Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi
Afyon Kocatepe University – Journal of Science and Engineering
https://dergipark.org.tr/tr/pub/akufemubid

Araştırma Makalesi / Research Article
e-ISSN: 2149-3367
DOI: https://doi.org/10.35414/akufemubid.1776539
CITE: Afyon Kocatepe University Journal of Science and Engineering **26(2)** (2026) 489-496

Tribological Performance of Additively Manufactured Tungsten-Reinforced PLA Composites

***Makale Bilgisi / Article Info**
Alındı/Received: 02.09.2025
Kabul/Accepted: 01.12.2025
Yayımlandı/Published: 08.04.2026

Eklemeli İmalat ile Üretilmiş Tungsten Takviyeli PLA Kompozitlerin Tribolojik Performansı

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Abstract

In this study, the tribological properties of PLA (polylactic acid) composite materials reinforced with Tungsten (W) were investigated. Composite samples were produced by additive manufacturing in ⌀10×20 mm dimensions, and wear tests were performed using a pin-on-disk apparatus under loads of 5N, 10N, and 15N; and at sliding distances of 120m, 240m, and 360m. The obtained volume loss, specific wear rate, and coefficient of friction values were analyzed comparatively. As a result, tungsten reinforcement provided a more significant performance improvement, especially under low and medium loads. The volume loss in PLA was approximately 6 mm³, compared to ~4 mm³ for PLA+W under 5N load and 120m sliding distance. In other words, under a 5N load, PLA exhibited 50% greater volume loss than PLA+W. While unreinforced PLA samples appeared advantageous in terms of friction due to their low coefficient of friction values, this decrease also caused the soft surface to wear quickly. Although the coefficient of friction in PLA+W composites was higher, this stability resulted in a more controlled and predictable wear profile. Consequently, PLA+W composites can be considered a promising candidate for tribological applications.

Keywords: *Additive Manufacturing; Polilactic Asid; Tungsten; Tribology; Fused deposition modeling*

Öz

Bu çalışmada, Tungsten (W) takviyesi yapılmış PLA (polilaktik asit) kompozit malzemelerin tribolojik özellikleri incelenmiştir. Kompozit numuneler eklemeli imalat yöntemi kullanılarak ⌀10×20 mm boyutlarında üretilmiş, ardından pin-on-disk cihazı ile 5N, 10N ve 15N yükler altında; 120m, 240m ve 360m kayma mesafelerinde aşınma testleri gerçekleştirilmiştir. Elde edilen hacim kaybı, spesifik aşınma oranı ve sürtünme katsayısı değerleri karşılaştırmalı olarak analiz edilmiştir. Sonuç olarak, Tungsten takviyesi özellikle düşük ve orta yüklerde daha belirgin performans artışı sağlamıştır. PLA'daki hacim kaybı yaklaşık 6 mm³ iken, 5N yük ve 120m kayma mesafesi altında PLA+W'de bu kayıp yaklaşık 4 mm³ olmuştur. Başka bir deyişle, 5N yük altında PLA, PLA+W'ye göre %50 daha fazla hacim kaybı sergilemiştir. Takviyesiz PLA numuneler, düşük sürtünme katsayısı değerleri ile sürtünme açısından avantajlı görünse de bu düşüş aynı zamanda yumuşak yüzeyin hızla aşınmasına sebep olmuştur. PLA+W kompozitlerinde sürtünme katsayısı daha yüksek olsa da bu sabitlik sayesinde daha kontrollü ve öngörülebilir bir aşınma profili elde edilmiştir. Sonuç olarak, PLA+W kompozitler, tribolojik uygulamalarda umut vadeden bir aday olarak değerlendirilebilir.

