



Tribological Performance of Green Composite Brake Pads Reinforced with Untreated Pineapple Leaf Fiber and Aluminum Chips

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Abstract. This study investigates the development of sustainable composite brake pad materials reinforced with mechanically extracted pineapple leaf fibers (PALF) without chemical processing and aluminum chip waste. The work was motivated by environmental and health concerns associated with conventional friction materials containing synthetic and potentially toxic fibers. A Taguchi L4 design of experiments was employed to evaluate the effects of pineapple leaf fiber length (20 and 40 mm), PALF mass fraction (5 and 7 wt.%), and aluminum chip mass fraction (3.3 and 6.7 wt.%) on tribological performance. Four formulations were fabricated while maintaining the remaining constituent's constant. The composites were tested using a pin-on-disc tribometer to determine the coefficient of friction and wear mass loss. The experimental data were analyzed descriptively using mean response values, main effects plots, and Delta analysis. The results showed that tribological performance was strongly influenced by formulation. Delta analysis indicated that PALF content had the greatest influence on the coefficient of friction, whereas fiber length most strongly affected wear mass loss. Sample 1 exhibited the lowest wear mass loss (0.0183%), while Sample 4 showed the least favorable overall tribological performance, combining the highest coefficient of friction (0.2308) and wear mass loss (0.0622%). These findings demonstrate the potential of PALF and recycled aluminum chips as sustainable constituents for composite brake pad materials.

Keywords: Aluminum Chips, Brake Pads, Pineapple Leaf Fiber

1 Introduction

The intensifying global focus on sustainability and environmentally responsible engineering has accelerated research into eco-friendly materials for automotive applications. Within this context, green brake pad composites have emerged as a significant area of investigation because they offer a pathway to reduce reliance on synthetic constituents that may be environmentally burdensome or potentially hazardous in conventional brake pad formulations (Carlevaris et al., 2023). Natural fibers, in particular, have attracted considerable attention as reinforcement materials owing to their renewability, biodegradability, and comparatively low-cost relative to synthetic alternatives such as glass and aramid fibers (Ammar et al., 2023).

Brake pad composites are tribological engineering materials designed to deliver stable frictional behavior and wear resistance under diverse operating conditions. Conventional brake pads typically depend on a complex mixture of synthetic fibers, resins, fillers, and mineral additives to achieve the friction coefficient and durability required for service performance (Carlevaris et al., 2025). Nevertheless, growing awareness of environmental impacts and life-cycle concerns associated with synthetic materials has stimulated increasing interest in alternative reinforcement systems derived from natural resources and industrial by-products. Prior studies on brake pad formulations reinforced with natural fibers, including pineapple leaf fiber (PALF), coconut fiber, and other agricultural residues, have demonstrated that certain bio-based constituents can provide promising tribological and mechanical characteristics, although the body of work remains limited and fragmented (Ali et al., 2022; Madnasri et al., 2022; Singh, 2021).

Among the available natural reinforcements, pineapple leaf fiber is regarded as a promising candidate due to its relatively favorable mechanical properties compared with several other natural fibers. Previous investigations have indicated that pineapple-fiber-based composites can exhibit competitive frictional performance when incorporated into suitably designed formulations (Krishnakumar et al., 2024; Singh et al., 2020). However, relatively few studies have explored the integration of untreated natural fibers with waste-derived metallic constituents. In many natural-fiber composite systems, chemical treatment is commonly employed to improve interfacial adhesion between the fiber and matrix; yet such treatment can diminish the environmental advantages that motivate the use of natural reinforcements in the first place. In this regard, the use of untreated pineapple leaf fiber presents a more sustainable alternative, provided that acceptable composite performance can still be achieved. At the same time, aluminum chip waste, a machining by-product generated in industrial manufacturing, offers technical potential as a metallic filler due to its functional similarity to conventional friction modifiers such as copper and bronze, which are widely used in commercial brake pad materials (Dirisu et al., 2024). The combined use of untreated pineapple leaf fiber and aluminum chip waste therefore presents a compelling opportunity to develop brake pad composites with improved mechanical integrity and thermal stability while maintaining a stronger sustainability profile.

