Radius: Journal of Science and Technology
Vol. 3, Issue 1, (2026) 261001 (15pp)

Study of the Wear & Tear Behavior of Resin-based Composites Reinforced with Al_2O_3 Ultrafine nanoparticles and Metal Wires applying DOE Techniques

Sunita Kumari[1] | Haris Arquam[2,*] | Raja Kumar[2] | Jaidev Kumbhakar[3] | Ajit Bahadur Verma[2]

[1]Department of Physics, Govt. Shakambhar P. G. College, Sambhar–Lake, Jaipur – 303604, Rajasthan (India)
[2]Department of Mechanical Engineering, Arya College of Engineering, Jaipur – 302028, Rajasthan (India)
[3]Department of Mechanical Engineering, Cambridge Institute of Polytechnic, Ranchi – 835103, Jharkhand (India)

*Corresponding author: harisarquam@aryacollegejpr.com

Abstract: The scientists investigate the mechanical characteristics of an epoxy-based biodegradable composite material reinforced with Al_2O_3 ultrafine particles and metal wires, and uses design of experiments (DOE) and simulation techniques to optimize its attributes. The Al_2O_3 nano powder was characterized by SEM and used in weight percentage of 0-5% to create composites with 50-100 nm nanoparticles. ANN models were trained on the resulting data to estimate the tensile strength and moisture absorbing behavior of the composite under different conditions, with mean absolute errors of 5% and 10% for the training and test sets respectively. The data demonstrate the effectiveness of computational learning in predicting the material properties of natural/jute composite materials and optimizing their design. Overall, this research paper provides valuable observation into the use of Al_2O_3 ultrafine nanoparticles and metal wire reinforcement for enhancing the overall material properties of biodegradable epoxy-based composites.

Keywords: Material Properties, Resin, Ultrafine Nano Particle, Simulation, ANN, Error analysis

1. Introduction

Epoxy resin composites (ERCs) are an extensively used class of materials in diverse industries such as automobile, gaming industry, aerospace, satellite, marine, building construction, biomedical, and others. The embedding of reinforcements into the epoxy resin matrix improves the characteristics of the resulting composite, making it more suitable for a diverse area of applications. The reinforcements enhance the mechanical characteristics of the matrix material, resulting in best performance in the composite. When two or more than two agents combine to produce greater effect of the reinforcement and matrix results in a structure that is tough and stronger than the individual components alone **[1-5]**.

Natural fiber reinforced multiphase are an area of research interest due to their decomposable nature, abundance, light weight, low cost, high tensile strength, & durability. Even so, poor

https://doi.org/10.5281/zenodo.19260652
Received: 18 January 2026 | **Revised:** 07 March 2026
Accepted: 12 March 2026 | **Published Online:** 30 March 2026

quality of fiber-matrix connection and considerable water absorption, can't limit their utilization. Nevertheless, filling epoxy with various fillers in appropriate ratio and curing the mixture can harness the chemical and physical properties of both epoxy-resin and fillers. For instance, a natural fiber reinforcing mat introduced in PCL, a biocompatible polymer, resulted in significant improvements in bending and tensile strengths. As well as, a PLA composite reinforced with natural fibers showed improved flexural and stiffness to elastic deformation. Although natural fiber reinforced composites show great potential in various applications, further research is required to improve their properties and overcome their limitations **[6-10]**.

Studies have given results the effects of incorporating various fillers, such as $CaCO_3$ and ZnO ultrafine nanoparticles, into jute/epoxy composites **[11]**. The results showed significant improvements in the mechanical characteristics and dynamic nature of the composites. Another study investigated the effect of altering the weight percentage of TiO_2 nanoparticles **[12]** in epoxy on the tensile and dynamic mechanical characteristics of the composite. The enhancement of mechanical characteristics was observed up to 7.5%wt. functionally graded and TiO_2-reinforced epoxy composites had a significant impact on the material's bending strength, tensile modulus, and inter laminar durability, regardless of the strength of the homogeneous composites. Tri-biological behavior of natural fiber/jute & epoxy composites was investigated at different orientations of jute mats, and the results indicated highly promising effects on wear and frictional performance. The mechanical properties and abrasion behavior of natural fiber reinforced composites with varied fiber alignment and the inclusion of titanium dioxide were also determined **[13]**.

Epoxy is a commonly used matrix substance in the field of composites manufacturing due to its ability to form strong bonds with natural fibers, low cost, and effortlessly of acquisition in the form of resin. This has led to worldwide usage of epoxy in reinforcing natural/jute fibers. Additionally, its rapid cooling properties allow for the creation of a diverse range of composite products with high load-bearing capacity **[14-20]**.

This study aimed to examine the effects of incorporating metal wire and Al_2O_3 nanoparticle filler materials on the physio-mechanical characteristics and wear properties of epoxy composite. The MW was handled with anti-oxidant chemicals, and the effect of this processing was examined. The Taguchi approach was employed for experimental design, using a matrix of four parameters with four levels. The primary attention of the research was on to improve the mechanical toughness, with further analysis utilizing simulation tools for estimating the machining capability of the developed composite, and used optimization methods for calibrating these properties [**21-25**].

The quality of being individual in this activity lies in the use of metal wire reinforcement along with aluminum oxide ultrafine nanoparticles to improve the tensile strength and stiffness of the composite material. The research also employs artificial neural networks to judge the mechanical characteristics of the composite material, which is a unique approach in the field. The results showed that the metal wire and nanoparticle reinforced composite had a better tensile strength and stiffness of elasticity than the nanoparticle-only composite, demonstrating the potential of this reinforcement method. Additionally, the employ of simulation software to estimate the mechanical characteristics of the composite gives the valuable insights for future composite design.

