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Tribological Behaviour of Silane/Alkali Treated Roystonea- Regia/Banana Fiber Reinforced Hybrid Polyester Composites

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Abstract: Natural fibre composites are utilized across a range of engineering fields because of their appealing properties. The presence of wear elevates the likelihood of material failure, presenting a common challenge in both structural and automotive domains. In this context, a novel composite was fabricated by reinforcing a polyester resin with Roystonea regia and banana fibers to investigate its wear characteristics. The inclusion of banana fibres increased the composite's density, which is attributed to an increase in the hardness of the composites. The fabricated fibers were subjected to silane and alkali treatments, which improved their adhesion and moisture resistance. Reduced wear loss is observed for samples reinforced with 10 wt.% of Banana fiber and 5 wt.% of Roystonea regia fibers under all the tested conditions. Worn surfaces were studied using scanning electron microscopy, and they revealed delamination, ploughing, and wear debris along the sliding direction. As the load increased from 30 N to 50 N, debris and delamination also increased, particularly in silane-treated fibers compared to alkali-treated ones. Alkali-treated fibers exhibit better wear resistance than silane-treated ones, with abrasive wear being the primary mechanism. The regression equation was used for confirmation testing, and the Taguchi methodology for Design of Experiment was employed to ascertain the most effective operating parameters. Results indicate that the lowest specific wear rate occurs under conditions of 50 N loads, 3 m/s velocity, and 10% banana fibre.

Keywords: natural fiber; polyester; wear; coefficient of friction; electron microscopy.

1. Introduction

The environmental and technical benefits of natural fibers generated from plants are driving the widespread usage of these fibers as reinforcement in polymer composites in today's world. Composites can be modified to meet specific requirements, exhibit advantageous properties in corrosive environments, offer increased strength while being lightweight, and result in lower expenses over their life cycle [1]. Among these important fibers are abaca, sisal, coir, banana, jute, and hemp, each finding its place in numerous applications ranging from civil infrastructure and consumer goods to housing solutions. The adoption of natural fibres in recent decades is due to their inherent benefits, setting them apart from synthetic alternatives in industrial and structural applications. These advantages encompass characteristics such as reduced density, cost-effectiveness, biodegradability, and renewability [2]. Notably, natural fibers exhibit distinct properties, including robust strength, resilience, thermal attributes, stiffness, and enhanced resistance [3]. Regarding the applications of natural fibers, abaca fibers, for instance, have found their place as underfloor protection in automotive vehicles and as a reinforcement material for ropes due to their inherent strength. Additionally, natural fibers play pivotal roles in the construction of roofs, bridges, and beams, while also serving as effective insulation materials [4]. The notable benefits of natural fiber include its lightweight nature, eco-friendliness, reduced cost, and simplified processing techniques. As these applications unfold, it becomes evident that natural fibers are becoming formidable contenders against synthetic alternatives, gradually reshaping the material landscape across industries [5].

An essential aspect to consider is the hydrophilic nature of natural fiber, which imparts a propensity to absorb moisture, potentially leading to structural degradation. Consequently, a meticulous analysis of the composition of natural fibers is imperative, as it holds the key to understanding their impact on the mechanical properties of the composite material [6, 7]. These versatile fibers can be used in various formats, such as mats, fabrics, yarn, and roving, allowing for adaptable usage across a range of applications [8-10]. Composite materials exhibit tribological behavior under abrasive sliding conditions for various applications. Wear can be classified into several distinct types: adhesive, abrasion, surface fatigue, tribo-chemical, fretting, erosion, and cavitation wear. Wear due to abrasion occurs when rigid protrusions on one surface traverse a more malleable surface, leading to the penetration and removal of material from that softer surface [11]. Currently, a diverse array of fibrous and dispersed fillers with different morphologies and particle sizes is employed to enhance the tribological characteristics of epoxy polymer composites [12]. In the pursuit of innovation, researchers are exploring new arenas by combining multiple natural fibers and reinforcing them with diverse polymer matrices, such as epoxy and polyester. These pioneering efforts result in the creation of hybrid composites, adding a new dimension to the realm of material engineering. Notably, limited attention has been directed towards exploring the durability of polymer composites that have been strengthened with natural fibres, which is the focus of the present study. Ahmed et.al. [10] studied the wear characteristics of SiC/Al_2O_3 and jute fibers reinforced in epoxy matrix and reported that the mixture of jute fibers and SiC/Al_2O_3 particles improved the wear characteristics of the fabricated composite. Bajpai *et al*. [13] fabricated Poly Lactic Acid composite reinforced with optiva and neetle fibers to study the wear behavior. The wear rate of the fibre-reinforced composite revealed a reduction compared to the net PLA, and the coefficient of friction (CoF) values were notably lower for the fibre-reinforced composite. Edoziuno *et al*. [14] conducted to explore the characteristics of a polyester composite that has been strengthened with periwinkle shell and wood charcoal. The enhancement in wear properties for the fabricated composite was attributed to the strong interfacial bonding between the fibres and the matrix. Babu *et al*. [15] used gigentea fruit fiber and reinforced it with a polyester matrix to fabricate the composite. It was concluded that the fiber-reinforced composite exhibited greater wear resistance compared to the neat matrix, and this resistance increased further with increasing fiber content. Ranganathan *et al*. [16] conducted a sliding wear test using sisal fiber reinforced cashew nutshell liquid and epoxy composite. They showed that wear rate reduction was achieved for the composite with a combination of sisal fiber and cashew nutshell compared to neat epoxy. Joszko *et al*. [17] explored the potential of utilizing ground peels from citrus fruits such as grapefruit, key lime, lemon, and orange as fillers in composite materials, with epoxy resin serving as the matrix. The tests ascertained that composite materials incorporating grapefruit and key lime as fillers exhibited superior tribological properties.

