engineering proceedings

Proceeding Paper

Experimental Investigation on the Mechanical Properties of Jute Fiber and Silica Nano Particles Using Artificial Neural Network †

Maridurai Thirupathy and Muthuraman Vadivel *

Department of Mechanical Engineering, Vels Institute of Science, Technology and Advanced Studies (VISTAS), Chennai 600117, India; maridurai.mechanical@gmail.com
* Correspondence: drvmuthuraman.se@velsuniv.ac.in
† Presented at the International Conference on Processing and Performance of Materials, Chennai, India, 2–3 March 2023.

Abstract: This study explores the impact of silica nanoparticles on jute fiber-reinforced composites with epoxy resin matrices. Silica nanoparticles were synthesized at three concentrations (3%, 6%, and 9%) and incorporated into composites at varying fiber–resin weight ratios. The composites were subjected to tests for tensile strength, flexural strength, impact strength, and hardness. The Taguchi signal-to-noise ratio method was employed for optimization. Results indicate that a 9% addition of silica nanoparticles significantly enhances the mechanical properties of jute fiber-reinforced composites. Tensile and flexural strength increased with higher silica nanoparticle content, while impact strength and hardness also improved. Notably, a 9% silica addition achieved a maximum tensile strength of 72 MPa, resulting in a 10% increase over that yielded by the 3% addition. Flexural and impact strengths improved by 23% and 20%, respectively, when compared to the 3% silica addition. Furthermore, a neural network model accurately predicted the composite's mechanical characteristics with 100% accuracy. These findings hold promise for the automobile and aircraft industries, as they require high-performance materials. The integration of jute fibers and silica nanoparticles into composites offers a sustainable and eco-friendly alternative to conventional materials. The enhancement strategy employed in this analysis can be applied to enhance the mechanical properties of other composite materials.

Keywords: nanoparticle; jute-fiber; ANN; silica; mechanical strength

Citation: Thirupathy, M.; Vadivel, M. Experimental Investigation on the Mechanical Properties of Jute Fiber and Silica Nano Particles Using Artificial Neural Network. *Eng. Proc.* **2024**, *61*, 23. https://doi.org/10.3390/engproc2024061023

Academic Editors: K. Babu, Anirudh Venkatraman Krishnan, K. Jayakumar and M. Dhananchezian

Published: 1 February 2024

1. Introduction

Composite materials are extensively utilized in diverse sectors, including aerospace, transportation, and construction, owing to their remarkable attributes like superior strength, stiffness, corrosion resistance, and low weight [1,2]. Traditionally, these materials are reinforced with synthetic fibers. However, there is growing interest in natural fibers due to their eco-friendly, cost-effective, and biodegradable nature [3].

Silica nanoparticles have been explored to enhance the mechanical and physical properties of composites. Nevertheless, their specific influence on jute fiber-reinforced composites with epoxy matrices remains relatively unexplored [4]. Recent years have seen the application of machine learning, particularly artificial neural networks (ANNs), to predict material characteristics accurately, thus reducing the need for extensive experimental testing. In this study, ANNs are employed to forecast the tribological properties of these composites [5].

The use of natural fibers in composites, notably jute fibers, has gained attention due to their affordability, strength, and eco-friendly characteristics. Epoxy resin, a commonly used matrix material, is selected for its outstanding mechanical properties and chemical resistance. However, its limited toughness and impact resistance have prompted various approaches to address these issues, including the incorporation of nanoparticles. Silica nanoparticles, known for their significant surface area and compatibility with different matrix materials, have been widely investigated for their ability to improve composite properties, such as rigidity, hardness, and fracture resistance [5,6].

The Taguchi method, a statistical approach, is applied in this study to optimize process parameters, reducing the number of experiments required to determine optimal settings. Previous research has successfully used the Taguchi method to enhance the physical characteristics of composite materials. In summary, this research delves into the impact of silica nanoparticles on the tribological properties of jute fiber-reinforced composites [7]. The addition of silica nanoparticles is expected to bolster the strength and impact resistance of these composites. Furthermore, the utilization of machine learning tools enables precise predictions of composite characteristics, reducing the reliance on extensive experimental testing. The outcomes of this study hold significant promise for the development of sustainable and eco-friendly composite materials, with potential applications in the automotive and aerospace industries. The integration of jute fibers and silica nanoparticles offers an environmentally responsible alternative to traditional materials.

