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An Experimental Investigation on Mechanical and Two Body Abrasive Wear Characteristics of Lignocellulosic Fiber Reinforced Polylactic Acid Sustainable Composites

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Abstract

This study aims to develop and investigate the mechanical and two-body abrasive wear characteristics of the low-cost, renewable, eco-friendly, abundantly available lignocellulosic fiber-reinforced Polylactic Acid (PLA) sustainable composites for low-to-medium load-bearing applications. The sustainable composites were prepared using untreated and chemically treated (alkali) lignocellulosic fibers ranging from 10 wt.% to 40 wt.% by extrusion followed by a hot compression molding process. A tensile, flexural, fracture toughness, and a two-body abrasive wear test were conducted as per ASTM standards. A 30-weight percent lignocellulosic fiber-filled PLA composite showed better mechanical and wear resistance characteristics compared to its counterparts. The study was further extended to analyze the effect of abrasive wear parameters on the Specific Wear Rate (SWR) of chemically treated and untreated 30 wt.% fiber-filled PLA composites using Taguchi (L9 orthogonal array) and ANOVA techniques. From the results of both treated and untreated composites, the applied load was the primary contributing factor to SWR rate followed by sliding speed and sliding distance. Results from the confirmation test agreed well with those from the regression models. Further, the untreated and treated composite abrasive surfaces showed no noticeable fiber pullout or ploughing of fibers in the matrix at lower loads. In conclusion, lignocellulosic fiber reinforced PLA sustainable green composites are cost-effective, eco-friendly, and suitable for low-to-medium load-bearing applications (automotive interiors, packaging goods, furniture, etc.

***Major Findings:** In the current study, the PLA/NLF30 composite exhibited higher tensile (65.78 MPa) and flexural (112 MPa) strengths than its counterparts. The chemical treatment enhanced the fracture toughness by 10.63% in PLA/NLFT30 composite. According to Taguchi analysis, the lowest SWR was found at a load of 10 N, a speed of 0.523 m/s, and a distance of 100 m.*

Keywords: *Abrasive Wear, Fracture Toughness, Lignocellulosic Fiber, Polylactic Acid, Sustainable Composites*

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1.0 Introduction

Composite materials have become increasingly prominent in recent years due to their superior properties[1]. The specific strength and stiffness properties of polymer-based composite materials are higher than those of metallic materials. These characteristics can also be tailored so that they can be used in a wide range of applications, making them a significant advantage over other engineering materials. The benefits of biodegradable materials such as low density, reduced environmental impact, cost-efficacy, excellent acoustic properties, and higher specific stiffness and strength over non-degradable materials are increasing their admiration in commercial applications[2-4]. Wood is a naturally available, inexpensive, and relatively fast-growing lignocellulosic material, whereas polylactic acid is durable, completely biodegradable, and possesses better properties than other biodegradable polymers[5,6]. Furthermore, a wood fiber derived from a wide range of renewable sources reinforced with polylactic acid can be used to develop a new class of completely degradable sustainable composites that are suitable for multiple engineering applications[7]. NaOH treatment is an important technique for improving natural fiber composite's wear resistance and interfacial bonding between lignocellulosic fibers and polylactic acid polymer matrix, while other techniques (acetylation, silane, isocyanates, etc.) have produced no effect or negatively affected fiber strength[8]. Thermoplastics are more flexible, fatigue-resistant, fracture-resistant, and can be easily recyclable compared to thermosetting plastics. There is an increasing interest in polylactic acid (processing temperature 210 ^{0}C), which is the most promising material derived from natural resources such as sugar cane, maize, etc.

Natural polymers and natural fiber-reinforced polymer composites are still in the infancy for applications require better mechanical characteristics such as tensile, flexural, impact and fracture toughness compared to metals and their alloys. However, in spite of some controversies related mainly to their (polymers and their composites) viscoelastic properties, tests for fracture toughness such as the K_{IC} and J-integral are crucial in the polymers field. The tensile, flexural and impact characteristics decide the suitability of many secondary load-bearing applications. Fracture toughness indicates how much stress or load is required for a pre-existing crack or flaw to propagate during its service conditions[9,10]. Wear and friction properties can also play a very crucial role in polymer composite materials. A good amount of research has already been reported on different types of polymer composites in the pursuit of understanding the importance of polymer composites in tribological applications. The work conducted by[11] showed that there was a tremendous improvement in wear properties when cotton was added to the polyester matrix. A study on abrasive wear characteristics of natural fiber or particle reinforced sustainable composite structures[12,13] can provide insights into the development of new materials for tribological applications, for example, anti-friction materials and wear-resistant materials[14]. In another study[15,16], the pigeon pea (agricultural residue) particle-reinforced epoxy composites revealed excellent mechanical and tribological properties.

This study aims to develop a new sustainable composite material composed of a polylactic acid (biodegradable matrix) reinforced with Neem Lignocellulosic (natural) Fibers (NLF). composites were characterized for tensile, flexural, impact and fracture toughness tests as well as two-body abrasive wear tests. In addition, a study on alkaline treatment of reinforcement on these properties was also conducted. From the literature review, the authors found that no studies have evaluated lignocellulosic fiber-reinforced (both treated and untreated) polylactic acid composites for these characteristics for the given configuration. Here, the study examined four compositions with pristine PLA to analyse the impact of fibers in the PLA matrix on mechanical and abrasive wear characteristics. A Taguchi experiment evaluated the effect of load, distance, and speed on SWR of both composites. The mechanical andwear characteristics of this new green composite material are indispensable for its structural or functional application, which presents magnificent scope in the civil, packaging, and automotive industries.