A significant research gap regarding the use of Roystonea regia and banana fibers in combination with a polyester composite is highlighted by the current state of the literature, particularly in the exploration of the tribological behavior of the fabricated composite. Addressing this gap, the present study investigates the tribological properties of polyester matrix composites reinforced with Roystonea regia fibers and banana fibers, both of which have undergone silane/alkali treatment. This investigation into the combined fiber system holds significant potential to expand the application spectrum of these fibers across various engineering domains, particularly in the automotive industry.

2. Materials and Methods

2.1. Materials.

The fabrication of composites requires the use of polyester resin in conjunction with Roystonea regia fibers and Banana fibers to enhance the material's strength. During the production process of composites, Methyl Ethyl Ketone Peroxide (MEKP) and cobalt were introduced to the resin at particular weight percentages of 1.5% and 0.02%, respectively. These substances served as hardeners and accelerators, respectively. Roystonea regia fibers and banana fibers were sourced from local royal palm and banana plants. The fibers were obtained through a process involving soaking, manual rubbing, and washing in a water tank.

Royal palm tree leaves and leaf stems were dried in the dark for three days, followed by immersion in a vat of water for an additional three days, and then subjected to pressing and washing to remove grease. After the fibers were extracted, they were cleaned and then left in the sun for a week to dry, after which they were used. The extracted fibers had dimensions of approximately 1.5 m in length and 0.2–0.3 mm in diameter, as shown in Figure 1. This outer layer, containing primary fibers, was removed through a process called tuxying. Tuxies were soaked for 48 hours to remove lignin and pectin layers, then dried and crushed. The crushed fibers were cut to 6 – 10 mm in length and further treated to remove dust and fibers shorter than 6 mm. The processed fibers had a thickness ranging from 0.3 to 2 mm.

Figure 2 displays a schematic of the surface treatment of fibers, which involves alkali and silane treatment. Alkali treatment involved soaking the fibers in a concentrated sodium hydroxide solution (5%) for 2 hours, followed by washing and drying. This process removes lignin, wax, and oils from the fibers, improving wettability with the matrix resin. Following the soaking process, the fibers were extracted from the mixture and completely rinsed with distilled water.

Figure 1. Extracted Roystonea regia fibres from the royal palm tree.

Subsequently, they underwent a drying phase at a temperature of 60°C in an oven. This meticulous procedure serves to augment the surface roughness of the fibers, thereby significantly enhancing their ability to interact favorably with the matrix resin through improved wettability. Silane treatment utilized 3-Amino-Propyl Tri-ethoxy Silane (APTS). Fibers were immersed in 1% APTS in acetone for 1.5 hours, washed thrice with water, and naturally dried for three days. Subsequently, fibers were oven-dehydrated at 80°C for 12 hours. The application of silane treatment significantly boosted adhesion and moisture resistance, resulting in enhanced mechanical properties within the composites. In order to cure the composite assembly, it was subjected to a process that lasted for a full twenty-four hours at ambient temperature.

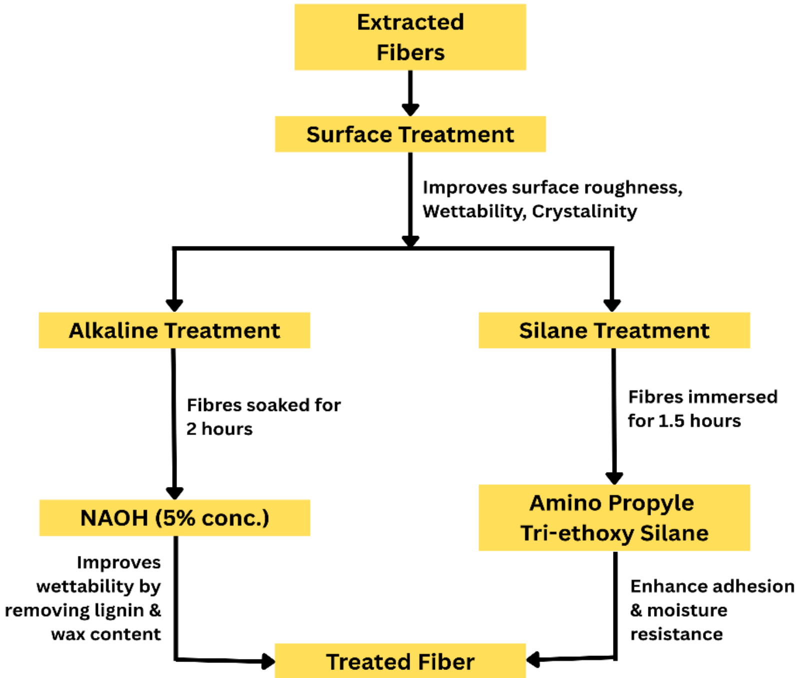


Figure 2. Schematic of surface treatment of fibers.