2. Material Preparation

We enhance composite properties by adding uniformly dispersed silica nanoparticles, employing the cost-effective magnetic stirring technique. Silica nanoparticles, preheated to 300 °C, are incorporated at 3%, 6%, and 9% weight percentages as shown in Table 1. A 30 min stirring process ensures uniform dispersion, aided by heating the epoxy resin to 60 °C to reduce viscosity. Our method involves a hand lay-up technique, manually placing jute fibers in a mold and pouring resin over them, suitable for small-scale production. Specimens cure at room temperature for 24 h. The material preparation is shown in Figure 1.

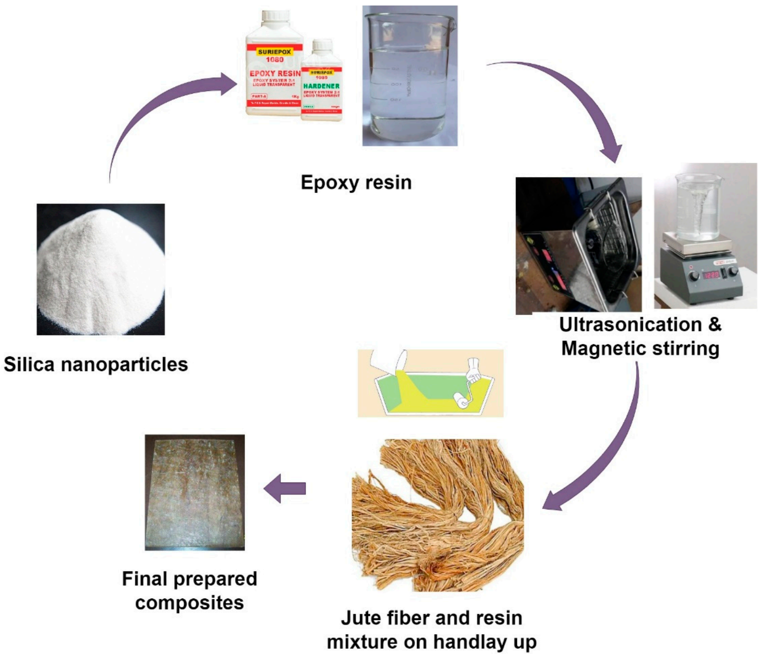

Figure 1. Material preparation.

Following the curing process, we cut specimens from the prepared laminates according to ASTM standards for a battery of mechanical tests. These tests encompassed tensile, flexural, impact, and hardness assessments. Tensile tests determined the composite's breaking strength, while flexural tests measured its bending capabilities. Impact tests gauged the composite's energy absorption during sudden impacts, and hardness tests evaluated its resistance to indentation or scratching. By employing different weight percentages, we thoroughly assessed the composite's mechanical properties. For optimization, we employed the Taguchi method, a recognized statistical approach for process enhancement.

Table 1. Composition of composite prepared in this research.

S. No	Jute Fiber Composition in %	Epoxy Material Composition in %	% of Nanoparticles of Silica
1	50	47	3
2	50	44	6
3	50	41	9

3. Result and Discussion

After curing jute fiber-reinforced composites with varying silica nanoparticle contents (3%, 6%, and 9%), we conducted crucial mechanical tests. Tensile tests measured breaking points, revealing the impact of silica on strength. Flexural tests assessed bending forces and silica's effect on flexibility. Impact tests gauged energy absorption in sudden impacts. The Brinell test assessed composite rigidity, and a wear test machine quantified material loss for wear resistance, crucial for practical use.

3.1. Tensile Strength

Table 2 summarizes the tensile test results for the three composites with varying silica nanoparticle levels. The first column identifies each composite, while the second column indicates the silica percentage in the epoxy resin matrix. The third column displays the yield strength, the stress causing permanent deformation. The fourth column shows the ultimate strength, the stress at which the material breaks. Increasing silica nanoparticle content generally improves both responses, with Composite 3 (9% silica) exhibiting the highest values among the three composites. It is important to note that specific composite characteristics may vary due to factors like processing conditions and material quality [8].

Table 2. Tensile test result.