Anahtar Kelimeler: *Eklemeli imalat; Polilaktik asit; Tungsten; Triboloji; Eriyik yığma modelleme*

1. Introduction

Polylactic acid (PLA) is a biodegradable thermoplastic derived from renewable resources such as corn starch and sugarcane, offering an environmentally sustainable alternative to petroleum-based polymers. PLA is widely used in fused deposition modeling (FDM) additive manufacturing due to its ease of processing and dimensional stability (Yalçın and Ergene 2017, Beltrán *et al.* 2021, Aslani *et al.* 2020, Çelik *et al.* 2021, Yuran and Yavuz 2024). However, its inherent limitations—such as low impact strength, poor thermal resistance, and inadequate tribological performance—restrict its use in demanding engineering applications. (Ning *et al.* 2015, Song *et al.* 2017, Ali *et al.* 2025, Ma *et al.* 2025, Maraş and Bolat 2025, Yuran et. al 2024). To overcome these drawbacks, PLA composites have been developed by incorporating reinforcements such as fibers, carbon nanotubes, graphene, boron carbide, and metallic fillers. (Hussain *et al.* 2021, Rajak *et al.* 2021, Barreto *et al.* 2024, Lage-Rivera *et al*. 2024, Hasan *et al.* 2024). Metallic fillers, in particular, have been shown to improve load-bearing capacity and suppress surface deformation during wear, owing to their high hardness and stiffness. (Gohar and Rahnejat 2012, Arockiam *et al*. 2022, Acaroğlu et al. 2024, Sürmen and Güven 2024). Tungsten or Wolfram (W), has extremely high melting point (~3422 °C), high density (19.25 g/cm³), and excellent mechanical properties. Due to these superior features, it is highly preferred in applications such as aerospace, defense, and high-temperature environments. (Abulyazied *et al.* 2023, Vidakis *et al.* 2023). Although its use in polymer matrix composites is limited, prior studies indicate promising

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outcomes. Jatti et al. (2016) demonstrated that tungsten reinforcement in polymers reduced CoF and wear volume, while Zhang et al. (2020) and Li et al. (2019) reported improved wear stability and lower specific wear rate in metal-filled PLA composites, especially at low loads (Buj-Corral et al. 2022). Similarly, a recent study by Batista *et al.* (2024) reported that integrating aluminum and copper particles into an FFF-manufactured PLA matrix increased the material's hardness and reduced the volume of material lost due to wear by half. However, the inclusion of metallic fillers does not universally guarantee improved performance. A study by Vakharia *et al.* (2021) on PLA composites reinforced with bronze, copper, magnetic iron, and stainless steel found that the mechanical properties were highly dependent on the reinforcement concentration. While low-volume fractions (11-18 vol%) of iron and steel had minimal impact, high-volume fractions (~36 vol%) of bronze and copper significantly decreased the ultimate tensile strength and fracture toughness. The authors also observed significant particle 'pullout' during polishing, indicating weak interfacial adhesion, which they hypothesized would be detrimental for surfaces experiencing friction. Furthermore, recent literature has focused not only on experimental analysis but also on predictive modeling of these tribological behaviors. For instance, Abdulla et al. (2024) successfully employed an Artificial Neural Network (ANN) to predict the dry sliding wear of 3D printed PLA. Their model confirmed that parameters such as infill percentage and applied load are significant factors, noting that higher infill percentages contributed to lower specific wear rates. The mechanical and tribological properties of additively manufactured polymer parts, particularly PLA, have become a subject of intensive investigation in recent years (Subramaniyan et al., 2022). These studies have particularly highlighted that build orientation is a critical factor influencing wear properties.

This work aims to systematically examine the wear performance of additively manufactured tungsten-reinforced PLA under multiple load and distance conditions, comparing results with neat PLA to evaluate the potential of PLA+W as an engineering-grade tribological material.

2. Materials and Methods

2.1 Materials and sample fabrication

For the production of additive manufacturing samples, commercially available filaments from Filamet™ company were used as neat PLA and a tungsten-reinforced composite (PLA+W). According to the manufacturer's technical data, the PLA+W filament contains 10% tungsten content with an approximate particle size of 10 µm, which is homogeneously distributed within the PLA matrix. Figure 1 shows the distribution of Tungsten fillers on PLA matrix. The inclusion of tungsten significantly alters the mechanical properties; the neat PLA has a reported tensile strength of approximately 55 MPa and a hardness of 55 Shore D, whereas the PLA+W composite exhibits a much lower tensile strength of approximately 22 MPa but a significantly higher hardness of 75 Shore D. All test specimens were fabricated using the printing parameters recommended by the manufacturer (see Table 1), and no processing difficulties, such as nozzle clogging or inconsistent flow, were encountered during printing.