2. Material and Methods

For this study, the composite material selected was Epoxy Resin (LY-556), due to its unique mechanical, thermal, and anti-corrosion characteristics, with moisture resistant quality as supported by research have done in the past. The composite material was produced by doping the epoxy resin and hardener (HY-951) in a specific ratio of 10:1, as detailed in Table 1, with both materials sourced from the online website the name was Sigma-Aldrich. To improve the chemical and mechanical characteristics of the hybrid, reinforcing components such as Al_2O_3 ultrafine nanoparticles and chemically subjected metal wire (MW) were added. The grain size distribution measurements showed that the average grain size of the Al_2O_3 nanoparticles was between 50 to 100 nm. The ratio of this specific combination of matrix material and reinforcement components is expected to result in significant enhancement in the overall efficiency of the resin based composite material, including mechanical toughness, stiffness, thermal stability, resistance to corrosion & reduce moisture absorbing capacity.

Table 1: Physical & Chemical Properties of the Epoxy Resin (LY-556) and it's Hardener (HY-951) [**26**, **27**]

Physical & Chemical Property	Specifications	LY-556	HY-951	Unit
Density	ISO 1675	1.15-1.20	0.97-0.99	gm/cc
Viscosity	ISO 12058	10k-12k	10-20	mPa.s
Flash Point	ISO 2719	>200	>180	C
Ultimate Tensile Strength	-	82	50	MPa
Color	-	Clear Transparent	Clear Transparent	-

Table 2 presents the material descriptions used for resin based composite fabrication, providing a comprehensive list of all components used in this research.

Table 2: Materials Description required for fabrication of Composite

Constituents	Specifications	Purchase
Epoxy	LY-556	Online Supplier Sigma-Aldrich
Hardener	HY-951	Online Supplier Sigma-Aldrich
Nano Particle (As Filler)	Al_2O_3 (Approx 50-100 nm)	Online Supplier Sigma-Aldrich
Reinforcement	Metal Wire (Size 0.2 mm)	Online Supplier Sigma-Aldrich

In this research, a metal wire with a thickness of 0.2 mm was selected as reinforcement for the resin based composite material, procured from the online supplier Sigma-Aldrich. The thickness of the wire was measured by using a micrometer to ensure precision, as it was a critical factor in determining its appropriateness for the considered application. Wires of different lengths ranging from 10 mm to 50mm were cut after measurement to be utilized as reinforcement in the resin based composite material.

The composite material was reinforced with Al_2O_3 ultrafine nanoparticles, known for their outstanding tensile strength, stiffness and thermal characteristics. Figure 1 presents the particle distribution TEM images of these ultrafine nanoparticles, which demonstrate the dispersal of grain sizes in the resin based composite material. The figure shows that the average size of the nanoparticles falls within the range of 50 nm to 100 nm SEM. The use of nanoparticles as reinforcement in composite materials has gained significant consideration in recent time periods due to their exceptional properties. The small particle size of nanoparticles results in an increased surface area, leading to improved mechanical properties such as increased strength and durability. Additionally, the use of nanoparticles also results in enhanced thermal properties, making the composite material more heat-resistant.

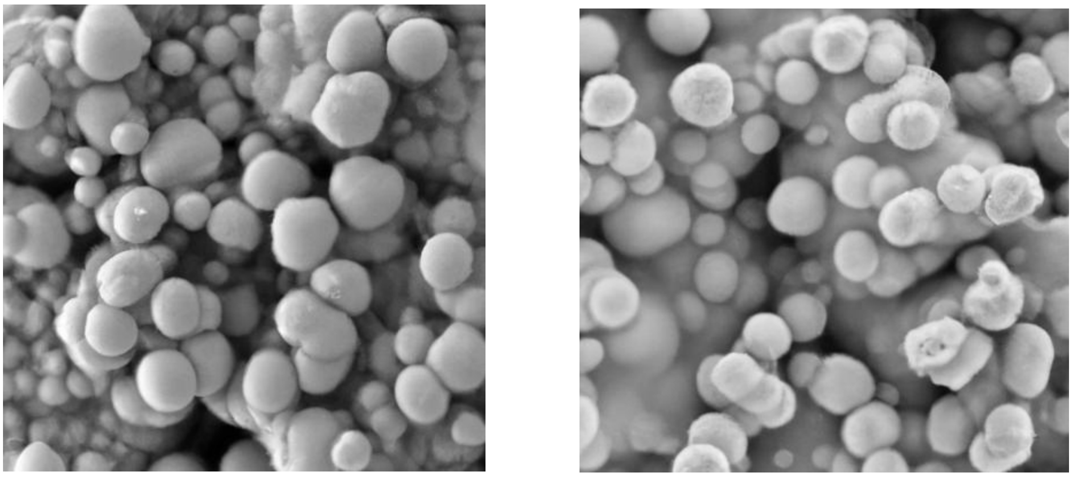


Figure 1: TEM images of Nanoparticle Al_2O_3 and refined with image processing software ImageJ **[28]**

2.1 Treatment of Metal Wires (MW) to prevent Corrosion

The metal wire selected for the present study was made of cu, so there was possibility of the corrosion of the wires, so proper hot-dip galvanization process was adopted for the present study. Corrosion can degrade the surface of the wire, reduce its mechanical toughness, and affect its electrical and structural parameters. Therefore, it was necessary to apply a suitable corrosion protection technique to enhance the durability and reliability of the wire during experimentation. In this study, a proper hot-dip galvanization process was adopted as a protective method. This process involves coating the metal surface with a protective zinc layer, which acts as a protective layer against corrosion. The method was selected based on previous studies **[29-31]**.

2.2 Controlling Parameters and Their Levels

In this research, a reinforced material was manufactured using a Design of Experiment (DOE) methodology. This perspective involved the ordered sampling of components and confirmation of their standard according to DOE guidelines. The final and last selections of approach made for the factors and levels used in the research have been compiled in Table 3. The use of Design of Experiment (DOE) makes sure that the selection of components and quantities was done in a controlled, systematic & standard manner, resulting in accurate, precise and reliable results. Moreover, this method allowed for the discovery of significant factors and their corresponding proportions that may affect the characteristics of the resin based composite material. Altogether, the utilization of Design of Experiment (DOE) in this investigation provided a thorough and comprehensive analysis of the resin based composite material fabrication process.