Composite	Silica Content	Yield Strength (MPa)	Tensile Strength (MPa)
Composite 1	3%	38	65
Composite 2	6%	40	68
Composite 3	9%	44	72

3.2. Flexural Strength

The three-point bend test, also known as the flexural test, assesses a material's behavior under bending loads. In this test, a composite sample is supported on two points, and a weight is applied at the midpoint to induce bending. The deflection amount is measured, following ASTM D790 standards. Table 3 summarizes the flexural strength test results. Composite 2, with a 9% silica content, exhibited the highest flexural strength among the three composites, reaching 64.8 MPa. This value significantly surpassed those of Composite 1 and Composite 3, with silica contents of 3% and 9%, respectively. These results indicate that adding silica nanoparticles at an appropriate weight percentage can notably enhance the composite's flexural strength.

Table 3. Result from the flexural test.

Composite	Silica Content (%)	Flexural Strength (MPa)
1	3	52.3
2	6	58.9
3	9	64.8

3.3. Impact Test

The impact test aimed to evaluate the impact resistance of the prepared composites [9,10]. It involved dropping a pendulum onto the composite's surface and measuring the energy absorbed during the impact, reflecting the material's ability to withstand sudden shocks or impacts. Table 4 displays the composite number, silica content percentage, and impact strength in kilojoules per square meter (kJ/m^2). The material containing 9% silica nanoparticles exhibited the highest impact resistance at 42.8 kJ/m^2. In comparison, composites with 3% and 6% silica nanoparticles displayed impact strengths of 35.7 kJ/m^2 and 38.9 kJ/m^2, respectively. These results highlight the effectiveness of adding reinforcing composites in improving the impact resistance of jute fiber-reinforced composites.

Table 4. Result from the impact test.

Composite	Silica Content (%)	Impact Strength (kJ/m^2)
1	3	35.7
2	6	38.9
3	9	42.8

3.4. Hardness Test Result

The Brinell hardness test was conducted to evaluate the hardness of the prepared composites [11]. This test entails pressing a hardened steel ball into the composite's surface and measuring the diameter of the resulting indentation, indicating the material's resistance to deformation or penetration by a hard object. Table 5 presents the composite number, silica content percentage, and Brinell hardness value in HB units. The composite containing 9% silica nanoparticles exhibited the highest Brinell hardness value at 72.5 HB. In comparison, composites with 3% and 6% silica nanoparticles displayed Brinell hardness values of 65.6 HB and 67.5 HB, respectively. These results underscore the effectiveness of reinforcing composites in enhancing the hardness of the prepared materials.

In Figure 2, we observe the experimental results depicting the impact of increasing silica content on the tribological properties of jute-reinforced composites. As the silica nanoparticle percentage rises, a notable improvement in tribological properties becomes evident. The consistent increase in responses with higher silica content affirms its effectiveness in enhancing the material's mechanical characteristics. Additionally, both impact strength and hardness of the composites significantly improve with silica nanoparticle reinforcement, reflecting enhanced impact resistance and deformation resistance. These findings hold great relevance for industrial applications requiring high-performance materials.

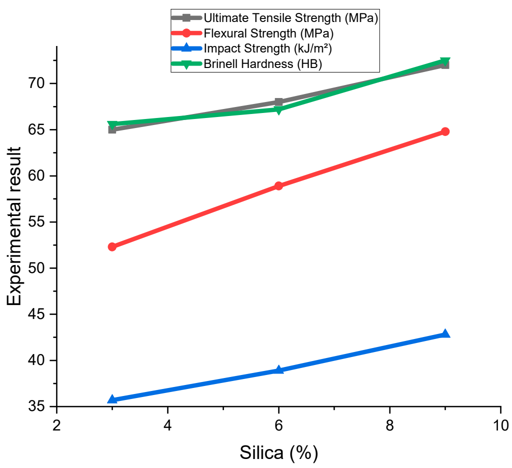

Figure 2. Experimental results.

Table 5. Result of the hardness test.

