

Influence of fiber content and applied load on the wear mechanisms of oil palm frond fiber/phenol-formaldehyde composites with functional fillers

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Received: 07 July 2025; *Revised:* 22 October 2025; *Accepted:* 29 October 2025

<https://doi.org/10.58712/jerel.v4i3.198>

Abstract: The tribological behavior of oil palm fiber (OPF)-reinforced polymer composites was investigated with varying fiber contents (10, 20, and 30 wt.%) under different applied loads (20, 40, and 60 N) at a sliding speed of 2.5 m/s. Experimental results show that wear rate decreases significantly with increasing fiber content up to 20 wt.% at all loads, reaching minimum values of 1.2, 2.1, and 3.9 ×10⁻⁴ mm³/Nm at 20, 40, and 60 N, respectively. Beyond 20 wt.%, wear rate increases, indicating fiber agglomeration and interfacial defects at higher loadings. A second-degree polynomial regression model was developed to predict wear rate as a function of fiber content and load. Model analysis and contour mapping identified an optimum wear resistance region centered at 20 wt.% fiber content and ~35–45 N load. The improved wear performance at this composition is attributed to enhanced fiber–matrix adhesion, improved stress transfer, and reduced microstructural discontinuities. These findings suggest that OPF composites with 20 wt.% reinforcement provide optimal wear resistance under moderate load conditions, making them promising candidates for tribological applications such as automotive and industrial components.

Keywords: oil palm fronds; phenol formaldehyde; pin-on-disc tribometer; tribology; natural fiber composites

1. Introduction

Natural fiber–reinforced polymer composites have gained considerable attention in recent decades due to their lightweight, cost-effectiveness, and environmental sustainability compared to conventional synthetic fiber composites (Musa & Onwualu, 2024; Muthu Samy & Lenin Singaravelu, 2025; Skosana et al., 2025). These materials combine renewable reinforcement fibers with thermosetting or thermoplastic matrices to achieve mechanical performance suitable for structural and tribological applications. Among various natural fibers, oil palm frond fiber (OPFF) stands out as an abundant agro-industrial byproduct with a high cellulose content, low density, and relatively good tensile properties ([Kumneadklang et al., 2019](#); [Ooi et al., 2017](#); [Yashim et al., 2021](#)). This makes OPF an attractive reinforcement candidate for polymer composites aimed at frictional and wear-related applications.

The integration of OPFF into polymer matrices for tribological use, however, remains challenging. Natural fibers are hydrophilic, leading to poor compatibility with hydrophobic resin systems, and are prone to thermal degradation during high-friction processes ([Adekomaya & Majozi, 2020](#); [Ali et al., 2018](#); [Karthikeyan et al., 2017](#)). Furthermore, inappropriate fiber loading levels can lead to fiber agglomeration, poor dispersion, and reduced interfacial bonding, all of which adversely affect mechanical integrity and wear performance ([Kumar et al., 2025](#); [Wang et al., 2023](#)). This necessitates optimization of fiber content in order to balance reinforcement and composite integrity.

Phenol Formaldehyde (PF) resins have been widely used in friction materials such as brake linings, clutch facings, and industrial wear components due to their superior thermal stability, low creep, dimensional stability, and strong adhesion to natural fibers ([Bilvatej et al., 2024](#); [Muthu Samy & Lenin Singaravelu, 2025](#); [Park, 2015](#)). In particular, PF resin is a novolac-type phenolic resin specifically formulated for high-friction environments. Its chemical structure provides excellent crosslinking density, which enhances mechanical strength, thermal resistance, and long-term wear stability in dry sliding conditions ([Stawarz et al., 2019](#)).