Table 3: Regulating Factors with Levels

Coded Name	Factors/Levels	I	II	III	IV
A	Al_2O_3 (wt%)	1	1.5	2.0	2.5
B	MW Length (mm)	10	20	30	40
C	Load (kg)	1.0	1.5	2.0	2.5
D	Speed (RPM)	300	350	400	450

2.3 Composite Fabrication (Hand Lay-Up Method)

To fabricate the resin based composite material, epoxy (LY-556) and hardener (HY-951) were mixed in a ratio of 10:1 and exposed to magnetic stirring for 15-20 minutes **[1]**. The resin-based composite was arranged in layers and compressed to form a straight composition applying the hand lay-up method **[32]**. The molds used in this method were in sheet form and made of silicon rubber sourced from online supplier Sigma-Aldrich. Once the epoxy and hardener mixture were prepared to use, it was poured into the mold and layers of resin-based composite were added based on the empirical standard design. The mold was then permitted to establish itself at ambient temperature for over 24 hours. More than two samples were fabricated for each mixture tested. After one day, the samples/specimens were extract from the mold, and test specimens were ready in accordance with American Society for Testing & Materials (ASTM) standard **[33-35]**.

Table 4: Total weight of the ingredient required for fabrication of composite

Ex. No.	Al_2O_3 (gm)	MW (gm)	ER (gm)	Total wt. (gm)
1	1	30	119	150
2	1	30	119	150
3	1	30	119	150
4	1	30	119	150
5	1.5	30	119	150
6	1.5	30	119	150
7	1.5	30	119	150
8	1.5	30	119	150
9	2	30	118.5	150
10	2	30	118.5	150
11	**2**	30	118.5	150
12	**2**	30	118.5	150
13	2.5	30	118	150
14	2.5	30	118	150
15	**2.5**	30	118	150
16	**2.5**	30	118	150

The aim of this research was to fabricate a resin based composite material using three components: Al_2O_3 ultrafine nanoparticles, epoxy resin/poly-epoxide, and metal wire. Table 3 outlines the specific factors and properties used for these items. Only one of the key disputes faced during this research was ensuring an even quantity distribution within the composite. To address this issue, a fixed total weight of 150 grams was established for each composite sample. The individual weights of the various components used in the composite are provided in Table 4.

2.4 DOE-Taguchi Method

The Taguchi method was applied to create an experimental matrix for a study on the mechanical and wear behavior of composites. Four levels of each variable were chosen and the L-16 orthogonal array and MINITAB-18 statistical program **[36, 37]** were employed. The results were evaluated using the signal-to-noise ratio and the smaller-is-better quality measure was taken into evaluation for the study of Al_2O_3 and MW-reinforced composites. The final experiment result was presented in Table 5.

$$S/_N = -10 \log \frac{1}{n} (\sum_{i=1}^{n} y_i^2) \quad (1)$$

Where S/N shows the ratio of the signal to noise ratio (dB) of the response parameters, n is the experiment repetition for more precise results, y represents the response data for i^{th} experiment run (i).

Table 5: Experiment design by Taguchi method using L-16 orthogonal array

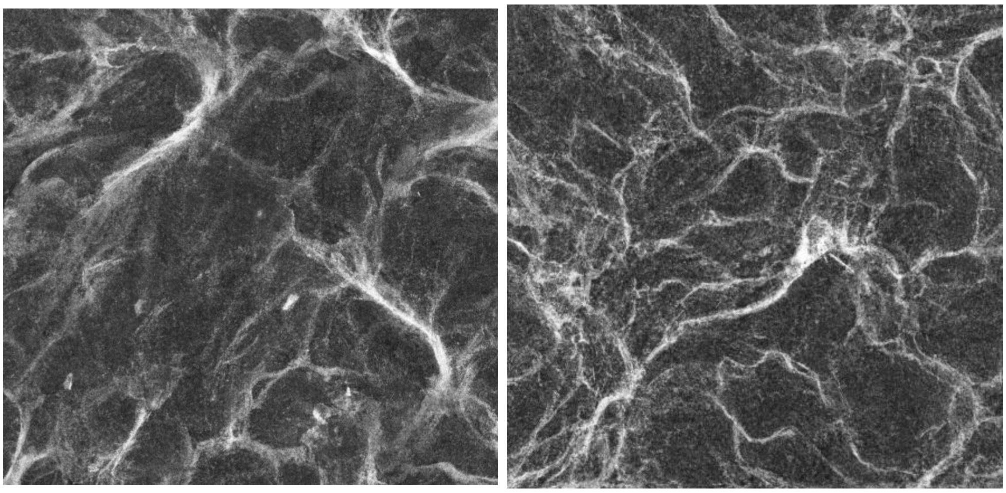
Run Order	A	B	C	D
	Al_2O_3	**MW Length**	**Load (kg)**	**Speed (RPM)**
1	1	10	1	300
2	1	20	1.5	350
3	1	30	2	400
4	1	40	2.5	450
5	1.5	10	1.5	400
6	1.5	20	1	450
7	1.5	30	2.5	300
8	1.5	40	2	350
9	2	10	2	450
10	2	20	2.5	400
11	**2**	30	1	350
12	**2**	40	1.5	300
13	2.5	10	2.5	350
14	2.5	20	2	300
15	**2.5**	30	1.5	450
16	**2.5**	40	1	400