The literature clearly demonstrates that FDM process parameters, such as layer thickness and build orientation (Zhiani Hervan *et al.,* 2021, Yavuz and Yildirim 2023), as well as infill percentage (Portoacă *et al*., 2023), have a direct and significant effect on the wear behavior and surface quality of neat PLA. To eliminate these variables and isolate the net effect of the material composition (neat PLA vs. PLA+W) on tribological performance, all printing parameters in this study were held constant, as detailed in Table 1. The manufacturing parameters for the Ender Pro 3 FDM (Fused Deposition Modelling) printer are given in Table 1.

Table 1. Printing parameters for sample fabrication

Properties	Value	Unit
Layer thickness	0,1	mm
Infill rate	100	%
Infill type	Line	
Printing speed	50	mm/s
Nozzle temperature	230	˚C
Build plate temperature	70	˚C
Raster angle	45/-45	˚
Fan speed	100	%

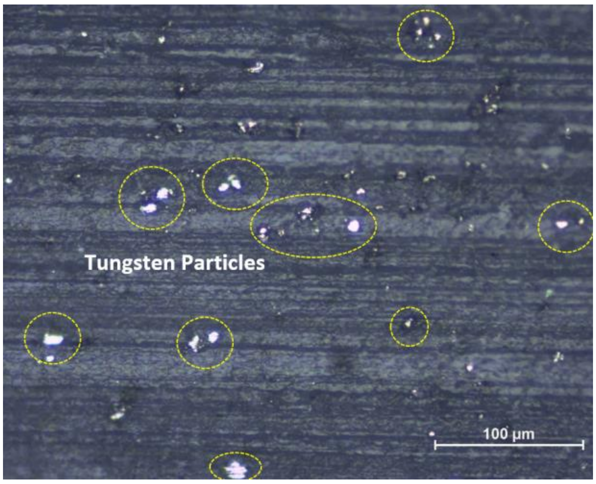

Figure 1. The distribution of Tungsten fillers on PLA matrix

2.2 Wear test procedure

Wear experiments were carried out using a pin-on-disk tribometer in accordance with ASTM G99 standard.

Specimens (⌀10×20 mm) were used as pins, while a 200-mesh SiC sandpaper was used as abrasive that fixed on the rotating disk. Tests were performed at 5 N, 10 N, and 15 N loads, with sliding distances of 120 m, 240 m, and 360 m, at constant room temperature, and a 2m/s sliding speed. The schematic representation of experimental procedure and pin-on-disc device produced by Turkyus company is given in Figure 2 and Figure 3 respectively.