2.0 Experimental Work

2.1 Materials

The neem wood fibers (lignocellulosic fibers) were collected locally. Polylactic acid of grade 3052D, and sodium hydroxide (analytical grade) were procured

Table 1. Designation and composition of green composite specimens

Composites	Sample Designation	Weight Fraction of PLA (%)	Weight Fraction of NLF particles (%)	Treatment	Thickness (mm)
Neat PLA	PLA/NLF0	100	0	-	5±0.23
PLA/10% NLF	PLA/NLF10	90	10	Untreated	5±0.18
PLA/20% NLF	PLA/NLF20	80	20	Untreated	5±0.28
PLA/30% NLF	PLA/NLF30	70	30	Untreated	5±0.24
PLA/30% NLF	PLA/NLFT30	70	30	Alkali-Treated	5±0.13
PLA/40% NLF	PLA/NLF40	60	40	Untreated	5±0.52

from the local market.The weight fractions of wood particles and polylactic acid matrix used are provided in Table 1.

2.2 PLA/NLF Green Composite Development

In this work, untreated and chemically (alkali) treated NLF were used to develop sustainable green composites. In this work, PLA granules and a fiber mixture as per the different weight fractions were fed directly into the hopper. The barrel temperature at different zones of the twin-screw extruder is given in Figure 1(a). The pellets from the extruder were dried in the oven at 80 ^{0}C for 24 hours. Furthermore, the PLA/NLF laminates were developed by utilizing a hot compression machine. To guarantee adequate fiber wetting, prevent excessive porosity, fiber damage, and excessive resin squeeze-out, the optimal pressure must be determined. The current study utilized a temperature of 185° C and a pressure of 4 MPa.The compression-molded PLA/NLF green composite plates are provided in Figure 1(b).

2.3 Testing PLA/NLF Green Composites

2.3.1 Tensile and Flexural Characteristics

Tensile (dog-bone shaped specimens) and flexural (rectangular specimens) tests on the specimens that were developed in accordance with the ASTM requirements were done using UTM. A total of five specimens were tested, and the average values together with the standard deviations were recorded.

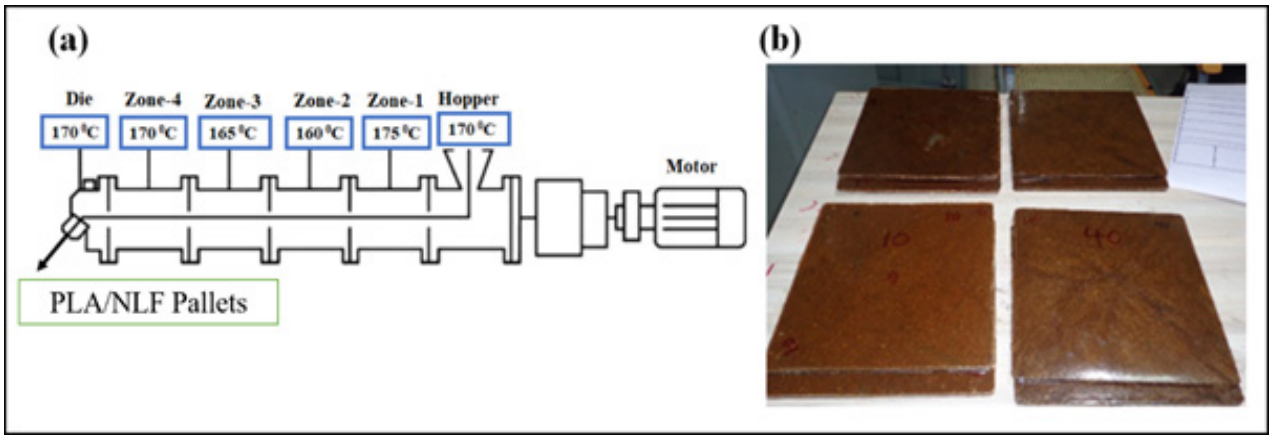


Figure 1. **(a)**. Compounding process, **(b)**Developed PLA/NLF green composites.

2.3.2 Fracture Toughness

A fracture toughness was performed on CT (compact-tension) green composite specimens in accordance with the standard guidelines established by ASTM D5045-14. The diagrammatic representation of the CT specimen and the composite specimen is presented in Figures 2(a) and (b), respectively. The Equations 1 and 2 are used to determine the fracture toughness of the composite specimens.

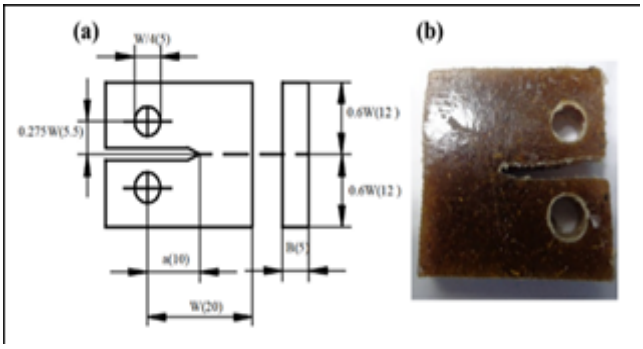


Figure 2. **(a)**.Schematic diagram,**(b)** PLA/NLF specimen for CT test.

$$K_1 = \frac{P_1}{B * W^{\frac{1}{2}}} f(x) \qquad \text{Equation (1)}$$

$$f(x) = \frac{(2+x)(0.886 + 4.64x - 13.32x^2 + 14.72x^3 - 5.62x^4)}{(1-x)^{\frac{3}{2}}} \qquad \text{Equation (2)}$$

2.3.3 Two-body Abrasive Wear

Pin-on-disc abrasive equipment was used to test the abrasive wear properties of PLA/NLF green composites, which is comprised of a horizontally rotating disc against which a square-shaped pin (8x8 mm^2) with the composite specimen (track radius of 50 mm) is pressed with the application of pre-defined load. A silicon carbide abrasive paper (40 grit size) is pasted onto the disc to provide an abrading counterface. The parameters considered for the two-body abrasive wear test to evaluate the volume as well as SWR of the untreated PLA/NLF sustainable composites are tabulated in Table 2.