3. Result and Discussion

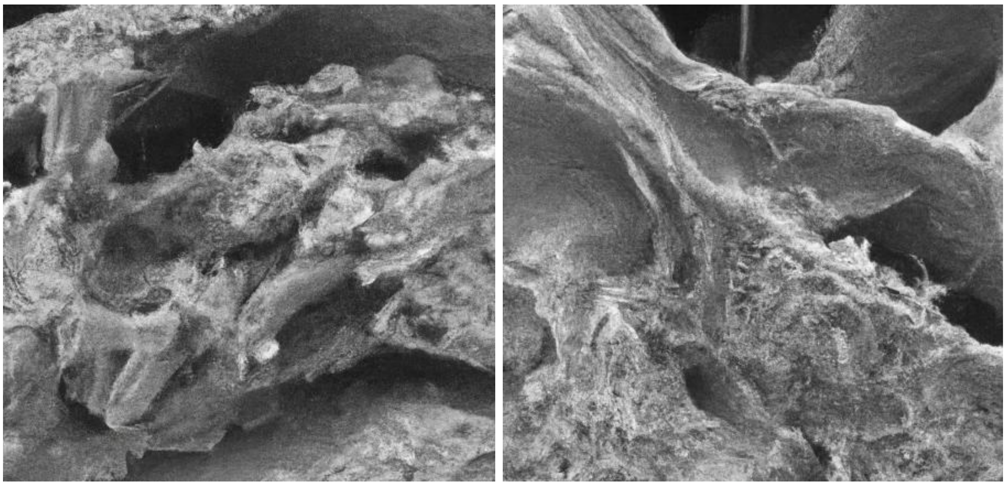
3.1 Micro Structure Investigation

The SEM image examination of the composite material disclose a combination of epoxy resin, Al_2O_3 nanoparticles, and metal wire reinforcement. This examination demonstrates the dispersal and band of the various components within the composite. The presence of nanoparticles and metal wire reinforcement recommend an improvement in the mechanical characteristics and strength of the composite. Additionally, the use of epoxy resin as a matrix material provides good adhesion and preservation to the reinforcement. Figure 2 displays the

SEM image examination of the neat composite made with epoxy resin earlier to tensile strength testing.



(a) Neat Epoxy SEM images for different samples



(b) Neat Epoxy SEM images for different samples after tensile testing fracture

Figure 2: SEM images of Neat Composite made by ER and processed by software ImageJ **[38]**

3.2 Specific Wear Investigation

The investigation of the sliding wear specification of a composite material was performed in accordance with the ASTM G-99-17 norms **[39]**. The composite specimen was applied by surface finishing method like polished and cleaned, then pressed against a steel disc with an HRC-65 finish **[1]**. To examine the sliding wear nature, the normal load was kept in accordance with the orthogonal array, and the speed was also regulated accordingly. The wear rate of the composite specimen was determined using equation 2. The outcomes of the wear examination are elaborated as signal-to-noise ratios and listed in Table 6, where the specific wear rate was intended based on the equation provided.

$$Specific\ Wear\ Rate = \frac{\Delta m}{\rho_{com}.speed.Time.F_{load}} \quad (2)$$

Table 6: Specific Wear rate analysis of composite L-16 experiment. **A**: Wt% of Al_2O_3, **B**: Metal Wire Length, **C**: Load, **D**: Rotation Speed

Run Order	A	B	C	D	Specific Wear Rate ($mm^3/N\cdot m$)	S/N Ratio
1	1	10	1	300	2.46	-7.8187
2	1	20	1.5	350	2.58	-8.2324
3	1	30	2	400	3.27	-10.2910
4	1	40	2.5	450	3.46	-10.7815
5	1.5	10	1.5	400	2.69	-8.5950
6	1.5	20	1	450	3.05	-9.6860
7	1.5	30	2.5	300	2.25	-7.0437
8	1.5	40	2	350	2.55	-8.1308
9	2	10	2	450	2.55	-8.1308
10	2	20	2.5	400	2.51	-7.9935
11	**2**	30	1	350	1.87	-5.4368
12	**2**	40	1.5	300	1.66	-4.4022
13	2.5	10	2.5	350	1.81	-5.1536
14	2.5	20	2	300	1.72	-4.7106
15	**2.5**	30	1.5	450	1.81	-5.1536
16	**2.5**	40	1	400	1.72	-4.7106

The main effect plots for all controlling factors are shown in Figure 3.

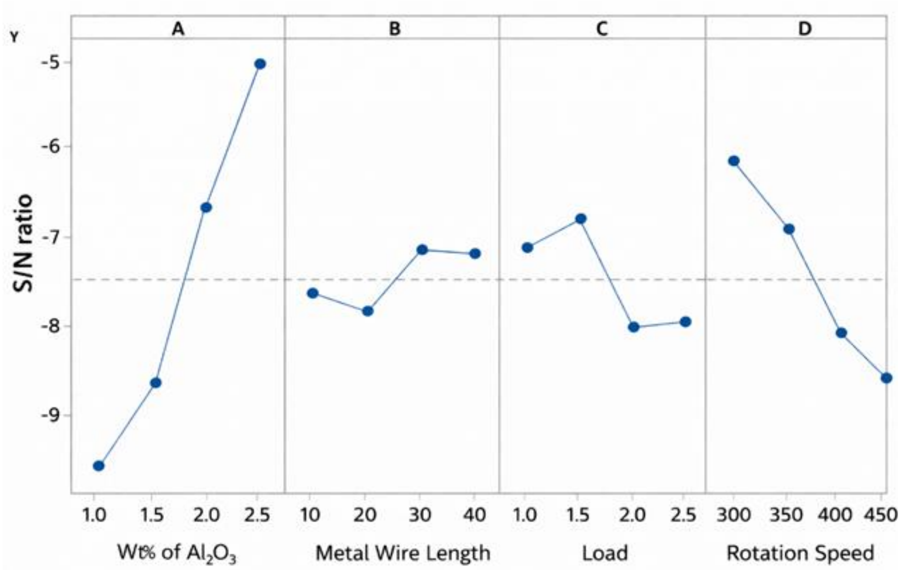


Figure 3: Signal to noise ratio analysis of specific wear rate (Smaller is better)

The signal-to-noise ratio (SNR) gives precious insight into the impact of control elements such as the weight percentage of Al_2O_3, metal wire length, load, and speed on the sp. wear rate. The importance of each control element can be understood by examining the difference between the maximum and minimum means of SNR. The greater the difference between the means, the more dominant the control element tends to be **[40]**. Table 7 outlines the effect of numerous control factors on wear rate.