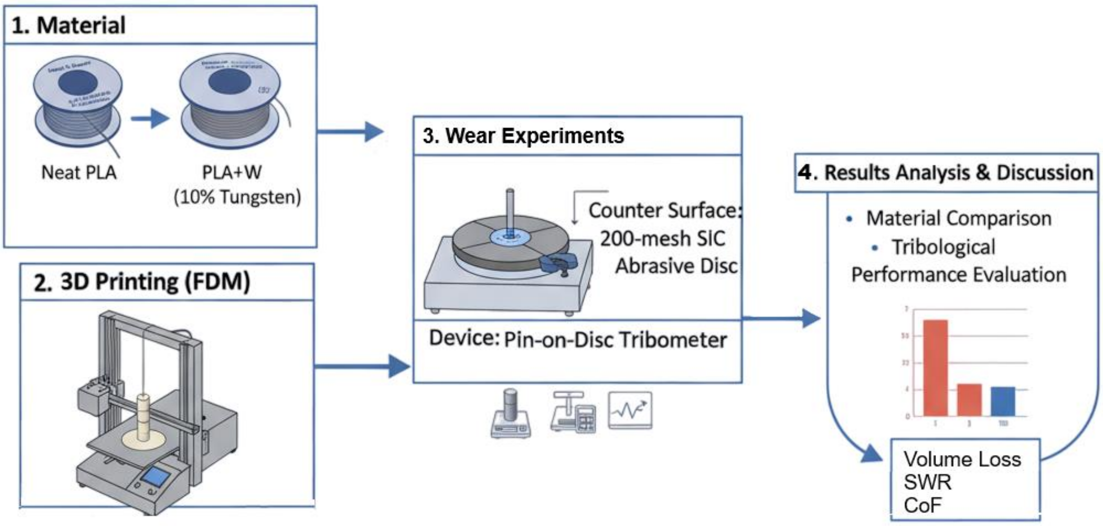

Figure 2. Schematic representation of experimental procedure

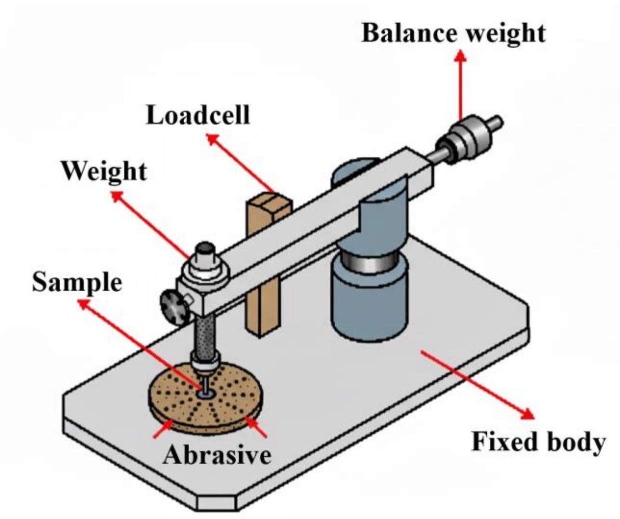

Figure 3. Schematic illustration of pin-on-disk wear test

At the end of the test, volume loss was calculated from the weight loss, and specific wear rate and coefficient of friction values were obtained. An ultrasonic cleaner was used to remove contaminants from sample surfaces before measurement. The applied load during the wear test was recorded to calculate the coefficient of friction. The friction coefficient was calculated via Equation (1). The coefficient of friction is

$$\mu = \frac{F}{P} \quad (1)$$

The frictional force and the normal load on the sample are denoted as F and P, respectively. Equation (2) was used to calculate the volume loss from the weight loss.

$$\textit{Volume Loss } (mm^3) = \frac{weight\ loss\ (g)}{Density\ (g/mm^3)} \quad (2)$$

Equation (3) defines the specific wear rate (SWR). *Specific Wear rate (mm³/Nm)* is

$$\frac{Volume\ Loss\ (mm^3)}{Sliding\ Distance\ (m)\ x\ Load\ (N)} \quad (3)$$

3. Results and Discussion

This section presents a comparative evaluation of the obtained results against relevant literature, with a detailed discussion on the influence of tungsten reinforcement on tribological performance.

3.1. Evaluation of volume loss

Figure 4 and Figure 5 show the volume loss graphs obtained from the pin-on-disc wear tests of Tungsten reinforced and unreinforced PLA.

The obtained wear data indicate that volume loss in both PLA and PLA+W specimens increases steadily with higher loads and longer sliding distances. Under a load of 15 N and a sliding distance of 360 m, the volume loss for PLA was approximately 38 mm³, whereas for PLA+W specimens this value remained around 36 mm³. Although this difference appears small, it becomes more pronounced at lower loads. At 5 N and 120 m, the volume loss in PLA was approximately 6 mm³, compared to ~4 mm³ for PLA+W. In other words, under a 5 N load, PLA exhibited 50% greater volume loss than PLA+W, suggesting that tungsten reinforcement improved the wear resistance of PLA by about 50%. This effect is particularly evident at low and medium loads, indicating greater effectiveness in enhancing wear resistance under such conditions.

