Global NEST Journal, Vol 27, No 3, 05840

Sustainable enhancement of mechanical and wear properties in natural fiber composites: integration of bio-waste fillers and taguchi optimization for bio medical applications

Mary Vasanthi.S[1], Nandakumar Mandya Basavaraj[2], Jani S.P[3] and, Sujin Jose Arul[4]*

[1]Department of Electronics and Communication Engineering, St.Xavier'S Catholic College of Engineering, Nagercoil, Tamil Nadu, India

[2]Department of Automobile Engineering, Dayananda Sagar College of Engineering, Bangalore, India

[3]Department of Mechanical Engineering, Marri Laxman Reddy Institute of Technology and Management, Hyderabad, India

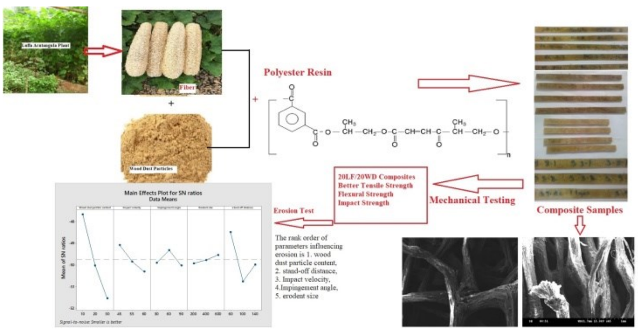
[4]Department of Mechanical Engineering, New Horizon College of Engineering, Bangalore, India

Received: 21/02/2024, Accepted: 01/12/2024, Available online: 19/12/2024

*to whom all correspondence should be addressed: e-mail: sujinjoseer@gmail.com

https://doi.org/10.30955/gnj.05840

Graphical abstract



Abstract

This study investigates the effect of teak wood dust (TWD) particles on the mechanical properties and erosion wear characteristics of Luffa acutangula fiber (LAF) reinforced phenol formaldehyde (PF) composites. Test samples were prepared with 20% LAF and varying TWD content (5%, 15%, and 25%). The addition of 15% TWD showed a significant improvement in mechanical performance, with tensile strength increasing by 17.56%, flexural strength by 48.78%, and impact strength by 54.64%. The optimum parameters for minimizing erosion wear were determined using Taguchi analysis, achieving a minimum erosion rate of 199.82 mg/Kg. This combination included 15% TWD, 40 m/s impact velocity, 60° impingement angle, 450 µm erodent size, and 60 mm standoff distance. Inspired by signal processing and classification methodologies, this study employs a structured approach to enhance mechanical and erosive wear properties, akin to wavelet-based data optimization techniques. The results demonstrate that TWD particles significantly improve the properties of natural fiber-reinforced composites, presenting a novel, sustainable material solution for industrial applications. This study provides a novel approach to enhancing composite materials by integrating TWD into LAF/PF composites, offering sustainable solutions for lightweight and durable industrial applications. These composites hold potential for applications beyond traditional industries, extending to biomechanical systems and prosthetic design, where lightweight and durability are critical, much like EMG-based gesture recognition systems in human-machine interaction.

Keywords: Luffa Acutangula Fiber, Teak wood dust, Mechanical Characters, Wear Analysis, Taguchi analysis

1. Introduction

The growing demand for eco-friendly and sustainable materials has led to an increased focus on natural fibers as viable alternatives to synthetic fibers in various industrial applications. These natural fibers offer numerous advantages, such as high mechanical strength, cost-effectiveness, and environmental benefits like biodegradability [Issam Elfaleh *et al.* 2023; Kozlowski 2018]. The use of natural fibers in material development has attracted growing interest among researchers because of their promising potential. The high cellulose content in these fibers enhances the mechanical properties of the resulting materials [Azizatul Karimah *et al.* 2021; Karimah *et al.* 2021]. Polymers, commonly used in plastic industries to manufacture engineering products, are integral to this process. Phenol formaldehyde is widely recognized for its excellent thermal stability and mechanical strength, making it a common choice in the manufacture of engineering products. However, the inherent brittleness and wear susceptibility of PF composites can limit their application, particularly in environments where durability is critical [Rodriguez *et al.* 2022; Ravindran and Thomas 2022; Zheng *et al.* 2021]. Nevertheless, its brittleness and vulnerability to wear limit its broader applications [Pandey et al. 2021; Wang et al. 2021]. To overcome these challenges, researchers have explored the incorporation of various natural fibers and fillers, such as coir, sisal, flax, and hemp, into PF composites, resulting in improved mechanical properties and wear resistance [Muhammad Yasir Khalid et al. 2021; Kamarudin et al. 2021; Tissera and Siriwardhana 2021]. Among them, Luffa acutangula fiber (LAF), derived from the ridge gourd plant, has shown promising mechanical properties that make it suitable for reinforcing polymers, particularly phenol formaldehyde (PF) resin. The natural fiber materials have lot of advantages over synthetic materials and chemically treated fibers enhance the mechanical properties and durability of materials [Rangappa et al. 2022; Sanjay et al. 2018]. In this context, the addition of bio-waste materials, such as teak wood dust (TWD), as fillers in natural fiber composites has garnered increasing attention. TWD, rich in cellulose and lignin, has been shown to enhance the tensile, flexural, and impact strength of composites by improving fiber-matrix bonding and reducing void formation. Similar to how the Hilbert Huang Transform optimizes EMG signal classification, our integration of TWD particles provides a novel material enhancement pathway through sustainable natural fibers. Moreover, incorporating TWD into composites not only improves mechanical performance but also contributes to environmental sustainability by utilizing waste materials [Zhang et al. 2020; Hoi-yan Cheung et al. 2009; Kannan and Arunachalam 2021]. Recently, there has been increasing interest among researchers in utilizing lignocellulosic natural or bio fibers as alternatives to synthetic and chemically derived fibers. The production of bio fiber-based materials is both environmentally friendly and cost-effective. Additionally, these fibers offer several advantages, including high specific strength, lightweight, accessibility, affordability, waste reduction, and improved mechanical, thermal, and wear properties [Manikandan and Sathiyamoorthy 2021; Abdulrahman Adeiza Musa and Azikiwe Peter Onwualu 2024]. Luffa Acutangula, commonly known as ridge gourd fiber, is a natural plant fiber with strong mechanical properties, making it suitable for commercial applications. Composites made from Luffa fiber (LF) and groundnut fiber, reinforced with epoxy resin, demonstrate notable strength, with 40% fiber content being the optimal reinforcement level [Suresh Kumar and Uthayakumar 2011; Sivakandhan et al. 2020; Sankar et al. 2020; Alhijazi et al. 2019]. Hybrid composites incorporating sisal, ridge gourd, and coconut spathe fibers with epoxy resin show superior tensile performance, with ridge gourd-sisal hybridization achieving a 65% higher tensile strength compared to other composites [Mohanty et al. 2021; Singh and Singh 2022; Girisha et al. 2012]. Additionally, chemically treated sponge gourd fibers exhibit a 10–35% increase in compressive strength and improved tensile properties [Varma et al. 2021; Al-Mobarak et al. 2018].