Despite the known thermal and mechanical advantages of PF resins, limited studies have systematically evaluated OPFF/PF composites for wear applications, particularly considering optimal fiber loading under varying applied loads. Most research has focused either on other natural fibers such as jute, kenaf, and sisal, or on OPF with alternative matrices like epoxy or polyester ([Rashid et al., 2017](#); [Shinoj et al., 2011](#); [Sreekala et al., 2005](#)). This creates a knowledge gap in understanding how PF resin can be leveraged to optimize OPF composites for tribological performance. In tribological systems, applied load and reinforcement fraction are critical factors affecting wear mechanisms. Excessive load increases contact stress and frictional heating, accelerating matrix softening and fiber debonding, whereas insufficient fiber content limits load transfer capacity ([Birleanu et al., 2025](#); [Cao et al., 2025](#)). Conversely, optimized fiber loading can enhance load distribution, crack deflection, and resistance to material removal, while minimizing the defects that lead to premature failure ([Bilvatej et al., 2024](#); [Birleanu et al., 2025](#); [Sreekala et al., 2005](#)).

The present study aims to evaluate the wear behavior of OPFF/PF composites under dry sliding conditions at different fiber contents (10, 20, and 30 wt.%) and applied loads (20, 40, and 60 N). A pin-on-disc tribometer was employed to simulate service conditions, and wear rate was determined in accordance with ASTM G99-17 standards. A second-degree polynomial regression model was developed to predict wear performance as a function of fiber content and load, and contour mapping was used to identify the optimum wear resistance zone. The novelty of this work lies in identifying the optimum fiber loading for OPFF/PF composites in moderate-load tribological applications, and in providing mechanistic insight into the interaction between fiber content, applied load, and wear rate. The results are expected to contribute to the design of sustainable, high-performance natural fiber composites for automotive and industrial wear components.

2. Methods

2.1 Material preparation

Oil palm fibers (OPF) were sourced from Riau Province, Indonesia, cleaned to remove impurities, and oven-dried at 80 °C for 24 h. The polymer matrix was a novolac-type Phenol Formaldehyde (PF) resin (FRJ551, SI Group, USA), chosen for its thermal stability and strong adhesion to natural fibers. In addition to the OPF reinforcement, the composites were modified with functional fillers:

- Graphite (10 wt.%) – acts as a solid lubricant, reducing friction and surface temperature during sliding ([Mushtaq & Wani, 2018](#)).
- Barium sulfate (BaSO₄, 10 wt.%) – improves dimensional stability, enhances compressive strength, and contributes to wear debris compaction ([Pai et al., 2020](#)).
- Vermiculite (5 wt.%) – provides thermal insulation and acts as a friction stabilizer ([Guney & Akbulut, 2023](#)).
- Alumina (Al₂O₃, 5 wt.%) – enhances hardness and abrasion resistance ([Al-Qutub et al., 2006](#)).

All fillers were supplied by chemical local store and used in their as-received form. Hexamethylenetetramine (HMTA) was used as a curing agent in accordance with PF resin specifications.

2.2 Composite fabrication

Composites were prepared with OPF fiber contents of 10, 20, and 30 wt.% (relative to the total composite mass) as shown in Table 1. The OPF fibers (Figure 1a) and PF resin FRJ 551 (Figure 1b), and the functional fillers (graphite, barium sulfate, vermiculite, and alumina) were weighed according to the designed formulations. The mixing process involved mechanical stirring at 500 rpm for 10 min to ensure uniform dispersion of fibers and fillers in the resin. The homogeneous mixture was poured into a steel mold (Figure 1c) and subjected to hot pressing at 150 °C and 5 MPa for 10 min. Post-curing was carried out at 165 °C for 3 h to ensure full crosslinking of the PF resin. The cured composites were then demolded and machined into pin specimens for tribological testing.

Table 1. Composite formulations of OPF/PF FRJ-551 composites with functional fillers

Composite code	OPF fiber (wt.%)	PF resin FRJ-551 (wt.%)	Graphite (wt.%)	Barium sulfate (BaSO ₄) (wt.%)	Vermiculite (wt.%)	Alumina (Al ₂ O ₃) (wt.%)
C10	10	60	10	10	5	5
C20	20	50	10	10	5	5
C30	30	40	10	10	5	5



(a)



(b)



(c)