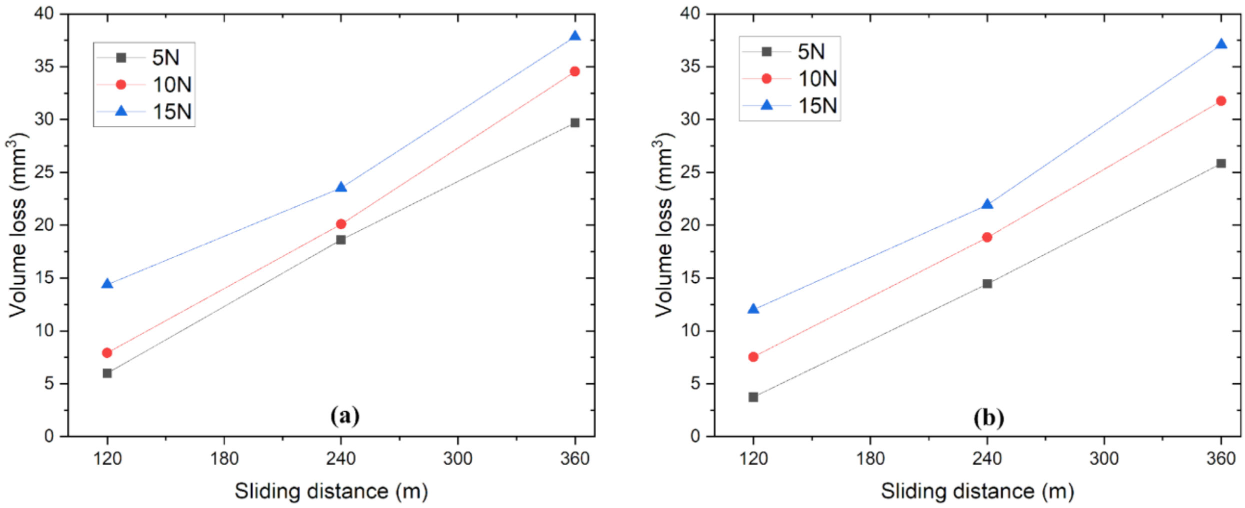

Figure 4. Comparison of volume loss between (a) PLA and (b) PLA+W under varying loads

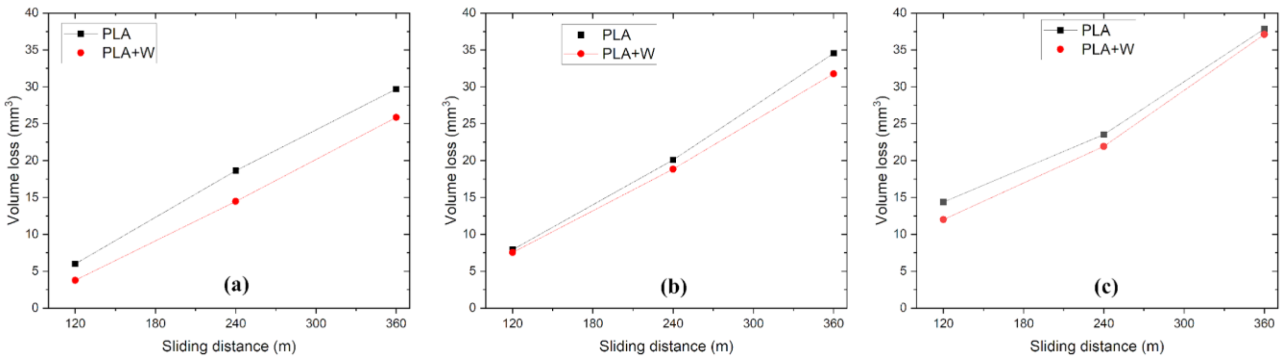

Figure 5. Comparison of volume loss between PLA and PLA+W according to applied load a)5N b)10N c)15N

Metallic fillers limit wear in composites by suppressing micro-cutting and surface plasticity. A similar phenomenon was reported by Jatti *et al.* (2016), who observed up to a 15% reduction in wear rate when tungsten powder was incorporated into a polymer matrix. Furthermore, Zhang *et al.* (2020) showed that in metal-filled PLA composites, volume loss increased with load, but the reinforced samples exhibited a slower rate of volume loss. This finding is in full agreement with the trends observed in the present study.

