Thermal Analysis and Tribological Characterization of Bamboo-fiber-reinforced Polylactic Acid Composites

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Bamboo-fiber-reinforced polylactic acid (B-PLA) composites have emerged as promising materials for sustainable engineering applications due to their biodegradability, favorable mechanical properties, and renewability. This work systematically evaluated the thermal behavior and tribological performance of B-PLA composites using methods such as Vicat softening temperature measurement (VST), thermogravimetric analysis (TGA), and abrasive wear testing under varying loads, distances, and abrasive types. The results demonstrated that bamboo fiber reinforcement significantly increased the Vicat softening temperature compared with neat PLA, indicating enhanced thermal resistance. Thermogravimetric analysis revealed that the maximum degradation temperatures of the composites (303 to 317 °C) were comparable to neat PLA, confirming good thermal stability without phase separation. Tribological evaluation showed that specimens fabricated at a nozzle temperature of 245 °C exhibited approximately 37.5% lower wear mass loss than those fabricated at 195 °C, owing to improved interfacial bonding and higher surface hardness. Furthermore, Al_2O_3 abrasives produced the highest wear because of their greater hardness and density, while SEM observations confirmed reduced abrasive embedding and improved fiber-matrix adhesion in high-temperature processed composites. These findings demonstrate that optimized FDM processing significantly enhanced the thermal and wear performance of sustainable bamboo/PLA composites.

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INTRODUCTION

Polylactic acid (PLA) has emerged as a promising sustainable alternative to conventional petroleum-based polymers due to its biodegradability and renewable sources. However, the intrinsic limitations in its mechanical and thermal properties often restrict its broader industrial applications (Nirmal Kumar and Dinesh Babu 2024; Davim 2024). To overcome these limitations, the incorporation of natural fibers, such as bamboo, has gained significant attention in the development of biocomposites (Behera *et al.* 2025). Bamboo fibers offer favorable physico-mechanical properties, making them an attractive reinforcing component for various polymer matrices. They can contribute to reduced carbon emissions and lower material costs. These bamboo-reinforced PLA composites are increasingly being explored for diverse applications, necessitating comprehensive characterization of their thermal and tribological performance (Oliver *et al.* 2023).

Thermal analysis, particularly Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC), is crucial for understanding the heat resistance and degradation behavior of these biocomposites. The TGA assesses the mass loss of materials as a function of temperature, providing insights into the decomposition temperatures of the PLA matrix and the bamboo fibers, as well as the overall thermal stability of the composite (Raja *et al.* 2021; Kumar *et al.* 2024). For instance, studies have demonstrated that the addition of natural fibers and certain nanoparticles can significantly influence the thermal degradation profiles of PLA composites (Kubiak *et al.* 2025). The integration of nano-magnesium oxide (mMgO) into PLA, for example, has been shown to impact the thermal stability, with varying concentrations affecting degradation temperatures and heat flow characteristics observed through TGA and DSC analyses (Cai *et al.* 2025). Specifically, DSC curves illustrate how the addition of mMgO alters the melting behavior of PLA, leading to shifts in melting peaks and variations in their shape and intensity, which are indicative of changes in crystallinity and interactions between the filler and the polymer matrix.

Tribological characterization, specifically through three-body abrasive wear tests, is equally essential for assessing the material's resistance to wear under abrasive conditions, which is crucial for applications subjected to friction and mechanical stress (Kumar *et al.* 2022; Hou *et al.* 2026, Davim 2011, 2013; Irawan *et al.* 2022). Research on short bamboo fiber-reinforced polypropylene composites has revealed that wear rates tend to increase with rising temperatures, illustrating the importance of understanding environmental factors on performance. Similarly, the incorporation of various bio-fillers into PLA matrices, such as rice husk and walnut shell fibers, significantly influences tribological properties (Babu *et al.* 2023). Studies utilizing a rubber wheel abrasion tester (RWAT) for three-body abrasive wear on rice husk-filled PLA composites have demonstrated that higher filler content and specific loading conditions affect wear behavior (Kumar *et al.* 2022). Furthermore, advancements in enhancing the tribological capabilities of PLA-based biocomposites include the addition of graphene oxide (GO) (Laraba *et al.* 2023), which has been shown to improve wear resistance. The processing technique and type of graphene filler also play a role in the tribological performance of 3D-printed PLA-graphene composites. The comprehensive understanding derived from both thermal and tribological analyses is vital for optimizing the design and application of bamboo-PLA biocomposites, contributing to the development of more sustainable and high-performance materials. This introductory section sets the stage for a detailed examination of these critical properties in bamboo-PLA composites, emphasizing the need for rigorous characterization to fully realize their potential.