Typically, natural fiber particles like coir and wood dust are discarded as waste into the environment after use. However, being plant-based, these fibers are rich in cellulose and other chemical compounds similar to natural fibers. When incorporated into composites, these natural fiber particles significantly enhance mechanical properties [Majid Mohammadi et al. 2024; Saha et al. 2021; Ramesh et al. 2022]. In particular, reducing the particle size in saw dust filled composites improves their tensile strength and hardness [Barik et al. 2021; Hossain et al. 2021; Jose et al. 2017; Gh and Israa 2017]. The addition of bio particles as fillers in micro level and nano level with the natural fibers enhances the mechanical and wear properties of materials [Shravanabelagola Nagaraja Setty et al. 2021; Rangappa et al. 2022]. Incorporating coir particles into prosopis juliflora phenol formaldehyde composites enhances their mechanical performance, while the addition of wood dust particles to the same fiber-polymer composites improves both mechanical and wear properties [Jose et al. 2017]. The inclusion of agro waste fillers, wood based and animal based fillers plays a vital role in the wear property of bio composites [Harikrishnan Pulikkalparambil et al. 2023]. The researchers used ANN and Taguchi methods for wear analysis on various composite materials [Athith et al. 2017; Mishra et al. 2024]. The Taguchi method is effective for optimizing process parameters related to wear rate. In particular, the optimization of process parameters to achieve an improved wear rate in bagasse fiber composites was carried out using the Taguchi L9 experimental design [Sivarajan and Syamala 2021; Prusty and Das 2021; Kumar et al. 2021; Suryawanshi and Sutar 2021; Gujjala Raghavendra et al. 2012]. Despite the growing body of research on natural fiber-reinforced composites, there has been limited exploration of LAF-reinforced PF composites combined with TWD. The novelty of this study lies in the innovative integration of teak wood dust (TWD) particles into Luffa acutangula fiber (LAF)-reinforced phenol formaldehyde (PF) composites. While natural fibers and bio-fillers have been explored individually, the synergistic combination of LAF and TWD in this research addresses both mechanical enhancements and environmental sustainability. This approach leverages the cellulose and lignin content in TWD to improve fiber-matrix bonding, reducing voids and brittleness, thereby enhancing the mechanical properties and wear resistance. Furthermore, the application of the Taguchi method to optimize process parameters provides a statistically robust framework for minimizing erosion wear, offering a practical pathway for industrial adoption. The composites developed in this study exhibit superior properties, such as a 17.56% increase in tensile strength and a 54.64% improvement in impact strength, making them suitable for lightweight, durable applications in the automotive, aerospace, and construction industries [Muh. Ilham Akbar et al. 2024]. This study directly addresses the growing industrial demand for eco-friendly and sustainable materials. By repurposing bio-waste (TWD), it not only reduces environmental impact but also enhances the composite's performance. The findings hold significant potential for industrial applications, particularly in sectors where durability and sustainability are critical. For instance, the improved tensile and impact strengths of these composites make them viable candidates for automotive components, while their lightweight and erosion-resistant properties align with the needs of aerospace and construction materials

2. Materials and methods

2.1. Materials

The primary materials used for fabricating the composite specimens in this study include Luffa acutangula fibers (LAF), teak wood dust (TWD) particles, and phenol formaldehyde (PF) resin. The Luffa acutangula fibers were sourced from the fruit of ridge gourd, obtained via India Mart. Teak wood dust was collected from Kumar Woods and Sawmill in Karaikudi, Tamil Nadu, India, and sieved to achieve an average particle size of 800 µm. The PF liquid resin, along with the cross-linking agent divinylbenzene and the acidic catalyst hydrochloric acid, was purchased from POOJA Chemicals in Madurai, Tamil Nadu, India. The images of materials shown in Figure 1.

2.2. Specimens preparation for analysis

Composite plates were fabricated using the hand lay-up method, employing a mold cavity with dimensions of 150 mm × 150 mm × 3 mm. Four variations of composite samples were prepared, each with a constant LAF mass fraction of 20%, while the TWD particle content was varied at 0%, 5%, 15%, and 25% by mass. To ensure proper moisture removal, TWD particles were dried in sunlight for 12 hours prior to processing.

Table 1: Composition of Materials & Designation

PF resin (Weight percentage)	LAF layer (Weight percentage)	WD particles (Weight percentage)	Designation of test samples
80	20	0	20FL/0TWD
75	20	5	20FL/5TWD
65	20	15	20FL/15TWD
55	20	25	20FL/25TWD

The process included mixing phenol formaldehyde resin with TWD particles at room temperature for 30 minutes using a mechanical stirrer. The cross-linking agent and acidic catalyst were then added to the mixture, which was further stirred for an additional 15 minutes. A 20% layer of LAF was arranged within the mold cavity, over which the PF-TWD mixture was poured. The setup was left to cure at room temperature for 24 hours, resulting in composite plates with the following designations: 20FL/0TWD, 20FL/5TWD, 20FL/15TWD, and 20FL/25TWD as shown in Table 1.

Figure 1: Fibers: Luffa Acutangula fiber & Teak wood dust particles

2.3. Composite specimens for testing

The mechanical properties of the composite samples were evaluated using tensile, flexural, and impact tests. The tensile strength was measured using an FIE-UTE 40 HGFL universal testing machine, following ASTM D638-10 standards. Flexural tests were performed on the same machine in accordance with ASTM D790-10 standards. Impact strength was assessed using an Izod impact testing machine, following ISO 180 standards.

All mechanical tests were conducted at room temperature and under ambient pressure to ensure consistency in the results. The images of samples are shown in Figure 2.

2.4. Set up for erosion test

To analyze the erosion wear behavior of the FL/TWD/PF composites, an erosion test apparatus was used. As shown in Figure 3, the experimental setup included essential components such as an erodent feeder box, nozzle, mixing chamber, sample holder, and air-flow vent. Dry silica sand was used as the erodent in three different particle sizes: 250 µm, 350 µm, and 450 µm.