A digital weighing machine (accuracy of 0.001 mg) was used to measure the weight of pristine PLA and PLA/NLF composite samples. Equations 3 and 4 determine volume loss and SWR. The time set during wear testing is calculated from Equation 5.

$$(V_l) = \frac{(IW - FW)}{Density} \qquad \text{Equation (3)}$$

$$SWR = \frac{(V_l)}{(force \times distance)} \qquad \text{Equation (4)}$$

$$Time = \frac{(SD * 60)}{(\pi \times TD \times SD)} \qquad \text{Equation (5)}$$

Taguchi Experimental Design (L9 orthogonal array)

In order to identify the optimum wear parameters on wear behavior, Taguchi L9 (three-parameter design with three levels given in Table 3) orthogonal array is considered for the evaluation of both PLA/NLF30 and PLA/NLFT30 green composites. This study uses the statistical package MINITAB 19 software with the "smaller the better" concept, given in Equation 6. Furthermore, the confirmation test verifies the experimental results.

$$\frac{S}{N} = -10\ log_{10}\left[\frac{\sum_{i=1}^{n}(y_i^2)}{n}\right] \qquad \text{Equation (6)}$$

Table 2. Test conditions for wear test

Speed (rpm)	Distance (m)	Time (s)	Force (N)
150	200	255	10
-	-	-	20
-	-	-	30

Table 3. Factors and levels considered in the study

Levels	Factors		
	Load (N)	Distance (m)	Speed (m/s)
	10.0	200.0	0.523
	20.0	300.0	0.785
	30.0	400.0	1.05

2.3.4 Morphological Analysis

Abraded surfaces of both the treated and untreated PLA/NLF30 composites specimens were analysed using Zeiss (EVO 18) SEM at various load, distance, and speed factors. Gold sputtering has been considered for the PLA/NLF green composites due to the non-conductivity issue.

3.0 Results and Discussion

3.1 Tensile Characteristics

The Tensile Strength (TS) of composites is influenced by the strength of both the fibers and the matrix[17]. Figure 3 illustrates the changes in TS, Young's modulus, and deflection of PLA/NLF composites. When comparing the PLA specimen, the TS of the PLA/NLF20, PLA/NLF30, and PLA/NLFT30 composites showed increases of 1.9%, 5.6%, and 9.9%, respectively. In contrast, the TS decreased by 3.2% and 6.1% in the PLA/NLF10 and PLA/NLF40 composites. The improvement may result from the optimal ratio of fiber in the composite, while a decline could stem from either inadequate or excessive fiber content within the matrix. An analogous impact has been seen in sugarcane/PLA composites[18].

3.2 Flexural characteristics

When it comes to determining the bending resistance of any material, flexural properties are a crucial factor worth considering[19]. The Flexural Strength (FS) of the material

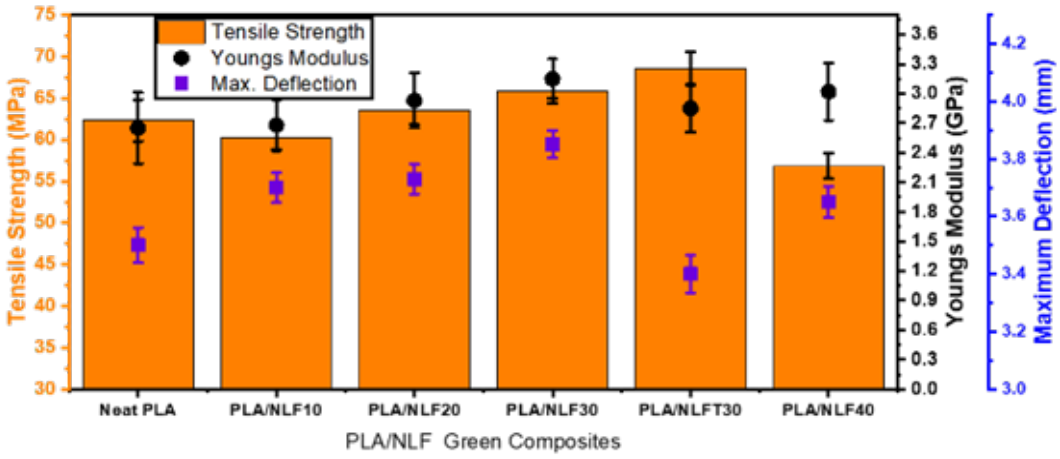


Figure 3. Tensile characteristics of pristine PLA and PLA/NLF sustainable composites.

