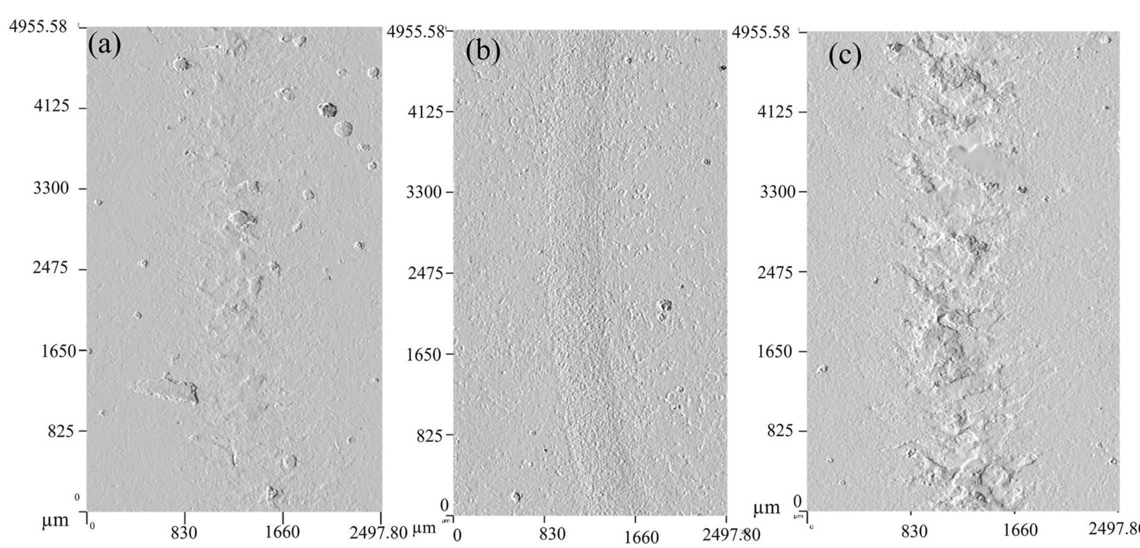


**Figure 6:** 2D surface profile images of tribology test path: (a) BFC 5, $R_a$ = 5.28 μm, (b) BFC 15, $R_a$ = 2.35 μm, and (c) BFC 25 BF content, $R_a$ = 17.57 μm for tribology test performed at 7 N load and 150 cm $s^{-1}$ sliding speed.

## 3.2 Analysis of tribological behavior

The tribological behavior of BFC with varying BF content revealed significant differences in performance. *COF* profiles varied for all tribology tests performed with varying load and speed conditions.[32] During the tribology, microstructures of epoxy and BF content in the true contact area were different. Additionally, the properties of epoxy changed with the change in temperature in true contact of rotating ball-on-disc tribology tests. Hence, provided dissimilar *COF* profiles for all tested conditions. In these profiles, variations due to material adhesion and plastic deformation are analyzed in detail. Table 1, shows the mean *COF* calculated for the tribology test conducted at varying load and sliding speed conditions for BFC5, BFC15, and BFC25 composite materials.

For 2 N load, the *COF* profile of BFC5 samples starts slightly lower than the BFC15 samples and shows a very gradual increase over the distance to show similar friction, as shown in Figure 8a–c. This profile pattern relates to the abrasion wear mechanism and increased contact area of ball on disc. Gradual increase in friction over distance indicates a slightly increasing wear rate, but the overall stability suggests it is well-suited for long-term applications with low wear requirements.[7] Figure 8 reveals that the mean *COF* of BFC15 and BFC25 is higher than BFC5 samples for all tested speeds (50 cm $s^{-1}$–150 cm $s^{-1}$) at 2 N load. Figure 8b shows that BFC15 samples exhibit a consistent wear rate, with matrix and BF equally dominating the tribological properties. BFC25 samples show a specific patten at 2 N load, starting at peak *COF* followed by a valley, after which gradual increase in *COF* as presented in Figure 8c. This suggests that the initial indentation in the path takes more energy dissipated in the form of friction. Once the path is developed a sudden drop in *COF* is observed which increases with time due to increase in contact area of ball on disc. Sticking phenomenon increases with temperature and sliding speed.[33] Peak and valley patterns found in *COF* profiles of all samples are due to the adhesion wear mechanism where epoxy material sticks to the ball. Increasing speed from 50 cm $s^{-1}$ to 150 cm $s^{-1}$, also increases adhesion due to reduced repeating (cooling) time, which ultimately increases the contact temperature. Epoxy has very low melting point compared to BF which resulted in increased adhesion as the contact temperature increases.