Despite the expanding interest in environmentally benign friction materials, a clear knowledge gap remains concerning the tribological behavior of brake pad composites produced from untreated pineapple leaf fiber and aluminum chip waste, particularly with respect to the effects of fiber length and constituent proportions. The influence of these formulation parameters on coefficient of friction and wear resistance has not been sufficiently clarified, even though such variables are expected to play a decisive role in determining composite performance. Accordingly, the present study addresses this gap by systematically evaluating the effect of material formulation on the tribological response of green brake pad composites fabricated from untreated pineapple leaf fiber and aluminum chip waste through a structured experimental approach.

2 Methodology

This study utilized pineapple leaf fiber (PALF) extracted without chemical processing and aluminum chip waste as reinforcing constituents for the fabrication of sustainable composite brake pads. An epoxy resin system was employed as the binder matrix. The pineapple leaf fibers were mechanically extracted from pineapple leaves without the application of chemical treatment or surface modification, thereby preserving their natural characteristics while maintaining a more environmentally sustainable processing route.

The aluminum chips were obtained from a local machining workshop and manually cut into flake-shaped particles prior to composite fabrication. An epoxy resin system with a resin-to-hardener weight ratio of 2:1 was used as the binder. The remaining constituents were maintained at constant proportions in all formulations, with the calcium carbonate content adjusted to compensate for variations in the pineapple leaf fiber and aluminum chip contents, thereby ensuring a constant total composition.

A Taguchi L4 orthogonal array was employed to investigate the effects of three formulation factors on the tribological performance of the composite brake pads. The selected factors were pineapple leaf fiber length, pineapple leaf fiber mass fraction, and aluminum chip mass fraction, each evaluated at two levels. Fiber lengths of 20 mm and 40 mm were selected, while the PALF and aluminum chip mass fractions were varied between 5 and 7 wt.% and 3.3 and 6.7 wt.%, respectively.

The experimental design consisted of four formulations arranged according to the Taguchi L4 orthogonal array, enabling the evaluation of the main effects of the selected factors using a minimum number of experimental runs. The factor-level combinations used in this study are presented in Table 1.

Table 1. Composite composition

Run	Fiber Length (mm)	Fiber wt. %	Aluminum wt. %	CaCO ₃ wt. %	Resin wt. %	Rubber powder wt. %	Graphite Powder wt. %
1	20	5	3.33	11.67	70	5	5
2	20	7	6.67	6.33	70	5	5
3	40	5	6.67	8.33	70	5	5
4	40	7	3.33	9.67	70	5	5

The composite brake pad specimens were fabricated using a compression molding process. The mechanically extracted pineapple leaf fibers and aluminum chips were weighed using a balance with a readability of 0.01 grams according to the prescribed formulations and manually mixed with the epoxy resin system until a homogeneous mixture was obtained. The mixture was then transferred into the mold cavity and compressed under a pressure of 2.32 kPa. After curing, the specimens were removed from the mold and cut into test specimens measuring 60 mm × 60 mm.

The tribological characteristics of the fabricated composites were evaluated using a pin-on-disc tribometer (Ducom® TR 20 Neo Series). The performance of each formulation was assessed in terms of the coefficient of friction and wear mass loss. The tribological

tests were conducted under a normal load of 20 N, a rotational speed of 1100 rpm, and a test duration of 10 minutes.

The coefficient of friction was continuously recorded throughout each test. Wear performance was evaluated by measuring the specimen mass before and after testing using a precision balance. The wear mass loss was calculated as the difference between the initial and final specimen masses.

The experimental data from Taguchi L4 design were analyzed using Delta analysis to evaluate the influence of pineapple leaf fiber length, pineapple leaf fiber mass fraction, and aluminum chip mass fraction on the tribological performance of the composite brake pads. As only one experimental observation was available for each formulation, the analysis was limited to a descriptive evaluation based on the mean response values.