According to the ranking, the weight percentage of Al_2O_3 ultrafine nano particles has the greatest impression on the wear of composites, while metal wire has the minimum impact. Rotation speed of the disk is the second most valuable characteristic affecting wear rate.

Table 7: Specific Wear rate analysis of composite L-16 experiment. **A**: Wt% of Al_2O_3, **B**: Metal Wire Length, **C**: Load, **D**: Rotation Speed

Level	**A**	**B**	**C**	**D**
1	-9.281	-7.425	-6.913	-5.994
2	-8.364	-7.656	-6.596	-6.738
3	-6.491	-6.981	-7.816	-7.898
4	-4.932	-7.006	-7.743	-8.438
Delta	4.349	0.674	1.220	2.444
Rank	**1**	**4**	**3**	**2**

The main effect plots for all controlling factors are shown in Figure 4.

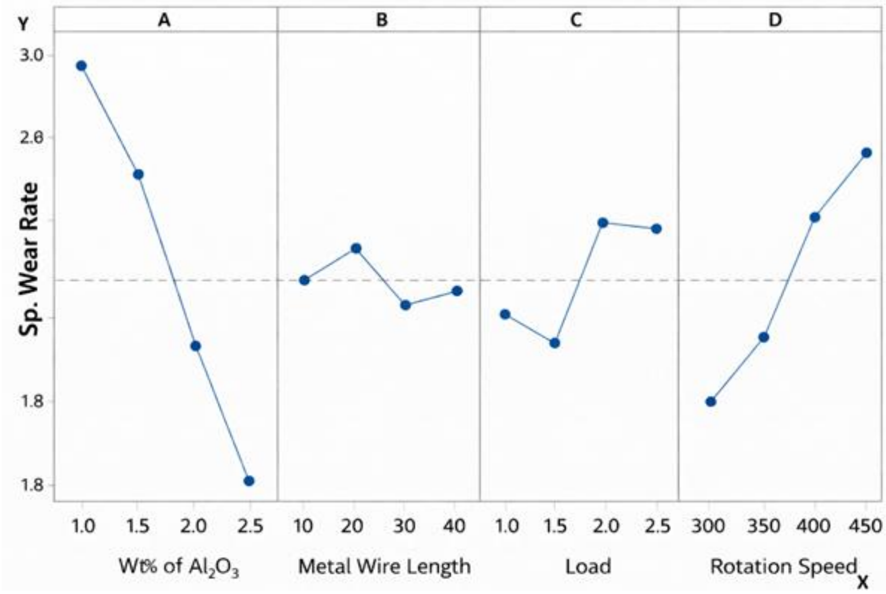


Figure 4: Mean analysis of specific wear rate

The specific wear rate analysis of the L-16 experimental design shows that factor A (Wt% of Al_2O_3) has the highest significant influence on wear behavior, as evidenced by the highest delta value (4.349) and rank 1. Figure 4, which shows the specific wear rate trends, factor A shows a intense decreasing pattern from level 1 to level 4, shows that increasing the Al_2O_3 content significantly reduces the wear rate and enhance wear resistance. Factor D (Rotation Speed) has the second highest effect (delta = 2.444), and the figure shows a notable increase in wear rate with increasing speed. Factor C (Load) reveal a tolerable influence (delta = 1.220), with tiny alteration across levels, while B (Metal Wire Length) shows minimal impact (delta = 0.674) with relatively small variation in wear rate. Overall, organized results and Figure 4 confirm that reinforcement content is the governing factor controlling specific wear rate.

3.3 Enhancement of Specific Wear Rate using ANN

The research explains the study on the properties of composite materials fabricate of epoxy with nano particle Al_2O_3 and reinforced by metal wire. The study employs a design of experiments (DOE) approach and uses simulation techniques to enhance the composite material properties. The research focuses on the use of artificial neural networks (ANNs) and compares the presentation of three different activation functions. The activation functions considered in the study are sigmoid, hyperbolic tangent, and rectified linear unit (ReLU). The outcomes of the research explained that the ANN models using ReLU activation function outperformed the models using sigmoid and hyperbolic tangent activation functions in terms of prediction accuracy and robustness. The results suggest that ReLU activation functions are well suited for modeling complex relationships in composite materials, such as those present in the epoxy with ultrafine nano particle Al_2O_3 and reinforced by metal wire composite. The research provides valuable insights into the enhancement of composite materials using simulation-based regression approaches and demonstrates the potential of ANNs as a predictive tool for material science applications. The neural network-based regression selected for the present research paper was shown in Table 8 for three activation functions selected.

Table 8: Neural Network Regression for different Activation Functions

S. No.	AF	HL	Nodes	N (Train)	N (Validation)	N (test)	MSE Validation	MSE Test
1	Logistic Sigmoid	8	39	10	3	3	0.869	1.642
2	hyperbolic tangent	3	23	10	3	3	0.126	2.194
3	ReLU	7	36	10	3	3	0.195	0.562

In this research the regression-based enhancement was performed using Neutral network-based simulation techniques. In this research it was shown that in mechanical based study the number of test data was limited, so it was important to check the accuracy level of simulation methods in this type of conditions. So, in present study three different most common activation functions was used for compare with each other and the compression-based outcomes was present in Tables 8 and 9.

Table 9: Neural Network Regression Evaluation Metrics

Description	Logistic Sigmoid	hyperbolic tangent	ReLU
MSE	1.642	2.194	0.562
RMSE	1.281	1.481	0.75
MAE/MAD	1.065	1.466	0.671
MAPE	76.39%	283.84%	79.97%
R2	0.997	0.647	0.713

The network structure selected for the present study was shown in Figure 5 for all three cases selected for the ML modeling.