Although numerous studies have investigated the mechanical and thermal characteristics of bamboo-fiber-reinforced PLA composites, most have focused on isolated material properties or conventional fabrication methods (Long *et al.* 2019; Nirmal Kumar and Dinesh Babu 2024). Recent investigations have primarily emphasized tensile strength, flexural behavior, or thermal degradation, whereas comprehensive studies integrating thermal stability with tribological performance of additively manufactured bamboo/PLA composites remain scarce. The influence of FDM processing parameters, particularly nozzle temperature, on the combined thermal and abrasive wear behavior has received limited attention. Existing studies rarely correlate thermal stability, wear resistance, and microstructural evolution to explain the processing–structure–property relationship. A systematic investigation combining Vicat softening temperature, thermogravimetric analysis, abrasive wear testing, and SEM characterization is essential to establish the suitability of bamboo/PLA composites for engineering applications subjected to thermal and tribological loading. This research work investigated the thermal stability and degradation temperature of bamboo-PLA composites. Moreover, the tribological characterization explored the wear and friction characteristics of the composites, providing useful information for determining whether or not they are appropriate for usage in situations where mechanical interactions are common. Researchers and industry professionals can make well-informed decisions about the prospective applications and wide variety of products of these composites by developing a greater understanding of their thermal and tribological characteristics.

EXPERIMENTAL

Materials

Commercial polylactic acid (PLA) filament (1.75 mm diameter) supplied by 3D Crafts, Madurai, India, was used as the matrix material. The PLA filament was selected because of its excellent printability, biodegradability, and suitability for fused deposition modeling (FDM). Bidirectional woven bamboo fiber mats were procured from Vruksha Composites, Andhra Pradesh, India, and used as the reinforcement material. The bamboo fiber reinforcement was selected owing to its high specific strength, low density, renewability, biodegradability, and excellent compatibility with PLA. The bamboo mat was incorporated into the PLA matrix without the addition of any fillers, nanoparticles, or chemical additives to evaluate the sole influence of bamboo fiber reinforcement and processing temperature on the thermal and tribological performance of the composites.

Bamboo-fiber-reinforced PLA (B-PLA) composites were fabricated using the fused deposition modeling (FDM) technique. During fabrication, the bamboo fiber mat was embedded within the printed PLA layers to produce laminated composite specimens. Three nozzle temperatures, namely 195 °C, 220 °C, and 245 °C, were selected while keeping all other printing parameters constant. These temperatures represent the lower, intermediate, and upper limits of the recommended processing window of the PLA filament and were selected to investigate their influence on polymer flow, fiber impregnation, interfacial bonding, thermal stability, and wear performance.

EXPERIMENTAL

Vicat Softening Temperature (VST) Testing

The Vicat Softening Temperature (VST) test determines the temperature at which a polymer or bituminous material begins to soften and lose rigidity under heating, indicating its thermal stability and high-temperature performance. The test was conducted according to ASTM D1525-17e1 (2017), where a 10 N load was applied to the specimen immersed in an oil bath. The temperature was increased at 120 °C per hour until a 1 mm penetration was achieved, which was recorded as the Vicat softening temperature.

Thermogravimetric Analysis

Thermogravimetric Analysis (TGA) is a useful technique that may be used to characterize the thermal properties of bamboo-PLA composites. The TGA was performed to quantify mass loss in the composite material due to filler residue, molecular decomposition, moisture evaporation, and volatilization of solvents as a function of temperature. The analysis was performed using a Perkin Elmer thermal analyzer (TGA 8000) over a temperature range of 30 to 600 °C to monitor the thermal stability and degradation behavior. The experiment was conducted under a nitrogen atmosphere (19.8 mL/min) using an alumina crucible with a pinhole, with a controlled heating rate of 5 °C per minute.

Tribological Analysis

A dry sand wheel abrasion tester was used for the three-body abrasive wear tests as per ASTM G65-16 (2021) standards. The schematic diagram of the sample size and sample wear face is shown in Fig. 1.