In conclusion, the volume loss–reducing effect of tungsten reinforcement in PLA is more pronounced under low-load and short-distance conditions, providing a performance advantage in micro-wear and light-loading scenarios.

3.2. Evaluation of specific wear rate

Figure 6 presents Specific Wear Rate (SWR) data obtained from the pin-on-disc wear tests of reinforced and unreinforced PLA. SWR is a key parameter in tribological testing, involves with respect to load and sliding distance.

In this study, unreinforced PLA exhibited a relatively high SWR at low loads (5N) and sliding distance (120m) of approximately 10×10^{-3} mm³/Nm, which decreased as the applied load increased. In contrast, PLA+W specimens demonstrated lower and more stable values, averaging around 6×10^{-3} mm³/Nm.

This behavior indicates that tungsten reinforcement enhances the load-bearing capacity of the composite and suppresses plastic deformation at the surface. Hussain et al. (2021) reported that hard fillers in PLA-based composites improve not only mechanical strength but also tribological stability. Similarly, Li *et al.* (2019) noted that metallic fillers can reduce SWR by up to 30%. The SWR data confirms the trend observed in volume loss. The reinforcing effect of tungsten is most pronounced at lower loads (5N), while at higher loads (15N), the SWR values of both materials begin to converge. Gohar and Rahnejat (2012) emphasized that, in tribological systems, the dominance of reinforcing particles improves surface contact conditions and minimizes wear.

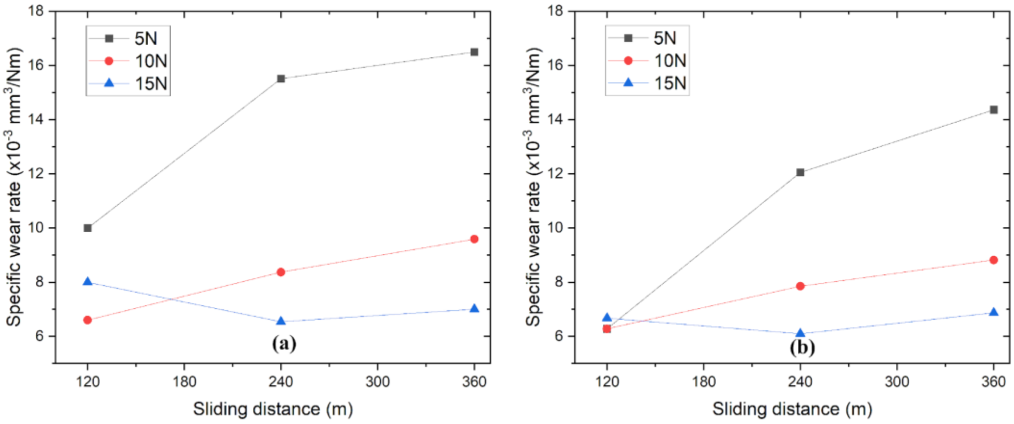

Figure 6. Comparison of Specific Wear Rate between (a) PLA and (b) PLA+W under varying loads

3.3 Evaluation of coefficient of friction

In Figure 7, the Coefficient of Friction (CoF) values of reinforced and unreinforced PLA samples under 5N, 10N, and 15N loads and 360m sliding distance are presented during wear test. The general findings are as follows;