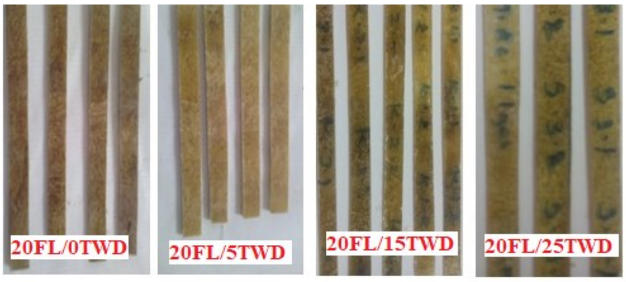


Figure 2: Composite Specimens for testing

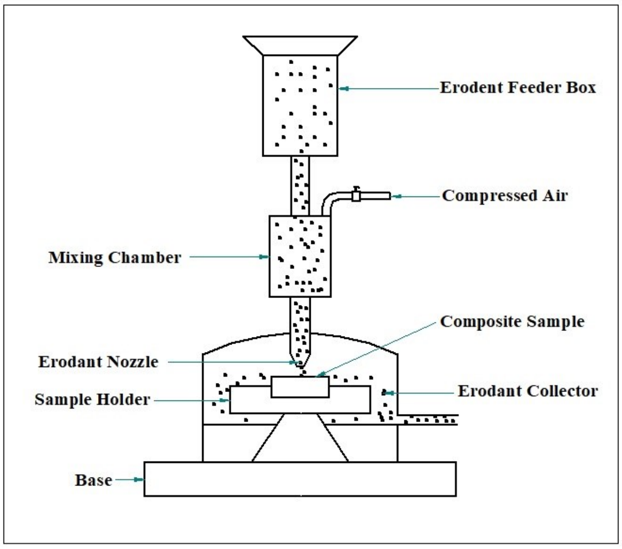


Figure 3: Experimental set up for Erosion Test

After testing, each sample was cleaned with acetone to remove residual contaminants and dried for accurate weight measurements. The erosion rate was calculated by weighing the composite specimens before and after testing. The weight loss was divided by the weight of the eroding particles to determine the rate of erosion. The test was repeated until the erosion rate stabilized.

2.5. Experimental design:taguchi

The Taguchi experimental design was employed to optimize the parameters for minimizing erosion wear in the composite samples.

An orthogonal array (L27) was selected to reduce the number of experimental trials from 243 to 27, while maintaining comprehensive evaluation across different process parameters. These parameters included TWD particle content, impact velocity, impingement angle, erodent size, and stand-off distance. The objective function, signal-to-noise (S/N) ratio, was used to analyze the results, with the "smaller-is-better" criterion applied to minimize the erosion rate. The process parameters and their levels for the erosion wear test are shown in Table 2. The fixed testing parameters included a silica feed rate of 10.0±1.0 g/min, a nozzle length of 80 mm, and a nozzle diameter of 3 mm. The 27 combinations of process parameters shown in Table 3.

Table 2: The erosive test : Process parameters and levels

Process parameters	TWD	Impact velocity in m/Sec	Impingement angles in degree	Erodent size in µm	Stand-off distance
Designation	A	B	C	D	E
Level I	5	40	30	250	60
Level II	15	50	60	350	100
Level III	25	60	90	450	140

Table 3: for 27 groupings (combinations) of process parameters

Experiment No	Wood dust particle content in wt %	Impact velocity in m/sec	Impingement Angle in degree	Erodent size in µm	Stand-off distance
1	5	40	30	250	60
2					100
3					140
4		50	60	350	60
5					100
6					140
7		60	90	450	60
8					100
9					140
10	15	40	60	450	60
11					100
12					140
13		50	90	250	60
14					100
15					140
16		60	30	350	60
17					100
18					140
19	25	40	90	350	60
20					100
21					140
22		50	30	450	60
23					100
24					140
25		60	60	250	60
26					100
27					140

3. Results and discussion

3.1. Tensile strength analysis

The influence of teak wood dust (TWD) content on the tensile strength of Luffa acutangula fiber (LAF)-reinforced phenol formaldehyde (PF) composites was evaluated, and the results are shown in Figure 4. The composite sample without TWD (20FL/0TWD) exhibited a tensile strength of 36.12 MPa and a modulus of 1258.4 MPa. It is evident that the incorporation of LAF enhances the tensile properties of the composites. The inclusion of TWD particles led to a significant increase in tensile strength. Specifically, the addition of 5% TWD improved the tensile strength to 40.313 MPa, reflecting a 10.66% enhancement compared to the sample without TWD. The maximum tensile strength of 47.163 MPa was recorded for the composite containing 15% TWD (20FL/15TWD), representing a 17.56% increase over the control sample (20FL/0TWD). However, further addition of TWD beyond 15% resulted in a decrease in tensile strength, as the 20FL/25TWD composite exhibited a lower tensile strength, likely due to fiber overloading, which diminishes fiber-matrix compatibility and resin wettability.

The mechanical property improvements observed in this study align with and expand upon existing literature. For instance, composites reinforced with sisal and coir fibers have shown tensile strength improvements of up to 10–15%, as reported by researchers. The 17.56% enhancement achieved in this study with 15% TWD content surpasses these benchmarks, highlighting the effectiveness of TWD as a filler. Similarly, the 48.78% improvement in flexural strength exceeds the flexural performance improvements reported in hybrid composites using coconut spathe fibers

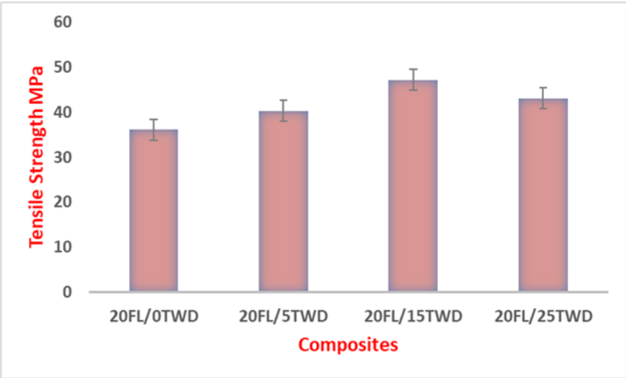


Figure 4 : Effect of wood dust particles on tensile strength

3.2. Flexural strength analysis

The flexural strength of the composites also showed significant variation with the inclusion of TWD particles.