**Table 1:** Mean *COF* calculated for the tribology test conducted at varying load and sliding speed conditions for BFC5, BFC15, and BFC25 composite materials.

| Load (N) | Sliding speed (cm $s^{-1}$) | Mean coefficient of friction | | |
|---|---|---|---|---|
| | | 5 % BF content | 15 % BF content | 25 % BF content |
| 2 | 50 | 0.162 | 0.197 | 0.398 |
| 2 | 100 | 0.229 | 0.246 | 0.414 |
| 2 | 150 | 0.267 | 0.305 | 0.400 |
| 5 | 50 | 0.150 | 0.087 | 0.316 |
| 5 | 100 | 0.163 | 0.095 | 0.232 |
| 5 | 150 | 0.164 | 0.089 | 0.238 |
| 7 | 50 | 0.269 | 0.227 | 0.341 |
| 7 | 100 | 0.368 | 0.351 | 0.362 |
| 7 | 150 | 0.308 | 0.158 | 0.351 |

The *COF* of BFC5 and BFC15 samples starts at a moderate value and remains relatively stable throughout the test with minor fluctuations for many conditions. This indicates consistent tribological performance with moderate wear characteristics. *COF* profiles of these samples are relatively smooth and stable, suggesting that 5 % and 15 % BF content provides a balanced and stable friction profile, which indicates improved wear resistance and reduced wear rate. It is the most suitable tribological behavior for epoxy-based bamboo composites. However, BFC25 samples have shown stability for very small durations, which leads to abrupt change in wear mechanism for all tested conditions likely due to higher BF exposure and less effective load transfer through the matrix. This suggests that the higher content of BFC25 is not suitable for epoxy-based bamboo composites as the abrupt behavior will lead to higher wear, shock and vibration in relative motion of surfaces in intimate contact. Comparing *COF* profiles between BFC5 and BFC15, BFC25 samples reveals similar *COF* profiles at 2 N load (shown in Figure 8) and better *COF* profiles at 5 and 7 N load (shown in Figures 9 and 10 respectively) suggesting optimum tribological performance at the tested load and sliding speed, low and moderate friction levels throughout the travel distance indicate that the BFC15 provides sufficient reinforcement without excessive fiber–matrix interactions. BFC15 composition provides an optimal balance, reducing friction due to better load distribution, lower stickiness and interfacial shear.

Tribological behavior varies with test conditions as the lowest mean *COF* is obtained at 5 N load, 100 cm $s^{-1}$ sliding speed with BFC15 samples, shown in Figure 9a–c. BFC15 samples showed similar or reduced *COF* with travelled distance at 5 N. This represents a very low wear rate of tested samples with the matrix material providing a protective layer over the BFs. This composition likely exhibits a mix of mild abrasive and adhesive wear, leading to steady-state friction. BFC15 offers optimal wear resistance, low friction, and stability over long distances, making it the best choice for high-performance applications. The *COF* profile of BFC25 seems to have gone through a change in wear mechanism as well as initial indentation. For 2 N load at all tested speeds