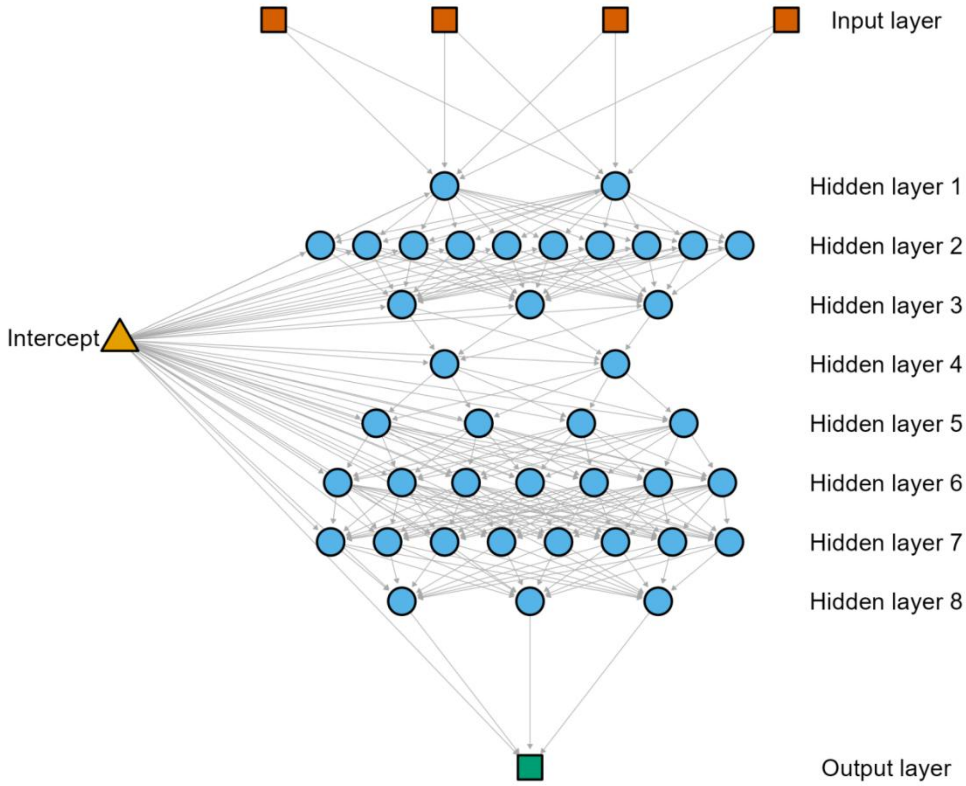


Figure 5: Network Structure Plot for ANN regression modeling in present research

ReLU is a common activation function used in deep learning. It has earned popularity due to its simplicity and effectiveness in giving better results compared to other activation functions such as the logistic sigmoid and hyperbolic tangent. ReLU is a piecewise linear function that returns the input if it is positive and 0 if it is negative. This makes it computationally efficient and helps to keep away the vanishing gradient problem that is present in the sigmoid and tanh (hyperbolic tangent) activation functions. Moreover, ReLU has been shown to converge faster in deep neural networks than other activation functions, leading to faster training times and improved precision. Overall, ReLU's simplicity, efficiency, and improved performance have made it a popular choice for deep learning models.

4. Conclusion

This paper investigates the mechanical characteristics of a reinforced material that consists of aluminum oxide metal nanoparticles, epoxy, and metal wire reinforcement. The study suggests that the optimal Al_2O_3 nanoparticles weight percentage should be within the range of 0 to 5%, and SEM is used to measure the grain size of the Al_2O_3 ultrafine nanoparticles. The research also tests the tensile strength and elasticity of the Al_2O_3 nanoparticle and metal mesh wire, disclosing that the use of 1 mm wire in the composite produces an augmented tensile strength compared to the nanoparticles only composite. The introduction of nanoparticles significantly improves the tensile strength, elasticity and toughness particularly when combined with metal wire reinforcement. The use of simulation allows for the prediction of the composite's tensile strength, with a mean absolute error of 5% for the training set and 10% for the test set. This research shows the future scope and potential of machine learning in the design of hybrid resin based composite materials.

The fabrication method of the epoxy resin composites exploits the hand lay-up technique, which show beyond doubt to be highly productive and successful. However, the process needs highly skilled engineers and is therefore challenging, and the Taguchi method was used to construct the experiment results for the composite's work parts. The results indicated that the weight % of Al_2O_3 nano particle had play the most significant role on wear, while the effect of metal wire on wear rate was minimum. Additionally, the rotational speed of the disk was found to be the second most notable factor affecting wear rate.

On the whole, this research focusses on the potential of fabrication metal nanoparticles and metal wire reinforcement in the progress of hybrid resin based composite materials. The results shown the importance of optimizing the volume ratio of Al_2O_3 nanoparticles and the impact of reinforcement/doping on the mechanical characteristics of the resin based composite material. The use of simulation to predict mechanical properties offers a valuable tool for improve the composite design and optimization.