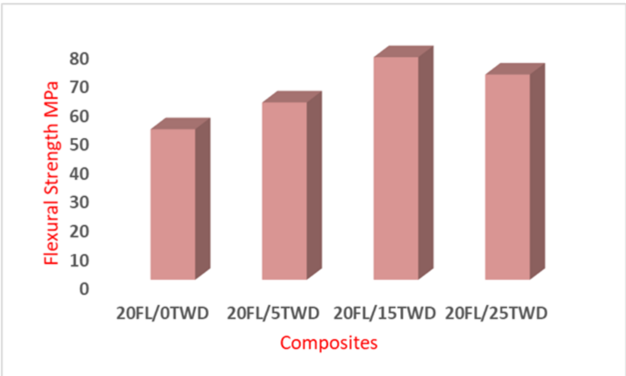


Figure 5. Effect of wood dust particles on flexural strength

The control sample (20FL/0TWD) exhibited a flexural strength of 52.18 MPa, as presented in Figure 5. The addition of 5% TWD increased the flexural strength to 61.431 MPa, reflecting an 18.11% improvement. The maximum flexural strength of 77.12 MPa was observed in the sample containing 15% TWD (20FL/15TWD), showing a 48.78% increase compared to the control sample. The improvement in flexural strength can be attributed to the enhanced interfacial bonding between the LAF and the PF matrix, as well as the improved dispersion of TWD particles. However, similar to the tensile strength results, further increases in TWD content (beyond 15%) led to a reduction in flexural strength, likely due to fiber clustering and the formation of microcracks, which negatively affect the overall composite strength.

3.3. Impact strength analysis

The impact strength of the LAF/PF composites exhibited a similar trend, as shown in Figure 6. The sample without TWD (20FL/0TWD) demonstrated the lowest impact strength of 1.112 KJ/m². The inclusion of 5% TWD increased the impact strength by 35.41%, reaching 1.506 KJ/m². The highest impact strength of 3.022 KJ/m² was achieved in the composite containing 15% TWD, representing a 54.64% improvement over the control sample. As with tensile and flexural properties, the impact strength declined when the TWD content exceeded 15%. The sample with 25% TWD showed a decrease in impact strength due to the excessive fiber content, which reduces the composite's ductility and contributes to the formation of microcracks.

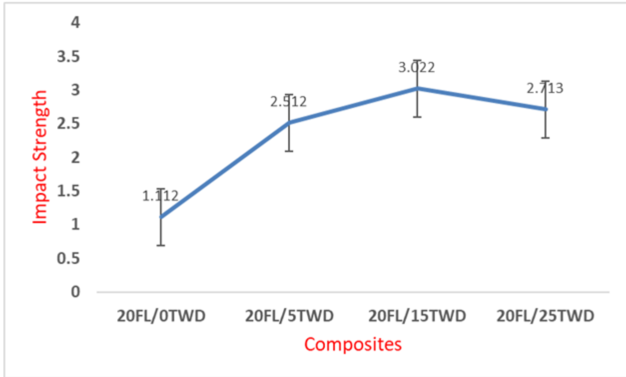


Figure 6 : Effect of wood dust particles on Impact strength

3.4. Erosion rate – analysis

Erosive wear testing was conducted on the composite samples using various combinations of process parameters, as listed in Table 3.

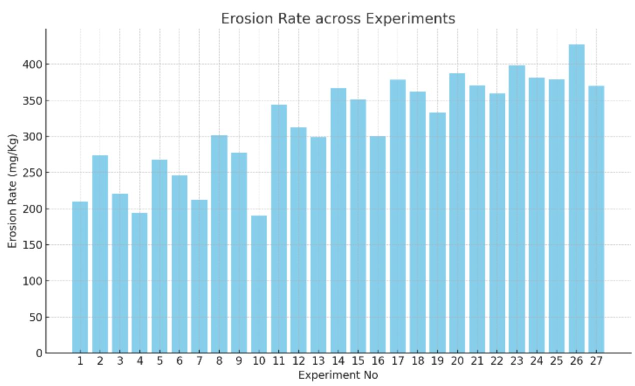


Figure 7: Erosion (wear) Rate of FL/TWD/PF composites

The minimum erosion rate of 199.82 mg/kg was observed in the composite containing 15% TWD (20FL/15TWD), with the following optimal process parameters: 40 m/s impact velocity, 60° impingement angle, 450 µm erodent size, and a 60 mm stand-off distance. This result corresponds to experiment number 10 in Table 3. The next lowest erosion rate was recorded for the sample with 5% TWD (20FL/5TWD), with slightly different process parameters. The combination of lower TWD content, increased impact velocity, and a smaller erodent size resulted in marginally higher erosion rates. These findings suggest that the addition of TWD particles plays a critical role in reducing the erosion rate of LAF/PF composites, particularly when combined with the appropriate process parameters. The erosion rate for all the specimens shown in Figure 7.

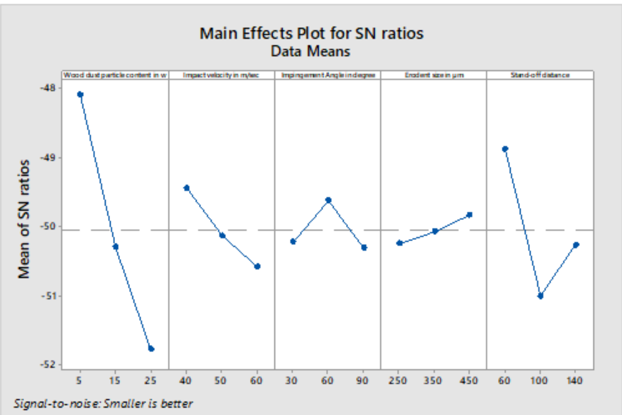
The graphical analysis in Figure 8 (a) & (b) highlights that the erosion rate is significantly influenced by wood dust particle content, which increases as fiber content rises, likely due to increased brittleness. Particle content and stand-off distance play a crucial role in determining the erosion rate, while impact velocity and impingement angle have moderate effects, and erodent size has a minor impact. Figure 9 further confirms that wood dust content and stand-off distance are key factors. The optimal conditions for minimizing erosion are: particle content at Level II, impact velocity at Level I, impingement angle at Level II, erodent size at Level III, and stand-off distance at Level III.

