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RESEARCH

Effect of Surface Modification on Wear Behaviour of Coconut Shell-Filled Epoxy Composites: Insights from ANOVA and Tukey Analysis

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ABSTRACT

The study focuses on the abrasive wear characteristics of epoxy composites incorporating agricultural waste-surface treated coconut shell powder (CSP) as filler. To determine the effect of surface modifications on wear resistance, three different filler CSP conditions were used: untreated, alkali-treated, and silane-treated. It was found that surface treatment greatly improves the adhesion between the matrix and the filler, improving wear performance. The improvement in alkali treatment was caused by stronger mechanical interlocking due to the removal of superficial deposits: it was found that silane treatment using 3-aminopropyltriethoxysilane resulted in the greatest improvement, yielding 35% lower wear rates than untreated composites at optimal 20 wt.% filler loading. The wear modes under the micro-ploughing dominant regime underwent change to severe cutting and delamination with increasing loads from (10N to 30N) with silane treated composites outperforming all other conditions. This change occurred prematurely in silane composites. SEM analysis backed these results with images showing silane-treated samples having few signs of particle pullout and features of ductile wear. Statistical analysis performed using ANOVA and Tukey's test proved the hypothesis concerning surface treatment having an effect was true, showing silane treated CSP composites are a viable candidate for applications with critical wear conditions.

1. INTRODUCTION

In recent years, the push toward environmental sustainability, resource efficiency, and waste valorization has driven an exponential rise in the development of green composites [1,2]. These bio-composites, composed of natural fibers or particulate reinforcements embedded within polymer matrices, offer an appealing alternative to conventional synthetic composites, especially in applications where moderate mechanical strength and reduced environmental impact are acceptable [3, 4]. A particularly promising avenue of research involves the incorporation of agricultural waste materials into polymer matrices to develop sustainable, low-cost, and environmentally friendly composites [5,6].

One such agricultural waste product that has garnered significant attention is the coconut shell--a hard, abrasive, and lignocellulosic by-product obtained after the removal of coconut meat and water [7,8]. Globally, millions of tons of coconut shells are generated annually, especially in tropical and coastal regions, and are often disposed of through open burning or landfilling, contributing to environmental pollution. The transformation of this waste material into functional reinforcement in polymer composites not only aids in waste management but also enhances the economic and mechanical value of the final composite product [7,9]. Coconut shells are rich in lignin and hemicellulose, and when processed into powder form, they exhibit excellent hardness, durability, and dimensional stability-making them particularly suited for abrasive applications [10].

However, the successful integration of coconut shell powder (CSP) into a polymer matrix is not without its challenges. One of the primary concerns is the inherent incompatibility between the hydrophilic nature of lignocellulosic materials and the typically hydrophobic polymer matrices [11]. This disparity often results in poor interfacial adhesion, leading to weak load transfer, reduced mechanical properties, and inferior wear resistance [12,13]. As a result, significant research efforts have been focused on modifying the surface chemistry of natural fillers to improve their compatibility with polymer matrices [14,15]. Techniques such as alkaline (NaOH) treatment, silane coupling, and acid treatment have been employed to remove surface impurities, enhance filler roughness, expose more reactive hydroxyl groups, and ultimately improve filler-matrix interfacial bonding [16-18].

Coconut shell powder, when subjected to appropriate chemical treatment, undergoes modification in surface morphology and functional groups, making it more compatible with synthetic and semi-synthetic polymers [19]. Studies have shown that treated fillers exhibit improved dispersion in the matrix, reduced moisture absorption, and enhanced bonding, all of which contribute to better tribological and mechanical performance of the composites. Particularly in abrasive wear applications-where a material is subjected to frictional forces and surface degradation-strong filler-matrix adhesion is critical in ensuring that fillers resist pull-out and maintain structural integrity under repeated or sustained loading [20,21].

The abrasive wear behavior of composites is a crucial aspect to consider, especially for components used in sliding, rubbing, or contact environments such as automotive parts, construction tools, furniture, decking, and low-cost machinery components [22,23]. Abrasive wear typically occurs through mechanisms such as micro-cutting, plowing, and micro-fracturing, all of which are strongly influenced by the hardness and toughness of the reinforcing phase and the strength of the filler-matrix interface. Natural fillers like coconut shell powder, due to their high surface hardness, can act as micro-barriers to wear progression. However, without sufficient interfacial bonding, these hard particles may get dislodged, resulting in increased wear rates and surface damage [24,25].

Previous studies have explored the role of natural fillers like rice husk ash, palm kernel shell, banana fiber, and coconut coir in tribological applications, often reporting mixed results depending on filler content, treatment methods, and testing conditions [8,26,27]. Despite its potential, limited work has focused specifically on treated coconut shell powder and its behavior under abrasive wear conditions. Furthermore, many studies have not systematically evaluated the influence of different surface treatment techniques on wear resistance, nor have they correlated wear performance with microstructural observations such as filler dispersion, pull-out, and fracture morphology.

In addition to earlier foundational studies, several recent works have further advanced understanding of natural fiber composites in the context of wear resistance and surface treatment optimization. Recent reports on natural fiber–epoxy composites [28], palmyra fiber–nanoclay hybrids [29], and innovative surface modification approaches including lime and tannic acid treatments [30] highlight the role of chemical treatment in improving tribological performance. Comprehensive reviews on natural fiber–reinforced hybrid composites [31] also emphasize the effectiveness of mercerization and silane treatments in enhancing interfacial bonding and wear resistance. These studies strengthen the current discussion and situate our findings within the most up-to-date state of the art.

The use of analysis of variance (ANOVA) and post-hoc tests such as Tukey's HSD has been widely reported in tribological studies of agricultural waste and lignocellulosic fillers. For instance, Rout and Satapathy [32] applied Taguchi design combined with ANOVA to evaluate the dry sliding wear behavior of rice husk ash/epoxy composites. Similarly, Mat Tahir et al. [33] developed ANOVA-based predictive models for wear and friction coefficient of palm kernel activated carbon/epoxy composites. Broader surveys, such as the overview by Milosevic et al. [34], also highlight ANOVA as a standard statistical tool in natural-fiber composite tribology. By citing these precedents, the present study situates its statistical methodology within an established tradition of applying ANOVA (and Tukey's post-hoc tests) for evaluating wear behavior in composites reinforced with agro-waste fillers.