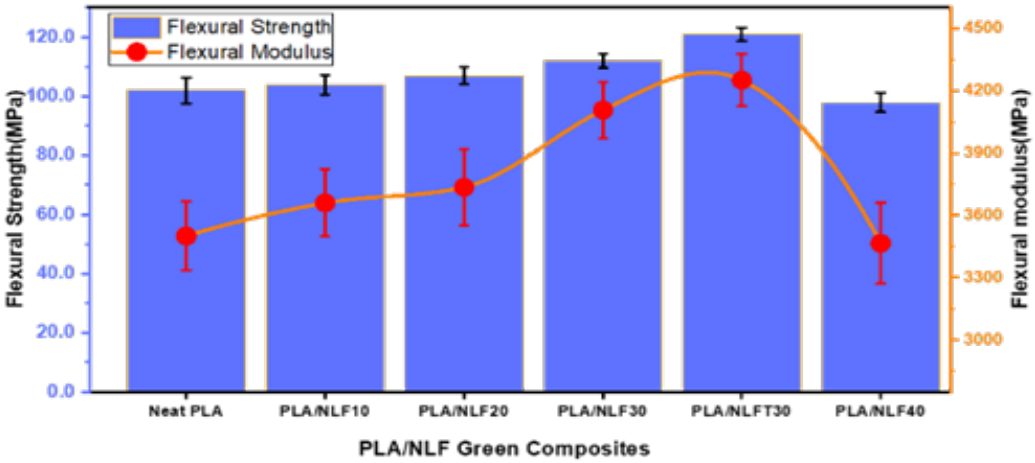


Figure 4. Flexural characteristics of pristine PLA and PLA/NLF sustainable composites.

continues to rise with an increase in reinforcement up to 30 percent as depicted in Figure 4. After that point, however, it begins to decrease because of an excessive amalgamation of fiber particles in the matrix. The chemical treatment contributes to an even greater increase in strength. This is because the adherence of particles is closer to the matrix than it was in the past. In comparison to the strength of neat PLA, the FS of the composites made of PLA/NLF10, PLA/NLF20, and PLA/NLF30 showed increases of 2%, 4.9%, and 9.8%, respectively. When compared to the PLA/NLF30 composite, the PLA/NLFT30 composite showed an increase of 8.01%. Flexural modulus exhibits a similar trend that is comparable to that of flexural strength.

3.3 Fracture Toughness

CT (Compact Tension) test was conducted on PLA/NLF green composites to evaluate the degree to which they can resist fracture with existing sharp crack in terms of critical-stress-intensity factor (K_{1c}) in mode I fracture under tensile loading conditions[20]. Figure 5 shows the fracture toughness values of pristine PLA and PLA/NLF green composites. From Figure 5, it is clear that PLA/NLF30 composite has maximum fracture toughness compared to the rest of the composites. This reveals that the optimum fiber content in a PLA matrix to get maximum fracture toughness is 30 wt.%. However, this is 7.4 % lower when compared to pristine PLA laminate.

The fracture toughness of the PLA/NLFT30 composite was improved by 10.63% when compared to the untreated PLA/NLF30 composite and by 2.4% when compared to the pristine PLA matrix. The results of this study demonstrate that chemical treatment results in a more favorable interface between the reinforcement and the matrix in composites.

3.4 Two-Body Abrasive Wear Behavior

To evaluate the two-body abrasive wear behavior of PLA/NLF green composites, testing samples measuring 5x5 mm^2 were prepared according to the dimensions of the pin utilized in the abrasive testing machine. Figure 6(a) illustrates that the volume loss (Vl) diminishes with increasing fiber content up to a maximum of 30 wt.%, beyond which the wear loss experiences a significant increase. In addition, it is observed that all three loading conditions exhibited a similar trend of declining volume loss as fiber content increased to 30 wt. %. A significant increase in volume loss is observed at 30 N compared to 10 N and 20 N. The untreated fibers embedded in the PLA matrix demonstrate significant resistance to abrasive wear, reaching up to 20 N. At 30 N, fibers lose firm contact with the PLA matrix, leading to a significant increase in volume loss. The SWR is lowest for the PLA/NLF30 composite in comparison to its counterparts and the PLA matrix, as illustrated in Figure 6(b). The results indicate that PLA/NLF30 (30 wt.% fiber reinforced) demonstrates

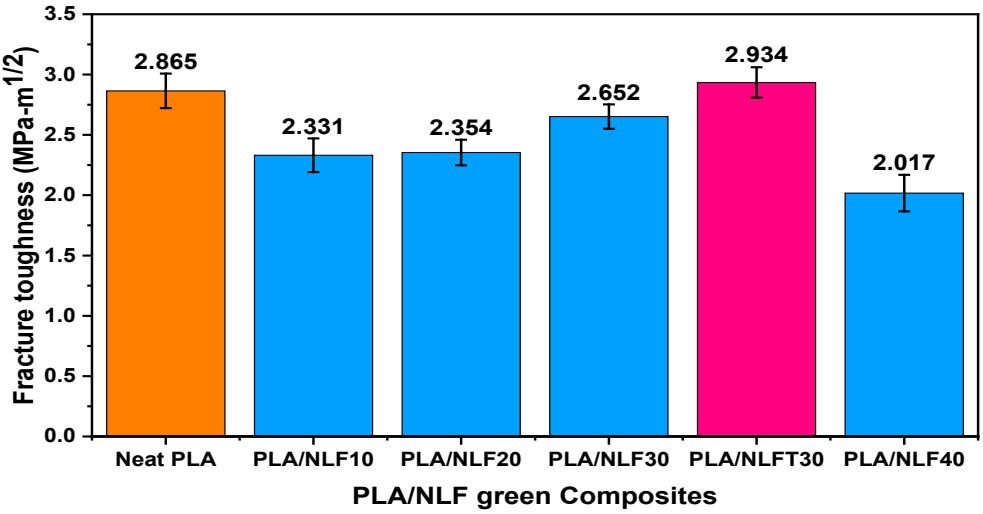


Figure 5. Fracture toughness of pristine PLA and PLA/NLF sustainable composites.

