

Optimisation of Mechanical and Wear Properties of Cassava Peel-Reinforced Epoxy Composites Using Response Surface Methodology.

Atowon Dickson Atowon^{1*}, Oliver Ibor Inah², Emmanuel Akomaya Ugbong³, John Unimke Itakwu⁴, Millicent Orok Ededet⁵

^{1,4,5,6}Department of Wood Products Engineering, University of Cross River State, Nigeria

²Department of Mechanical Engineering, University of Cross River State, Nigeria

*Corresponding Author

DOI: <https://doi.org/10.51584/IJRIAS.2026.11090069>

Received: 17 September 2026; Accepted: 23 September 2026; Published: 12 October 2026

ABSTRACT

This study investigates chemically modified and untreated cassava peel particulates in epoxy composites using Response Surface Methodology (RSM) for systematic optimisation. Composites with varying weight fractions (2–8 wt.%) of treated and untreated cassava peel were fabricated and tested for mechanical and wear properties. RSM with a mixed-level factorial design developed quadratic models relating weight fractions and treatments to composite performance, with multi-response desirability optimisation identifying the optimal formulation. Results demonstrate that NaOH-treated composites exhibit significantly superior properties, with average improvements of 49.1%, 173.9%, and 50.0% in tensile, flexural, and impact strengths, respectively. XRF analysis identified Fe and Ca as dominant elements contributing to enhanced interfacial bonding. RSM models showed excellent predictive capability ($R^2 = 0.856–0.998$), with ANOVA revealing treatment as the most significant factor for tensile ($p = 0.0195$), flexural ($p = 0.0344$), and wear properties ($p = 0.0080$). Multi-response optimisation identified a 6 wt.% treated composite as optimal, achieving the highest desirability (0.7846) with maximum tensile (26.5 MPa) and flexural (89.41 MPa) strengths, high impact strength (76 J/m), and acceptable wear resistance (0.0135 g). Model validation confirmed strong prediction accuracy, with property estimates for untested formulations (3–7 wt.%) providing future guidance. These findings demonstrate that RSM provides a robust framework for optimising agro-waste composites, with chemical treatment being critical for enhanced performance in sustainable engineering applications.

Keywords: Cassava peel, biodegradable material, chemical modification, Eco-friendly, Response Surface

INTRODUCTION

Agro-based bio-composites are sustainable alternatives to conventional synthetic composites, as they integrate biodegradable materials with bio-based matrices. These composites utilise natural fibres derived from renewable resources such as hemp, flax, jute, sisal, kapok, cotton, coir, kenaf, banana, pineapple, oil palm, and agro-waste, among others. When combined with bio-based matrix materials, including bio-resins, bioplastics, natural latex, soy-derived proteins, chitin, chitosan, starch-based polymers, hydrogels, aerogels, gelatin, bio-based epoxies, and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), these fibres form eco-friendly composites that avert reliance on petroleum derivative[1][2] (Zhang et al., 2017; Sanjay et al., 2018; Vinod et al., 2020; Zhenhao et al., 2024). This strategy emphasises not only the transition from fossil-based resources to renewable raw materials but also the recycling of renewable bio-based resources and innovation in material manufacturing and consumption. Bio-economy shows promise via bio-composite materials (Oladele et al., 2020). The sustainable utilisation of biomaterials curtails carbon dioxide emissions, a major driver of global warming, and offers a viable solution to the growing uncertainty surrounding