Figure 1. (a) OPF fiber, (b) Phenol formaldehyde resin, and (c) Steel mold

2.3 Tribological testing

Wear behavior was evaluated using a THT-1000 pin-on-disc tribometer from Anton Paar, following ASTM G99-17 standards for dry sliding wear testing. The composite pins (fabricated according to ASTM G99 geometry) were tested against a hardened steel counterface disc (HRC 60, surface roughness Ra ≈ 0.3 μm). The tests were conducted at a constant sliding speed of 2.5 m/s under applied normal loads of 20, 40, and 60 N. Each test ran for a sliding distance of 1000 m, which corresponds to a test duration of approximately 6.7 min at 2.5 m/s. All tests were performed under ambient laboratory conditions (25 ± 2 °C, relative humidity 50 ± 5%) without lubrication.

2.4 Test procedure

Prior to testing, the disc surface was cleaned using acetone to remove contaminants. Each composite pin was weighed using a high-precision analytical balance (accuracy ±0.1 mg) before and after each wear test. The tribometer was run continuously for the specified sliding distance at the designated load. The coefficient of friction (COF) was recorded in real-time by the tribometer's data acquisition system. After each test, the worn pins were carefully cleaned with compressed air and reweighed to determine mass loss.

2.5 Wear rate calculation

The specific wear rate (SWR) was calculated using the Archard wear equation according to ASTM G99, as presented in Equation 1.

$$WR = \frac{\Delta V}{L \cdot D} \quad (1)$$

Composite density was determined by the Archimedes principle (ASTM D792). Each test condition was repeated three times to ensure statistical reliability, and the mean \pm standard deviation values were reported.

2.6 Data analysis

Experimental results were analyzed to investigate the effects of fiber content and load. The second-degree polynomial regression model demonstrated excellent predictive capability, with a coefficient of determination $R^2 = 0.9740$, indicating that 97.4% of the variation in wear rate is explained by the combined effects of fiber content and applied load. The fitted coefficients ($a = 5.9333$, $b = -0.5633$, $c = -0.01417$, $d = 0.01400$, $e = 0.001125$, $f = 0.000750$) describe a physically meaningful surface with a clear global minimum near 20 wt% fiber. The residuals were randomly scattered around zero with no visible pattern, confirming that the quadratic model is statistically adequate and free from systematic bias. This validates the suitability of the model for wear-rate prediction and for identifying the optimum operating window of the composite system. Contour plots and 3D surface maps were generated using OriginPro 2024 to identify the optimum wear resistance zone. The fitted model is presented in Equation 2.

$$SWR = a + bF + cL + dF^2 + eL^2 + fFL \quad (2)$$

3. Results and discussion

3.1 Influence of fiber content on wear behavior

Fiber loading plays a critical role in determining the tribological response of natural fiber-reinforced phenolic composites. As shown in Table 2 and Figure 2, the wear rate exhibits a non-linear dependence on OPF content, reflecting the balance between reinforcement efficiency and interfacial compatibility. At 10 wt.%, the wear rate remains relatively high across all loads, suggesting insufficient reinforcement to effectively support interfacial stresses during sliding. At this low fraction, load transfer is matrix-dominated, making the PF resin susceptible to micro-plastic deformation, adhesive junction formation, and surface fatigue under sliding contact. Similar behaviour has been reported for natural fiber composites with sub-optimal reinforcement, where the resin undergoes extensive shear deformation and material detachment under moderate loads ([Parikh & Gohil, 2015](#); [Rashid et al., 2017](#)).

Table 2. Wear rate ($\times 10^{-4}$ mm³/Nm) at varying fiber content and load (speed: 2.5 m/s)