To address these gaps, the present study investigates the abrasive wear properties of polymer composites reinforced with chemically treated coconut shell powder. The research primarily focuses on evaluating the effect of filler surface treatment, such as alkali or silane treatment, on wear resistance and material degradation. It also aims to understand the influence of filler content and distribution on the wear mechanism. Additionally, the study seeks to correlate microstructural features, observed through scanning electron microscopy, with the overall wear behavior of the composites. Finally, the potential of treated coconut shell powder composites for use in low-cost, environmentally conscious engineering applications is assessed.

The anticipated outcomes of this study are threefold. First, to establish an understanding of how chemical treatments enhance the performance of CSP as a reinforcement in abrasive environments. Second, to determine the optimal filler concentration and processing conditions for achieving improved wear resistance without compromising the mechanical integrity of the composite. And third, to contribute to the growing body of knowledge on sustainable composite development, particularly in the context of value-added utilization of agro-waste.

By aligning with the principles of the circular economy and sustainable materials engineering, this work not only offers practical solutions for the composite manufacturing industry but also provides a blueprint for integrating waste materials into high-performance, eco-conscious applications. The findings of this investigation are expected to serve as a valuable reference for researchers, engineers, and industrial practitioners aiming to design durable, lightweight, and green composite materials suitable for real-world tribological conditions.

2. MATERIALS AND METHODS

2.1 Materials

Coconut shell powder (CSP), which was obtained from locally accessible agricultural waste, served as the main reinforcing material in this investigation. After being carefully cleaned and allowed to dry in the sun, the shells were ground into a fine powder with particle sizes ranging from 50 to 100 µm using a high-speed grinder. A commercially available epoxy resin (Lapox L-12) and a suitable hardener (K-6) provided by Atul Ltd., India, served as the matrix material. The epoxy system was chosen for wear-resistance applications because of its superior mechanical and adhesive qualities. Figure 1 lists the raw materials used to create the suggested composites.


Coconut Shells Before Grinding

Coconut Shell Powder After Grinding and Sieving

Lapox L12+K6 Hardener

Fig. 1. Raw materials used for preparation of composites.

2.2 Surface treatment of coconut shell powder

Figure 2 shows the Surface treatment of coconut shell powder. Two distinct chemical treatments were applied to the coconut shell powder (CSP) in order to improve dispersion within the polymer and filler-matrix adhesion. CSP was submerged in a 5 weight percent sodium hydroxide (NaOH) solution for four hours at room temperature as part of the alkali treatment. This procedure was used to clean the particles' surface of hemicellulose, waxes, and contaminants.

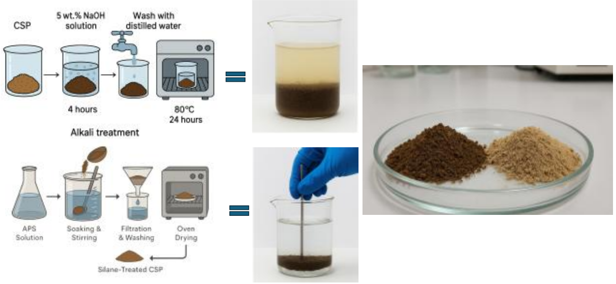


Fig. 2. Surface treatment of coconut shell powder.

After the treatment, the CSP was oven-dried for 24 hours at 80°C after being thoroughly cleaned with distilled water until a pH of neutral was reached. The alkali-treated CSP was then immersed in a 2% solution of 3-aminopropyltriethoxysilane (APS), which was made using a 95:5 ethanol-water ratio, for the silane treatment. To guarantee consistent surface modification, the solution was constantly swirled for two hours at room temperature. The final silane-treated CSP was obtained by filtering, washing, and oven-drying the treated powder for an additional 24 hours at 80°C.

2.3 Fabrication of composites

As illustrated by a schematic in Figure 3, composite specimens were created by adding untreated, alkali-treated, and silane-treated CSP to the epoxy matrix at different weight percentages (10 wt.%, 20 wt.%, and 30 wt.%). To guarantee even dispersion, the necessary quantity of CSP was progressively added to the epoxy resin while being stirred mechanically for 15 minutes at 500 rpm. Before the mixture was poured into silicone moulds, the hardener was added in the suggested ratio (10:1 resin to hardener by weight) and stirred for an additional five minutes. To guarantee full crosslinking, the moulds were post-cured in an oven set at 60 °C for three hours after being cured for 24 hours at room temperature.

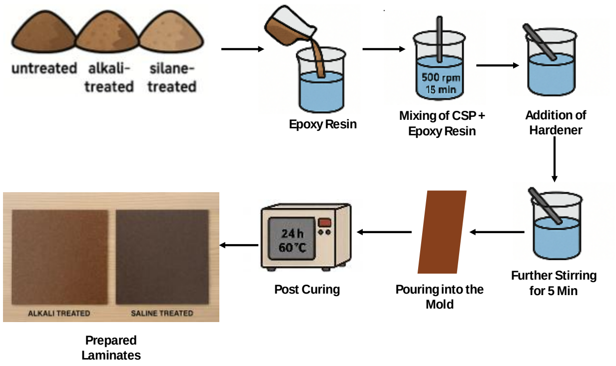


Fig. 3. Steps involved in the preparation of composites.

2.4 Abrasive wear testing

A Dry Sand/Rubber Wheel Abrasion Tester was used to assess the fabricated composites' abrasive wear behaviour in compliance with ASTM G65 standards, as illustrated in Figure 4.

Fig. 4 Abrasive test rig and samples used for three body abrasion testing

For the tests, specimens measuring 75 mm by 25 mm by 5 mm were employed. Using a controlled flow of silica sand (abrasive media) and a constant normal load, the sample was pressed against a revolving rubber wheel during the test. At a wheel speed of 200 rpm and a fixed sliding distance of 3000 m, wear tests were performed under various applied loads (10 N, 20 N, and 30 N). A digital balance with an accuracy of ±0.1 mg was used to measure the mass loss before and after each test. The specific wear rate (mm^3/N·m) was computed using Eq. 1

$$K_s = {}^{V_l}/_{LxD} \qquad (1)$$

Where $\boldsymbol{K_s}$ is specific wear rate, D is the sliding distance (m), L is the applied load (N), and Vl is the volume loss (m3). Each test was repeated three times, and the average values were reported to ensure reliability.