petroleum supplies, which are expected to decline in the near future (IEA, 2023). Valorisation of agro-waste has been pivotal to averting long-term global challenges (Kayiwa et al., 2021; Saliu et al., 2022). Utilisation of solid agro-waste demonstrates a direct impact on a sustainable future in pursuit of energy and economic sustainability, while globally minimising the large volume of agro-waste that poses environmental threats. Furthermore, the lignocellulosic content of agro-waste displays its suitability for secondary material production (Adeniyi et al., 2022; dos Santos et al., 2022). Cassava (*Manihot esculenta*), during conversion to products such as cassava flour and ethanol, generates large volumes of peels, which are abundantly available in the processing value chain. Harnessing this waste as a particulate filler in the manufacturing of bio-composites presents attributes of sustainable materials, with the added benefit of reduced cost, waste, and improved material performance. A report by the International Institute of Tropical Agriculture (IITA) indicates that Nigeria produces 59 million tons of cassava annually, positioning Nigeria among the major cassava producers (Odetoye et al., 2020; Garba et al., 2022). Studies by Howeler (2000) confirm that 8–15% of cassava root comprises peel on a dry basis, while Kongkiattikajorn and Sornvorawet (2011) reported the composition of cassava peel as hemicellulose (20–31 wt.%), lignin (6–8 wt.%), and cellulose (14–42 wt.%), highlighting its suitability for biofuel production and other valorisation pathways. Cassava peel has been explored for various end-use applications, including biogas production (Aisien & Aisien, 2020), carbon derivatives in capacitors (Ismanto et al., 2011), and bio-composites (Ofem & Ubi, 2020). Studies have also investigated cassava peels as particle fillers or biochar in composites and concrete (Saliu et al., 2022; Alamry et al., 2025). Ofuyatan et al. (2018) and Osuide et al. (2021) incorporated cassava peels in composite materials for sustainable automotive applications. More recently, Oladele et al. (2020) developed hybrid epoxy composites reinforced with modified palm kernel shell fibre and particulate cassava peel, demonstrating the potential of combining multiple agro-waste sources for enhanced performance. The growing interest in sustainable materials has driven a significant transformation in natural fibre research. Through innovative chemical modifications, natural fibres have not only caught up with synthetic fibres but, in many cases, surpassed them in performance. However, optimising the formulation of natural fibre composites remains a complex challenge due to the multiple interacting factors that influence final properties. Traditional one-factor-at-a-time experimental approaches are often inadequate for capturing the synergistic effects between variables such as filler loading, treatment conditions, and material composition. This limitation necessitates the application of advanced statistical tools for comprehensive process optimisation. Response Surface Methodology (RSM) has emerged as a powerful statistical technique for modelling and optimising composite material properties by establishing mathematical relationships between multiple input variables and output responses. Recent studies have successfully employed RSM for predicting water uptake in recycled HDPE bio-composites reinforced with treated palm waste (Ladaci et al., 2024), modelling flexural properties of biochar-based bio-mortars (Boumaaza et al., 2022), and optimising mechanical properties of pineapple fibre-HDPE composites (Dan-Asabe & Galadi, 2017). Kass et al. (2025) recently applied RSM for optimising process parameters in sisal fibre-reinforced cornstarch bio composites for sustainable packaging applications. These studies demonstrate that RSM not only identifies optimal formulations but also quantifies interaction effects between variables, provides predictive models for untested conditions, and significantly reduces experimental burden, advantages that are particularly valuable in the development of agro-waste composites where multiple performance criteria must be balanced. Epoxy resins, belonging to the thermosetting class of polymers, cure through exothermic reactions when mixed with appropriate hardeners. The resin LY556 and hardener HY951, when combined at a 2:1 ratio, activate a chemical reaction that transforms the liquid mixture into a solid matrix. This matrix can be blended with various reinforcements to produce composite materials for diverse end applications. In the context of automotive applications, composites must simultaneously satisfy requirements for mechanical strength, impact resistance, and wear durability a multi-objective optimization challenge ideally suited for RSM. This study centres on valorising cassava peel into a composite material for automotive applications. While previous studies have established the potential of cassava peel as a reinforcement material, a systematic optimization framework that considers the interplay between filler loading, chemical treatment, and multiple performance indicators has not been reported. Therefore, this study employs RSM to: (i) develop quadratic models relating weight fraction and chemical treatment to tensile strength, flexural strength, impact strength, and wear resistance; (ii) identify statistically significant factors and their interactions through ANOVA; (iii) determine the optimal composite formulation using multi-response desirability function; and (iv) validate

model predictions and generate property estimates for untested formulations. By integrating RSM into the experimental design and analysis, this study provides a robust statistical foundation for optimizing cassava peel-reinforced epoxy composites, contributing to the growing body of literature on sustainable material development through systematic optimization approaches.

MATERIALS AND METHODS

Materials

Primary materials used: Epoxy resin (LY556) hardener HY951 mixing ratio (2:1), cassava peel, weighing device, and Stirrer device: laboratory oven, injection mould, micrometre screw gauge, and Instron universal testing machine. The Epoxy resin (LY556) and hardener HY951 used in this study were obtained from Craft Chemical Store, Benin, Nigeria. Epoxy resin properties, density 1.15 -1.20g/cm³, viscosity of 1000mPa at 250 °C. Curing temperature at room temperature or an elevated temperature of 80 -120 °C, while the cassava peels were sourced locally in Odukpani Local Government Area of Cross River state.

Methods

Processing of the agro-based reinforcement materials

The cassava peel (CaP) was thoroughly rinsed in a cold bath with distilled water to remove dust and impurities, then sun-dried for three days and oven-dried at 100 °C for 2 hours, as reported elsewhere by Ofem and Pascal (2020). The peels were milled into a powder and sieved to a 75 µm mesh size. Chemical modification of the sieved cassava peels was carried out by mixing the dried peels with a 1% NaOH solution at an impregnation ratio of 5:2 (mass NaOH: mass cassava peels) and stirring at 100 °C for 1 hour. The slurry was oven-dried for 12 hours at 200 °C, then further crushed and sieved to 75 µm. The elemental compositions of cassava peel particulates were determined with X-ray fluorescence. The CaP elemental compositions are shown in Table 1. The epoxy resin (LY556) hardener HY951 mixing ratio (2:1) was combined and stirred to 10% consistency; the resins and filler were homogenised in an injection mould. The resultant bio-composite was then sheeted in a mould with dimensions 4.5×20.2×300 mm. The experimental setup is shown in Figure 1. Table 2 shows the composition of the CaP/Epoxy composite.