Table 4: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	103215	34405.1	42.31	0.000
Teak Wood dust particle content	1	78842	78841.6	96.95	0.000
Impact velocity	1	7574	7573.7	6.12	0.022
Impingement angle	1	11	11.4	0.01	0.925
Erodent size	1	835	835.0	0.68	0.420
stand off distance	1	24374	12186.8	14.99	0.000
Error	23	18704	813.2		
Lack-of-Fit	5	4071	814.2	1.00	0.445
Pure Error	18	14633	812.9		
Total	26	121919			

Table 5: Response Table - S/N) Signal to Noise Ratios (Smaller is better)

Level	Wood dust particle content	Impact velocity	Impingement angle	Erodent size	Stand-off distance
1	-48.09	-49.44	-50.22	-50.25	-48.88
2	-50.30	-50.13	-49.63	-50.07	-51.01
3	-51.77	-50.58	-50.30	-49.83	-50.27
Delta	3.68	1.13	0.68	0.42	2.13
Rank	1	3	4	5	2



(a)

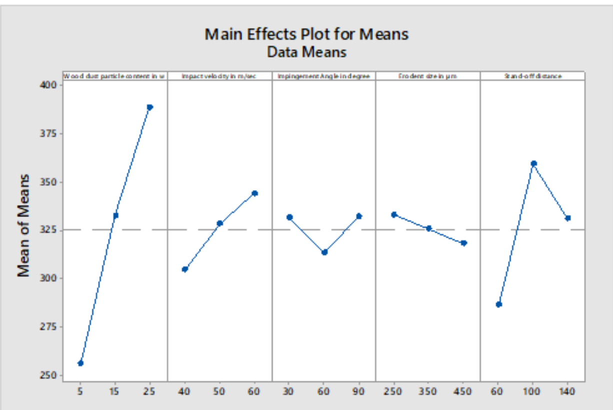


Figure 8: Main Effects for (a). S/N (Signal – Nose) ratio (b). Means

In terms of erosion wear, the optimized process parameters identified through the Taguchi analysis yielded a minimum erosion rate of 199.82 mg/kg. This value is significantly lower than the rates reported in previous studies on agro-waste-reinforced composites demonstrating the superior erosion resistance of the TWD-LAF/PF composites. The ANOVA analysis underscores the critical role of TWD content and stand-off distance, which contributed most significantly to the erosion resistance. The findings corroborate earlier studies that emphasized the importance of particle-matrix interactions in determining wear behavior

3.5. Analysis of variance for erosion rate

Table 4 outlines the contributions of each parameter to the erosion (wear) rate of FL/TWD/PF composites. The ANOVA method was employed to determine the impact of process parameters on the erosion rate. The p-value indicates the significance of each parameter and its effect on the erosion rate, with the smallest p-value identifying the most significant factor. According to the table, wood dust particle content plays a highly significant role in the erosion rate, with a p-value of 0.000. Similarly, the stand-off distance is another important factor, with a p-value of 0.011. Impact velocity, with a p-value of 0.022, is also considered significant. In contrast, the p-values for erodent size (0.420) and impingement angle (0.925) suggest that these factors have minimal impact on the erosion rate.

The rank order of the parameters affecting the erosion rate is as follows: teak wood dust particle content, stand-off distance, impact velocity, impingement angle, and erodent size.

Table 5 presents the signal-to-noise (S/N) ratios of the process parameters, reflecting their contributions to the wear rate in FL/TWD/PF composites. The S/N ratio analysis follows the "smaller is better" principle. The particle content in the composite significantly influences the erosion rate. Table 5 also ranks the process parameters based on their contribution, identifying the optimal combination for minimizing erosion.

Regression analysis was conducted to confirm the correlation between the predicted values and the experimental results. A strong correlation between the predicted and experimental data is observed, as illustrated in Figure 10. The normal probability plot demonstrates the close alignment of the values, while the bell-shaped histogram further confirms the accuracy of this fit. Table 6 presents the coefficients for the process parameters, providing detailed insights into their contributions.

3.6. Process parameters : Regression Analysis

Table 6. Coefficients for Process Parameters

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-7.45	67.2	-0.21	0.923	
Wood dust particle content	6.793	0.819	8.17	0.000	1.00
Impact velocity	2.49	1.19	2.457	0.021	1.01
Impingement angle	0.036	0.286	0.11	0.935	1.01
Erodent size	-0.0431	0.0424	-0.92	0.440	1.01
Stand-off distance	0.588	0.217	2.89	0.021	1.01

The erosion (wear) rate can be calculated by the equation

Stand-off distance			
60	Erosion Rate (mg/Kg)	=	187.2 +6.618Wooddustparticlecontent
100	Erosion Rate (mg/Kg)	=	260.1 +6.618Wooddustparticlecontent
140	Erosion Rate (mg/Kg)	=	232.0 +6.618Wooddustparticlecontent

Based on the residual graphs in Figure 10, the deviation between the predicted erosion rate and the experimental data is minimal. Parameters A and E have a highly significant impact on the erosion rate of FL/TWD/PF composites.