OPF Fiber (wt.%)	20 N	40 N	60 N
10	1.8	3.2	5.6
20	1.2	2.1	3.9
30	2.0	3.8	6.4

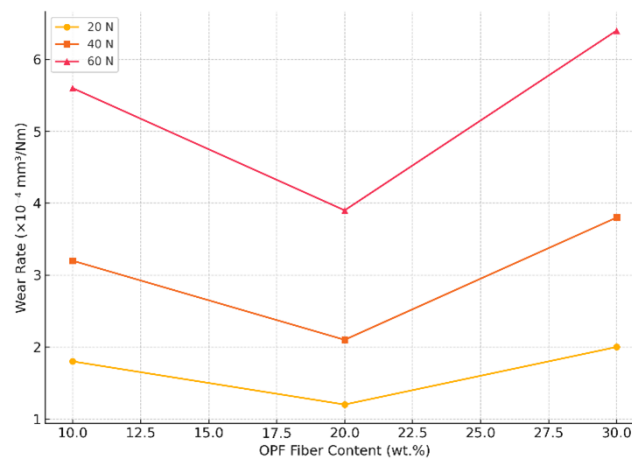


Figure 2. Variation of wear rate ($\times 10^{-4}$ mm³/Nm) with OPF fiber content at different applied loads

Increasing the OPF content to 20 wt.% significantly reduces the wear rate, demonstrating an optimal reinforcement threshold. In this composition, fibers are sufficiently abundant to form an effective stress-distributing network while remaining well-dispersed within the PF matrix. The reduction in wear rate is attributed to improved fiber–matrix interfacial adhesion and more uniform load distribution, which restricts the formation of large adhesive junctions and minimize crack propagation along the sliding surface. The frictional contact is further stabilized by the functional fillers like graphite, alumina, BaSO₄, and vermiculite, which contribute lubricating films, abrasive resistance, and debris compaction. Together, these mechanisms promote a transition from an adhesive-dominated regime to a mixed, mild-abrasive, fatigue-controlled wear regime. Comparable trends have been reported in kenaf/phenolic and sisal/phenolic systems, where optimal fiber loading produces the highest wear stability ([Sreekala et al., 2005](#); [Yousif & Chin, 2012](#)).

At 30 wt.% OPF, the wear rate increases again, surpassing even the 10 wt.% formulation at higher load levels. Excessive fiber content tends to deteriorate composite integrity by promoting fiber agglomeration, incomplete resin wetting, and the formation of interfacial voids. These structural discontinuities act as stress concentrators during sliding, facilitating micro-crack nucleation, fiber pull-out, and accelerated material removal. Such behaviour is characteristic of natural fiber composites with over-saturated reinforcement fractions, where fiber clustering disrupts stress transfer and destabilizes the tribological interface ([Birleanu et al., 2025](#)). Overall, the non-linear wear response confirms that 20 wt.% OPF represents the optimum reinforcement level, offering the best synergy between fiber distribution, matrix integrity, and filler contributions to interfacial stability.

3.2 Effect of applied load on wear performance

Applied load strongly influences wear mechanisms by altering real contact area, frictional heating, and interfacial stress concentration. For all fiber contents, wear rate increases with load from 20 N to 60 N, reflecting the classical behaviour of thermoset-based friction materials under dry sliding. At higher loads, the increased normal force magnifies shear stresses at the pin–disc interface, causing localized matrix softening, reduced interfacial adhesion, and enhanced material detachment.

The severity of load sensitivity, however, differs markedly across fiber contents. The 10 wt.% OPF composite displays the steepest rise in wear rate with load, confirming that insufficient reinforcement leaves the matrix highly vulnerable to stress-induced degradation. In contrast, the 20 wt.% composite exhibits the lowest wear slope, indicating superior load-bearing capability. The reduced load sensitivity is attributed to improved mechanical interlocking between fibers and matrix, enhanced by the fillers that form a more stable tribological layer. This behaviour is consistent with load-dependent tribological transitions documented for

natural fiber composites, where optimized reinforcement mitigates interfacial damage at elevated loads (Cao et al., 2025). Although the 30 wt.% composite contains more reinforcement, its performance deteriorates rapidly with load. Fiber agglomeration and weakly bonded zones become critical failure points under high stress, leading to extensive fiber debonding and brittle flake detachment. These results highlight that excessive reinforcement does not necessarily improve tribological performance and may instead introduce structural defects that accelerate wear.