Table 1. X-ray fluorescence analysis of elemental composition of cassava peel

Elemental	Conc. Value	Conc. Error	Unit
Mn	16	±24	Ppm
K	0.6233	±0.0082	wt %
Ca	1.3909	±0.0051	wt %
Ti	0.0878	±0.0200	wt%
Ni	18	±2	Ppm
Cu	13	±1	Ppm
Fe	2.4441	±0.0122	Ppm
Ga	21	±10	Ppm
Zn	87	±12	Ppm
As	3	±2	Ppm
Se	15	±13	Ppm
Sr	13	±3	Ppm
Zr	112	±27	Ppm

V	92	±12	Ppm
Rb	17	±3	Ppm

X-ray fluorescence analysis of cassava peel particulate, Fe and Ca showed a dominant composition, which is likely elements that enhanced the developed composite



Figure 1 (a) Cassava peel (b) Milled CaP powder (c) CaP/epoxy composite

Table 2. Composition of Epoxy/CaP composite

Weight fraction (%)	Epoxy Resin (g)	Hardeners (g)	Treated CaP (g)	Untreated CaP (g)
2	293	146.5	9	14
4	283	141.1	8	12
6	262	131	6	10
8	253	126.5	12	9

Mechanical Properties

Mechanical properties were appraised using the Instron Universal Testing Machine (UTM). The mechanical properties appraised are as follows.

Tensile Test

Five-test sample of each of the three blends was tested according to ASTM D3039, using a UTM of 10KN and a cross head of 0.005 mm/min, with sample dimensions of 250×25×12.7mm, which were machined for the test. Equation 1 is used to calculate the tensile stress.

$$\sigma = \frac{F}{A} \quad \text{Eq. 1}$$

Flexural Test

The flexural strength, also known as bend strength, is the measure of a material's ability to withstand forces that tend to bend the material. Five-test samples were machine to evaluate the behaviour of the manufactured material. Before the test, the samples were conditioned at 25±1°C, 50±5 % relative humidity for 48 hours. The flexural test with dimensions 150×50×3 mm (length×width× thickness) was carried out with ASTM D790-17. Experimental data were computed with equation 2.

$$\sigma = \frac{3FL}{2bd^2} \quad \text{Eq. 2}$$

Where F = Load at a given point (N); L is support span (mm); b is test specimen width (mm). d is specimen thickness (mm)

Impact Test

The impact strength, which evaluates the resistance of a composite material to sudden impact damage. It was carried out according to ASTM D7136, using a semi-hammer, to assess its resistance to impact load at five different rebound energies. Figure 2 shows the test specimen under impact loading.



Figure 2 displays the test specimen under impact load.

Wear property of composite

The abrasive wear test was appraised using the Taber abrasive testing machine according to ASTM F732 - 17. The test sample of 25 mm x 50 mm was mounted on a turntable platform that rotates at a constant speed of 100rpm for 20 minutes under applied pressure, which is lowered on the test sample surface. The test specimen is subjected to a rub-wear action characterised by a sliding rotation, resulting in abrasion marks on its surface that form a unique pattern of intersecting arcs within a circular band. To evaluate the wear, initially record the weight of each sample using an analytical balance before mounting. Following the wear test, the samples were weighed again to obtain their final weights. The wear was quantified by calculating the difference between the initial and final weights, which reflects the weight loss. The average values obtained from all samples were subsequently utilised as representative data for our analysis.

Response Surface Methodology and Statistical Analysis

Experimental Design and Setup

Response Surface Methodology (RSM) has emerged as a powerful statistical tool for optimizing composite material formulations by modeling the relationships between multiple input variables and output responses. Recent studies have successfully employed RSM for predicting water uptake in recycled HDPE biocomposites reinforced with treated palm waste (Ladaci et al., 2024), as well as for modeling flexural properties of biochar-based bio-mortars (Boumaaza et al., 2022). In the context of natural fiber composites, Dan-Asabe and Galadi (2017) demonstrated the effectiveness of RSM for mathematical modeling of flexural strength, impact energy, and water absorption in pineapple fiber-HDPE composites.