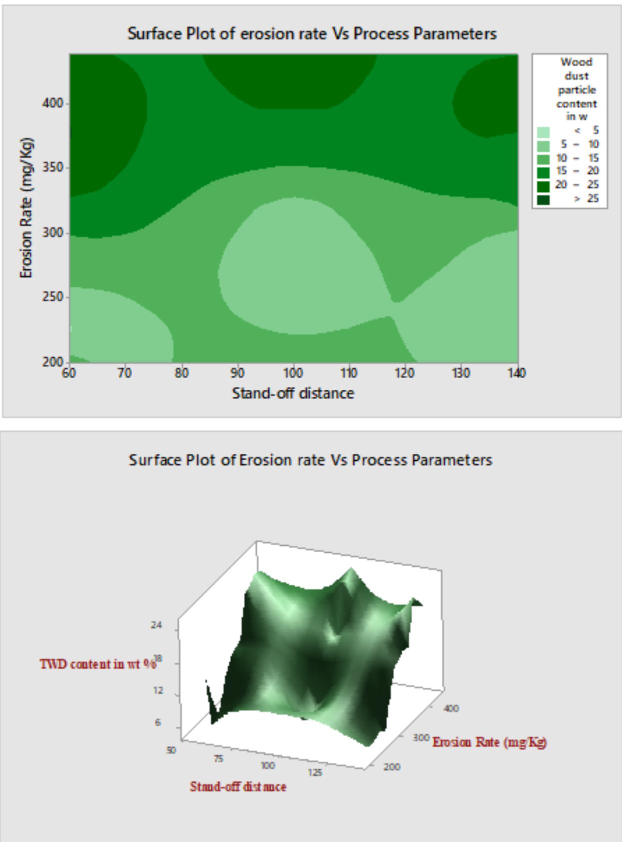


Figure 9 : Surface Plot of erosion rate Vs Process Parameters

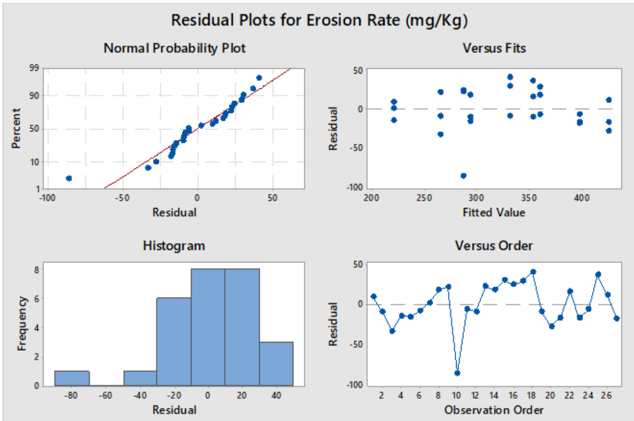


Figure 10: Residual Plots for Erosion rate mg/kg

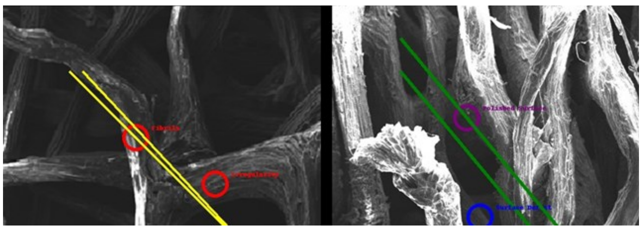


Figure 11: SEM Images of LAF – Normal & Compressed

3.7. Scanning electron microscopy of LAF

Figure 11 presents the scanning electron microscopic images of Luffa acutangula fiber, showcasing both the untreated and compressed forms. These images highlight the fiber's surface texture, displaying irregularities, microfibrils, and its long, cylindrical shape. The presence of chemical components such as lignin, pectin, hemicellulose, and wax creates a polished fiber surface, clearly visible in the images. These chemical constituents hinder effective bonding between the fiber and the matrix, leading to reduced mechanical properties. Therefore, chemical treatment is necessary to create a rougher fiber surface. The images also reveal fiber alignment and surface defects.

4. Conclusion

In this study, Luffa acutangula fiber (LAF)-reinforced phenol formaldehyde (PF) composites, filled with varying amounts of teak wood dust (TWD) particles, were successfully fabricated using the hand lay-up method. The mechanical and erosion wear properties of these composites were analyzed in detail.

The results indicate that the inclusion of TWD particles significantly enhances the mechanical properties of LAF/PF composites. The composite containing 15% TWD (20FL/15TWD) exhibited the highest tensile strength (47.163 MPa), flexural strength (77.12 MPa), and impact strength (3.022 KJ/m²). These improvements can be attributed to better fiber-matrix bonding, enhanced particle dispersion, and the cellulose content in TWD, which increases the strength and stiffness of the composite.

Additionally, the Taguchi experimental design (L27) proved to be a practical approach to optimize the process parameters affecting the erosion rate. The lowest erosion rate of 199.82 mg/kg was achieved with the composite containing 15% TWD, under optimal conditions of 40 m/s impact velocity, 60° impingement angle, 450 µm erodent size, and a 60 mm stand-off distance. The analysis of variance (ANOVA) further confirmed that TWD content, stand-off distance, and impact velocity are the most significant factors influencing the erosion rate.

Overall, this study demonstrates that incorporating teak wood dust into Luffa acutangula fiber-reinforced composites not only improves their mechanical performance but also reduces wear, making these materials suitable for applications in industries such as automotive, aerospace, and construction, where sustainability and durability are critical. Future research could explore the use of other bio-waste materials and optimization of fiber-matrix combinations to further improve the properties of these composites. The interdisciplinary approach highlights how integrating bio-waste fillers into composites mirrors the innovative methodologies used in EMG signal processing, offering both material and technological advancements.

References

Abdulrahman Adeiza Musa and Azikiwe Peter Onwualu. (2024). Potential of lignocellulosic fiber reinforced polymer composites for automobile parts production: Current knowledge, research needs, and future direction, Heliyon, Volume 10, Issue 3, e24683,ISSN 2405–8440, https://doi.org/10.1016/j.heliyon.2024.e24683.

Alhijazi, M., Safaei, B., Zeeshan, Q., Asmael, M., Eyvazian, A. and Qin, Z. (2019). Recent Developments in Luffa Natural Fiber Composites: Review. Sustainability, 12(18), 7683. https://doi.org/10.3390/su12187683

Al-Mobarak, T., Mina, M. and Gafur, M. (2018). Material properties of sponge-gourd fiber–reinforced polylactic acid biocomposites: Effect of fiber weight ratio, chemical treatment, and treatment concentrations. Journal of Thermoplastic Composite Materials. https://doi.org/10.1177/0892705718772880

Athith, D., Sanjay, M., Yashas Gowda, T., Madhu, P., Arpitha, G., Yogesha, B. and Omri, M. A. (2017). Effect of tungsten carbide on mechanical and tribological properties of jute/sisal/E-glass fabrics reinforced natural rubber/epoxy composites. Journal of Industrial Textiles. https://doi.org/10.1177/1528083717740765

Azizatul Karimah, Muhammad Rasyidur Ridho, Sasa Sofyan Munawar, Danang Sudarwoko Adi, Ismadi, Ratih Damayanti, Bambang Subiyanto, Widya Fatriasari, Ahmad Fudholi. (2021). A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations, Journal of Materials Research and Technology, Volume 13, Pages 2442–2458, ISSN 2238–7854, https://doi.org/10.1016/j.jmrt.2021.06.014.

Barik, R.K., Biswas, S. and Patra, R.C. (2021). Effect of Particle Size on the Mechanical Properties of SaTWDust Reinforced Epoxy Composites. Journal of Polymers and the Environment, 29(3), pp.881–894

Gh, Israa. (2017). Study the Effect of the Particle Size on Mechanical Properties of Particulate Natural Composite Materials.

Girisha C. and Sanjeevamurthy. R. G. (2012). Tensile properties of natural fiber-reinforced epoxy-hybrid composites. International Journal of Modern Engineering Research. 2. 471–474.

Gujjala Raghavendra, S.K. Acharya, C.R. Deo and Mishra P. (2012). Fabrication-Modelling and Analysis on Tribological Performance of Natural Composites Using Taguchi Approach, Procedia Engineering, Volume 38, Pages 2635–2644, ISSN 1877–7058, https://doi.org/10.1016/j.proeng.2012.06.310.

Harikrishnan Pulikkalparambil, Ajish Babu, Anusree Thilak, N.P. Vighnesh, Sanjay Mavinkere Rangappa, Suchart Siengchin. (2023). A review on sliding wear properties of sustainable biocomposites: Classifications, fabrication and discussions, Heliyon, Volume 9, Issue 3, e14381, ISSN 2405–8440, https://doi.org/10.1016/j.heliyon.2023.e14381.

Hoi-yan Cheung, Mei-po Ho, Kin-tak Lau, Francisco Cardona and David Hui. (2009). Natural fibre-reinforced composites for bioengineering and environmental engineering applications, Composites Part B: Engineering, Volume 40, Issue 7, Pages 655–663, ISSN 1359–8368, https://doi.org/10.1016/j.compositesb.2009.04.014.