Main effects analysis was performed separately for the coefficient of friction and wear mass loss by calculating the average response at each factor level. The corresponding main effects plots of means were used to visualize the influence of each factor on the measured responses. The relative influence of each factor was determined using Delta analysis, in which the difference between the highest and lowest mean response at each factor level was calculated and ranked. Factors with larger Delta values were considered to have a greater effect on the corresponding tribological response.

For the coefficient of friction, higher mean values were considered desirable, whereas lower wear mass loss indicated superior wear resistance. Accordingly, the optimal factor levels were identified by comparing the mean responses of each factor for both performance characteristics.

3 Result and Discussion

3.1 Result

To assess the tribological performance of the developed composite brake pads, both the coefficient of friction and wear loss were measured. The experimental results showed that the four formulations exhibited distinct performance trends, indicating that the variations in pineapple leaf fiber length, pineapple leaf fiber content, and aluminum chip content had a measurable influence on the tribological response of the composites. Among the tested formulations, Sample 1, consisting of 20 mm fiber length, 5% pineapple leaf fiber, and 3.3% aluminum chip content, exhibited the lowest wear mass loss of 0.0183%, indicating the best wear resistance among the four samples. However, its coefficient of friction was relatively low at 0.0188. Sample 2, with 20 mm fiber length, 7% pineapple leaf fiber, and 6.7% aluminum chip content, produced moderate values for both responses, with a coefficient of friction of 0.0328 and wear mass loss of 0.0322%.

Sample 3, prepared with 40 mm fiber length, 5% pineapple leaf fiber, and 6.7% aluminum chip content, recorded the lowest coefficient of friction at 0.0145, but its wear mass loss increased to 0.0415%, suggesting that the lower friction level was accompanied by reduced wear resistance. In contrast, Sample 4, which used 40 mm fiber length, 7% pineapple leaf fiber, and 3.3% aluminum chip content, showed the

highest coefficient of friction at 0.2308 and the highest wear mass loss at 0.0622%, indicating the least favorable overall tribological performance.

Table 2. Coefficient of Friction and Wear Mass Loss result

Run	Fiber Length (mm)	Fiber wt. %	Aluminum wt. %	Coefficient of Friction	Wear Mass Loss
1	20	5	3.33	0.0188	0.0183%
2	20	7	6.67	0.0328	0.0322%
3	40	5	6.67	0.0145	0.0415%
4	40	7	3.33	0.2308	0.0622%

These results in Table 2. suggest that the composite formulation strongly influenced both frictional behavior and wear resistance. In general, formulations containing the shorter fiber length of 20 mm tended to exhibit lower wear mass loss, while the 40 mm fiber length produced more variable tribological behavior. The incorporation of higher pineapple leaf fiber content and lower aluminum chip content was associated with an increase in coefficient of friction, although this trend was also accompanied by higher wear in some cases. Therefore, the balance between friction generation and wear resistance appears to depend on the interaction of fiber length and material composition.

Because only one experimental observation was available for each Taguchi run, the analysis was limited to descriptive evaluation using the mean response values. The main effects plot of means was used to observe the influence of each factor level on coefficient of friction and wear mass loss.