References

1. Li, C., Fei, J., Zhang, T., Zhao, S., & Qi, L. (2023). Relationship between surface characteristics and properties of fiber-reinforced resin-based composites. *Composites Part B: Engineering*, *249*, 110422. https://doi.org/10.1016/j.compositesb.2022.110422
2. Xia, Y., Zhang, F., Xie, H., & Gu, N. (2008). Nanoparticle-reinforced resin-based dental composites. *Journal of dentistry*, *36*, 450-455. https://doi.org/10.1016/j.jdent.2008.03.001
3. Ilie, N. (2021). Microstructural dependence of mechanical properties and their relationship in modern resin-based composite materials. *Journal of dentistry*, *114*, 103829. https://doi.org/10.1016/j.jdent.2021.103829
4. Jandt, K. D., & Sigusch, B. W. (2009). Future perspectives of resin-based dental materials. *Dental Materials*, *25*, 1001-1006. https://doi.org/10.1016/j.dental.2009.02.009
5. Kahler, B., Kotousov, A., & Swain, M. V. (2008). On the design of dental resin-based composites: a micromechanical approach. *Acta biomaterialia*, *4*, 165-172. https://doi.org/10.1016/j.actbio.2007.06.011
6. Rafique, I., Kausar, A., & Muhammad, B. (2016). Epoxy resin composite reinforced with carbon fiber and inorganic filler: Overview on preparation and properties. *Polymer-Plastics Technology and Engineering*, *55*, 1653-1672. https://doi.org/10.1080/03602559.2016.1163597
7. Zhao, X., Zhang, Z., Pang, J., & Su, L. (2023). Preparation of carbon fibre-reinforced composite panels from epoxy resin matrix of nano lignin polyol particles. *Journal of Cleaner Production*, *428*, 139170. https://doi.org/10.1016/j.jclepro.2023.139170
8. Keulemans, F., Palav, P., Aboushelib, M. M., van Dalen, A., Kleverlaan, C. J., & Feilzer, A. J. (2009). Fracture strength and fatigue resistance of dental resin-based composites. *Dental Materials*, *25*, 1433-1441. https://doi.org/10.1016/j.dental.2009.06.013
9. Curtis, A. R., Shortall, A. C., Marquis, P. M., & Palin, W. M. (2008). Water uptake and strength characteristics of a nanofilled resin-based composite. *Journal of dentistry*, *36*, 186-193. https://doi.org/10.1016/j.jdent.2007.11.015
10. Li, X., Pongprueksa, P., Van Meerbeek, B., & De Munck, J. (2015). Curing profile of bulk-fill resin-based composites. *Journal of dentistry*, *43*, 664-672. https://doi.org/10.1016/j.jdent.2015.01.002
11. Li, Z., Wei, X., Gao, Z., Xu, J., Ma, P., & Wang, M. (2020). Manufacturing and mechanical characterisation of polyurethane resin based sandwich composites for three-dimensional fabric reinforcement. *Materials today communications*, *24*, 101046. https://doi.org/10.1016/j.mtcomm.2020.101046

12. Ahmadijokani, F., Alaei, Y., Shojaei, A., Arjmand, M., & Yan, N. (2019). Frictional behavior of resin-based brake composites: Effect of carbon fibre reinforcement. *Wear*, *420*, 108-115. https://doi.org/10.1016/j.wear.2018.12.098
13. Khaled, S. M. Z., Miron, R. J., Hamilton, D. W., Charpentier, P. A., & Rizkalla, A. S. (2010). Reinforcement of resin based cement with titania nanotubes. *Dental Materials*, *26*, 169-178. https://doi.org/10.1016/j.dental.2009.09.011
14. Li, X., Zhao, X., & Liu, Y. (2025). A resin-based perforated sound absorption composite reinforced with polyethylene geotextile: Research on UV resistance, aging resistance, chemical corrosion resistance, thermal stability and wear resistance. *Composites Communications*, *58*, 102536. https://doi.org/10.1016/j.coco.2025.102536
15. Wang, R., Zhang, M., Liu, F., Bao, S., Wu, T., Jiang, X., Zhang, Q., & Zhu, M. (2015). Investigation on the physical–mechanical properties of dental resin composites reinforced with novel bimodal silica nanostructures. *Materials Science and Engineering: C*, *50*, 266-273. https://doi.org/10.1016/j.msec.2015.01.090
16. Babu, T. N., Singh, R., & Dogra, S. (2018). Wear characteristics of epoxy resin based composites reinforced with aloe fibers in combination with Al2O3/SiC. *Materials Today: Proceedings*, *5*, 12649-12656. https://doi.org/10.1016/j.matpr.2018.02.248
17. Yi, G., & Yan, F. (2007). Mechanical and tribological properties of phenolic resin-based friction composites filled with several inorganic fillers. *Wear*, *262*, 121-129. https://doi.org/10.1016/j.wear.2006.04.004
18. Bandaru, A. K., Chouhan, H., Ma, H., Kothandan, D. K., & O'Higgins, R. M. (2026). Ballistic response of Elium® thermoplastic composites reinforced with high-performance fibres in monolithic and hybrid configurations. *Composites Part B: Engineering*, *309*, 113030. https://doi.org/10.1016/j.compositesb.2025.113030
19. Zhang, Z., Zhou, Y., Cai, L., Xuan, L., Wu, X., & Ma, X. (2022). Synthesis of eugenol-functionalized polyhedral oligomer silsesquioxane for low-k bismaleimide resin combined with excellent mechanical and thermal properties as well as its composite reinforced by silicon fiber. *Chemical Engineering Journal*, *439*, 135740. https://doi.org/10.1016/j.cej.2022.135740
20. Kerche, E. F., da Silva, V. D., Fonseca, E., Salles, N. A., Schrekker, H. S., & Amico, S. C. (2021). Epoxy-based composites reinforced with imidazolium ionic liquid-treated aramid pulp. *Polymer*, *226*, 123787. https://doi.org/10.1016/j.polymer.2021.123787
21. Hahnel, S., Dowling, A. H., El-Safty, S., & Fleming, G. J. (2012). The influence of monomeric resin and filler characteristics on the performance of experimental resin-based composites (RBCs) derived from a commercial formulation. *Dental Materials*, *28*, 416-423. https://doi.org/10.1016/j.dental.2011.11.016
22. Sekkat, H., Khallouqi, A., & Halimi, A. (2026). Characterization of lead-free epoxy resin composites reinforced with high-density fillers for X-Ray shielding applications. *Radiation Physics and Chemistry*, *240*, 113414. https://doi.org/10.1016/j.radphyschem.2025.113414
23. Wu, M., Chen, C., Peng, A., Zeng, Z., Zhang, Z., Liu, X., & Huang, Y. (2025). Self-catalyzed bio-benzoxazines containing phthalonitrile with high thermal stability and intrinsic flame retardancy as well as its composite reinforced by aramid fiber. *Polymer Degradation and Stability*, *242*, 111705. https://doi.org/10.1016/j.polymdegradstab.2025.111705
24. Yang, G., OuYang, Q., Ye, J., & Liu, L. (2022). Improved tensile and single-lap-shear mechanical-electrical response of epoxy composites reinforced with gridded nano-carbons. *Composites Part A: Applied Science and Manufacturing*, *152*, 106712. https://doi.org/10.1016/j.compositesa.2021.106712
25. Xia, J., Li, J., Zhang, G., Zeng, X., Niu, F., Yang, H., Sun, R., & Wong, C. (2016). Highly mechanical strength and thermally conductive bismaleimide–triazine composites reinforced by