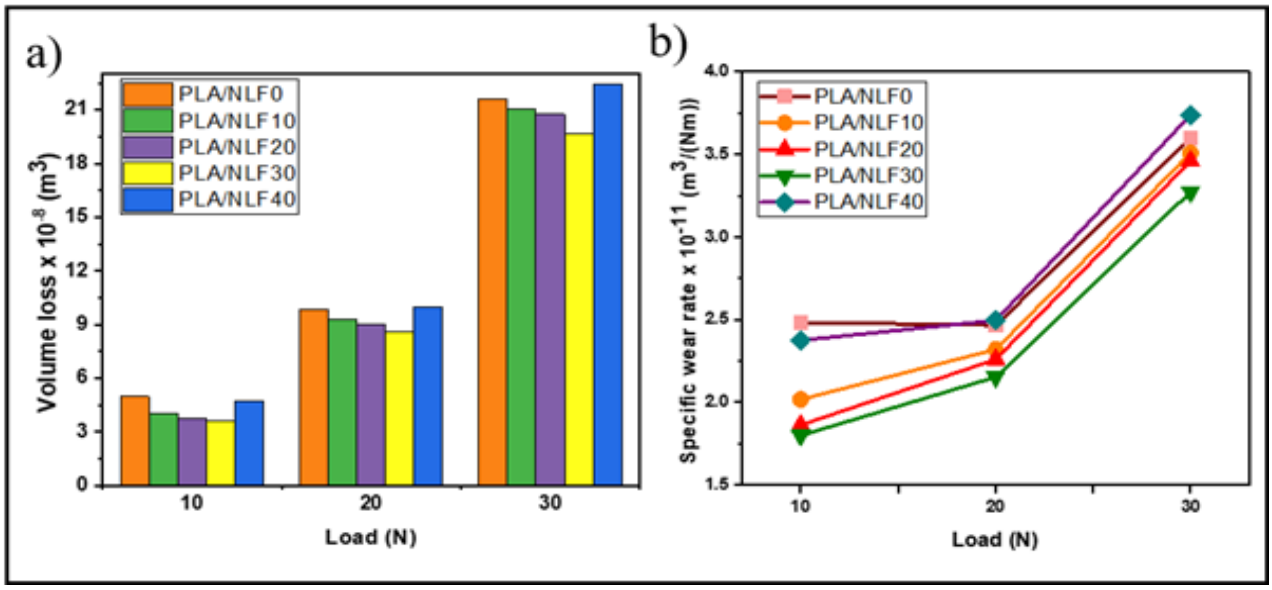


Figure 6. Abrasive characteristics of PLA and PLA/NLF green composites:**(a)** Volume loss, **(b)**SWR

superior resistance to wear. Similar trend[21] can be observed in the study done by Almeda. The theoretical density is calculated based on the rule of mixture formula for different compositions.

3.5 Wear Assessment of PLA/NLF30 and PLA/NLFT30 by Taguchi Method

The previous study demonstrated that the PLA/NLF30 green composite exhibited superior wear behavior compared to its counterparts at a constant sliding distance and speed across three different loads. The authors continued the study to assess the impact of loads, distances, and speeds on the SWR of PLA/NLF30 and PLA/NLFT30 green composites. Table 4 presents the results (SWR) of PLA/NLF30 and PLA/NLFT30 composites under specified parameters and levels, following the Taguchi L9 orthogonal design methodology, alongside the signal-to-noise ratio (S/N). Table 5 presents the ranking of wear parameters on SWR for both green

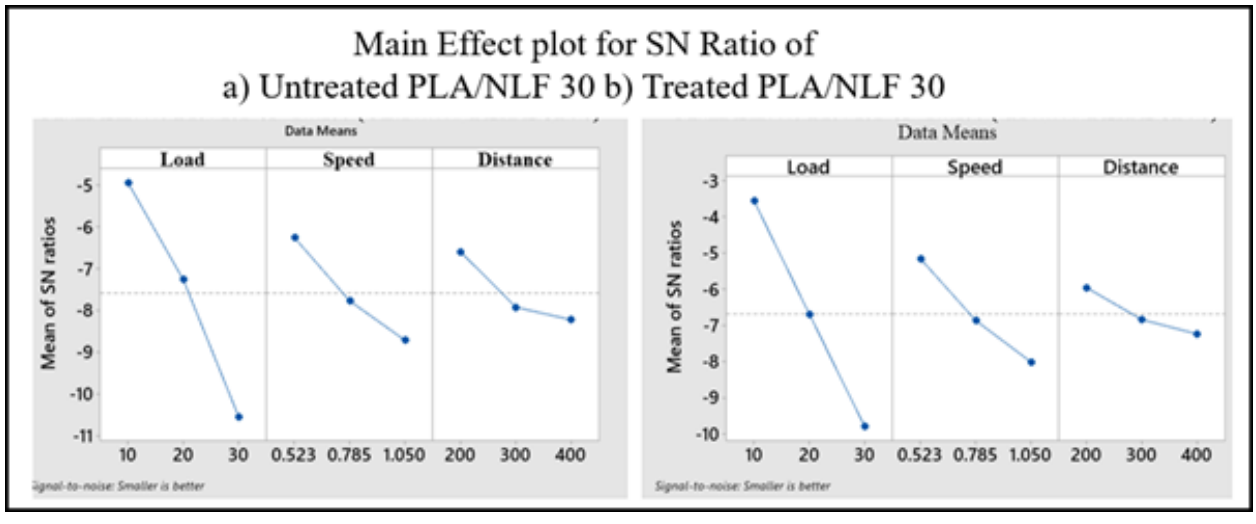


Figure 7. Main effect plots for PLA/NLF30 composites: **(a)** untreated, **(b)** alkali-treated.