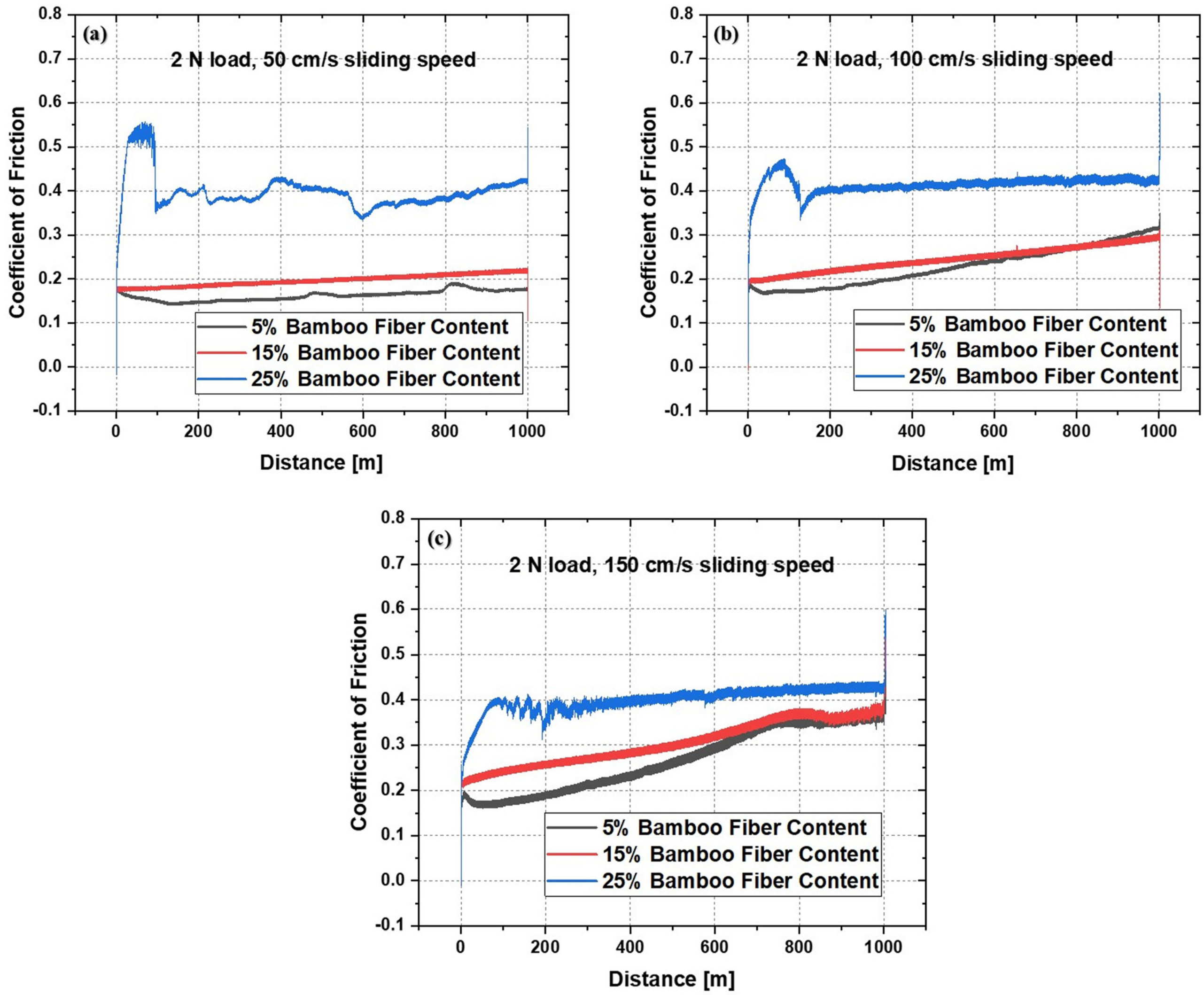


**Figure 8:** *COF* versus travelled distance for the tribology tests performed at 2 N load for sliding speed at (a) 50 cm $s^{-1}$, (b) 100 cm $s^{-1}$, and (c) 150 cm $s^{-1}$ BFC composite materials.

and for 5 N load at 50 cm $s^{-1}$ speed, BFC25 showed different profile through travelled distance due to bamboo reinforcement increases the toughness of the matrix. With increase in sliding speed at 5 N load, BFC25 showed similar starting *COF* as for BFC5. However, the *COF* increases at accelerating higher rate for BFC25 due to higher wear.

Compared to BFC5 and BFC15 tribology tests at 2 and 5 N load, the *COF* increases with higher slope angle for BFC25. Figure 10a–c show that BFC5 sample reached the higher load limit very early before 200 m of travelled distance at 7 N load and 150 cm $s^{-1}$ sliding speed. This is due to the strong adhesiveness of epoxy material at elevated contact temperature. However, the steel ball can release the stuck BFC5 material at 100 cm $s^{-1}$. At 7 N load, BFC15 showed much more stable friction with minor fluctuations. In some cases, at higher speed after reaching a *COF* higher than 0.3, the *COF* profile shows significant fluctuations in all type of samples. These noticeable spikes and variability in the *COF* indicate inconsistent tribological behavior due to delamination type of wear mechanism and potential BF-matrix debonding. This type of *COF* profiles is mostly observed at higher load of 7 N and higher speed of 100 and 150 cm $s^{-1}$ for BFC25 samples.