The hybrid composites, developed with various weight percentages of reinforcements and incorporating both treated and untreated fibers, were assigned distinct names, as detailed in Table 1. The analysis indicated that the maximum reinforcing weight percentage achievable in these hybrid composites reached 15%.

Table 1. Composite designation.

Nomenclature	Matrix % wt.	Roystonea regia fiber %wt.	Banana fiber% wt.	Total fiber content
P_R	85	15	---	15
P_{RB1}	85	10	05	15
P_{RB2}	85	05	10	15
P_{RB3}	85	7.5	7.5	15

2.2. Specimen preparation.

Samples measuring 5 mm × 5 mm were precisely sectioned from the laminate utilizing a diamond cutter, sticking to the guidelines as instructed by the ASTM standard G99. These samples were then refined to the precise dimensions needed, using an emery paper. The specimens were fastened on 6 mm-long and 30 mm-wide metal pins for the purpose of wear testing. A parallel alignment of the contact surface with the lamination plane was achieved by carefully arranging the orientation. To ensure consistent engagement with the rotating disc, the contact region was meticulously polished using 600-grit emery paper. This preparatory procedure guarantees standardized contact conditions for ensuing evaluations.

2.3. Dry sliding wear setup.

Dry sliding wear experiments were performed by employing a pin-on-disc wear test apparatus supplied by Novus Tribo Solutions (NTS-POD-V03) in the laboratory, as illustrated in Figure 3. The surfaces of both the disc and the specimen underwent a thorough cleaning with acetone to ensure optimal conditions were preserved.

A high-precision digital electrical balance with 0.0001 g accuracy was used to weigh the specimen-pin configuration. The subsequent action involved positioning the specimen onto the holder supplied by the wear testing apparatus. Every single test was carried out over a sliding distance that was always the same, which was 1800 m, and the track radius was always kept at 50 millimeters. Substantial typical loads of 30, 40, and 50 N were used to conduct wear tests on all composite compositions. The sliding velocities that were used were 3, 4.5, and 6 m/s. Following each test, the specimen was reweighed, allowing for the calculation of wear loss. The control unit of the machine recorded the frictional force, aiding in the derivation of the CoF (μ). For each composition, a set of three identical specimens was subjected to testing, and the presented results are the average of these trials with their respective deviations.

Figure 3. Pin-on-disc (POD) apparatus set up.

2.4. Microstructural studies.

After the wear tests, the rubbed surfaces of specific samples underwent examination using a scanning electron microscope. The objective was to detect the wear mechanism. For SEM analysis, the specimens were gold sputtered before examination. This procedure was carried out to increase their electrical conductivity, thus facilitating comprehensive and insightful microscopy.

2.5. Experimental design by the Taguchi approach.

The Taguchi method is an effective tool for conducting experiments, focusing on testing specific combinations of manufacturing and operating parameters rather than exhaustively testing all possible combinations, as in factorial design. The order of impacted parameters on the response is determined using designs such as Taguchi, factorial, and response surface designs when it comes to design of experiments (DoE) concerns. Taguchi design also investigates the permutations of response-influencing factors [18].

To determine the impact of control parameters and their interactions on the overall wear rate, the Taguchi method was employed. Using the experimental data, a signal-to-noise ratio (also known as S/N ratio) was calculated to evaluate the performance of the composite materials. Analyzing the signal-to-noise ratio, this study determined the optimal wear rate, which implies that a lower value is preferable. Eq. (1) expresses the computation of the signal-to-noise ratio for this attribute:

$$S/N = -10 \log (1/n)\Sigma(q^2{}_n) \qquad (1)$$

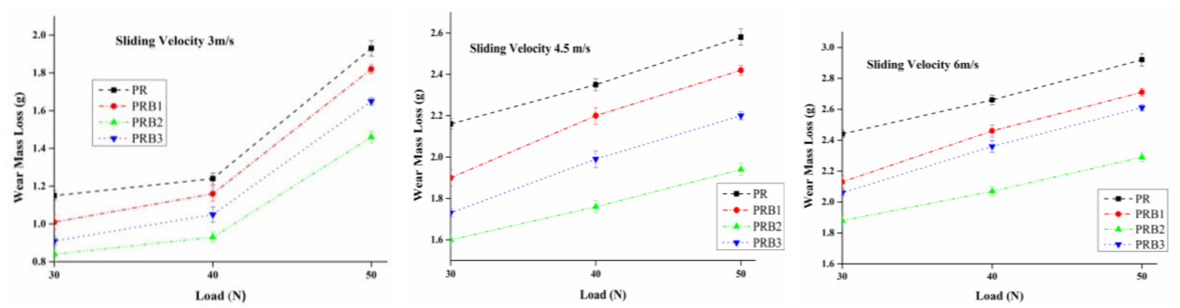
Where ‘q’ represents the specific wear-rate and ‘n’ denotes the number of experiments.