Table 4. Results of two-body abrasive wear test (Alkali treated and untreated PLA/NLF30 composite)

Sl. No.	Wear parameters Exp. results Statistical results			Untreated (PLA/NLF30) composite		Alkali Treated (PLA/NLFT30) composite	
				Exp. Results	Statistical results		
	Load (N)	Sliding Speed (m/s)	Sliding Distance (m)	SWR (m^3/Nm) $\times 10^{-11}$	Signal to noise ratio (dB)	SWR (m^3/Nm) $\times 10^{-11}$	Signal to noise ratio (dB)
1	10	0.523	200	1.22800	-1.7840	1.07800	-0.6524
2	10	0.785	300	1.94167	-5.7635	1.54167	-3.7598
3	10	1.050	400	2.30350	-7.2478	2.05350	-6.2499
4	20	0.523	300	2.19083	-6.8122	2.02417	-6.1249
5	20	0.785	400	2.30700	-7.2610	2.18200	-6.7771
6	20	1.050	200	2.43125	-7.7166	2.28125	-7.1635
7	30	0.523	400	3.22142	-10.1609	2.72142	-8.6959
8	30	0.785	200	3.27167	-10.2954	3.18833	-10.0713
9	30	1.050	300	3.62856	-11.1947	3.40633	-10.6457

Table 5. Response table (S/N ratio)

PLA/NLF30 composite				PLA/NLFT30 composite			
Level	Load	Speed	Distance	Level	Load	Speed	Distance
1	-4.932	-6.252	-6.599	1	-3.554	-5.158	-5.962
2	-7.263	-7.773	-7.923	2	-6.688	-6.869	-6.843
3	-10.55	-8.72	-8.223	3	-9.804	-8.02	-7.241
Delta	5.619	2.467	1.625	Delta	6.25	2.862	1.279
Rank	1	2	3	Rank	1	2	3

composites, determined using the S/N ratio. Furthermore, the main effect plots for both treated and untreated green composites are presented in Figures 7(a) and (b).

Table 4 illustrates that the SWR of the chemically treated (alkali) PLA/NLFT30 composite is low compared to the untreated composite. In the PLA/NLF30 composite, the load emerges as the primary influencing factor (rank 1), succeeded by speed (rank 2), and sliding distance (rank 3). Figure 5 reveals a significant slope change of the load curve between 20 N and 30 N, in contrast to the interval from 10 N to 20 N. This suggests that an extended sliding distance, the heat generated between the composite specimen and the rotating disc elevates the temperature, consequently diminishing the COF (friction constant) and leading to lower the SWR. Furthermore, the increased load results in debonding at the fiber-matrix interface, causing the fibers to loosen, which subsequently contributes to fiber shearing and an increase in the specific wear rate.

3.6 Analysis of Variance (ANOVA)

The investigation involved a thorough examination of the significance of each wear parameter and the relevant errors, utilizing Analysis of Variance (ANOVA) to observe the sum of square deviation alongside the overall mean of the S/N ratio. To assess the extent of influence exerted by all parameters on the quality characteristic, the optimal combination of control factors was forecasted utilizing ANOVA[1]. The analysis of the experimental data (SWR) employed ANOVA to assess the effect of the three variables: force, speed, and sliding distance. The findings of the ANOVA are presented in Tables 6 and 7, detailing the results for the two-body abrasive wear tests conducted on both untreated and treated PLA/NLF30 composites. The SWR of untreated PLA/NLF30 composites was notably influenced by load (73.76%), with speed (14.34%) and sliding distance (6.92%) following in significance. In a comparable manner, the SWR of alkali-treated PLA/NLF30 composites was notably influenced by load (76.21%), with speed (16.18%) and sliding distance (3.34%) following in significance. The findings from both the treated and untreated composites distinctly indicate that the alkali treatment significantly diminishes the percentage impact of sliding distance on wear loss.

3.7 Linear Regression Model

The regression equations (from Minitab software) of PLA/NLF30 and PLA/NLFT30green composites are given in Equations 7 and 8 respectively.

$$SWR=(-0.354+0.0775\times L+1.09\times S+0.0015\times D)\times 10^{-11} \quad \text{Equation (7)}$$

$$SWR=(-0.43+0.0774\times L+1.213\times S+0.00068\times D)\times 10^{-11} \quad \text{Equation (8)}$$

3.8 Confirmation Test

In the confirmation experiment, three new sets of values were taken using the same parameter combinations (load, speed, and distance) and three arbitrary different levels as shown in Table 8. The results (SWR)

Table 6. ANOVA for S/N ratio (PLA/NLF30 composite)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	R-Sq. (adj.)	Contribution
Load	2	47.809	47.809	23.905	14.83	0.063	80.10%	73.76%
Speed	2	9.296	9.296	4.648	2.88	0.258		14.34%
Sliding distance	2	4.484	4.484	2.242	1.39	0.418		6.92%
Residual Error	2	3.224	3.224	1.612	-	-		4.97%
Total	8	64.814	-	-	-	-	-	100.00%

Table 7. ANOVA for SN ratio (PLA/NLFT30 composite)

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	R-Sq. (adj.)	Percentage of contribution
Load	2	58.599	58.599	29.3	17.89	0.053	82.96%	76.21%
Speed	2	12.444	12.444	6.222	3.8	0.208		16.18%
Sliding distance	2	2.569	2.569	1.285	0.78	0.56		3.34%
Residual Error	2	3.276	3.276	1.638	-	-		4.26%
Total	8	76.888	-	-	-	-	-	100.00%