The superior tribological performance of BF15 can be attributed to the optimal balance between fiber reinforcement and matrix integrity. At 15 % bamboo fiber content, the composite exhibits efficient load transfer and reduced stress concentrations, contributing to its lower wear rates and stable coefficient of friction (*COF*). The uniform distribution of bamboo fibers in the epoxy matrix at 15 % creates a protective tribological film effectively during sliding. Such layer acts as a barrier, minimizing direct contact between the sliding surfaces and enhancing wear resistance.

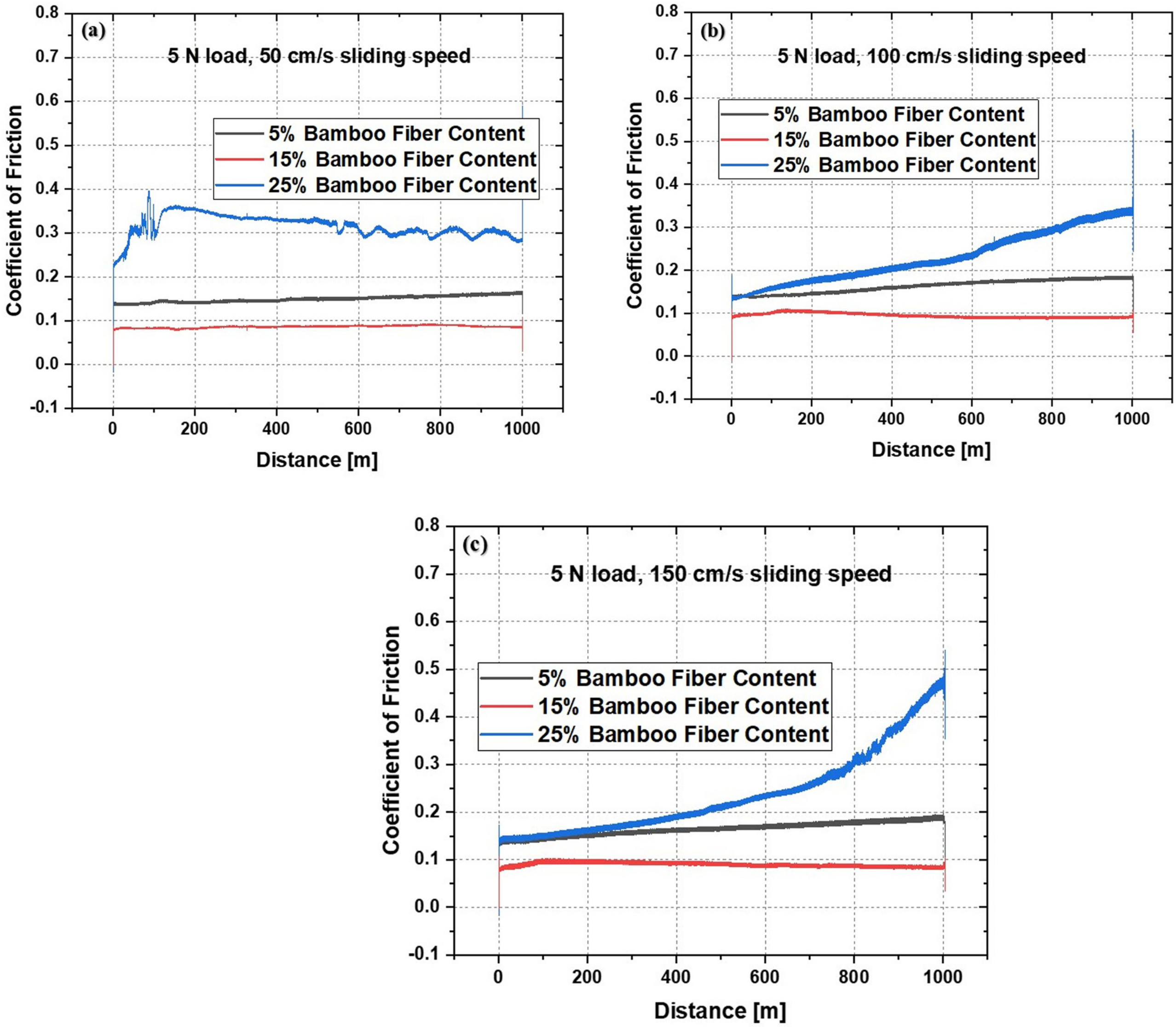


**Figure 9:** *COF* versus travelled distance for the tribology tests performed at 5 N load for sliding speed at (a) 50 cm/s, (b) 100 cm/s, and (c) 150 cm/s BFC composite materials.

In comparison, BF5 lacks sufficient reinforcement to support effective wear resistance, while BF25 shows evidence of fiber pull-out and matrix disruption, leading to increased wear and surface roughness. This highlights that 15 % bamboo fiber content strikes an optimal balance, making it suitable for tribologically demanding applications. Bamboo fibers combine excellent mechanical and tribological properties compared to other natural fibers, such as sisal, flax, jute, sugarcane or hemp fibre composites[34] which exhibit higher coefficients of friction due to fiber surface roughness, whereas bamboo fibers provides a relatively smoother interface, leading to better frictional stability.[35] Compared to synthetic fibers such as glass, bamboo fibers have the advantage of being lightweight, renewable, and sustainable, while still offering comparable wear resistance[18,35] but require treatments to mitigate moisture sensitivity for long-term use.[19,36]

## 4 Conclusions

Epoxy-based composites reinforced with *Phyllostachys bambusoides* BFs from Arunachal Pradesh, India, with varying weight percentages (5 %, 15 %, and 25 %) of bamboo inclusions have been successfully synthesized. A detailed tribological evaluation was conducted by varying critical parameters such as load, speed, and BF content. Surface analysis using profilometry, 3D surface morphology