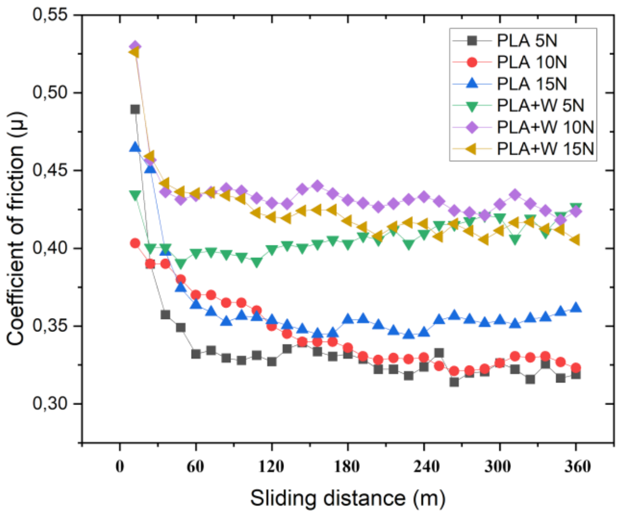

Figure 7. Coefficient of friction of PLA and Tungsten reinforced PLA during wear test

For both reinforced and unreinforced PLA samples, higher initial coefficients of friction (CoF) (~0.45–0.52) were observed under all three load conditions. This behavior is attributed to the frictional effects during the initial contact and running-in stage of the material surface. In PLA specimens, the CoF decreased markedly as sliding progressed, stabilizing at approximately 0.32–0.34. In PLA+W specimens, the CoF stabilized at higher levels (~0.38–0.44) but exhibited more consistent behavior with fewer abrupt fluctuations.

The gradual reduction in CoF over time is typically associated with the formation of a tribofilm on the surface, a decrease in surface roughness, or the transition to a steady-state wear regime (Gohar and Rahnejat 2012, Sing *et al.* 2024). This trend is evident in PLA, where the CoF rapidly drops and stabilizes after the first few meters of sliding, indicating adaptation of the material to the counter surface and the presentation of a lower CoF value in combination with elastic deformation under low loads.

In contrast, tungsten-reinforced PLA exhibited a different trend. The initial CoF was generally higher; however, the values showed less variation over time and remained more stable. This phenomenon has been attributed in the literature to the stronger mechanical interaction of hard reinforcement particles with the contact surface. Jatti et al. (2016) reported that hard fillers may initially increase CoF but enhance the surface load-bearing capacity, thereby suppressing sudden decreases.

In summary, while neat PLA appears advantageous in terms of lower CoF, this decrease also indicates rapid wear of the softer surface. Although PLA+W composites exhibit higher CoF values, their stability enables a more controlled and predictable wear profile—an attribute particularly desirable in engineering applications (Rajak et al., 2021, Vishal *et. al* 2022). The key tribological performance indicators for both materials (PLA and PLA+W) are summarized in Table 2 for easier comparison.

The findings of the present study are parallel with the expanding literature from the last five years, which indicates that the tribological performance of metal-reinforced PLA composites varies significantly depending on the reinforcement material. Our finding that tungsten reinforcement significantly reduces volume loss and specific wear rate compared to neat PLA is consistent with numerous recent studies confirming the potential of metallic reinforcements to enhance wear resistance. For example, Batista et al. (2024) reported that aluminum and copper reinforcements reduced wear volume by half, while Zhang et al. (2020) also noted that metal-filled composites exhibited a slower rate of volume loss. Similarly, Vakharia et al. (2021) demonstrated that bronze-reinforced PLA achieved up to a 45% reduction in wear rate.

Table 2. Comparison of key tribological properties of PLA and PLA+W

	Condition	PLA	PLA+W
Volume Loss	Low Load (5N, 120m)	~6 mm³	~4 mm³
Volume Loss	High Load (15N, 360m)	~38 mm³	~36 mm³
Specific Wear Rate	Low Load (5N, 120m)	~10×10⁻³ mm³/Nm	~6 × 10⁻³ mm³/Nm
Specific Wear Rate	High Load (15N, 360m)	~7×10⁻³ mm³/Nm	~6.8 × 10⁻³ mm³/Nm
CoF	Average Range	~0.32 – 0.34	~0.38 – 0.44