Table 8. Confirmation test results of PLA/NLF30 and PLA/NLFT30 composites

Exp No.	Control parameters SWR (m^3/Nm) $\times 10^{-11}$			PLA/NLF30 (untreated) composite			PLA/NLFT30 (treated) composite		
	Load (N)	Speed (m/s)	Distance (m)	Error (%) Experiment	SWR (m^3/Nm) $\times 10^{-11}$ Regression model		Error (%) Experiment	Regression model	
1	15	0.393	100	1.047	0.998	4.6%	0.925	0.890	3.8%
2	25	0.654	200	2.764	2.596	6.1%	2.569	2.438	5.1%
3	35	0.916	300	4.023	3.806	5.4%	3.780	3.599	4.8%

from both the experimental and regression model techniques of untreated and alkali-treated PLA/NLF sustainable composites with error are presented in Table 8.

The experimental value of SWR varies from the SWR calculated from the regression equation, ranging from 4.6% to 6.1% for PLA/NLF30 composite and 3.8% to 5.1% for PLA/TNLF30 composite. This indicates that the regression model predicts the experimental values with the least error.

3.9 Morphology of Worn Surfaces

Figures 8 and 9 present the Scanning Electron Microscopic (SEM) images of untreated and chemically treated green PLA/NLF30 composites subjected to loads of 10 N, 20 N, and 30 N, respectively. The surfaces exhibiting wear Figures 8(a) and (b) alongside Figures 9(a) and (b)) under reduced loads of 10 N and 20 N for both untreated and treated composites demonstrated minimal damage to the fiber and matrix. Furthermore, there was no significant accumulation of debris during the testing, resulting in reduced wear overall. Furthermore, there has been no discernible evidence of fiber pullout or the ploughing of fibers within the matrix. Nevertheless, a greater extent of damage was noted on sliding face Figure 8(c) and Figure 9(c) when subjected to an increased load of 30 N. This could be linked to the occurrence of fractures and the debonding of fibers, along with the ensuing removal of the PLA that leads to the development of deep ploughed grooves. Images obtained from a Scanning Electron Microscope (SEM) of specimens that have been shattered by tensile forces offer useful insights on the causes of fracture, the behavior of the material, and the microstructural properties. The presence of inclusions, voids, and second-phase particles that impact fracture behavior can be seen in these tensile cracked specimens that were analyzed using a Scanning Electron Microscope (SEM).

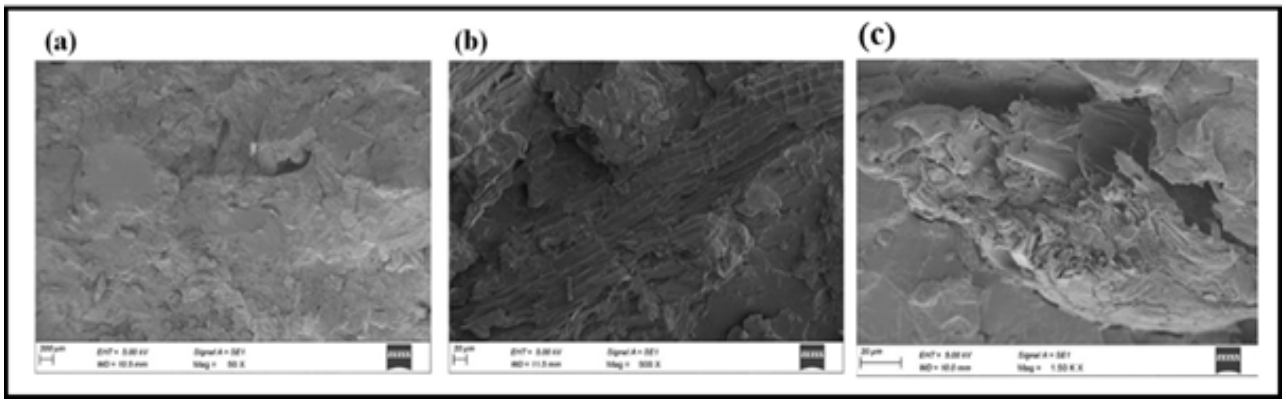


Figure 8. SEM images of Untreated PLA/NLF30 green composite: **(a)** 10N, **(b)** 20 N, **(c)** 30N.