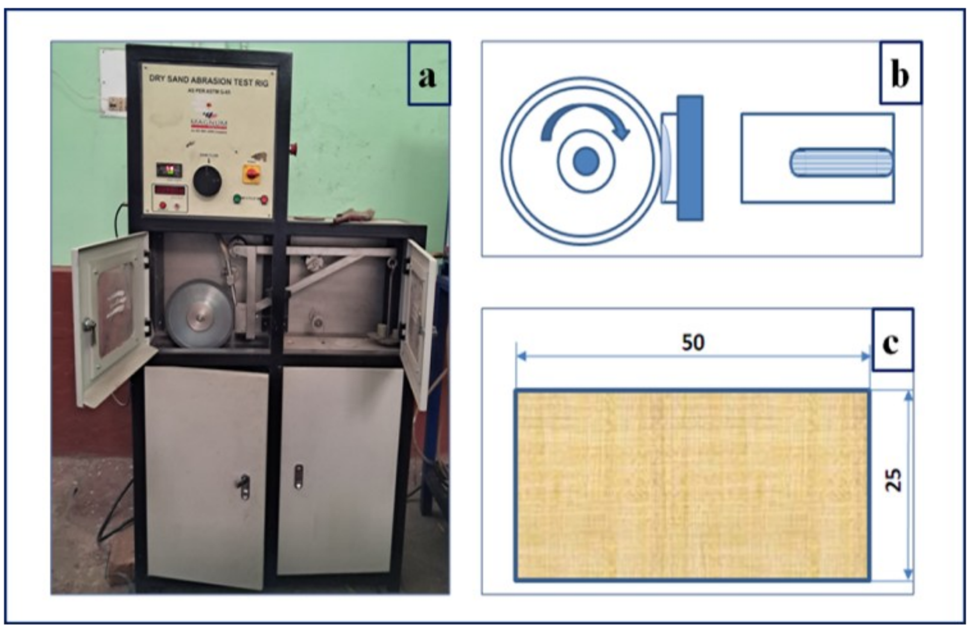


Fig. 1. (a) Dry sand abrasion test rig; (b) Schematic diagram of sample wear face; (c) Sample for testing (dimensions are in mm)

The apparatus includes an abrasive hopper, nozzle, rubber wheel, steel disc, sample container, abrasive particle collecting bag, and a load application arrangement. The rubber wheel employed in this study has a diameter of 228 mm and a rotational speed of 200 ± 5 rpm. A nozzle was used to direct the abrasive particle flow between the contact surface of the test specimen and the rotating abrasive wheel, made up of a steel disc with chlorobutyl rubber tyre (hardness: 605 shores). A lever arm forced the specimen against the rotating abrasive wheel at a specified force while a regulated flow of abrasive particles abraded the test surface. The lever arm's pivot axis is approximately normal to the horizontal plane where the load is applied and tangent to the rubber wheel surface. The wear tests were performed for the 10 N, 15 N, and 20 N loads for 500 m and 1000 m distances. The surface of the composite specimen was cleaned with a delicate piece of paper soaked in acetone cleanser prior to testing. Before the specimen was put into the sample holder, its initial weight was measured using a high-precision digital electronic scale.

Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) was used to examine the microstructure, surface morphology, and topography of composite materials with high resolution. It works by directing a focused high-energy electron beam onto the sample surface and detecting the emitted secondary electrons to generate detailed images. In this study, the fractured surfaces were analyzed using a ZEISS (BRUKER-USA) scanning electron microscope. At different magnifications, the fractured composites were scanned with an accelerated voltage of 20 kV.

RESULTS AND DISCUSSION

Thermal Characterization

Vicat softening testing

The measured VST for B-PLA composites, along with neat PLA value, is shown in Fig. 2.

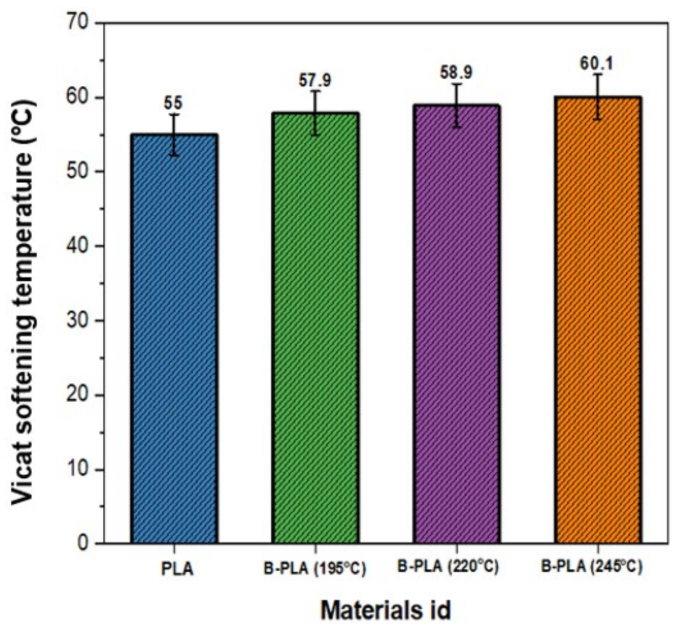


Fig. 2. Vicat softening temperature; the VST for pure PLA is provided in the material's brochure

The PLA exhibits thermoplastic behavior, allowing it to be melted and reprocessed multiple times with minimal property degradation. Its thermoplastic nature enables processing through conventional techniques such as injection molding, extrusion, and 3D printing. Bamboo fiber mats are sustainable reinforcement materials produced from bamboo stalk fibers through mechanical or chemical extraction, followed by spinning or weaving. These mats provide advantages such as durability, breathability, and potential antimicrobial characteristics. Because the bamboo mat acts as a strengthener, the composite materials show higher VST values compared to neat PLA. When comparing B-PLA composites to neat PLA, the improved VST results showed a greater improvement in the material's thermal stability and resistance to softening at high temperatures. The utilization of bamboo reinforcement in the PLA-based composite construction is responsible for this favorable result. Better load distribution and stress transfer are brought about by the bamboo fibers in the composite, which raises the material's strength and overall thermal stability.