Composite	Silica Content (%)	Brinell Hardness (HB)
1	3	65.6
2	6	67.2
3	9	72.5

3.5. Wear Test Result

The wear test involved standardizing the prepared composites to 10 mm diameter and 70 mm length [12]. Experiments followed the Taguchi design, a statistical method for optimizing performance by minimizing variability and enhancing output quality. This approach, applied to the composite materials with EN 31 alloy as the base material, improved wear resistance and identified optimal wear parameters. The study assessed various input responses, including composition (C), load (L), disc rotational speed (Sr), and sliding distance (Ds), to evaluate wear (Sw) and coefficient of friction (CoF). The results from the L9 experiments array are summarized in Table 6. Through Taguchi analysis, researchers determined the optimal parameter combination for minimizing Sw and CoF. The study revealed that the most effective combination includes C = 9%, L = 20 N, Sr = 150 RPM, and Ds = 90 m, resulting in the lowest responses (Figure 3). This indicates excellent wear resistance in the composite material, rendering it suitable for applications where friction and wear are critical considerations.

Table 6. Wear test result.

C (%)	L (N)	Sr (RPM)	Ds (m)	CoF	Sw (mm^3/Nm)
3	20	90	50	0.26	6.4
3	25	120	70	0.28	5.8
3	30	150	90	0.33	4.8
6	20	120	90	0.19	8.2
6	25	150	50	0.12	10.51
6	30	90	70	0.12	10.49
9	20	150	70	0.11	3.2
9	25	90	90	0.21	4.3
9	30	120	50	0.18	5.09

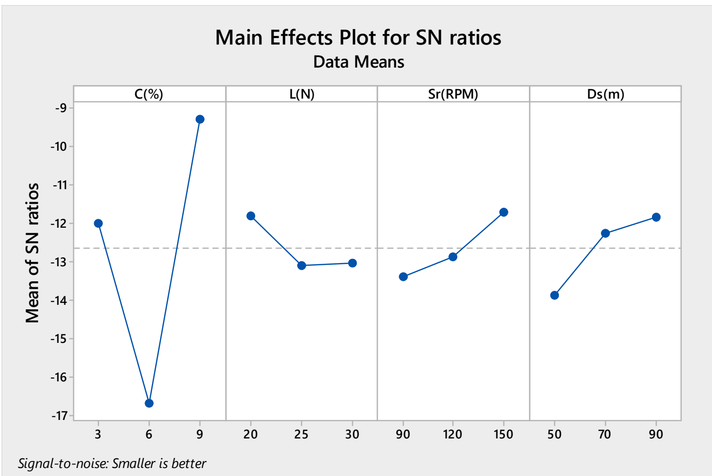

Figure 3. Optimization result.

A linear regression analysis was performed using MINITAB statistical tool to obtain a scientific equation for the responses. Equation (1) shows the equation for the specific wear rate (Sw), while Equation (2) illustrates the equation for the coefficient of friction (COF).

$$\text{Sw } (\text{mm}^3/\text{Nm}) = 10.4 - 2.45\text{ C} + 0.086\text{ L} - 0.0149\text{ Sr} - 0.0392\text{ Ds} \quad (1)$$

$$\text{CoF} = 0.186 - 0.2056\text{ C} + 0.00233\text{ L} - 0.000167\text{ Sr} + 0.00142\text{ Ds} \quad (2)$$

Following the determination of the optimal combination, an experiment was conducted, with results closely matching the predicted values obtained from regression analysis (Table 7). This confirms the reliability of the regression model in forecasting composite material behavior under different conditions. These findings demonstrate that composition, load, rotational speed, and sliding distance have a substantial impact on composite material responses. Optimizing these factors can enhance performance and prolong the composite material's service life.

Table 7. Wear test result.

Optimal Grouping	Experimental		Predicted	
	Sw (mm^3/Nm)	**CoF**	**Sw (mm^3/Nm)**	**CoF**
C = 9%, L = 20 N, Sr = 150 RPM, and Ds = 90 m	2.2	0.1	2.4	0.12

Scanning electron microscopy (SEM) analysis was conducted to study the surface morphology and wear mechanism of the material. The SEM image in Figure 4 provides insights into the wear patterns of the composites. At a 3% silica composition, severe wear is evident with prominent pits and grooves. This is attributed to the decreasing stiffness and increased particle size of silica at higher compositions, making the composite more prone to wear. Conversely, at a 9% silica composition, the wear track is less severe, with less prominent pits and grooves. This results from the increased stiffness and smaller particle size of silica, making the composite more wear resistant. Artificial neural network (ANN), a machine learning technique, is employed to forecast composite responses. The process involves data collection for input and output variables, with data separated into training and testing sets.