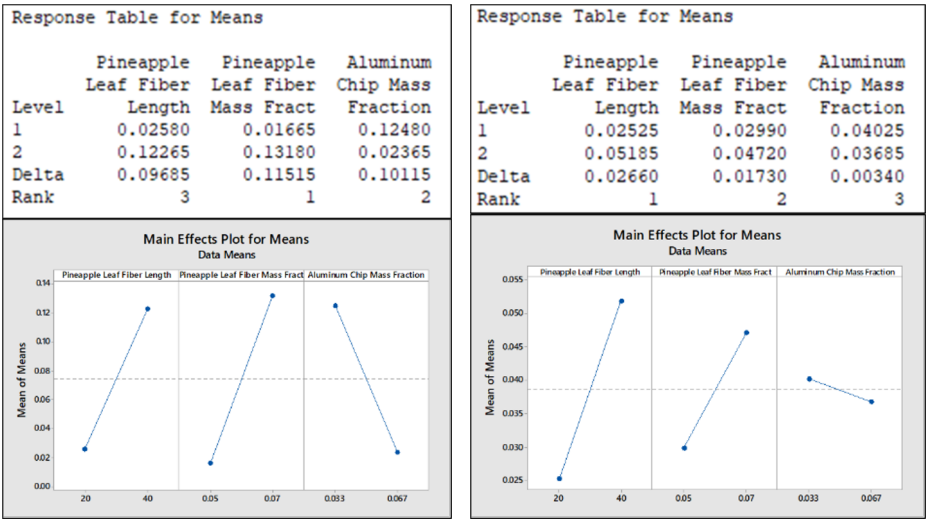


Figure 1. Main effect plot for means of coefficient of friction (a); and wear mass loss (b)

For coefficient of friction, the mean response increased markedly with longer fiber length, higher pineapple leaf fiber content, and lower aluminum chip content. Specifically, the mean coefficient of friction for 20 mm fiber length was 0.0258,

whereas the mean value for 40 mm fiber length increased to 0.1227. Similarly, the mean coefficient of friction increased from 0.0167 at 5% pineapple leaf fiber to 0.1318 at 7% pineapple leaf fiber. For aluminum chip content, the mean coefficient of friction decreased from 0.1248 at 3.3% to 0.0237 at 6.7%, suggesting that the higher aluminum chip content reduced frictional resistance as shown in Figure 1a.

For wear mass loss, the opposite trend was generally observed. The mean wear mass loss increased from 0.02525 at 20 mm fiber length to 0.05185 at 40 mm fiber length, indicating that shorter fibers contributed to better wear resistance. The mean wear mass loss also increased from 0.02990 at 5% pineapple leaf fiber to 0.04720 at 7% pineapple leaf fiber. In contrast, the higher aluminum chip content of 6.7% slightly reduced wear mass loss compared with 3.3%, with mean values of 0.03685 and 0.04025, respectively.

Overall, the main effects analysis indicates that fiber length was the most influential factor on wear performance, while pineapple leaf fiber content had the strongest effect on frictional response. Aluminum chip content also influenced both tribological responses, although its effect on wear mass loss was comparatively smaller. The main effects trends suggest that the most favorable compromise between friction and wear may be obtained by selecting the shorter fiber length and adjusting the reinforcement composition to balance friction enhancement with wear resistance as shown in Figure 1b.

3.2 Discussion

The tribological performance of the fabricated brake pad composites was found to be highly dependent on the material composition. Variations in pineapple leaf fiber (PALF) length, PALF content, and aluminum chip content produced measurable changes in both the coefficient of friction and wear mass loss, indicating that the formulation plays a critical role in determining brake pad performance. This observation is consistent with recent reviews on eco-friendly brake materials, which conclude that the tribological behavior of natural-fiber brake pads is governed by the combined effects of reinforcement content, binder proportion, and filler composition rather than by any single constituent (Ammar et al., 2023; Singh, 2021).

The descriptive analysis based on the mean response values showed that increasing the PALF content from 5 wt.% to 7 wt.% increased the average coefficient of friction from 0.0167 to 0.1318. Among the three investigated factors, PALF content exhibited the largest Delta value, indicating that it had the greatest influence on frictional performance. This trend agrees with the previous findings (Ammar et al., 2023) reported that the coefficient of friction of natural-fiber brake composites is strongly influenced by the fiber-to-resin ratio. The review further emphasized that natural fibers improve tribological performance only within an optimum composition range because insufficient fiber provides inadequate reinforcement, whereas excessive fiber reduces the amount of binder available to maintain structural integrity. Consequently, the coefficient of friction does not increase monotonically with fiber content but instead depends on achieving a balanced formulation.