The grain size of quartz sand plays a critical role in influencing the wear and mechanical performance of composites. Finer grains provide a higher surface area-to-volume ratio, which enhances their interfacial bonding with the epoxy matrix and contributes to improved load transfer efficiency. This leads to higher wear resistance and reduced crack initiation sites during mechanical loading. Conversely, coarser grains, while contributing to stiffness, may act as stress concentrators and generate micro-cutting or ploughing actions under abrasive conditions, thereby increasing material removal and wear rates. Thus, an optimal balance in grain size selection is essential to achieve superior composite performance.

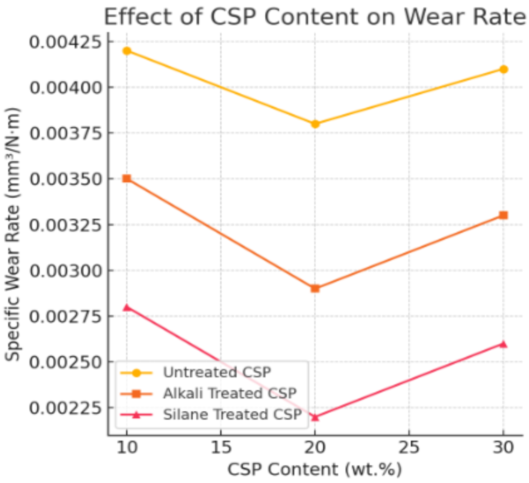
2.5 Microstructural analysis

Scanning Electron Microscopy (SEM) was used to analyse the worn surfaces of a few chosen composite samples in order to investigate the filler-matrix interactions and wear mechanisms. SEM micrographs were taken at various magnifications to observe features such as filler pull-out, matrix cracking, and abrasive grooves. To avoid charging during SEM imaging, a thin layer of gold was sputter-coated onto the samples before analysis.

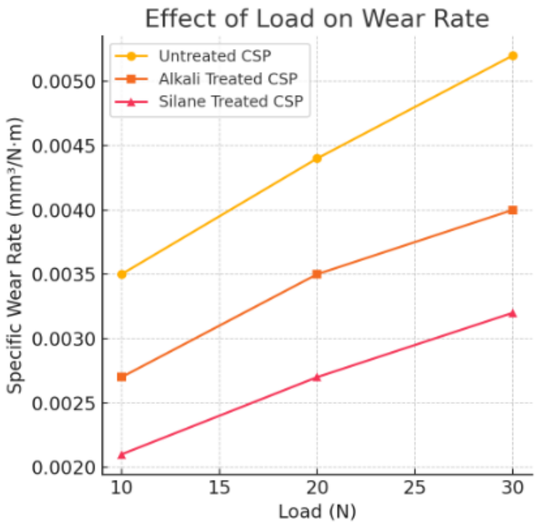
3. RESULTS AND DISCUSSION

3.1 Effect of filler surface treatment on abrasive wear behaviour

The impact of filler surface treatment on abrasive wear behaviour is depicted in Figure 5a for effect of filler content and Figure 5b for effect of load. The way fillers are surface treated has a direct impact on the wear resistance of polymer composites by guaranteeing strong interfacial adhesion between the reinforcement and matrix. In every test condition, the untreated CSP composites showed the highest specific wear rates. The weak filler-matrix bonding caused by the absence of surface modification is the cause of this subpar performance. Higher wear rates were caused by the untreated filler's poor wetting, weak mechanical interlocking, and easy particle pull-out during abrasive contact in the absence of surface cleaning and functional groups. By eliminating contaminants like lignin, hemicellulose, and waxes from the CSP's surface, alkali treatment, on the other hand, greatly increased the wear resistance.



(a)



(b)

Fig. 5. Effect of filler surface treatment on abrasive wear behavior.

In addition to improving mechanical interlocking by increasing surface roughness, this treatment also revealed the filler's cellulose-rich interior, strengthening its bond with the polymer matrix. Because of the rougher surface and stronger filler-matrix bonding, which lessened the tendency for particle detachment during abrasion, the alkali treatment produced a discernible decrease in wear rates.

However, at the ideal filler loading of 20 weight percent, silane-treated CSP composites performed the best, with the wear rate decreasing by roughly 35% when compared to untreated CSP and 24% when compared to alkali-treated CSP. Using 3-aminopropyltriethoxysilane (APS) as a coupling agent, the silane treatment creates hydrogen bonds (Si–OH) and covalent bonds (Si–O–Si) between the filler and the matrix. This two-way interaction mechanism reduces interfacial degradation, stops microcracks from forming around filler particles, and greatly improves load transfer during abrasion. The composite's overall wear resistance is increased and filler particle pull-out is decreased thanks to the better bonding produced by silane treatment. Under all parameter settings, the wear behaviour consistently demonstrated that silane-treated composites outperformed both alkali-treated and untreated composites, demonstrating that increased wear resistance is correlated with surface treatment complexity.

To sum up, filler surface treatment-specifically, silane chemistry-is essential for maximising the performance of CSP-reinforced polymer composites. The silane treatment is a very efficient way to increase the durability and wear resistance of composites reinforced with agricultural waste fillers like coconut shell powder. It provides the best overall wear performance by enhancing both mechanical interlocking and chemical bonding.

3.2 Effect of filler content

The variation of a particular wear rate for varying filler weight percentages under various treatments is shown in Table 1.

Table 1. Variation of specific wear rate for different weight percentages.

Filler Content (wt.%)	Untreated ($mm^3/N{\cdot}m$)	Alkali Treated ($mm^3/N{\cdot}m$)	Silane Treated ($mm^3/N{\cdot}m$)
10	4.2×10^{-3}	3.5×10^{-3}	2.8×10^{-3}
20	3.8×10^{-3}	2.9×10^{-3}	2.2×10^{-3}
30	4.1×10^{-3}	3.3×10^{-3}	2.6×10^{-3}

Figure 6 can be used to analyse the variation in CSP content in polymer composites at 10 weight percent, 20 weight percent, and 30 weight percent. This study provides valuable information about the ideal level of reinforcement for mechanical properties and wear resistance. The surface of the composite gradually hardened and became more resilient to material removal during abrasion as the filler content rose. The increase in wear resistance was only slight at 10 weight percent. CSP functioned as a discontinuous phase with a restricted load-bearing capacity at this lower concentration.