3. Results and Discussion

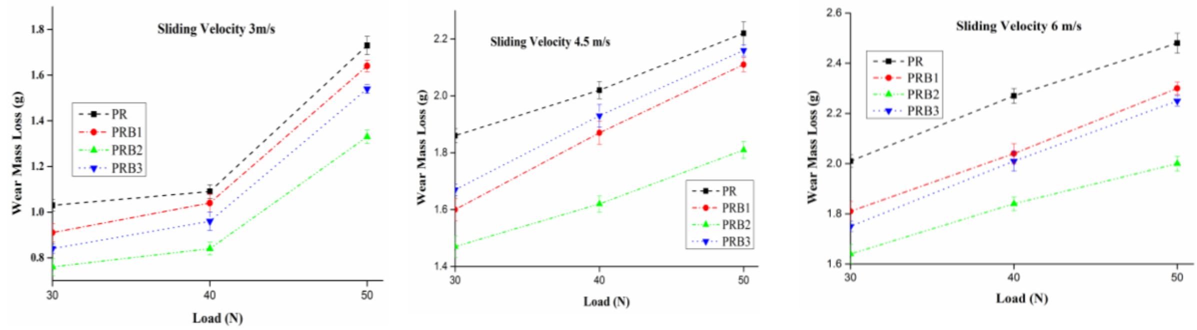
The investigation explored the wear properties of composites reinforced with Roystonea regia and banana fibers, using wear loss, which pertains to wear behavior, and CoF, which is indicative of friction behavior.

3.1. Analysis of wear mass loss.

Examine the effectiveness of composites enhanced with silane and alkali-treated fibres by assessing their wear loss. Figures 4 (a) and 4 (b) display the wear loss data for composites that have been reinforced with silane and alkali-treated fibres, respectively. The data is plotted against the normal loads at different sliding velocities, allowing us to analyze the impact of these loads on wear. The wear mass loss is found to be increasing with increasing normal load, irrespective of varying sliding velocities, type of composite, and surface treatment. The percentage wear loss increases in the range of 19.35–83.33% with increasing normal load for all the composites. The highest increase in wear loss percentage is obtained in the composite reinforced with an equal proportion of banana and Roystonea regia fibers (P_{RB3}) under both surface treatments. A significant increase in wear loss percentage is observed with a low sliding velocity of 3 m/s. As the applied load on the composites intensifies, the heat generated at the composite-disc interface increases, resulting in an increased brittle behavior of the composite. With increasing temperature, the thickness of the brittle layer also increases, leading to the easy removal of material from the surface and an increased wear loss of the material [19].



(a)



(b)

Figure 4. Wear loss of composite reinforced with **(a)** Silane; **(b)** Alkali-treated fibers under different loading and sliding velocities.

Wear mass loss also increases with the increasing sliding velocities, due to higher contact stresses and increased frictional heating. Composites reinforced with 10 wt.% of banana and 5 wt.% of Roystonea regia fibres (P_{RB2}) exhibit the lowest wear loss across all tested sliding velocities. Increasing the banana fiber content decreases the wear mass loss. The remarkable endurance of banana fibers contributes to an improvement in the performance of composites, which ultimately results in a reduction in wear mass loss [20]. As shown in Figures 4 (a) and (b), respectively, under normal load and sliding velocity circumstances, the wear mass loss of fiber-reinforced composites that have been treated with alkali is considerably lower than that of those composites that have been treated with silane. This is attributed to the changes in the physical and chemical properties of the fiber surfaces caused by the alkali-treatment process. A combination of the composite's improved wettability and rougher surface texture significantly boosts its mechanical performance. The composites strengthened with alkali-treated fibres exhibited a reduction in wear mass loss [21-23].

The wear mechanisms involved in the dry sliding wear of polymeric composites comprise matrix wear, fiber sliding wear, fiber fracture, and the debonding of the matrix from the reinforcing fibers. Matrix experiences microplowing and high friction, the latter of which increases as fibers peel due to the sliding process. As a result, the matrix cracked, and the reinforcement and matrix debonded [11]. Figure 5 depicts the wear-out surfaces of the silane and alkali-treated fibers P_{RB2} combination for 30 N, 40 N, and 50 N loads with a constant sliding distance of 1800 m and a sliding velocity of 6 m/s. The wear surfaces exhibited wear debris, delamination, and the formation of grooves by ploughing, caused by debris in the sliding direction. The percentage of debris formation and the amount of delamination vary with different load conditions for silane and alkali-treated fibers. With increasing load from 30 N to 50 N, the amount of debris and delamination increased. The data clearly show that silane-treated fibers have a greater debris and delamination rate than alkali-treated fibers. The alkali-treated fibres exhibit enhanced wear resistance compared to the silane-treated fibres, suggesting a distinct mechanism of wear known as abrasive wear. A similar type of observation was recorded for other natural fibers, such as areca [24], kenaf [25], and tasar silk [26].