A similar tendency has been reported in optimization studies of natural-fiber brake composites. In particular, investigated brake friction materials reinforced with

pineapple, hemp, and ramie fibers and demonstrated that the optimum tribological performance was achieved at an intermediate fiber content rather than at the maximum reinforcement level. Likewise, found that natural-fiber brake composites exhibited the best overall performance only at specific fiber weight fractions when multiple tribological responses were considered simultaneously. These findings suggest that increasing the amount of natural fiber alone is insufficient to guarantee improved braking performance, and that the interaction between fiber content and the remaining constituents must also be considered (Singh, 2021).

The wear results exhibited a different trend from the coefficient of friction. The main effects analysis indicated that fiber length produced the largest Delta value for wear mass loss, demonstrating that it was the most influential factor affecting wear resistance in the present study. The mean wear mass loss increased from 0.02525% for the 20 mm fiber length to 0.05185% for the 40 mm fiber length, indicating that under the specified testing conditions, composites containing shorter fiber lengths exhibited superior resistance to surface wear and mass loss. However, this trend should be interpreted within the specific formulation window investigated, as the optimum wear performance in natural-fiber composites is not necessarily achieved at the shortest fiber length. Instead, available evidence suggests that wear minimum often occurs at an intermediate short fiber length, depending on the matrix system, reinforcement content, and interfacial condition (Ammar et al., 2023; Sumesh et al., 2024).

The experimental results showed that Sample 1 exhibited the lowest wear mass loss but a relatively low coefficient of friction, whereas Sample 4 produced both the highest coefficient of friction and the highest wear mass loss. This trend is consistent with observations reported for composite brake pads, where higher friction may be accompanied by increased wear under certain operating conditions (Essam et al., 2026). Prior research highlights that the interaction between friction coefficient and wear rate is governed by parameters including contact load, sliding velocity, interface temperature, and tribofilm stability. Under higher contact loads, increases in the coefficient of friction have been accompanied by higher wear due to greater interfacial interaction between the contacting surfaces. Although stronger asperity interlocking and adhesive contact can increase friction, these conditions may also accelerate material removal through mechanisms such as micro-cutting, particle detachment, matrix cracking, and delamination. Furthermore, frictional heating generated under more severe operating conditions can promote adhesive, abrasive, and oxidative wear, leading to greater material loss. Therefore, the results obtained in the present study suggest that improving the coefficient of friction alone does not necessarily lead to improved wear resistance, highlighting the importance of considering both tribological responses simultaneously during brake pad formulation and optimization (Essam et al., 2026; Singh, 2021).

The contribution of aluminum chip waste appeared to be less pronounced than that of PALF content and fiber length. Based on the mean response values, increasing the aluminum chip fraction from 3.3 wt.% to 6.7 wt.% reduced both the average coefficient of friction and the average wear mass loss. Although the effect was relatively small, this trend indicates that recycled aluminum chips can function as a metallic filler that

modifies the tribological response while simultaneously providing an environmentally beneficial use for machining waste.

4 Conclusion

This study investigated the development of sustainable composite brake pad materials reinforced with pineapple leaf fiber (PALF) and aluminum chip waste. The research was motivated by the environmental and health concerns associated with conventional friction materials that rely on synthetic and potentially toxic fibers. Using a Taguchi L4 design of experiments, the effects of PALF length, PALF mass fraction, and aluminum chip mass fraction on tribological performance were evaluated through coefficient of friction and wear mass loss.

The experimental results, analyzed descriptively using mean response values, main effects plots, and Delta analysis, showed that the tribological properties of the composites were strongly influenced by the selected factor combinations. Among the four formulations, Sample 1, consisting of 20 mm fiber length, 5% PALF, and 3.3% aluminum chip fraction, exhibited the lowest wear mass loss, indicating the best wear resistance. Sample 3 produced the lowest coefficient of friction but with higher wear mass loss, while Sample 4 exhibited the least favorable overall tribological performance, as it combined the highest coefficient of friction with the highest wear mass loss. These results indicate that the composite response depends on the balance of reinforcement length and composition rather than on a single factor alone.