3.3 Combined influence of fiber content and load: Response surface trends

To analyze the combined effects of fiber content and load, a second-degree polynomial regression model was developed with Equation 2. The negative linear terms for F and L indicate that initial increases in fiber content and load reduce wear rate. The positive quadratic terms reflect the U-shaped wear behavior with respect to fiber content and the nonlinear increase in wear at higher loads. These findings align with similar regression models applied to natural fiber composites (Parikh & Gohil, 2015; Yousif & Chin, 2012). As shown in Figure 3, the interaction between fiber content and applied load was modelled using a second-degree polynomial regression, and the resulting 3D surface and contour maps reveal a distinct wear minimum centred at 20 wt.% OPF and loads between 35–45 N. The model predicts increasing wear when fiber content deviates from this optimum whether toward low or high reinforcement levels consistent with the experimental trends. The positive quadratic terms reflect non-linear sensitivity to both parameters, indicating that neither fiber content nor load influences wear rate independently or linearly.

At low fiber contents, insufficient reinforcement allows the matrix to dominate load-bearing, resulting in increased adhesive wear as load rises. At high fiber contents, structural discontinuities associated with fiber clustering amplify the effect of load by enabling crack growth and fiber pull-out. The model therefore captures a fundamental balance: optimal wear resistance emerges only when reinforcement, matrix continuity, and filler synergy are all simultaneously satisfied. Such response surface behaviours have been observed in multi-phase natural fiber composites, where an optimum reinforcement level maximizes interfacial stability while minimizing stress concentration (Parikh, 2023). The good agreement between model predictions and experimental results underscores the robustness of the identified optimum region and highlights the potential of OPF/PF composites for moderate-load tribological applications.

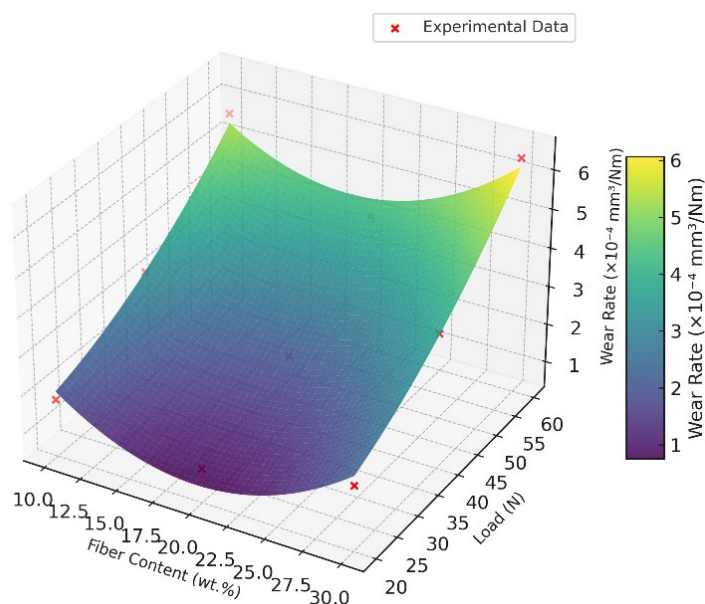


Figure 3. 3D surface plot of the polynomial regression model for wear rate as a function of OPF fiber content (wt.%) and applied load (N)

The contour plot (Figure 4) further identifies the optimum wear resistance zone at 20 wt.% fiber content and ~35–45 N load. Deviations from this range, either in fiber content or load, lead to higher wear. At loads above 50 N, even at optimal fiber content, wear rate increases due to elevated contact stresses and frictional heating, which weaken the fiber–matrix interface ([Al-Qutub et al., 2006](#)).