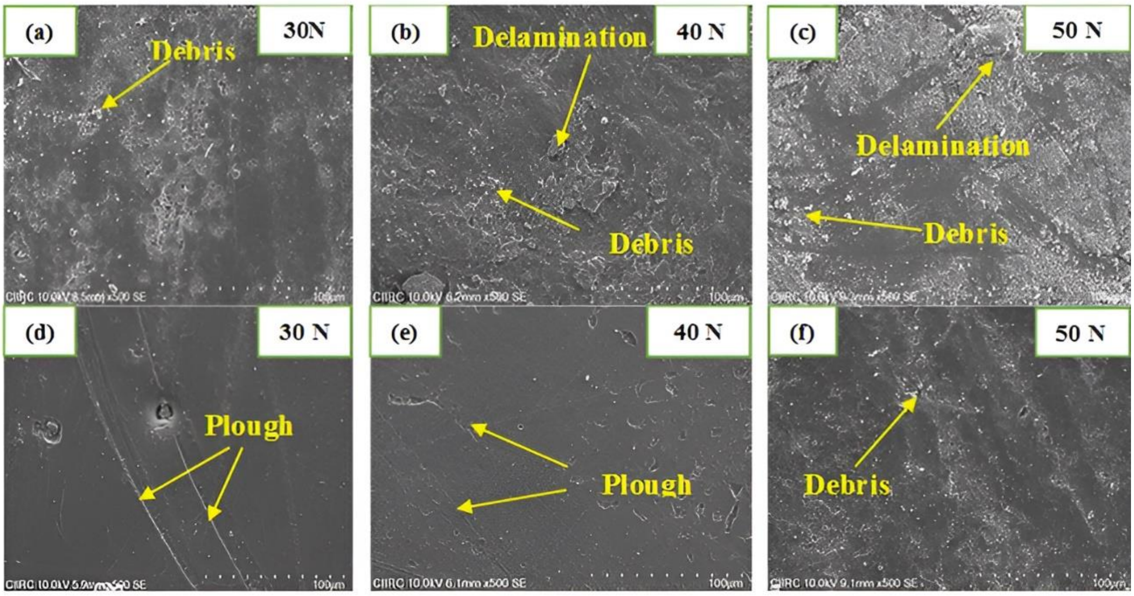
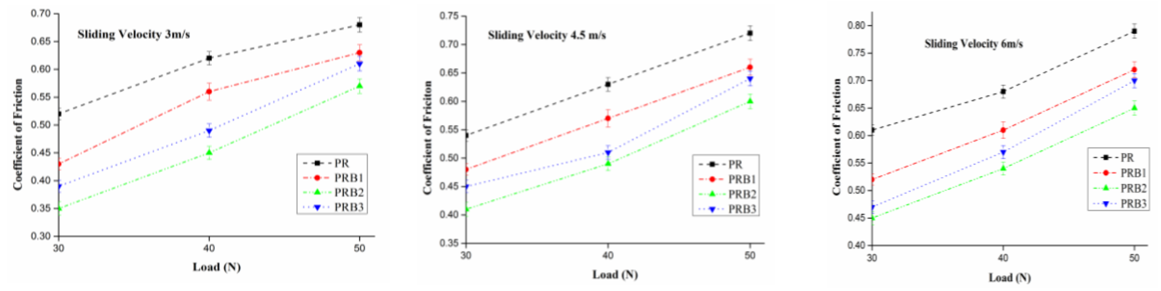


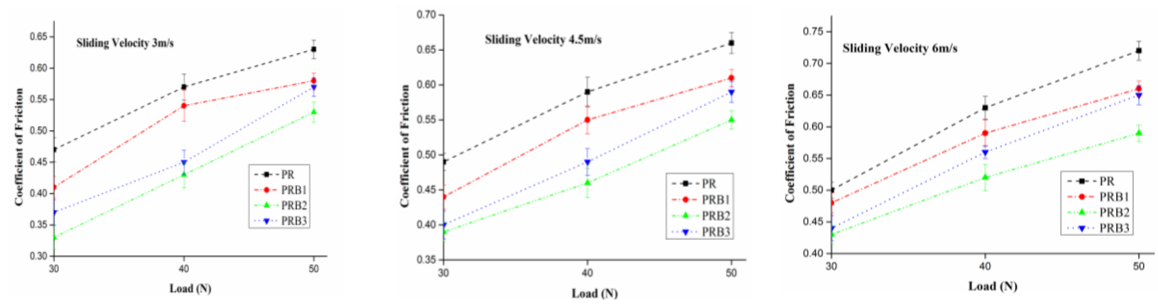
Figure 5. SEM images of worn surfaces of **(a-c)** silane; **(d-f)** alkali-treated fibers under different loading with sliding velocity 6 m/s.