Applications in which materials are exposed to different temperatures and mechanical loads may greatly benefit from this. Additionally, compared to pure PLA, the enhanced VST values for B-PLA composites imply that they might show greater dimensional stability and less deformation when exposed to heat. In many applications, it is important to preserve the shape and integrity of the material; in these situations, B-PLA composites' improved temperature stability can be useful. The higher VST of the B-PLA composites indicates improved resistance to thermal softening under the applied load. This behavior suggests enhanced thermal performance at elevated temperatures, which may be attributed to the reinforcing effect of bamboo fibers and improved fiber–matrix interaction. The measurement showed that the VST increased linearly with an increase in TFDM (FDM nozzle temperature), and it may also be connected to the bonding of PLA and bamboo fiber. Because a higher TFDM improves interface bonding, a higher temperature is also required to penetrate a given depth for a given load.

The increase in Vicat softening temperature with increasing nozzle temperature can be attributed to improved polymer chain diffusion during deposition, resulting in stronger interlayer bonding and reduced interfacial voids. Enhanced impregnation of bamboo fibers by the molten PLA improves stress transfer efficiency and restricts polymer chain mobility under thermal loading, thereby delaying softening. This indicates that processing temperature plays a critical role in determining the thermo-mechanical stability of natural fiber reinforced composites.

Thermogravimetric analysis

Figure 3 depicts the TGA curves of B-PLA composites for various TFDM along with neat PLA. It is known that polymeric materials with natural fibers contain water molecules and volatile chemical compounds (Nurazzi *et al.* 2021). Generally, these compounds will evaporate during the initial heating of the sample before the material starts its decomposition. This phenomenon was also observed in the present study and can be readily seen in the temperature range from 30 °C to ~250 °C (see Fig. 3). Beyond ~250 °C, both neat PLA and B-PLA composites exhibited a rapid loss in mass. The nearly identical degradation temperatures observed for neat PLA and B-PLA composites indicate that bamboo fiber reinforcement did not adversely affect the thermal degradation mechanism of PLA. In this stage, it is reported that carbon-hydrogen and carbon-carbon bonds will disintegrate in bamboo fiber and PLA matrix (Huda *et al.* 2005; Verney *et al.* 2008).

Using the derivatives of the TGA profile, the temperature corresponding to maximum material loss was found to be 314 °C, 317 °C, and 303 °C for TFDM at 195 °C, 220 °C, and 245 °C. There was a similar temperature for maximum mass loss in neat PLA is 317 °C. Further, from the TGA profiles beyond ~500 °C, it can be concluded that both neat PLA and B-PLA composites did not leave any noticeable residue. The single weight-loss peak observed in the TGA curves of B-PLA indicated no phase separation between the bamboo and PLA components. Therefore, the TGA analysis found that the difference in the degradation temperatures and mass loss profiles of neat PLA and B-PLA for various TFDM was not enough to consider, which is consistent with Rasheed *et al.* (2021). Through the use of TGA, important details on the thermal stability of bamboo-PLA composites can be uncovered, providing valuable understanding of the materials' behavior at varying temperatures. The absence of multiple degradation peaks further suggests good compatibility between the bamboo fibers and the PLA matrix, minimizing phase separation. This confirms that thermal performance is governed primarily by the stability of the polymer matrix while the reinforcement contributes mainly to improved structural integrity. The aforementioned data is crucial in evaluating the appropriateness of these composite materials for a range of real-world uses, particularly those that need exposure to high temperatures.