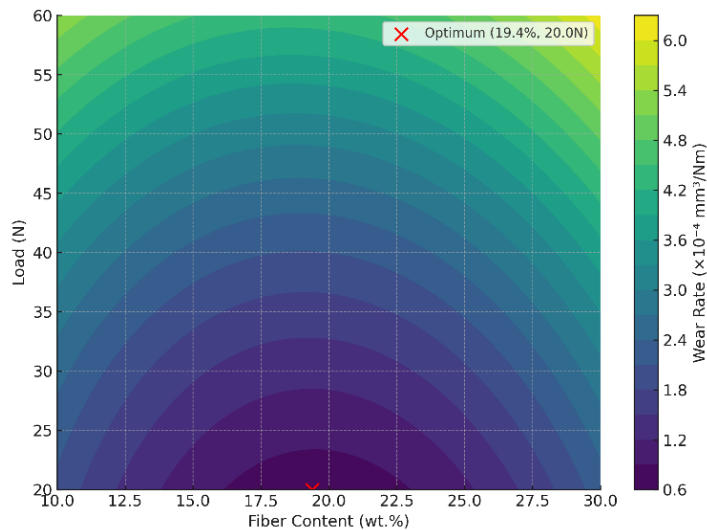


Figure 4. Contour map of wear rate ($\times 10^{-4} \text{ mm}^3/\text{Nm}$) predicted by the polynomial model

The combined results confirm that 20 wt.% OPF fiber content consistently delivers the lowest wear rates and the most stable performance across varying loads. This composition balances reinforcement efficiency with matrix integrity, avoiding the defects associated with excessive fiber loading while ensuring sufficient load-bearing capacity ([Parikh & Gohil, 2015](#); [Yousif & Chin, 2012](#)). The optimal zone at 20 wt.% fiber and ~35–45 N load represents the most favorable configuration for tribological applications, aligning with the findings of prior studies on natural fiber composites in moderate-load environments ([Parikh & Gohil, 2015](#); [Yousif & Chin, 2012](#)).

4. Conclusion

The tribological performance of OPF fiber-reinforced polymer composites was systematically evaluated as a function of fiber content (10, 20, and 30 wt.%) and applied load (20, 40, and 60 N) at a sliding speed of 2.5 m/s. The results demonstrate that both fiber content and applied load significantly influence wear behavior. An optimum fiber content of 20 wt.% was identified, yielding the lowest wear rates across all load conditions. This composition exhibited superior load-bearing capability, with the smallest rate of wear increase under load escalation, attributed to balanced fiber–matrix adhesion and uniform dispersion. Composites with 10 wt.% OPF suffered from insufficient reinforcement, while those with 30 wt.% experienced performance degradations due to fiber agglomeration and interfacial defects. Polynomial regression modeling and contour analysis confirmed the optimum wear resistance zone at 20 wt.% fiber content and ~35–45 N load, where wear rate is minimized. Outside this zone, wear performance declines due to increased matrix damage at low fiber levels and defect-induced weakening at high fiber levels. Overall, 20 wt.% OPF fiber-reinforced composites are recommended for tribological applications under moderate loading conditions. This composition provides an effective balance between reinforcement and structural integrity, making it suitable for automotive, industrial, and machinery components where wear resistance and environmental sustainability are critical.

Author's Declaration

Author contribution

Budi Istana: Conceptualization, methodology, software, investigation, writing-original draft, formal analysis, visualization. **Indra Hasan:** Methodology, data validation, writing -review & editing. **Kuntang Winangun:** data analysis, writing-review & editing, visualization.

Funding statement

This research received grant from the Muhammadiyah National Research Grant, Batch VIII, Year 2024, for funding and implementation of this research under Contract No. 0258.138/I.3/D/2025.

Acknowledgement

The authors gratefully acknowledge the support and contributions provided by the lecturers of the Mechanical Engineering Department, Faculty of Engineering Universitas Muhammadiyah Riau and Universitas Muhammadiyah Ponorogo, Indonesia, which supported and facilitated the completion of this research.

Competing interest

The authors declare that there are no competing interests related to the research or publication of this article.

Ethical clearance

This research does not involve humans as subjects.

Data availability

The data will be available upon request.

AI statement

The grammatical structure of this article was improved by using Grammarly and the authors have rechecked the accuracy and correctness of the generated sentences with the topic and data of this study. The data and language use in this article have been validated and verified by an English language expert and none of the AI-generated sentences include in this article.

Publisher's and Journal's Note

Researcher and Lecturer Society as the publisher, and the editor of Journal of Engineering Researcher and Lecturer state that there is no conflict of interest towards this article publication.

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Nomenclature

ΔV	= Volume loss (mm^3)
L	= Applied normal load (N)
D	= Sliding distance (m)