Overall, the findings demonstrate the potential of pineapple leaf fiber and aluminum chip-based composites as eco-friendly brake pad materials. The study also shows that formulation optimization is necessary to achieve an appropriate balance between friction performance and wear resistance. Further work should include replicated testing and microstructural characterization to strengthen the interpretation of the observed tribological trends and to refine the optimum formulation.

Acknowledgment

The authors gratefully acknowledge the financial support provided by the Center for Research and Community Service (P3M) of Politeknik Negeri Bali under Contract No. 06891/DST/PL8/AL.04/2026. The authors also express their appreciation to all individuals and laboratory staff who contributed to the completion of this research.

References

- Ali, S., Kumar, N., Grewal, J. S. G., Thakur, V., Chau, K. W., & Kumar, M. (2022). Coconut waste fiber used as brake pad reinforcement polymer composite and compared to standard Kevlar-based brake pads to produce an asbestos free brake friction material. *Polymer Composites*, 43(3), 1518–1525. <https://doi.org/10.1002/pc.26472>

- Ammar, Z., Ibrahim, H., Adly, M., Sarris, I., & Mehanny, S. (2023). Influence of Natural Fiber Content on the Frictional Material of Brake Pads—A Review. In *Journal of Composites Science* (Vol. 7, Number 2). MDPI. <https://doi.org/10.3390/jcs7020072>
- Carlevaris, D., Leonardi, M., Straffelini, G., & Gialanella, S. (2023). Design of a friction material for brake pads based on rice husk and its derivatives. *Wear*, 526–527. <https://doi.org/10.1016/j.wear.2023.204893>
- Carlevaris, D., Nogueira, A. P. G., Rita, D. A., Candeo, S., Fambri, L., Menapace, C., & Straffelini, G. (2025). Novel ingredients for sustainable brake pad friction materials: Benzoxazine resins and rice husk. *Wear*, 564–565. <https://doi.org/10.1016/j.wear.2024.205698>
- Dirisu, J. O., Okokpujie, I. P., Apiafi, P. B., Oyedepo, S. O., Tartibu, L. K., Omotosho, O. A., Ogunkolati, E. O., Oyeyemi, E. O., & Uwaishe, J. O. (2024). Development of eco-friendly brake pads using industrial and agro-waste materials. *Journal of Engineering and Applied Science*, 71(1). <https://doi.org/10.1186/s44147-023-00345-y>
- Essam, M. A., Faragallah, M. M., Abdeltawab, N. M., & Ali, M. (2026). Tribological characteristics of composite brake pads under variable load and speed. *Scientific Reports*, 16(1). <https://doi.org/10.1038/s41598-025-33326-7>
- Krishnakumar, S., Mohanavel, V., Venkatesh, R., & Balasubramanian, K. (2024). Enhancement of tribology behaviour by the addition of different fiber length of pineapple fiber reinforced polyester composite. *Journal of Mechanical Science and Technology*, 38(1), 201–206. <https://doi.org/10.1007/s12206-023-1217-8>
- Madnasri, S., Astika, G., & Marwoto, P. (2022). The Effects of Natural Fiber Orientations on the Mechanical Properties of Brake Composites. *Journal of Natural Fibers*, 19(8), 2980–2991. <https://doi.org/10.1080/15440478.2020.1838989>
- Singh, T. (2021). Optimum design based on fabricated natural fiber reinforced automotive brake friction composites using hybrid CRITIC-MEW approach. *Journal of Materials Research and Technology*, 14, 81–92. <https://doi.org/10.1016/j.jmrt.2021.06.051>
- Singh, T., Pruncu, C. I., Gangil, B., Singh, V., & Fekete, G. (2020). Comparative performance assessment of pineapple and Kevlar fibers based friction composites. *Journal of Materials Research and Technology*, 9(2), 1491–1499. <https://doi.org/10.1016/j.jmrt.2019.11.074>
- Sumesh, K. R., Ajithram, A., Anjumol, K. S., & Sai Krishnan, G. (2024). Influence of natural fiber addition and fiber length in determining the wear resistance of epoxy-based composites. *Polymer Composites*, 45(4), 3029–3042. <https://doi.org/10.1002/pc.27968>

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