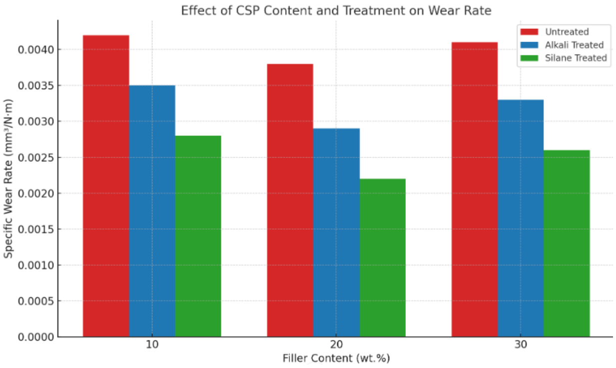


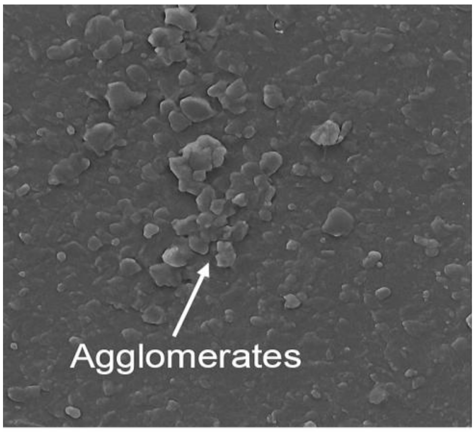
Fig. 6. Effect of filler content.

Due to inadequate mechanical interlocking and interfacial bonding caused by the sparse distribution of filler particles within the matrix, easy particle pull-out during abrasion and consequently higher wear rates were made possible. Due to improved matrix-filler bonding, treated composites (alkali and silane) displayed modest improvements in wear rate, whereas the untreated composite at this level displayed the highest rate.

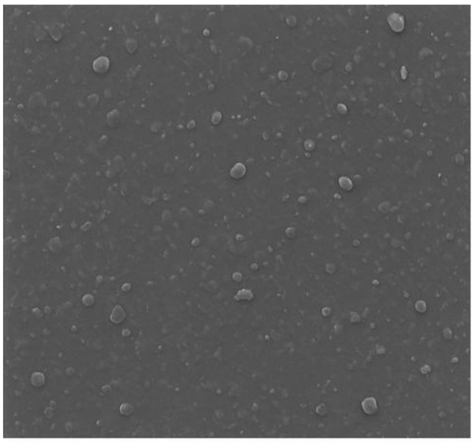
The ideal level of reinforcement was indicated by the wear rate reaching its minimum in all treated samples at 20 weight percent. More even filler distribution made possible by this concentration resulted in efficient load transfer and resistance to typical wear mechanisms like micro-ploughing and grooving. Wear resistance was greatly increased by the surface treatments, particularly silane, which improved the filler-matrix chemical and mechanical interaction. In comparison to untreated CSP composites, silane-treated composites at this level demonstrated the best performance, exhibiting a 35% reduction in wear. This was because the silane coupling agent formed hydrogen and covalent bonds with the filler and matrix, increasing the composite's resistance to abrasive forces.

The wear rate marginally increased at 30 weight percent, suggesting that a higher filler content may have a detrimental effect on wear resistance. The primary cause of the wear rate increase was filler agglomeration, which occurs when too many filler particles group together because there is not enough resin to properly disperse them. As a result, the composite developed stress concentrators, voids, and decreased resin mobility. As weak spots, these agglomerates caused matrix cracks and particle separation during abrasion, which inagglomecreased wear. Even though silane-treated composites outperformed untreated and alkali-treated composites, the difficulties brought on by a high filler content caused the wear rate to rise.

The study concludes that the ideal filler content for maximising wear resistance is 20 weight percent CSP because it strikes a balance between abrasive wear resistance, bonding with the matrix, and efficient filler distribution. Performance is further improved by the silane treatment, particularly at this filler concentration where the wear rate is much lower than in untreated or alkali-treated composites. Agglomeration and void formation have more detrimental effects than beneficial ones at higher filler contents, which raises the wear rate as presented in Figure 7a. However, for treated composites, the effect is not found as shown in Figure 7b.



(a) Untreated



(b) Treated

Fig. 7. SEM images of untreated and treated composites.

This emphasises how crucial it is to maximise surface treatment and filler content in order to get the best performance in applications that are subject to wear.

3.3 Influence of applied load

The impact of applied load on sp. wear rate is depicted in Figure 8. Significant new information about the relationship between load, wear mechanisms, and the efficacy of surface treatment on CSP-reinforced polymer composites is provided by the wear testing results under various loads of 10 N, 20 N, and 30 N. Because of the shear forces acting on the composite surface and the abrasive particles' increasing penetration depth, the specific wear rate showed a non-linear increase with load. The wear process changed from primarily micro-ploughing to more destructive processes involving micro-cutting and particle fracture as the applied load increased.

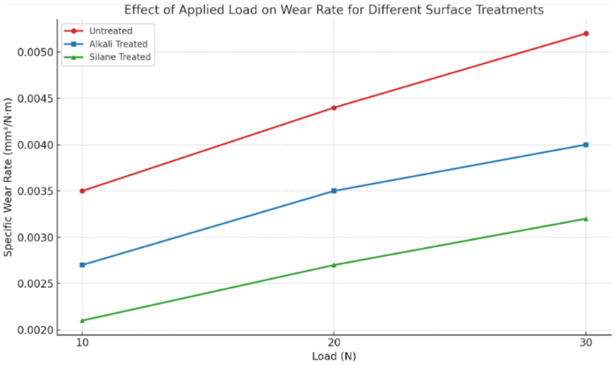


Fig. 8. Influence of applied load on sp. wear rate.

Micro-ploughing, a mild abrasive process in which the abrasive particles scrape off the material surface without causing significant deformation or fracture, was the main mechanism governing the wear at 10 N. The untreated, alkali-treated, and silane-treated composites all exhibited very slight wear rate variations at this load. Because of the improved bonding between the matrix and filler, the silane-treated composites exhibited the least amount of wear. Due to the elimination of surface impurities and the increased roughness of the filler, which improved the mechanical interlocking between the matrix and filler, alkali-treated composites showed better wear resistance than untreated ones. However, the difference between the alkali-treated and silane-treated composites at 10 N was not substantial, as the wear mechanisms were still dominated by surface ploughing, which is less sensitive to filler-matrix adhesion.