Al2O3@ polyimide hybrid fiber. *Composites Part A: Applied Science and Manufacturing*, *80*, 21-27. https://doi.org/10.1016/j.compositesa.2015.09.009

26. Li, W., Huang, W., Kang, Y., Gong, Y., Ying, Y., Yu, J., Zheng J., Qiao L., & Che, S. (2019). Fabrication and investigations of G-POSS/cyanate ester resin composites reinforced by silane-treated silica fibers. *Composites Science and Technology*, *173*, 7-14. https://doi.org/10.1016/j.compscitech.2019.01.022
27. Borges, A. L., Münchow, E. A., de Oliveira Souza, A. C., Yoshida, T., Vallittu, P. K., & Bottino, M. C. (2015). Effect of random/aligned nylon-6/MWCNT fibers on dental resin composite reinforcement. *Journal of the mechanical behavior of biomedical materials*, *48*, 134-144. https://doi.org/10.1016/j.jmbbm.2015.03.019
28. Kaushik, V., Suresh, K., & Adusumalli, R. (2025). Structure–property relationships in 3D-printed onyx-based composites reinforced with continuous fibers: Role of temperature and fiber orientation. *Composites Part C: Open Access*, *18*, 100649. https://doi.org/10.1016/j.jcomc.2025.100649
29. Biswas, B., Bandyopadhyay, N. R., & Sinha, A. (2019). Mechanical and dynamic mechanical properties of unsaturated polyester resin-based composites. In *Unsaturated polyester resins* (pp. 407-434). Elsevier. https://doi.org/10.1016/B978-0-12-816129-6.00016-8
30. Yang, D. L., Sun, Q., Niu, H., Wang, R. L., Wang, D., & Wang, J. X. (2020). The properties of dental resin composites reinforced with silica colloidal nanoparticle clusters: Effects of heat treatment and filler composition. *Composites Part B: Engineering*, *186*, 107791. https://doi.org/10.1016/j.compositesb.2020.107791
31. Feng, J., Safaei, B., Qin, Z., & Chu, F. (2023). Nature-inspired energy dissipation sandwich composites reinforced with high-friction graphene. *Composites Science and Technology*, *233*, 109925. https://doi.org/10.1016/j.compscitech.2023.109925
32. Singh, A. P., Garg, P., Alam, F., Singh, K., Mathur, R. B., Tandon, R. P., Chandra, A., & Dhawan, S. K. (2012). Phenolic resin-based composite sheets filled with mixtures of reduced graphene oxide, γ-Fe2O3 and carbon fibers for excellent electromagnetic interference shielding in the X-band. *Carbon*, *50*, 3868-3875. https://doi.org/10.1016/j.carbon.2012.04.030
33. Saba, N., & Jawaid, M. (2017). Epoxy resin based hybrid polymer composites. *Hybrid polymer composite materials*, *2017*, 57-82. https://doi.org/10.1016/B978-0-08-100787-7.00003-2
34. Yum, S. H., Kim, S. H., Lee, W. I., & Kim, H. (2015). Improvement of ablation resistance of phenolic composites reinforced with low concentrations of carbon nanotubes. *Composites Science and Technology*, *121*, 16-24. https://doi.org/10.1016/j.compscitech.2015.10.016
35. Tzeng, S. S., & Lin, Y. H. (2013). Formation of graphitic rods in carbon/carbon composites reinforced with carbon nanotubes. *Carbon*, *52*, 617-620. https://doi.org/10.1016/j.carbon.2012.10.010
36. Adeniyi, A. G., Abdulkareem, S. A., Odimayomi, K. P., Emenike, E. C., & Iwuozor, K. O. (2022). Production of thermally cured polystyrene composite reinforced with aluminium powder and clay. *Environmental Challenges*, *9*, 100608. https://doi.org/10.1016/j.envc.2022.100608
37. Liu, L., Ying, G., Wen, D., Zhang, K., Hu, C., Zheng, Y., Zhang, C., Wang, X., & Wang, C. (2021). Aqueous solution-processed MXene (Ti3C2Tx) for non-hydrophilic epoxy resin-based composites with enhanced mechanical and physical properties. *Materials & Design*, *197*, 109276. https://doi.org/10.1016/j.matdes.2020.109276
38. Shi, J. F., Li, N., Zhang, F., Zong, Z., Li, Z. Y., Wang, Y. Y., & Yan, D. X. (2024). Enhanced mechanical property, high-temperature oxidation and ablation resistance of carbon fiber/phenolic composites reinforced by attapulgite. *Composites Part A: Applied Science and Manufacturing*, *187*, 108469. https://doi.org/10.1016/j.compositesa.2024.108469

39. da Silva, A. O., de Castro Monsores, K. G., Oliveira, S. D. S. A., Weber, R. P., & Monteiro, S. N. (2018). Ballistic behavior of a hybrid composite reinforced with curaua and aramid fabric subjected to ultraviolet radiation. *Journal of materials research and technology*, *7*, 584-591. https://doi.org/10.1016/j.jmrt.2018.09.004
40. Nakib, K. I. A., Rahman, R., Lithi, I. J., Oishi, M. S., Ali, M. F., Wara, A. K. M. K, Sarwaruddin, A. M., & Hossain, M. S. (2025). Fabrication of waste natural fiber reinforced epoxy resin-based composite and evaluation of diverse environmental interactions. *Journal of Environmental Chemical Engineering*, *13*, 120213. https://doi.org/10.1016/j.jece.2025.120213