3.2. Coefficient of friction.

The Variation of the CoF of fabricated composites under various normal loads, sliding velocities, and surface treatments is shown in Figure 6. Increasing the normal load increases the CoF values of all types of composites irrespective of sliding velocities. CoF increases in the range of 29.51% – 62.86 % with the increasing normal load. The temperature at the composite and disc interface increases due to the increased normal load resulting from increased contact pressure. This rise in interface temperature increases the frictional force, resulting in higher CoF values [27]. Similar to wear loss, the composite reinforced only with Roystonea regia fibers showed the highest CoF under all tested conditions. The lowest CoF is recorded for the composites with 10 wt.% of Banana fibers and 5 wt.% of Roystonea regia fibers. Increasing reinforcement contents increases wear characteristics of the composites, which in turn reduces the CoF values of the composites [28]. Increasing the sliding velocity increases the CoF values of all the types of composites under all conditions. At the beginning of the test, the disc and specimen surfaces at the interface are at ambient temperature. However, when the disc is set into motion at a certain velocity, frictional forces arise, resulting in an increased temperature at the interface. As the sliding velocity increases, the frictional force also increases due to more frequent and vigorous contact between the surface irregularities of the disc and the specimen. Frictional forces cause an increase in interface temperature, which in turn causes the composite to soften and ultimately leads to higher CoF values [29, 30]. Increasing the reinforcement content decreases the CoF values of the composites. The density of banana fibre surpasses that of Roystonea regia fibre, and composites reinforced with a high weight percentage of banana fibres demonstrate lower coefficients of friction values. The percentage increase in CoF with normal load is found to be more significant in composites reinforced with silane-treated fibers in comparison with the composites reinforced with alkali-treated fibers. Since the alkali treatment chemically modifies the fibers by removing certain organic components such as lignin and hemicellulose, it increases the surface energy of the fibers, thereby enhancing their wettability. Other researchers observed natural fibers reinforced in epoxy resin [31-33]. Improved wettability means that the matrix material can more thoroughly coat and adhere to the fibers, further improving the mechanical bonding and the efficiency of stress transfer throughout the composite material, leading to lower COF values in alkali-treated fiber-reinforced composites. Saravanakumar *et al*. [34] studied the combination of NaOH treatment and ceramic fillers in Roselle fiber-reinforced epoxy composites, which resulted in a reduced coefficient of friction (CoF).



(a)



(b)

Figure 6. Variation of the COF of composite reinforced with **(a)** silane; **(b)** alkali-treated fibers under different loading and sliding velocities.

3.3. Taguchi analysis.

The experiments were conducted for varying levels of Load, Velocity, and percentage of banana as presented in Table 2. The specific wear rate (SWR) was determined by using equation 2.

$$SWR = \Delta V/(L \times D) \qquad (2)$$

Where V is velocity, L is length, and D is sliding distance.

The wear rate and S/N ratio of the experimental data are given in Table 3. To predict the performance measure, the potential interactions between the control parameters were taken into consideration.

Table 2. Response table for signal-to-noise ratios.

Control factor	Level		
	1	2	3
A-Load(N)	30	40	50
B-Velocity(m/s)	3	4.5	6
C-% Banana	5	10	7.5

The response table conveys the average S/N ratio for each level of every factor, accompanied by ranks determined by Delta statistics. Delta statistics measure the difference between the highest and lowest values. Upon examining the response table (Table 4), it is evident that velocity has the highest rank, followed by the percentage of banana and the load applied. Figures 7 and 8 illustrate the effect of the control factors on the specific wear rate of the composites. A main effects plot depicts the response of the S/N ratio and mean for each factor level. The control factor that yields the minimum specific-wear-rate is determined by identifying the level with the highest mean value of the S/N ratio. Table 4 illustrates the response for the S/N ratio. This suggests that a composition of 10% banana, when subjected to a 50 N load and a velocity of 3 m/s, will yield the lowest specific wear rate.

Table 3. Response table for signal-to-noise ratios.

	Variables			Response	
Exp. No.	**Applied load (N)**	**Velocity m/s**	**% of Banana**	**Specific wearrate ($\times10^{-3}$ mm^3/Nm)**	**S/N Ratio**
	(H)	**(D)**	**(L)**	**(SWR)**	**(S/N)**
1	30	3	5	13.1	37.6546
2	30	3	10	10.7	39.4123
3	30	3	7.5	11.7	38.6363
4	30	4.5	5	24.7	32.1466
5	30	4.5	10	20.4	33.8074
6	30	4.5	7.5	22.3	33.0339
7	30	6	5	27.6	31.1818
8	30	6	10	23.9	32.432
9	30	6	7.5	26.6	31.50237
10	40	3	5	11.3	38.93843
11	40	3	10	11.2	39.0156
12	40	3	7.5	10.1	39.91357
13	40	4.5	5	21.4	33.39172
14	40	4.5	10	16.8	35.4938
15	40	4.5	7.5	19.3	34.2888
16	40	6	5	23.9	32.4320
17	40	6	10	19.8	34.0667
18	40	6	7.5	22.8	32.8413
19	50	3	5	14.2	36.9542
20	50	3	10	8.9	41.0122
21	50	3	7.5	12.8	37.8558
22	50	4.5	5	18.8	34.5168
23	50	4.5	10	14.8	36.5947
24	50	4.5	7.5	17.1	35.3401
25	50	6	5	21.1	33.5144
26	50	6	10	17.5	35.1392
27	50	6	7.5	20.2	33.8929

Visualizing possible interactions becomes possible with the use of an interaction plot, which shows how the level of another factor influences the effect of one factor. Figure 9 displays the interaction plot, which clearly demonstrates that the interaction between velocity and the percentage of banana has a notable impact on the specific wear rate.