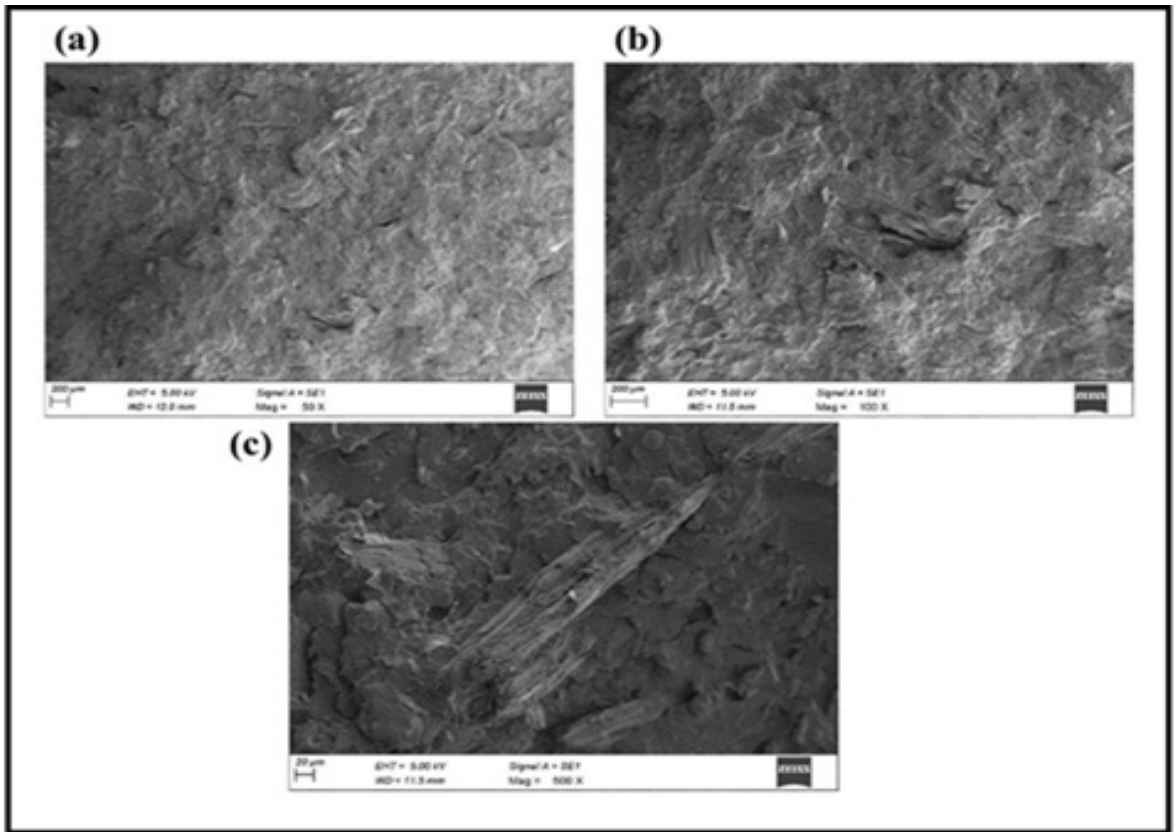


Figure 9. SEM images of chemically treated (PLA/NLFT30) green composite: **(a)** 10N, **(b)** 20 N, **(c)** 30N.

3.10 Comparative Assessment

The mechanical and flexural properties of the developed composites have been compared to various PLA-based composites and are given in Table 9. From the table, it is clear that the developed composites can be used to replace wood and wood-based products.

Table 9. Assessment of mechanical properties of PLA/NLF composites

PLA-based Composites			Tensile Properties			Flexural Properties		Reference
Fiber type & Fabrication Technique	**Fiber Loading (Wt.%)**	**Chemical Treatment**	**UTS (MPa)**	**EM (GPa)**	**δ (%)**	**FS (MPa)**	**FM (GPa)**	
Neem Wood Particles Extrusion-compression	10	No	60.25	2.68	3.7	104	3.65	Present Work
	20	No	63.5	2.93	3.73	107	3.73	
	30	No	65.78	3.15	3.85	112	4.18	
	40	No	56.84	2.85	3.4	98	3.46	
	30	Yes	68.54	3.02	3.65	121	4.25	
Agave Extrusion-compression	10	Yes	47	2200	2.3	72	3800	[22]
	20		42	2300	2.3	56	3700	
	40		29	1800	1.8	35	3000	

Pineapple Leaf Hot Pressing	30	Yes	21.86	5110	-	38.53	5560	[23]
Coir, Hot pressing	30	Yes	13.96	435		24.6	3960	
Banana Peel Direct Injection, Extrusion Injection, Extrusion-Compression	20	Yes	52	1430	-	104	4800	[24]
		Yes	55	1610	-	104	5600	
		Yes	18.5	1520	-	30	4100	

4.0 Conclusions

Taking into consideration the outcomes of the PLA/NLF treated and untreated green composites in terms of their tensile, flexural, fracture toughness, and two-body abrasive wear behaviors are noted as below.

In the current study, the PLA/NLF30 composite exhibited higher tensile (65.78 MPa) and flexural (112 MPa) strengths than its counterparts. Additionally, the Young's modulus in both tensile and bending tests was higher than those of pristine PLA. The tensile strength was increased by 9.1% compared to neat PLA and the flexural strength by 8.1% due to chemical treatment.

The PLA/NLF30 composite noticed better fracture toughness than its counterparts. The chemical treatment enhanced the fracture toughness by 10.63% in PLA/NLFT30 composite. With a load of 30 N, the specimen surfaces showed deeper grooves caused by the radical rise in volume loss and SWR.

The PLA/NLF30green composite exhibited the least volume loss and SWR compared to rest of the composites (untreated) at various loads. PLA/NLFT30 composite revealed a lower SWR compared to PLA/NLF30 composite. From fracture toughness and two-body abrasive wear tests, it is concluded that PLA/NLF30 (30 wt.% fiber reinforced) is the best combination among all four combinations for proving excellent toughness and abrasive wear characteristics.

According to Taguchi analysis, the lowest SWR was found at a load of 10 N, a speed of 0.523 m/s, and a distance of 100 m. ANOVA results of the PLA/NLF30 and PLA/NLFT30 composites showed that the load was the primary contributing parameter (76.21% and 73.76%), followed by speed (16.18% and 14.34%), and distance (3.34% and 9.92%) respectively, on SWR.

Examination of the surfaces of both the treated and untreated composites using SEM revealed microcracks, debris, and fiber fractures. The study concludes that low-cost, eco-friendly, renewable lignocellulosic fiber reinforced PLA sustainable green composites can be used for low-to-medium load-bearing applications.

5.0 References

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