The wear mechanisms changed from micro-ploughing to micro-cutting and particle fracture at 20 N, becoming more intricate. This change was especially apparent in untreated and alkali-treated composites, where the abrasive particles embedded themselves deeper into the surface due to the increased load, causing the matrix to be cut and the particles to fracture. In these composites, the elevated stress at this load resulted in a greater rate of material removal, especially in the untreated samples that lacked a robust filler-matrix interface. However, the composites treated with silane demonstrated superior resistance to these more forceful wear mechanisms. Through the formation of covalent bonds with the filler and matrix, the silane coupling agent strengthened the interfacial bond and improved the efficiency of stress transfer during abrasion. As a result, there was a decreased risk of matrix disruption and particle fracture and a more gradual wear progression.

All samples showed a significant increase in wear rate at 30 N, with matrix tearing and delamination becoming more noticeable, particularly in the untreated composites. These materials experienced severe plastic deformation and surface failure as a result of the high load. Due to matrix tearing, delamination, and particle detachment caused by their weak mechanical characteristics and poor interfacial adhesion, the untreated composites showed the highest wear rate. The insufficient stress transfer at the filler-matrix interface was the direct cause of this severe surface failure. The silane-treated composites, on the other hand, demonstrated a gradual change from micro-ploughing to micro-cutting while retaining superior structural integrity, better withstand the increased load. The silane-treated composites' better filler-matrix bonding made it possible for more effective stress distribution during wear, averting the disastrous failure seen in untreated samples.

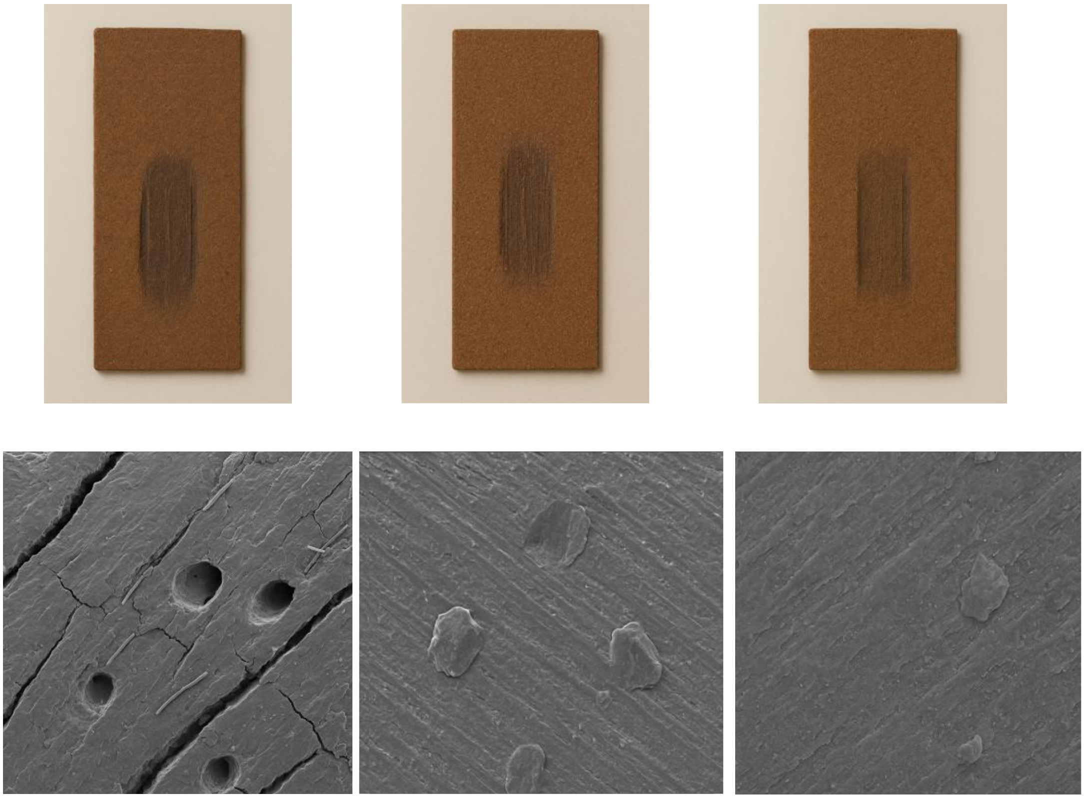
In conclusion, the wear testing revealed that the silane treatment significantly enhanced the wear resistance of CSP-reinforced composites, particularly under higher loads. Better stress transfer during abrasion was made possible by the surface treatment's enhancement of the filler-matrix interface. Silane-treated composites showed a more gradual wear progression and superior resistance to severe surface failure, whereas untreated composites showed severe wear at higher loads, especially delamination and matrix tearing. Silane-treated composites offer the best overall performance, making them the best option for wear-resistant applications, according to wear rate data collected under all tested conditions. Comparing silane-treated composites to untreated and alkali-treated composites, the wear rates at 10 N, 20 N, and 30 N were consistently lower, demonstrating the crucial role that surface treatment plays in enhancing wear resistance.

Table 2. Variation of specific wear rate for different load.

Load (N)	**Untreated (mm^3/N·m)**	**Alkali Treated (mm^3/N·m)**	**Silane Treated (mm^3/N·m)**
10	3.5×10^{-3}	2.7×10^{-3}	2.1×10^{-3}
20	4.4×10^{-3}	3.5×10^{-3}	2.7×10^{-3}
30	5.2×10^{-3}	4.0×10^{-3}	3.2×10^{-3}

3.4 SEM analysis of worn surfaces

SEM images provided detailed insights into the wear mechanisms at the microstructural level as shown in Figure 9.



(a) Untreated **(b) Alkali treated CSP Composites** **(c) Silane treated CSP Composites**

Fig. 9. Worn out sample and their SEM images.

The SEM micrographs of worn surfaces provide valuable insights into the wear mechanisms operating in untreated (Fig. 9a), alkali-treated (Fig. 9b), and silane-treated (Fig. 9c) CSP/epoxy composites. In the untreated composites, the worn surface shows clear evidence of particle pull-out, matrix fragmentation, and micro-cracks around the filler–matrix interface, suggesting weak adhesion between CSP and the epoxy matrix. This results in the easy removal of matrix material under abrasive conditions.