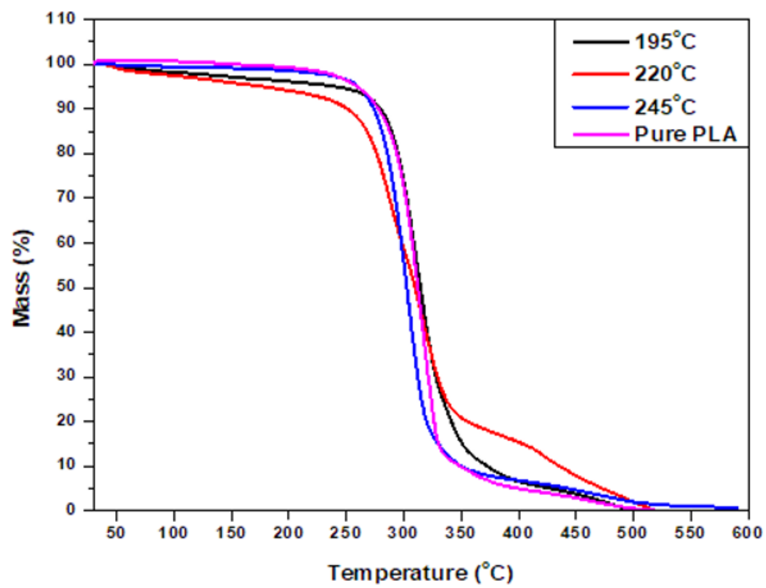


Fig. 3. Thermogravimetric profiles of B-PLA composites and pure PLA

Tribological analysis

The abrasive wear responses of additively manufactured B-PLA composites were studied systematically. Before the wear test, the composite specimen's surface was cleaned with a soft piece of paper soaked in acetone cleaner. The initial weight of the sample was measured using a high-precision digital electronic scale before it was placed in the sample holder. To comprehend the impact of sliding distance and normal load on the particular wear rate, steady-state studies of the composites were conducted. The sample was removed from the test frame and cleaned thoroughly; finally, the weight of the worn-out sample was recorded. The mass loss due to the abrasive wear was measured using the recorded weight before and after the test. Although three nozzle temperatures (195, 220, and 245 °C) were investigated for thermal characterization, the tribological evaluation was performed only on specimens fabricated at 195 and 245 °C. These temperatures represent the lower and upper limits of the selected processing window and were chosen to investigate the maximum influence of nozzle temperature on wear behavior. Since the specimen fabricated at 220 °C represents an intermediate processing condition, its tribological response was expected to lie between those of the two extreme temperatures. The wear analysis was focused on the limiting conditions to provide a clear comparison of the influence of processing temperature on tribological performance. Three specimens were tested for each experimental condition, and the average value was reported. As shown in Table 1, only slight variation was observed among the three specimens, indicating good experimental repeatability.

Table 1. Repeatability of Three Sample Data for Nozzle 195 and 245 ºC

Load (N)	Nozzle 195 ºC Wt. Loss (g)		Nozzle 245 ºC Wt. Loss (g)	
	500 m	1000 m	500 m	1000 m
10	0.1298, 0.1324, 0.1344 **(0.1322)**	0.2868, 0.2901, 0.2928 **(0.2899)**	0.1098, 0.1125, 0.1146 **(0.1123)**	0.2719, 0.2745, 0.2777 **(0.2747)**
15	0.1949, 0.1987, 0.2019 **(0.1985)**	0.3654, 0.3690, 0.3723 **(0.3689)**	0.1538, 0.1560, 0.1585 **(0.1561)**	0.3039, 0.3076, 0.3107 **(0.3074)**
20	0.2786, 0.2824, 0.2856 **(0.2822)**	0.3987, 0.4022, 0.4054 **(0.4021)**	0.2163, 0.2190, 0.2214 **(0.2189)**	0.3180, 0.3215, 0.3244 **(0.3213)**

Effect of wear test conditions

For the tribological analysis, the samples fabricated with the nozzle temperature (T_n) of 195 °C (lowest) and 245 °C (highest) were considered. The sample with T_n = 245 °C exhibited excellent mechanical properties, particularly the surface hardness, whereas the sample corresponding to T_n = 195 °C yielded inferior mechanical performance. Thus, these two extreme cases were considered for the wear tests. Further, to understand the effect of wear test conditions, three different wear loads for two different travel distances were considered. Specifically, the wear tests were performed for the 10 N, 15 N, and 20 N loads for 500 m and 1000 m distances. In turn, both the samples, *i.e.*, T_n = 195 and 245 °C, were tested for six different wear conditions. The measured mass losses for all six different wear test conditions are shown in Fig. 4.

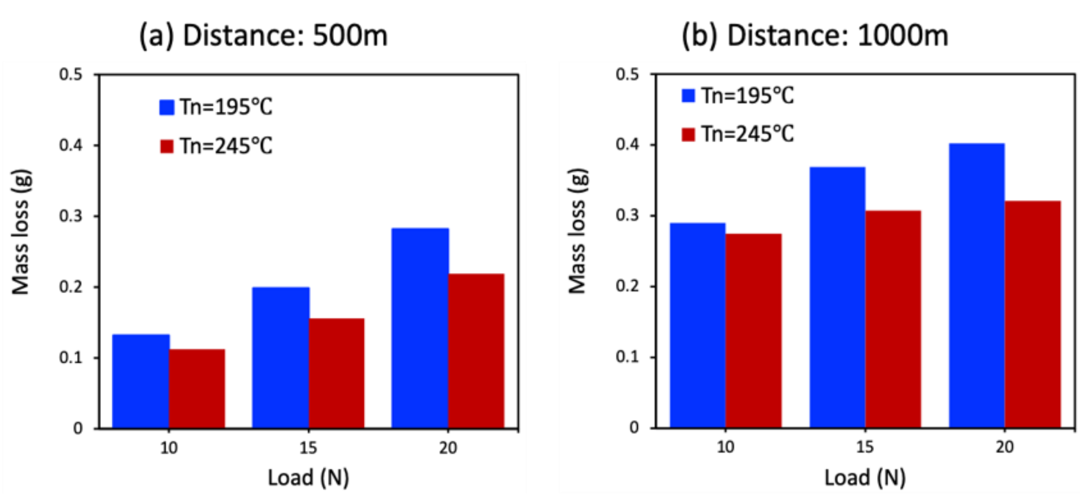


Fig. 4. Role of wear load and distance on the material loss of B-PLA composites fabricated with two different nozzle temperatures

First, the mass loss for the samples fabricated with T_n= 245 °C was less than that of those with T_n = 195 °C. The surface hardness of the T_n = 245 °C sample was notably higher than that of the T_n = 195 °C sample. It suggests that the observed wear responses directly correlate with the mechanical properties. Furthermore, as expected, the mass loss increases with an increase in imposed load for both samples (T_n = 195 and 245 °C).