Hossain, S.S., Islam, M.S. and Hossain, M.M. (2021). Investigation of Tensile Strength and Hardness of SaTWDust Filled Epoxy Composites. Journal of Materials Science Research and Reviews, 5(3), pp.68–78

Issam Elfaleh, Fethi Abbassi, Mohamed Habibi, Furqan Ahmad, Mohamed Guedri, Mondher Nasri, Christian Garnier. (2023). A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials, Results in Engineering, Volume 19, 101271, ISSN 2590–1230,https://doi.org/10.1016/j.rineng.2023.101271.

Jose, A. S., Athijayamani, A., Ramanathan, K. and Sidhardhan, S. (2017). Effects of addition of Prosopis juliflora fiber on the physical and mechanical properties of wood dust and coir pith particle reinforced phenol formaldehyde hybrid composite. Advanced Journal of Chemistry, 13, 6558–6562.

Jose, A., Athijayamani, A., Ramanathan, K. and Sidhardhan, S. (2017). Effects of an addition of coir-pith particles on the mechanical properties and erosive-wear behavior of a wood-dust-particle-reinforced phenol formaldehyde composite. Materiali in Tehnologije. 51. 805–811. 10.17222/mit.2016.284.

Kamarudin, S. H., Mohd Basri, M. S., Rayung, M., Abu, F., Ahmad, S., Norizan, M. N., Osman, S., Sarifuddin, N., Desa, M. S., Abdullah, U. H., Syafinaz, I. and Abdullah, L. C. (2021). A Review on Natural Fiber Reinforced Polymer Composites (NFRPC) for Sustainable Industrial Applications. Polymers, 14(17), 3698. https://doi.org/10.3390/polym14173698

Kannan, M. and Arunachalam, V. P. (2021). A review on natural fiber composites for sustainable applications: Prospects and challenges. Polymer Composites, 42(6), 2294–2313. doi: 10.1002/pc.25835

Karimah, A., Ridho, M.R., Munawar, S.S., Adi, D.S., Damayanti, R., Subiyanto, B., Fatriasari, W. and Fudholi, A. (2021). A review on natural fibers for development of eco-friendly bio-composite: characteristics, and utilizations. Journal of Materials Research and Technology. 13. 10.1016/j.jmrt.2021.06.014.

Kozlowski, R. M. (2018). Natural fibers: Properties, processing, and applications. Journal of Natural Fibers, 15(4), 395–404. doi: 10.1080/15440478.2017.1325625

Kumar V., Venkateswarlu N., and Satyanarayana K.V. (2021). Optimization of Wear Rate of Bagasse Fiber Reinforced Polymer Composite Using Taguchi Method" by published in Journal of Composite Materials, Volume 55, Issue 12, pp. 1549–1560

Majid Mohammadi, Ebrahim Taban, Wei Hong Tan, Nazli Bin Che Din, Azma Putra, Umberto Berardi. (2024). Recent progress in natural fiber reinforced composite as sound absorber material, Journal of Building Engineering, Volume 84, 108514, ISSN 2352–7102, https://doi.org/10.1016/j.jobe.2024.108514.

Manikandan, V. and Sathiyamoorthy, D. (2021). A review on natural fiber-reinforced composite materials for eco-friendly engineering applications. Materials Today: Proceedings, 45, 3377–3383. doi: 10.1016/j.matpr.2021.02.376

Mishra, S.K., Dahiya, S., Gangil, B. et al. (2024). Mechanical, morphological, and tribological characterization of novel walnut shell-reinforced polylactic acid-based biocomposites and prediction based on artificial neural network. Biomass Conv. Bioref. 14, 15609–15620. https://doi.org/10.1007/s13399-022-03670-z

Mohanty S. S., Nayak S. K., and Verma S. K. (2021). Mechanical Properties of Natural Fiber Reinforced Composites". Advanced Materials Letters

Muh. Ilham Akbar, Bidayatul Armynah, Dahlang Tahir. (2024). Comprehensive review of wood-based composites as microwave absorbers: Utilizing wood-derived materials such as carbon, metal/metal oxides, and polymer composites as fillers, Industrial Crops and Products, Volume 220, 119397, ISSN 0926–6690, https://doi.org/10.1016/j.indcrop.2024.119397.

Muhammad Yasir Khalid, Ans Al Rashid, Zia Ullah Arif, Waqas Ahmed, Hassan Arshad and Asad Ali Zaidi. (2021). Natural fiber reinforced composites: Sustainable materials for emerging applications, Results in Engineering, Volume 11, 100263, ISSN 2590–1230, https://doi.org/10.1016/j.rineng.2021.100263.

Pandey, J. K., Ahn, S. H. and Lee, C. S. (2021). Mechanical and wear properties of polymer composites: A review. Journal of Industrial and Engineering Chemistry, 97, 1–25. doi: 10.1016/j.jiec.2021.04.042

Prusty R. K. and Das. P. R. (2021). Investigation of Wear Behavior of Bagasse Fiber Reinforced Epoxy Composite Using Taguchi Method" by published in International Journal of Mechanical and Production Engineering Research and Development, Volume 11, Issue 2, pp. 825–834

Ramesh, Manickam, Rajeshkumar, Lakshmi Narasimhan, Srinivasan, Nagarajan, Kumar, Damodaran Vasanth and Balaji, Devarajan. (2022). "Influence of filler material on properties of fiber-reinforced polymer composites: A review" e-Polymers, vol. 22, no. 1, pp. 898–916. https://doi.org/10.1515/epoly-2022-0080

Rangappa, S. M., Parameswaranpillai, J., Siengchin, S., Jawaid, M. and Ozbakkaloglu, T. (2022). Bioepoxy based hybrid composites from nano-fillers of chicken feather and lignocellulose Ceiba Pentandra. Scientific Reports, 12. https://doi.org/10.1038/s41598-021-04386-2

Rangappa, S. M., Siengchin, S., Parameswaranpillai, J., Jawaid, M. and Ozbakkaloglu, T. (2022). Lignocellulosic fiber reinforced composites: Progress, performance, properties, applications, and future perspectives. Polymer Composites, 43(2), 645–691. https://doi.org/10.1002/pc.26413

Ravindran, L., S., S. M., S., A. K. and Thomas, S. (2022). A comprehensive review on phenol-formaldehyde resin-based composites and foams. Polymer Composites, 43(12), 8602–8621. https://doi.org/10.1002/pc.27059

Rodriguez, Ferdinand, Gent, Alan N. , Stevens, Malcolm P., Kauffman, George B., Bierwagen, Gordon P. and Preston, J. (1 Aug. 2022). "major industrial polymers". Encyclopedia Britannica, https://www.britannica.com/science/industrial-polymer. Accessed 19 October 2024.