Table 4. Response table for signal-to-noise ratios.

Level	Load	Velocity	% Banana
1	34.42	38.82	34.53
2	35.82	34.29	35.26
3	35.87	33.00	36.33
Delta	1.45	5.82	1.80
Rank	3	1	2

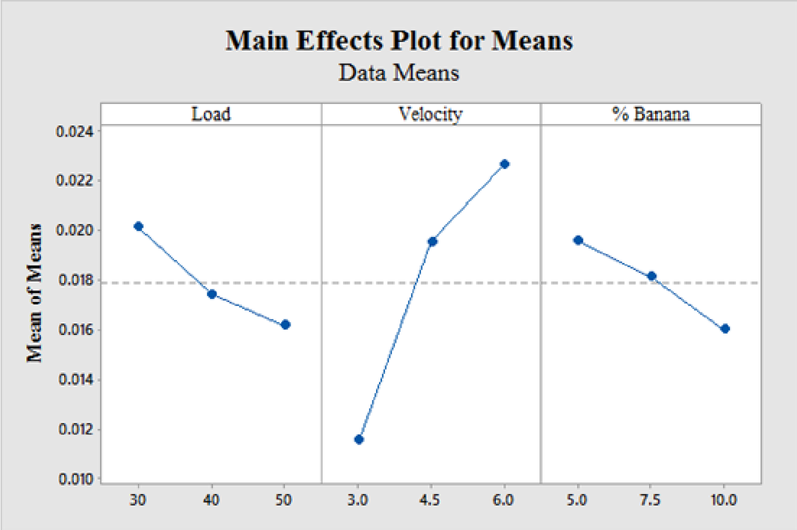


Figure 7. Main effect plot of means.

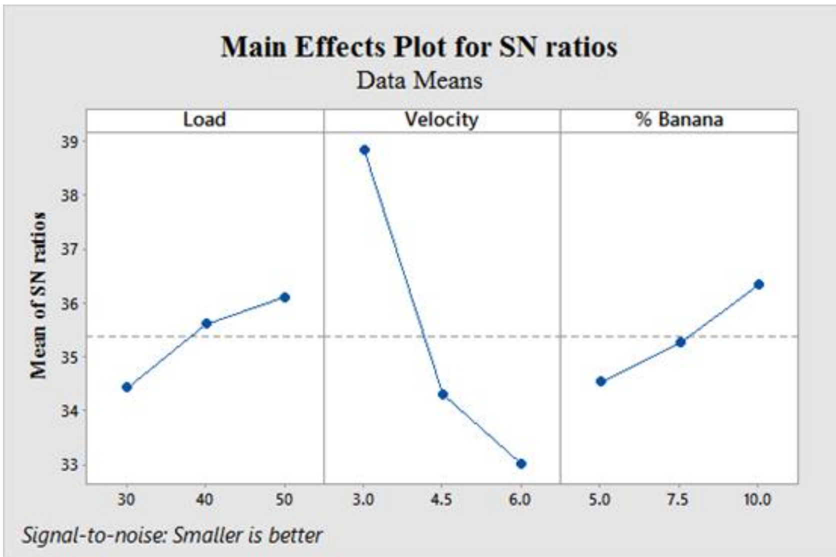


Figure 8. Main effect plot of S-N ratio.

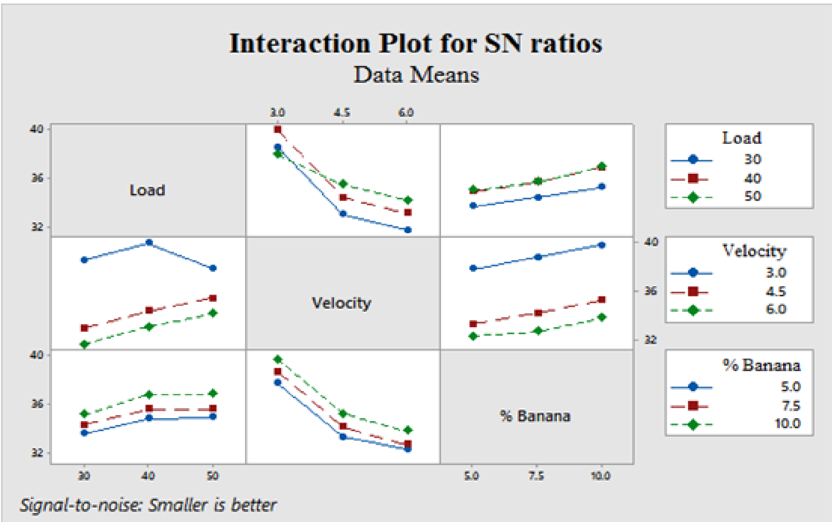


Figure 9. Interaction plot.