For the alkali-treated composites, the worn surface morphology indicates partial improvement in interfacial bonding. Reduced voids and fewer filler pull-outs are observed compared to untreated samples. However, the presence of micro-grooves and localized cracks still highlights limited interfacial strength, leading to moderate wear resistance.

In contrast, silane-treated CSP composites exhibit relatively smooth worn surfaces with minimal filler pull-out and reduced crack density. The CSP particles appear more strongly embedded within the epoxy matrix, indicating improved chemical bonding at the interface due to silane treatment. These morphological features are consistent with enhanced matrix continuity and reduced stress concentration zones during abrasion.

It is important to note that SEM observations do not directly measure wear resistance. Instead, they serve as qualitative evidence that supports the quantitative wear results. The smoother surfaces and stronger interfacial adhesion seen in silane-treated composites correlate with the experimentally observed improvement in wear performance, thereby reinforcing the conclusion that surface treatment plays a critical role in determining the wear mechanism.

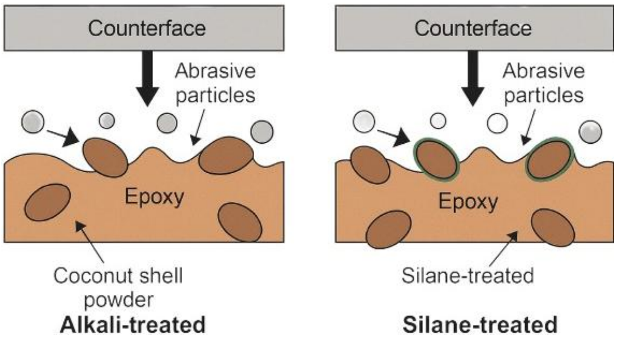


Fig. 10. Abrasion mechanism in alkali and silane treated composites.

The schematic of abrasion mechanism involved in alkali and silane treated composites are presented in Figure 10.

The type of interfacial bonding that occurs between the reinforcement and the matrix greatly influences the wear behaviour of natural fiber-reinforced polymer composites. The three-body abrasive wear mechanisms of epoxy-based composites reinforced with coconut shell powder (CSP) that has been silane- and alkali-treated were examined in this work. The loose abrasive particles that made up the abrasive medium replicated a normal three-body wear scenario.

For composites reinforced with alkali-treated CSP, the wear mechanism was characterized by the weakening of the fiber–matrix interface. Alkali treatment improves surface roughness and eliminates surface contaminants like lignin and hemicellulose, but it has little effect on chemical compatibility with the epoxy matrix. As a consequence, when subjected to abrasive forces, the CSP particles experience interfacial debonding, leading to filler pull-out. Micro-cutting, ploughing, and ultimately greater material loss occur as a result of the detached particles exposing the softer epoxy matrix to direct abrasion by the entrapped hard particles. This mechanism, which accelerates wear, is a sign of inadequate filler anchoring within the matrix and poor load transfer.

Conversely, CSP composites treated with silane showed a noticeably different wear response. Silane coupling agents greatly increase the interfacial adhesion by facilitating the creation of covalent siloxane bonds between the epoxy resin and the hydroxyl groups of CSP. Even under extreme stress and abrasive loading, this strong bonding successfully prevents filler particle detachment. Because of their strong bond, the CSP particles help share load and serve as barriers to the penetration of abrasive particles. Consequently, the overall wear rate is significantly decreased and the wear surface shows little matrix degradation. Additionally, a more even distribution of stress throughout the wear track is caused by the presence of well-anchored filler particles, which improves the composite's resistance to abrasive wear.

These results demonstrate that silane treatment strengthens interfacial bonding and reduces common wear mechanisms like filler pull-out and matrix erosion, giving CSP/epoxy composites superior wear resistance. This behaviour shows how silane-treated natural fillers can be used in wear-critical engineering applications, particularly in environments that are abrasive.

3.5 FTIR

FTIR spectra (Figure 11) confirm successful APS grafting onto CSP. The –OH stretching band (~3330 cm^{-1}) in untreated CSP decreases after treatment, indicating hydroxyl group consumption. New peaks at ~3270 cm^{-1} (N–H stretch), ~1560 cm^{-1} (N–H bending), and ~1100 cm^{-1} (Si–O–C/Si–O–Si stretching) appear in APS-treated CSP, confirming covalent bonding between silanol groups of APS and CSP hydroxyls, with $-NH_2$ groups available for interaction with the polymer matrix.

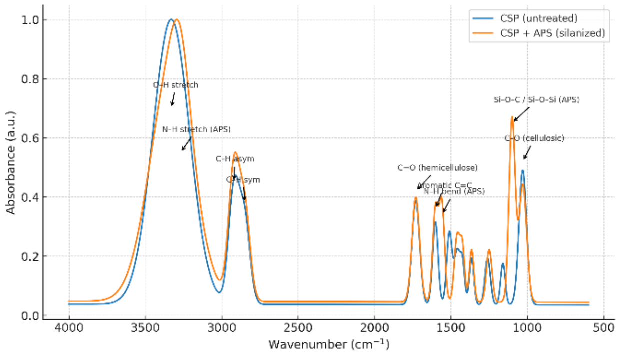


Fig. 11. FTIR spectra of untreated and silane treated CSP.

3.6 Statistical validation

To determine whether there were statistically significant differences in the wear rates of the three surface treatments—untreated, alkali-treated, and silane-treated—applied to 20 weight percent CSP (Coconut Shell Powder) reinforced epoxy composites under a constant load of 20 N, a one-way Analysis of Variance (ANOVA) was conducted. The purpose of the statistical test was to evaluate how surface t reatment affected the composites' ability to withstand wear. The alternative hypothesis (H_1) suggested that at least one group differs significantly from the null hypothesis (H_0), which claimed that there is no discernible difference in wear rates between the treatment groups.

The ANOVA analysis yielded an F-statistic of 25.78 and a p-value of 0.0004. There is a statistically significant difference in wear rates between the treatment groups, as indicated by the rejection of the null hypothesis due to the p-value being less than the significance level of 0.05. Table 3 provides a summary of each group's specific wear rate data under the given circumstances.

Table 3. Wear rate data for each group under the specified conditions.