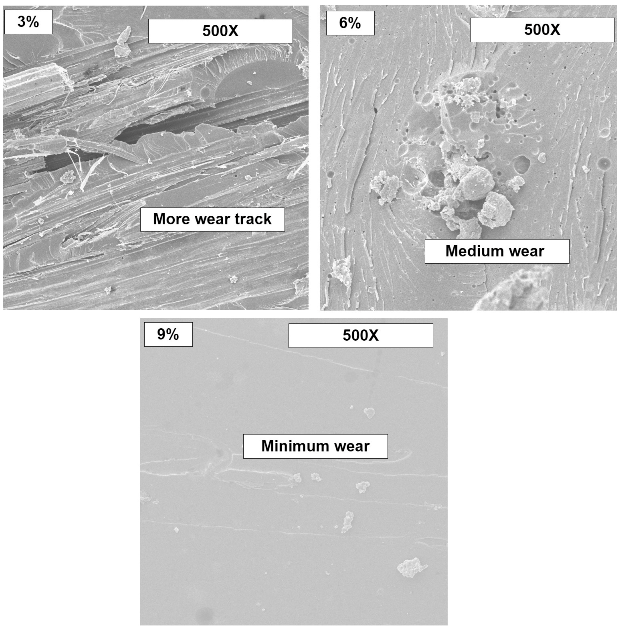

Figure 4. Result of SEM analysis.

The neural network structure is established, comprising three layers: the first layer with four neurons (matching the input variables), the second layer with eight neurons, and the third layer with two neurons (matching the output variables). The activation functions used are hyperbolic tangents for the first and second layers and a linear tangent for the third layer. The network is trained with the training dataset, utilizing the backpropagation method to optimize weights and biases. Training continues until the difference between predicted and actual outputs is minimized.

Performance is assessed with the testing dataset, where network predictions are compared to actual outputs for accuracy. The optimized network is then used to forecast output variables for new input data, resulting in a 100% prediction accuracy, as shown in Figure 5.

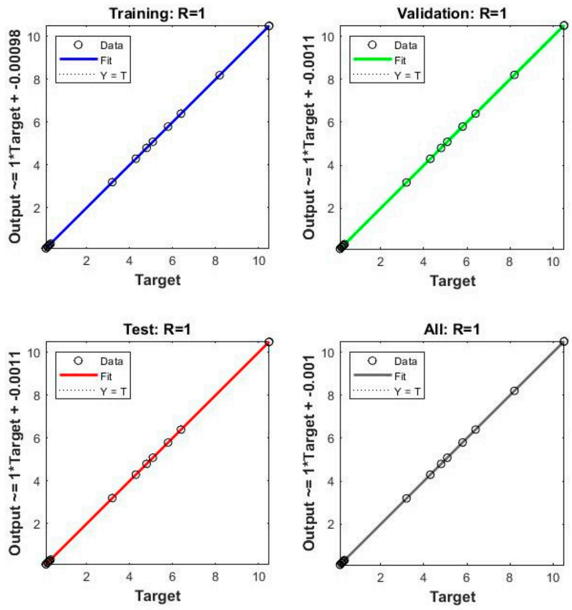

Figure 5. ANN accuracy in predicting the responses.

4. Conclusions

In summary, this research successfully demonstrates the positive impact of silica nanoparticle incorporation in jute fiber-reinforced composites.

- Silica nanoparticle inclusion in jute fiber-reinforced composites significantly enhances mechanical properties and reduces wear, as validated through Taguchi experiments and regression analysis, with an optimal composition of 9% silica, 20 N load, 150 RPM disc speed, and 90 m sliding distance, highlighting method effectiveness.
- The close alignment between predicted and experimental results underscores the predictive model's reliability, while SEM analysis reveals varying wear patterns at different silica concentrations, with 3% showing the most significant wear and 9% displaying superior wear resistance.
- The research emphasizes the potential of silica nanoparticles to improve the tribological properties of jute composites, making them suitable for diverse industries. The resulting composite, characterized by enhanced strength, stiffness, and wear resistance, is positioned to replace traditional materials in sectors like the automotive, aerospace, and construction industries. Its cost-effectiveness and eco-friendliness render it an attractive alternative to synthetic fibers in applications such as pipes, panels, and packaging materials, augmenting its versatility.