3.4. Taguchi confirmation Test.

Table 5 depicts the confirmation test conducted for the combination with optimal operating parameters: 40 N load, 3 m/s velocity, and 10% banana content. From the regression equation (3), the predicted specific wear rate of 8.73×10^{-3} mm^3/Nm is calculated. After the experiment, the specific-wear-rate(SWR) for the same combination is 8.9×10^{-3} mm^3/Nm. The percentage error between the predicted and experimental 1.95% is obtained. This confirms that the statistical approach adopted is accurate. The regression equation is given as:

$$SWR = 0.01407 - 0.000185\,(load) + 0.003681\,(sliding\ speed) - 0.000713\,(distance) \quad (3)$$

The close agreement between the predicted and experimental specific wear rates, with only a 1.95% error, confirms the accuracy and reliability of the regression model and the effectiveness of the adopted statistical approach.

Table 5. Comparison of natural fiber with its optimization parameter and major outcome.

Author	Year	Material	Optimization focus	Major outcome
Murthy *et al*. [35]	2023	Jute-Fiber-Reinforced Polymer	Minimize delamination in AWJM	Integrated Taguchi-RSM approach effectively minimized delamination during abrasive waterjet machining.
Thiagarajan *et al*. [36]	2023	Banana-Coir Fiber/PLA Composite	Analyze delamination failure	Taguchi optimization identified key factors influencing delamination in PLA composites.
Kumar *et al*. [37]	2024	Jute-Basalt/Epoxy Hybrid	Optimize mechanical properties	Basalt, jute orientation, and polyurethane significantly influenced tensile and flexural strength.
Prabhu *et al*. [38]	2024	Bamboo/Flax Epoxy with TiO_2	Reduce the specific wear rate	TiO_2 fillers improved tribological properties; normal load was the most significant factor affecting wear.
Thirupathi *et al*.[39]	2024	Prosopis Juliflora Fiber with SiC/Fly Ash	Improve wear resistance	SiC and fly ash fillers enhanced wear resistance under dry sliding conditions.
Rajagukguk *et al*. [40]	2024	HDPE-Pineapple Fiber Composite	Optimize tensile and flexural strength	5% fiber volume at 0° orientation yielded maximum tensile strength; fiber volume was the most influential parameter.
Patil *et al*. [41]	2024	PETG/CF	Infill parameters	Topological design factors significantly impacted strength.
Oyewo *et al*. [42]	2024	Banana Pseudostem Fiber Composite	Optimize tensile strength	Bonding capacity plays a major role in obtaining the highest strength.
Prabhu *et al*. [43]	2025	Bamboo fiber reinforced epoxy with TiO_2	Optimize molding parameters	Taguchi optimization improved mechanical properties by refining molding process parameters.
Assis *et al*. [44]	2025	Hand-woven jute fibre composite laminates	Optimize the mechanical property	Unidirectional fabrics have lower porosity and enhanced mechanical properties in the longitudinal direction compared to bidirectional reinforcements.

4. Conclusions

Hybrid composites were successfully fabricated using various combinations of Roystonea regia and banana fibers reinforced with polyester. The inclusion of banana fibers enhanced wear resistance by increasing composite density, making them superior to composites with only Roystonea regia fibers. Among all configurations, the prepared composite (10% banana, 5% Roystonea regia) exhibited the lowest wear loss across different sliding velocities. Alkali-treated fibers demonstrated improved performance compared to silane-treated ones, with reduced debris and delamination observed under increased loads. Taguchi analysis identified velocity as the most significant factor, and the optimal wear conditions were found to be a 50 N load, a 3 m/s speed, and 10% banana fiber, resulting in the lowest specific wear rate of 8.9×10^{-3} mm³/Nm. These observations suggest that hybrid composites with 10% banana and 5% Roystonea regia fibers, particularly when alkali-treated, exhibit superior wear resistance, with velocity being the most significant operating parameter. The study's findings indicate that the engineered material is suitable for use in the automotive sector, encompassing applications such as panels and mudguards.

Author Contributions

Conceptualization, H.R.A. and B.K.; methodology, M.S.S.; software, M.J.; validation, B.K., G.K.R., and S.P.C.; formal analysis, H.R.A.; investigation, M.S.S.; resources, M.J.; data curation, H.R.A.; writing—original draft preparation, H.R.A.; writing—review and editing, H.R.A., B.K., and S.P.C.; visualization, B.K.; supervision, S.P.C.; project administration, B.K.; funding acquisition, G.K.R. All authors have read and agreed to the published version of the manuscript.

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Data supporting the findings of this study are available upon reasonable request from the corresponding author.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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