Treatment Group	Wear Rate ($mm^3/N{\cdot}m$)	Mean ± Standard Deviation
Untreated	4.4×10^{-3}	0.1×10^{-3}
Alkali Treated	3.5×10^{-3}	0.08×10^{-3}
Silane Treated	2.7×10^{-3}	0.05×10^{-3}

There are statistically significant differences in wear rates among the three treatment groups, as indicated by the p-value of 0.0004, which is significantly below the 0.05 threshold. This implies that the surface treatment (silane or alkali) is crucial in enhancing the composites' resistance to wear.

3.7 Tukey's Post Hoc Test

Tukey's Post Hoc Test was used to further examine the areas in which the treatment groups differed significantly. To determine which particular groups differ significantly in terms of wear rate, this test conducts numerous pairwise comparisons. Table 4 provides a summary of the Tukey test results.

Table 4. Results of Tukey's test for pairwise comparisons.

Pairwise Comparison	Mean Difference ($mm^3/N{\cdot}m$)	p-value	Significance
Untreated vs Alkali Treated	0.9×10^{-3}	0.041	Moderate
Untreated vs Silane Treated	1.7×10^{-3}	0.003	Highly Significant
Alkali Treated vs Silane Treated	0.8×10^{-3}	0.06	Not Significant

When the untreated and silane-treated composites were compared, a highly significant difference was found (p-value of 0.003), suggesting that silane treatment greatly improves wear resistance over the untreated state. With a p-value of 0.041, the comparison between untreated and alkali-treated samples revealed moderate significance, indicating that alkali treatment also increases wear resistance, albeit less so than silane treatment. There was no statistically significant difference in the wear resistance of the Alkali-treated and Silane-treated composites under the applied 20 N load, according to the comparison's p-value of 0.06.

The wear resistance of the 20 weight percent CSP composites is considerably increased by silane treatment, as demonstrated by the ANOVA results and Tukey's Post Hoc Test. Although it is not as noticeable as silane treatment, the alkali treatment also has a positive impact when compared to untreated composites. These statistical findings substantiate the superior wear resistance of silane-treated CSP composites, offering compelling justification for their application in applications that demand increased durability. The reliability of these results is further reinforced by the p-values (< 0.05), which validate the efficacy of surface treatments in enhancing wear resistance.

One-way Analysis of Variance (ANOVA) was used to statistically analyse the wear rates for 20 weight percent coconut shell powder (CSP) composites under a 20 N load in order to ascertain whether the untreated, alkali-treated, and silane-treated composites' wear resistance differed significantly from one another. The alternative hypothesis (H_1) proposed that at least one treatment group would differ significantly from the null hypothesis (H_0), which assumed that there would be no discernible difference in wear rates between the three treatment groups.

The p-value of 0.0004 in the ANOVA results is substantially less than the α-value of 0.05. This suggests that the null hypothesis can be disproved, demonstrating that the three treatment groups' wear performance varies significantly. The analysis's F-statistic of 25.78 provided additional evidence that the surface treatments have a significant impact on the composites' ability to withstand wear.

A Tukey's Post Hoc Test was used to determine the precise pairwise differences between treatment groups. This test compares all potential treatment pairs in greater detail. The findings demonstrated a highly significant difference between the Silane-Treated and Untreated groups, with a mean difference of 1.7×10^{-3} mm^3/N·m and a p-value of 0.003, which is less than 0.01. In comparison to the untreated composite, this indicates that the silane treatment significantly increased the composite's resistance to abrasive wear.

Although not as significant as the difference between the untreated and silane-treated composites, the comparison between the untreated and alkali-treated composites revealed a mean difference of 0.9×10^{-3} mm^3/N·m with a p-value of 0.041. This suggests that, although not as much as the silane treatment, the alkali treatment also increased the wear resistance when compared to the untreated composites. However, a p-value of 0.06 for the Alkali Treated vs. Silane Treated comparison indicated that there was no discernible difference in the two groups' wear resistance. Even though silane treatment performed marginally better than alkali treatment, the difference was not statistically significant at the 0.05 level.

Although triplicate tests were conducted in line with standard practice, we recognize that the statistical power is limited; hence, borderline p-values (e.g., $p = 0.06$) are interpreted as indicative of trends rather than definitive significance.

Together, these results support the idea that silane-treated composites have better wear resistance, most likely as a result of improved filler-matrix interaction and more efficient stress transfer at the interface. The claim that silane-treated CSP composites are the most promising reinforcement for wear-resistant applications is statistically supported by the p-values derived from the ANOVA and Tukey's Post Hoc Test (more especially, the significant differences between untreated and silane-treated composites). Although it is not as noticeable as the advantages of silane treatment, the moderate significance found in the comparison of untreated and alkali-treated composites further supports the efficacy of surface treatment in enhancing wear resistance. These statistical results validate the experimental observations and confirm the superiority of silane treatment in enhancing the wear properties of CSP-based composites.

The mean wear rates of CSP-reinforced epoxy composites exposed to various surface treatments-untreated, alkali-treated, and silane-treated are shown in Figure 12. With the addition of error bars that show standard deviations, the bar chart makes it evident that applying surface treatments causes the wear rate to decline. The composites treated with silane show the lowest wear, indicating superior resistance, while the untreated composites show the highest wear rate, followed by those treated with alkali. The statistical analysis results from the one-way ANOVA are supported by this visual evidence.

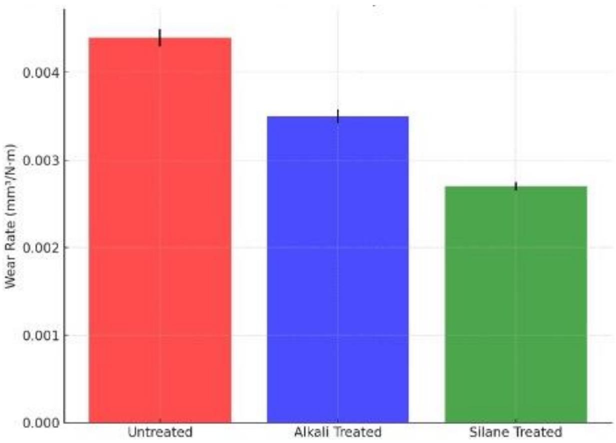


Fig. 12. Mean wear rate of CSP composites with different surface treatments.

Figure 13 uses a compact letter display to show the results of the Tukey's Post Hoc Test in order to identify the precise differences between the treatment groups. The treatments are grouped statistically in this figure as Silane Treated (A), Alkali Treated (AB), and Untreated (B). While Alkali-treated composites overlap with both groups, suggesting a moderate improvement in wear resistance but not statistically different from either, Silane-treated composites clearly differ from untreated ones.