However, the effect on the coefficient of friction (CoF) presents a more complex picture. Some studies, such as Vakharia et al. (2021) and Gupta et al. (2020), have reported that softer metals like bronze and copper also decrease the CoF. This presents a contrast to our findings, as in this study, tungsten reinforcement was observed to increase the CoF compared to neat PLA, although it provided a much more stable profile. This discrepancy is likely attributed to the difference in the hardness of the reinforcement materials. While softer metals like bronze may form a low-friction transfer film on the counter-surface, the high hardness of the tungsten particles used in our study may have inhibited this film formation, leading to a higher but more stable CoF. This stable behavior was also noted by Batista et al. (2024) as a "more stable performance" for metal-reinforced composites. Furthermore, while the weak metal-polymer interfacial bond (the "pullout" phenomenon) was identified by Vakharia et al. (2021) as a critical problem for tribological applications, the low wear rates in our study suggest that the tungsten particles remained strongly bonded to the matrix and protected the surface during friction. This finding supports the growing contemporary interest (Abulyazied *et al*., 2023; Vidakis et *al*., 2023) in the use of tungsten (or tungsten compounds) in PLA composites.

This study offers distinct advantages and novel contributions compared to similar investigations in the literature. First, while many recent studies have focused on more common and relatively softer metallic fillers such as copper (Batista et al., 2024) or bronze (Vakharia et al., 2021), this work systematically investigates Tungsten (W), a reinforcement less explored for PLA tribology yet known for its high hardness and density.

The second and most significant contribution is the detailed observation of the complex relationship between the coefficient of friction (CoF) and wear resistance. While many reports (Gupta et al., 2020) suggest that metallic fillers reduce both wear and the CoF, our findings demonstrate that wear resistance (particularly at low loads) was significantly improved despite an increase in the CoF. This finding challenges the common assumption that high friction necessarily leads to high wear, suggesting that hard particles (like Tungsten) operate via a different mechanism—such as resisting abrasive wear and maintaining surface integrity rather than forming a low-friction transfer film.

4. Conclusions

In this study, the tribological behavior of tungsten-reinforced PLA materials produced via additive manufacturing was investigated. The following conclusions were drawn from the experimental results:

1) Tungsten reinforcement significantly enhances the wear resistance of PLA, particularly under low to medium load conditions. At 5 N and 120 m, the PLA+W composite exhibited approximately 33% less volume loss (~4 mm³) compared to neat PLA (~6 mm³).
2) The Specific Wear Rate (SWR) was substantially improved, especially at low loads. Neat PLA exhibited a high initial SWR of ~10 × 10⁻³ mm³/Nm at 5 N, whereas the PLA+W composite showed a much lower SWR of ~6.5 × 10⁻³ mm³/Nm under the same load.
3) While neat PLA stabilized at a lower Coefficient of Friction (CoF) range (~0.32–0.34), it showed significant fluctuations. In contrast, the PLA+W composite exhibited a higher but significantly more stable CoF range (~0.38–0.44), indicating a more controlled and predictable wear regime.
4) The combination of improved wear resistance and a highly stable friction profile suggests that PLA+W composites are a promising candidate material for tribological applications where operational consistency and reliability are required

Finally, the limitations of this study must be acknowledged. The findings presented are based on a single test run for each condition, and as such, the statistical consistency of the measurements could not be determined. These results should therefore be interpreted as preliminary, and future studies must incorporate multiple test repetitions for robust statistical validation. Furthermore, this study did not include microscopic analysis (e.g., SEM) of the worn surfaces. Future investigations should include such analyses to definitively identify the dominant wear mechanisms (e.g., abrasive, adhesive) and to visualize the interaction of the tungsten particles at the tribological interface.

Declaration of Ethical Standards

The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement

Author-1: Conceptualization, investigation, methodology and software, visualization and writing – original draft.

Declaration of Competing Interest

The author has no conflicts of interest to declare regarding the content of this article.

Data Availability

All data generated or analyzed during this study are included in this published article

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