At the same time, the increase in mass loss with the load was lower for T_n = 245 °C sample compared to T_n = 195 °C sample. For instance, the mass loss in the T_n = 195 °C sample was 0.08 g/N, whereas for the sample of T_n = 245 °C was 0.05 g/N. This clearly suggests that the higher nozzle temperature not only lowered the mass loss for a fixed load but also it reduced the increase in mass loss for the increase in imposed load. Next, the effect of wear distance is considered. As one would expect, the experimental measurement showed that the increase in wear distance increases the mass loss. Additionally, the mass loss increase with an increase in wear distance was less for T_n = 245 °C sample compared to T_n = 195 °C sample. The improved wear resistance observed for specimens fabricated at higher nozzle temperatures can be explained by enhanced interfacial adhesion between bamboo fibers and the PLA matrix. Better consolidation reduces fiber pull-out and matrix cracking during abrasive loading, allowing the applied load to be distributed more uniformly throughout the composite.

Effect of abrasive type

To investigate the effect of abrasive particle type on the wear responses, two additional abrasives, SiC and Al_2O_3, were considered in addition to SiO_2. To focus only on the abrasive type effect, the wear test load and distance were fixed as 20 N and 1000 m, respectively. The measured mass loss for all three abrasive types is shown in Fig. 5 for both the samples, *i.e.*, with T_n = 195 °C and 245 °C.

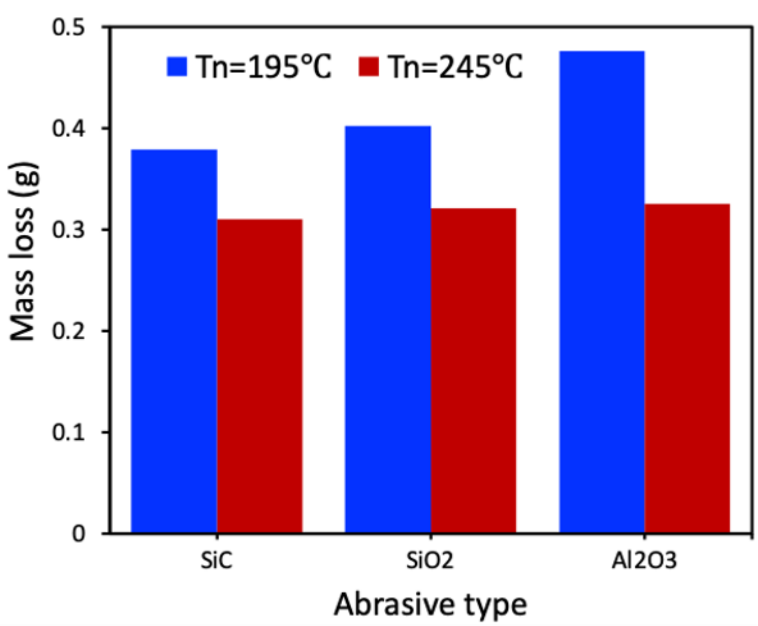


Fig. 5. Effect of dry abrasive particle type on the wear properties of B-PLA composites fabricated with two different nozzle temperatures

First, as one expects following the results of the previous section, the mass loss for T_n = 195 °C was higher than that for the T_n = 245 °C case. Second, the mass loss was higher for the Al_2O_3 abrasive particle case compared to the other two abrasive types. This was attributed to the physical properties of the abrasive particles. For instance, the mass density of SiC, SiO_2, and Al_2O_3, in g/cm^3, ranges from 3.1 to 3.2, 2.2 to 2.65, and 3.9 to 4.0, respectively (Sebayang *et al.* 2018). Similarly, the Vickers hardness of these three abrasive particles, such as SiC, SiO_2, and Al_2O_3, is 9, 7, and 9, respectively. According to these values, the abrasive particle Al_2O_3 is denser and harder compared to other particles. Finally, the changes in mass loss among abrasive particle types were very minimal for the T_n = 245 °C sample. From this, it is observed that the wear response of the B-PLA sample with T_n = 245 °C seemed unaffected by abrasive type.