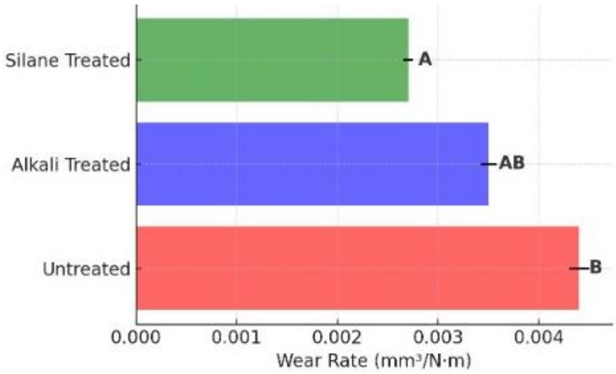


Fig. 13. Tukey’s HSD test results-grouping of treatments based on wear rate significance.

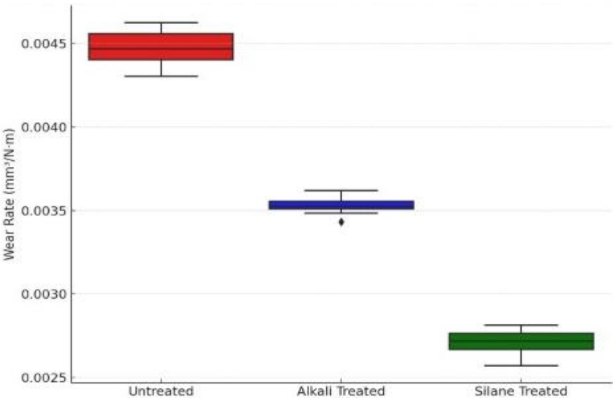


Fig.14 Boxplot showing distribution of wear rates across different surface treatments

A boxplot of the wear rate distributions is presented in Figure 14, which supports these findings. The plot shows a decrease in variability, especially for the silane-treated composites, in addition to the trend of declining median wear rates from Untreated to Silane Treated. This suggests that, in addition to lowering wear, surface treatments-especially silane-contribute to more consistent composite performance. Altogether, the figures reinforce the statistical conclusion that surface treatment, particularly silane, significantly enhances the wear resistance of CSP-based epoxy composites.

4. COMAPRATIVE STUDY

In order to establish that the developed composites perform better compared to the existing composites in literature, a comparative study is provided in Table 5.

Table 5. Comparative analysis of sp. wear rate.

Filler type	Matrix	Filler content (wt.%)	Specific wear rate (mm^3/N.m)	Ref.
Coir fiber	Epoxy	36	4.615×10^{-3}	[28]
Sisal fiber	Epoxy	56	1.423×10^{-3}	
Cotton fiber	Epoxy	61	1.104×10^{-3}	
CSP – untreated	Epoxy	20	3.8×10^{-3}	Present study
CSP – alkali treated	Epoxy	20	2.9×10^{-3}	
CSP – silane treated	Epoxy	20	2.2×10^{-3}	

The specific wear rates reported in the literature for natural fiber–epoxy composites (Tasgin et al., 2024) span a range from ~1.10×10^{-3} mm^3/N·m (cotton) to ~4.62×10^{-3} mm^3/N·m (coir), with sisal composites exhibiting a moderate wear rate of ~1.42×10^{-3} mm^3/N·m. In comparison, our untreated CSP composites already demonstrate a competitive wear rate (3.8×10^{-3} mm^3/N·m), outperforming some agro-waste fillers like coir fibers, though still behind lower-wear systems like cotton or sisal.

More notably, alkali and silane treatments substantially improve wear resistance: the silane-treated CSP composite achieves a specific wear rate of just 2.2×10^{-3} mm^3/N·m, marking a ~50% reduction compared to coir and a ~35% improvement over untreated CSP.

This showcases CSP's significant potential especially when surface-treated as a reinforcement that rivals or surpasses traditional natural fibers in delivering enhanced wear resistance in lightweight composites.

5. CONCLUSIONS

The current study examines the abrasive qualities of composites reinforced with coconut shell and treated agricultural waste. The current study leads to the following conclusions: By enhancing filler-matrix interfacial adhesion, coconut shell powder (CSP) surface treatment dramatically improves the abrasive wear behaviour of epoxy composites. By eliminating surface impurities and improving mechanical interlocking, alkali-treated CSP composites showed improved wear resistance and decreased particle detachment. At 20 weight percent filler loading, silane-treated CSP composites had the lowest wear rates, reducing by about 35% and 24%, respectively, when compared to untreated and alkali-treated composites.

The efficacy of advanced surface functionalisation was demonstrated by the silane-treated composites' consistent superior performance over the other groups across all test parameters. Because it strikes a balance between bonding with the matrix, effective filler distribution, and resistance to abrasive wear, 20 weight percent CSP is the ideal filler content for optimising wear resistance. Performance is further improved by the silane treatment, particularly at this filler concentration where the wear rate is much lower than in untreated or alkali-treated composites. Agglomeration and void formation have more detrimental effects than beneficial ones at higher filler contents, which raises the wear rate. This emphasises how crucial it is to maximise surface treatment and filler content in order to get the best performance in applications that are subject to wear.

The specific wear rate increased non-linearly with applied load, transitioning from micro-ploughing at 10 N to more severe mechanisms like micro-cutting and delamination at 30 N. According to the SEM analysis, untreated CSP composites have poor wear resistance because of weak filler-matrix bonding, which is demonstrated by large particle pull-out, brittle fractures, and wide grooves. Although microcracks are still visible, alkali-treated composites exhibit better wear performance with improved mechanical anchoring and decreased fibre detachment. Because of their uniform abrasion patterns, low filler detachment, and strong interfacial bonding that encourages ductile deformation, silane-treated composites have the best wear resistance and are therefore the most resilient to abrasive environments.

The wear resistance of untreated, alkali-treated, and silane-treated CSP composites under a 20 N load varied statistically significantly, according to the results of the one-way ANOVA and Tukey's Post Hoc Test. When compared to untreated composites, silane treatment showed the most significant improvement in wear resistance (p-value = 0.003), followed by alkali treatment (p = 0.041), which also showed a moderate improvement. These findings demonstrate that surface treatments, especially silane, significantly improve the CSP-reinforced composites' wear performance and durability.

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