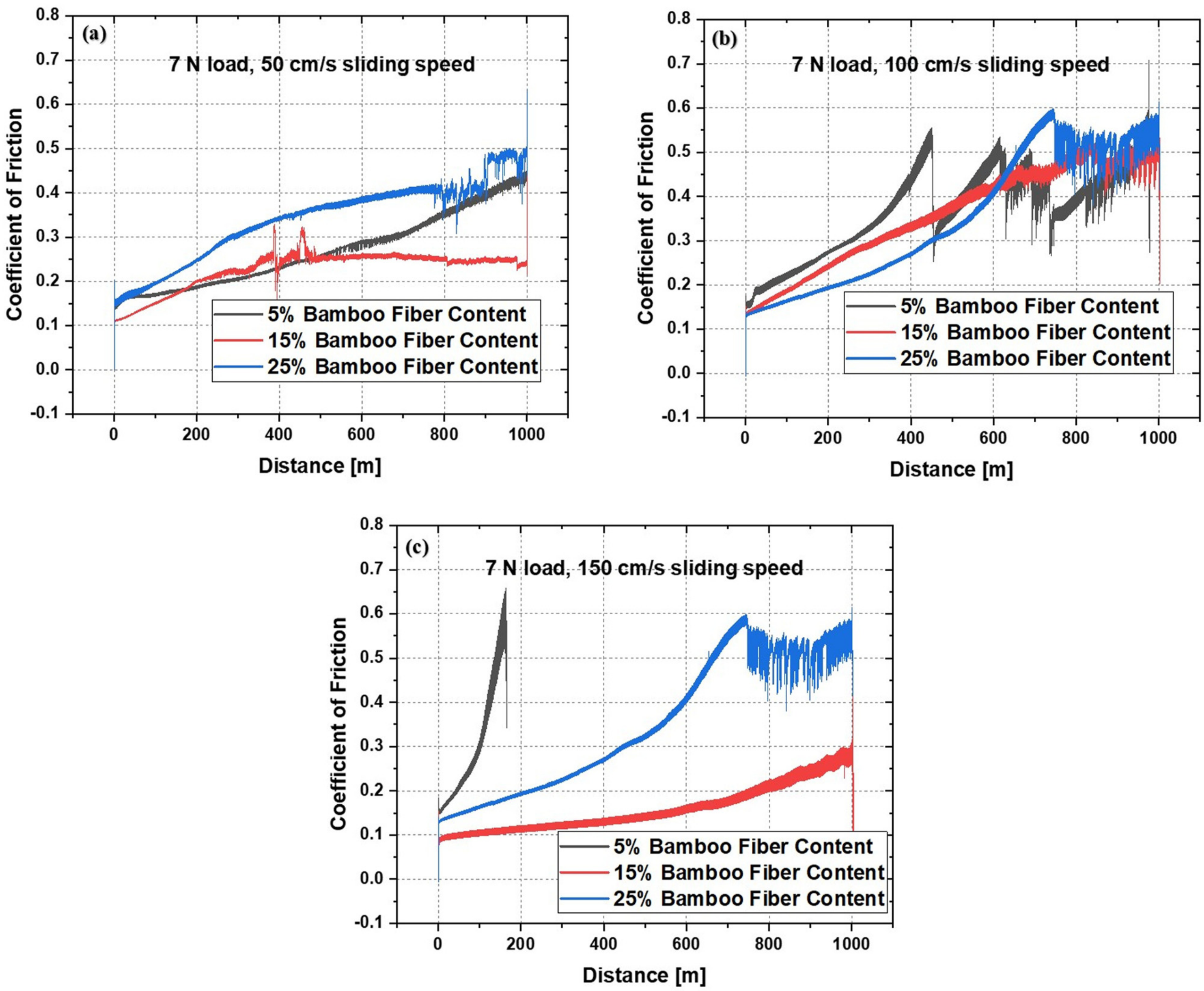


**Figure 10:** *COF* versus travelled distance for the tribology tests performed at 7 N load for sliding speed at (a) 50 cm $s^{-1}$, (b) 100 cm $s^{-1}$, and (c) 150 cm $s^{-1}$ BFC composite materials.

assessment, and optical microscopy was employed to measure wear depth, surface roughness, and porosity. The results demonstrate that BF content significantly influences the composite's tribological properties. As BF content increases, surface roughness also rises. The 5 % bamboo composite (BFC5) exhibited an $R_a$ of 0.15 µm, while the 15 % composite (BFC15) had an $R_a$ of 0.35 µm, and the 25 % composite (BFC25) reached an $R_a$ of 1.15 µm, indicating a considerable increase in surface roughness with higher BF content. The wear rate was notably lower in BFC15, where the maximum wear depth was measured at 2.35 µm, compared to 5.28 µm for BFC5 and 17.57 µm for BFC25.

The *COF* varied across the composites, with BFC15 showing optimal tribological performance. At 5 N load and 50 cm $s^{-1}$ sliding speed, BFC15 had a *COF* of 0.087, significantly lower than BFC5 (*COF* = 0.150) and BFC25 (*COF* = 0.316). Similarly, at 7 N load and 150 cm $s^{-1}$ speed, BFC15 exhibited a low *COF* of 0.158, compared to BFC5 (*COF* = 0.308) and BFC25 (*COF* = 0.351), confirming BFC15's superior wear resistance and frictional stability under varying conditions.

The novelty of this research lies in the systematic exploration of BF content in epoxy composites and its direct influence on wear resistance, surface roughness, and frictional behavior. The use of *P. bambusoides*, a species with superior mechanical properties, has resulted in the development of highly durable, lightweight, and sustainable biocomposites. These findings suggest that the BFC15 composite, in particular, holds significant potential for use in automotive and aerospace components, where long-lasting, low-wear, and environmentally friendly materials are highly desirable. The optimized tribological performance of BFC15 makes it a promising contender for applications such as brake pads, clutch components, and wear-resistant coatings, where controlled friction and enhanced wear resistance are critical.

Future studies should focus on the long-term durability and environmental exposure of BFC15 composites under real-world conditions. Investigating the effects of cyclic loading, temperature variations, and moisture absorption on the composite's performance could provide valuable insights into its performance over extended periods. Additionally, exploring the scalability of these biocomposites for large-scale manufacturing and their potential integration with other sustainable materials would be beneficial for advancing the use of these composites in industrial applications. Further research on alternative polymer matrices and variations in BF content can also optimize the mechanical and tribological properties, leading to the development of even more advanced, eco-friendly composite materials.

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