At the same time, the increase in mass loss with the load was lower for the T_n = 245 °C sample compared to the T_n = 195 °C sample. For instance, the mass loss in the T_n=195°C sample was 0.08 g/N, whereas for the sample of T_n = 245 °C was 0.05 g/N. This suggests that the higher nozzle temperature not only lowered the mass loss for a fixed load but also reduced the increase in mass loss for the increase in imposed load. Next, the effect of wear distance was considered. As expected, the experimental measurement showed that the increase in wear distance increased the mass loss. Additionally, the mass loss increase with an increase in wear distance was less for the Tn = 245 °C sample compared to the T_n = 195 °C sample. The dominant wear mechanism changed from severe abrasive removal toward mild micro-ploughing, leading to lower material loss.

Post-mortem microstructure characterization

The microstructural characterization of the worn-out surface of B-PLA composite, shown in Fig. 6, is presented. A scanning electron microscope was employed to analyze the surfaces (Sethu *et al.* 2024).

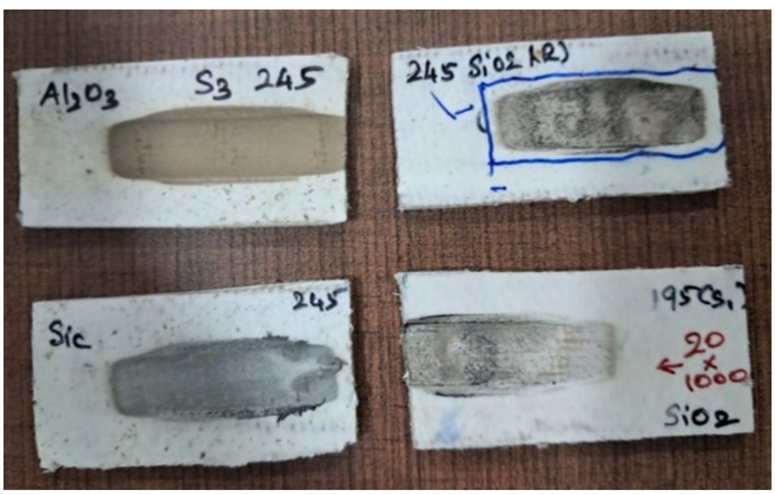
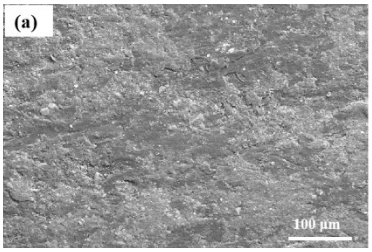


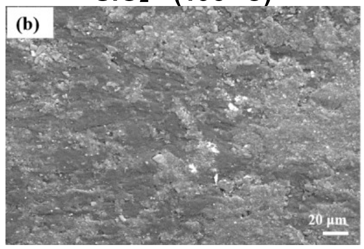
Fig. 6. Worn-out additively manufactured B-PLA composites after 1000 m wear distance under 20N load

To understand the effect of abrasive type on the worn-out surface morphology, the sample with T_n= 245 °C was considered for all three abrasive types. In addition, both T_n = 195 and 245 °C samples were considered for the abrasive of SiO_2 to study the effect of AM process nozzle temperature. The observed microstructural images of the worn-out surface for all four samples are shown in Fig. 7. The first column shows wide regions with coarse resolution, whereas the second and third columns show the focused smaller areas with fine resolution.

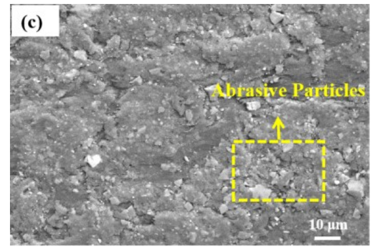
SiO_2 - (195 °C)



(a) Worn surface morphology of SiO_2 at 195 °C

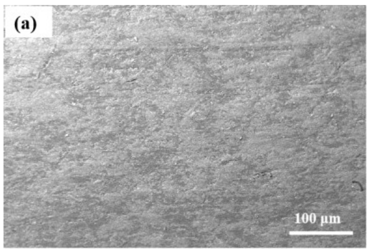


(b) The abrasive wear indicating micro-grooves and matrix deformation

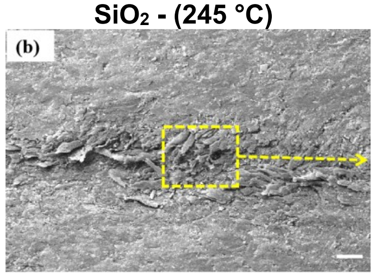


(c) Presence of embedded SiO_2 abrasive particles on the worn surface

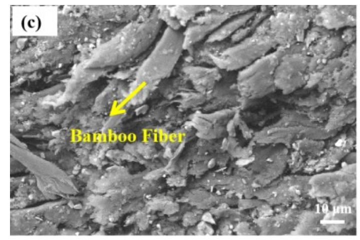
SiO_2 - (245 °C)