Saha S. K., Chowdhury S. G., and Hossain M. A. (2021). Mechanical and Thermal Properties of Wood Dust Filled Thermoplastic Composites: A Comprehensive Review" by published in Journal of Natural Fibers, Volume 18, Issue 2, pp. 155–176.

Sanjay M.R., Madhu P., Mohammad Jawaid, Senthamaraikannan P., Senthil S. and Pradeep S. (2018). Characterization and properties of natural fiber polymer composites: A comprehensive review, Journal of Cleaner Production, Volume 172, Pages 566–581, ISSN 0959–6526, https://doi.org/10.1016/j.jclepro.2017.10.101.

Sankar, S., Senthilkumar, P. and Arunachalam, V. P. (2020). Investigation on mechanical and thermal properties of Luffa acutangula fiber reinforced epoxy composites. Journal of Polymers and the Environment, 28, 1742–1752. doi: 10.1007/s10924-020-01822-6

Shravanabelagola Nagaraja Setty, V. K., Govardhan, G., Rangappa, S. M. and Siengchin, S. (2021). Raw and chemically treated bio-waste filled (Limonia acidissima shell powder) vinyl ester composites: Physical, mechanical, moisture absorption properties, and microstructure analysis. Journal of Vinyl and Additive Technology, 27(1), 97–107. https://doi.org/10.1002/vnl.21787

Singh R. K., Das R., and Singh A. (2022). Investigations on the Mechanical Properties of Hybrid Natural Fiber Reinforced Polymer Composites" Journal of Materials Science Research.

Sivakandhan C., Balaji R., Ganesh Babu Loganathan, Madan D., Murali G. (2020). Investigation of mechanical behaviour on sponge/ridge gourd (Luffa aegyptiaca) natural fiber using epoxy and polyester resin, Materials Today: Proceedings, Volume 22, Part 3, Pages 705–714, ISSN 2214–7853, https://doi.org/10.1016/j.matpr.2019.09.183.

Sivarajan S. S. and Syamala. S. (2021). "Optimization of Process Parameters for Wear Rate of Bagasse Fiber Reinforced Epoxy Composites Using Taguchi Method" by published in Journal of Minerals and Materials Characterization and Engineering, Volume 9, Issue 1, pp. 47–60

Suresh Kumar, M. and Uthayakumar, M. (2021). Study on the mechanical properties of Luffa acutangula reinforced polymer composite for commercial applications. Journal of Materials Research and Technology, 10, 470–482. doi: 10.1016/j.jmrt.2020.08.044

Suryawanshi S. M. and Sutar. S. S. (2021). Optimization of Wear Performance of Bagasse Fiber Reinforced Epoxy Composites Using Taguchi Method" by published in Materials Today: Proceedings, Volume 42, pp. 347–353

Tissera, N. D. and Siriwardhana, D. P. (2021). Tensile, flexural and impact properties of sisal fiber reinforced high-density polyethylene composites. Journal of Reinforced Plastics and Composites, 40(12), 476–487. doi: 10.1177/07316844211003422

Varma, K.S.K., Kumar, P. and Nayak, S.K. (2021). Mechanical and Water Absorption Properties of Sponge Gourd Fiber Reinforced Polymer Composites. Journal of Natural Fibers, 18(4), pp.559–572.

Wang, Q., Ma, X. and Peng, C. (2021). Wear-resistant composite coatings based on functional polymers: A review. Coatings, 11(6), 727. doi: 10.3390/coatings11060727

Zhang, X., Huang, S. and Xiong, L. (2021). Natural fiber-reinforced polymer composites for environmental protection: A review. Journal of Materials Science & Technology, 80, 136–149. doi: 10.1016/j.jmst.2020.12.012.

Zheng, Y., Zuo, C., Zhang, L. and Zhang, L. (2021). Synthesis and properties of a novel phenol-formaldehyde resin for high-performance coatings. Progress in Organic Coatings, 150, 106139. doi: 10.1016/j.porgcoat.2020.106139

Answer to the Questions

Check language use using a native speaker or a professional service, changes in the text must be highlighted using a different colour.

The manuscript corrected and highlighted in blue colour.

Explain the novelty and practical importance of your work, changes in the text must be highlighted using a different colour.

Included in abstract - This study provides a novel approach to enhancing composite materials by integrating TWD into LAF/PF composites, offering sustainable solutions for lightweight and durable industrial applications

Included in Introduction

The **novelty** of this study lies in the innovative integration of teak wood dust (TWD) particles into Luffa acutangula fiber (LAF)-reinforced phenol formaldehyde (PF) composites. While natural fibers and bio-fillers have been explored individually, the synergistic combination of LAF and TWD in this research addresses both mechanical enhancements and environmental sustainability. This approach leverages the cellulose and lignin content in TWD to improve fiber-matrix bonding, reducing voids and brittleness, thereby enhancing the mechanical properties and wear resistance. Furthermore, the application of the Taguchi method to optimize process parameters provides a statistically robust framework for minimizing erosion wear, offering a practical pathway for industrial adoption. The composites developed in this study exhibit superior properties, such as a 17.56% increase in tensile strength and a 54.64% improvement in impact strength, making them suitable for lightweight, durable applications in the automotive, aerospace, and construction industries [Muh. Ilham Akbar *et al.* 2024].

Practical Importance - This study directly addresses the growing industrial demand for eco-friendly and sustainable materials. By repurposing bio-waste (TWD), it not only reduces environmental impact but also enhances the composite's performance. The findings hold significant potential for industrial applications, particularly in sectors where durability and sustainability are critical. For instance, the improved tensile and impact strengths of these composites make them viable candidates for automotive components, while their lightweight and erosion-resistant properties align with the needs of aerospace and construction materials.

Discussion must be improved according to the original request of the reviewer. You cannot just describe the plots and tables. Compare with existing literature.

The mechanical property improvements observed in this study align with and expand upon existing literature. For instance, composites reinforced with sisal and coir fibers have shown tensile strength improvements of up to 10–15%, as reported by researchers. The 17.56% enhancement achieved in this study with 15% TWD content surpasses these benchmarks, highlighting the effectiveness of TWD as a filler. Similarly, the 48.78% improvement in flexural strength exceeds the flexural performance improvements reported in hybrid composites using coconut spathe fibers.

In terms of erosion wear, the optimized process parameters identified through the Taguchi analysis yielded a minimum erosion rate of 199.82 mg/kg. This value is significantly lower than the rates reported in previous studies on agro-waste-reinforced composites demonstrating the superior erosion resistance of the TWD-LAF/PF composites. The ANOVA analysis underscores the critical role of TWD content and stand-off distance, which contributed most significantly to the erosion resistance. The findings corroborate earlier studies that emphasized the importance of particle-matrix interactions in determining wear behavior