Author Contributions: Conceptualization, M.V.; methodology, M.T.; validation, M.V.; investigation, M.T.; data curation, M.T.; writing—original draft preparation, M.T.; writing—review and editing, M.T.; supervision, M.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not Applicable.

Informed Consent Statement: Not Applicable.

Data Availability Statement: All data are available in the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ramesh, M.; Palanikumar, K.; Reddy, K.H. Plant fibre based bio-composites: Sustainable and renewable green materials. *Renew. Sustain. Energy Rev.* **2017**, *79*, 558–584. [CrossRef]
2. Gnanavel, M.; Maridurai, T.; Km, K. Mechanical, thermal and dielectric behaviour of C-class fly-ash coarse and fine particles reinforced epoxy resin composite. *Mater. Res. Express* **2019**, *6*, 095507. [CrossRef]
3. Jayabalakrishnan, D.; Jayaseelan, V.; Patil, P.P.; Ramesh, B.; Bhaskar, K. Mechanical, wear, and dielectric properties of opuntia cladode fiber and pearl millet biochar-reinforced epoxy composite. *Biomass Convers. Biorefinery* **2022**, 1–11. [CrossRef]
4. Poomathi, S.; Roji, S.S.S. Experimental investigations on Palmyra sprout fiber and biosilica-toughened epoxy bio composite. *Biomass Convers. Biorefinery* **2022**, 1–9. [CrossRef]
5. Imamura, W.; Coelho, A.A.; Kupfer, V.L.; Carvalho, A.M.G.; Zago, J.G.; Rinaldi, A.W.; Favaro, S.L.; Alves, C.S. A new type of magnetocaloric composite based on conductive polymer and magnetocaloric compound. *J. Magn. Magn. Mater.* **2017**, *425*, 65–71. [CrossRef]
6. Gnanavel, M.; Maridurai, T. Effect of surface modification and particle size on dielectric properties of iron(III)oxide-epoxy composite film. *Dig. J. Nanomater. Biostruct.* **2018**, *13*, 39–48.
7. Lu, C.C.; Headinger, M.H.; Majidi, A.P.; Chou, T.W. Fabrication of a NicalonTM fiber/Si3N4-based ceramic-matrix composite by the polymer pyrolysis method. *J. Mater. Sci.* **2000**, *35*, 6301–6308. [CrossRef]
8. Ernest, E.M.; Peter, A.C. Application of selected chemical modification agents on banana fibre for enhanced composite production. *Clean. Mater.* **2022**, *5*, 100131. [CrossRef]
9. Senthilkumar, K.; Chandrasekar, M.; Alothman, O.Y.; Fouad, H.; Jawaid, M.; Azeem, M.A. Flexural, impact and dynamic mechanical analysis of hybrid composites: Olive tree leaves powder/pineapple leaf fibre/epoxy matrix. *J. Mater. Res. Technol.* **2022**, *21*, 4241–4252. [CrossRef]
10. Sirajunisha, H.; Balakrishnan, T.; Sakthivel, P.; Krishnaveni, A. Enhanced corrosion resistance, antibacterial and biological properties of sol-gel derived Ti-rGO-HAp nanocomposites. *Chem. Phys. Impact* **2023**, *6*, 100159. [CrossRef]
11. Stalin, B.; Ravichandran, M.; Karthick, A.; Meignanamoorthy, M.; Sudha, G.T.; Karunakaran, S.; Bharani, M. Investigations on Microstructure, Mechanical, Thermal, and Tribological Behavior of Cu-MWCNT Composites Processed by Powder Metallurgy. *J. Nanomater.* **2021**, *2021*, 3913601. [CrossRef]
12. Arpitha, G.R.; Jain, N.; Verma, A.; Madhusudhan, M. Corncob bio-waste and boron nitride particles reinforced epoxy-based composites for lightweight applications: Fabrication and characterization. *Biomass Convers. Biorefinery* **2022**, *6*, 0123456789. [CrossRef]