(a) Worn surface morphology of SiO2 at 245 °C

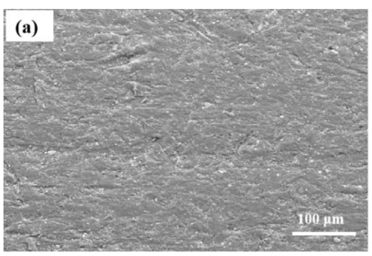


(b) Bamboo fiber pull-out observed within the wear track

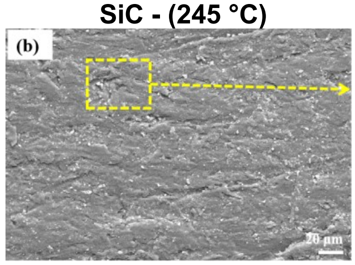


(c) Higher magnification of wear indicating bamboo fiber

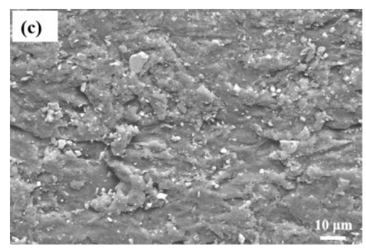
SiC - (245 °C)



(a) Worn surface morphology of SiC at 245 °C

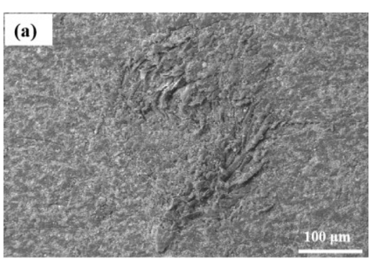


(b) Localized wear features of mild fiber pull-out

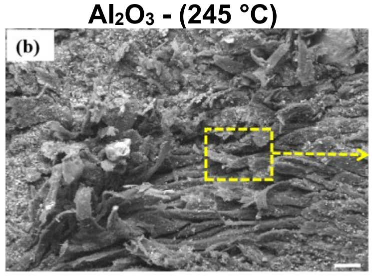


(c) Higher magnification of fiber pull-out

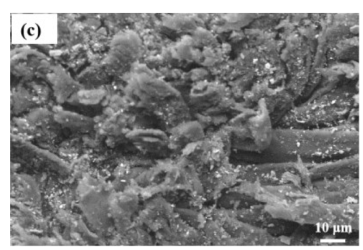
Al_2O_3 - (245 °C)



(a) Worn surface morphology of Al_2O_3 at 245 °C



(b) Debris accumulation and fiber pull-out damage



(c) Higher magnification of fiber pull-out

Fig. 7. Postmortem microstructure characterization of the worn-out surface of additively manufactured B-PLA composites at different temperatures

The specimen fabricated at 195 °C exhibits embedded abrasive particles and matrix deformation, indicating weak interfacial bonding. In contrast, the specimens fabricated at 245 °C show fewer embedded particles and only localized fiber pull-out, suggesting stronger fiber-matrix adhesion. These observations confirm that the improved tribological performance is primarily associated with enhanced microstructural integrity produced by higher processing temperatures.

The attachment of abrasive particles can be readily seen in the T_n = 195 °C sample for the SiO_2 abrasive case. Such attachment of abrasive particles was not observed in T_n = 245 °C samples for all three abrasive types. Furthermore, fiber pull-out was observed in the specimens fabricated at a nozzle temperature (T_n) of 245 °C for all three abrasive types, indicating localized interfacial debonding during the wear process. Apart from these minor differences, the morphology of the worn surfaces exhibited similar characteristics.

CONCLUSIONS

This study systematically investigated the thermal and tribological performance of additively manufactured bamboo-fiber-reinforced poly(lactic acid) (PLA) composites fabricated at different fused deposition modeling (FDM) nozzle temperatures. Based on the experimental investigation, the following conclusions were reached:

1. Bamboo fiber reinforcement significantly improved the thermal resistance of PLA by increasing the Vicat Softening Temperature, demonstrating enhanced dimensional stability under elevated temperatures.
2. Thermogravimetric analysis showed that the degradation behavior of B-PLA composites remained comparable to neat PLA, with maximum degradation temperatures ranging from 303 to 317 °C, indicating that bamboo fiber reinforcement did not adversely affect the thermal stability of the polymer matrix.
3. The composite fabricated at a nozzle temperature of 245 °C exhibited approximately 37.5% lower wear mass loss than the specimen fabricated at 195 °C, confirming that higher processing temperatures improve abrasion resistance through enhanced interfacial bonding and increased surface hardness.
4. The effect of abrasive type on wear was minimal for high-temperature (245 °C) B-PLA samples, indicating that increased surface hardness and better matrix-fiber adhesion rendered the composite less sensitive to abrasive variations.
5. Al_2O_3 produced the highest wear because of its greater hardness and density, whereas the influence of abrasive type became less pronounced in composites fabricated at higher nozzle temperatures, owing to improved microstructural integrity.
6. SEM observations confirmed that higher nozzle temperatures reduced abrasive particle embedding and promoted stronger fiber-matrix adhesion, thereby minimizing severe wear mechanisms such as matrix cracking and extensive fiber pull-out.

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