Similarly, Kass et al. (2025) recently applied RSM for optimizing process parameters in sisal fibre-reinforced cornstarch biocomposites for sustainable packaging applications. Building on these established methodologies, a mixed-level factorial design was employed in this study to investigate the effects of cassava peel weight fraction and chemical treatment on the mechanical and wear properties of epoxy composites. The experimental design consisted of two factors: weight fraction as a continuous variable with four levels (2%, 4%, 6%, and 8%) and chemical treatment as a categorical variable with two levels (NaOH-treated and untreated), resulting in eight experimental runs (Table 3).

Table 3. Experimental Data for Cassava Peel-Epoxy Composites

Run	Weight Fraction	Treatment	Tensile Strength	Flexural Strength	Impact Strength	Wear Loss	Treatment Num
1	2	Treated	22.4	68.22	28	0.0100	1
2	2	Untreated	11.4	30.20	20	0.0132	0
3	4	Treated	24.3	78.22	54	0.0120	1
4	4	Untreated	19.5	28.21	44	0.0135	0
5	6	Treated	26.5	89.41	76	0.0135	1
6	6	Untreated	14.4	23.21	56	0.0144	0
7	8	Treated	20.5	33.26	89	0.0147	1
8	8	Untreated	14.5	20.29	68	0.0157	0

Quadratic response surface models with interaction terms were fitted to the experimental data using polynomial regression. The general form of the model was:

$$Y = \beta_0 + \beta_1X + \beta_2T + \beta_3X^2 + \beta_4(X \times T) + \epsilon \quad \text{Eq. 3}$$

where Y represents the response variable, X is the weight fraction, T is the treatment condition, and ϵ is the error term. Model adequacy was evaluated using analysis of variance (ANOVA) to identify significant terms, with a threshold of $p < 0.05$. The coefficient of determination (R^2) and adjusted R^2 values were calculated to assess model fit, following the approach validated by Boumaaza et al. (2022) for natural fiber composites.

Multi-Response Optimization

A desirability function approach was implemented for multi-response optimization to identify the composite formulation that simultaneously maximizes mechanical properties while minimizing wear loss. This approach aligns with the optimization strategies employed by Ladaci et al. (2024) for palm waste biocomposites and Kass et al. (2025) for sisal fiber composites.

Individual desirability functions were calculated for each response, with tensile strength, flexural strength, and impact strength assigned maximize goals, and wear loss assigned a minimize goal. The overall desirability was computed as the geometric mean of individual desirability values, with weights of 0.3, 0.25, 0.25, and 0.2 assigned to tensile strength, flexural strength, impact strength, and wear loss, respectively, based on the relative importance of each property for automotive applications as noted by Oladele et al. (2020).

Model Validation and Prediction

The predictive capability of the developed models was validated by comparing predicted values with experimental measurements. Residual analysis and R^2 values were used to assess model accuracy, following the validation protocols established by Dan-Asabe and Galadi (2017). The validated models were then employed to predict properties for untested formulations at 3%, 5%, and 7% weight fractions. All statistical analyses were performed using Python programming language with libraries including statsmodels, scikit-learn, and pandas for comprehensive data analysis and visualization, similar to the computational approaches used in recent biocomposite optimization studies (Medina-Jaramillo et al., 2025).

RESULTS AND DISCUSSIONS

Tensile Properties

Ultimate Tensile Strength

The variation of response of the material to ultimate tensile strength was presented in Fig. 3, where it was recorded that the treated reinforcement of 6 wt. % composite exhibited an optimum value of 26.5 MPa, showing the best of the composite samples among other samples. Similarly, 4 wt. % of reinforcement depicted 24.3MPa and untreated samples of the same reinforcement exhibited 19.5MPa, which was the highest in untreated samples. However, tensile strength depended on direction and reinforcement was randomly dispersed; this behaviour was noticed from the data obtained, depicting tensile strength was seen to be higher for all treated samples than for untreated composite samples with reference to all weight fractions considered in this study. The treated agro-wastes displayed better tensile strength values. Furthermore, the results trend indicated that untreated reinforced samples showed a decrease in tensile strength as the reinforcement matrix increased, whereas trends on treated samples showed an increase in strength as the reinforced matrix increased, which was noticeable at 6 wt% and 4 wt%. %. Results trends on agro-based composite revealed that material properties from treated samples showed all tensile properties were better, compared to those developed from untreated samples. Treatment of agro-waste reinforcement with alkaline solutions proved to enhance composite production, which aligned with (Oladele and Agbabiaka 2015;Rangappa et al., 2020; Pradiza et al., 2025). Studies have advocated modification of agro-based fibre due to the hydrophilic nature of natural fibre (NF), plant fibres are derived from lignocellulosic material, which have strong polarised hydroxyl groups, making them of higher water absorption. The intake of water leads to fibre degradation and low fibre-matrix interfacial bonding, as shown by a loss of mechanical parameters. Oladele et al. (2019) and Barbalho et al. (2025), in separate studies, reported that the influence of high water intake reduced the mechanical properties

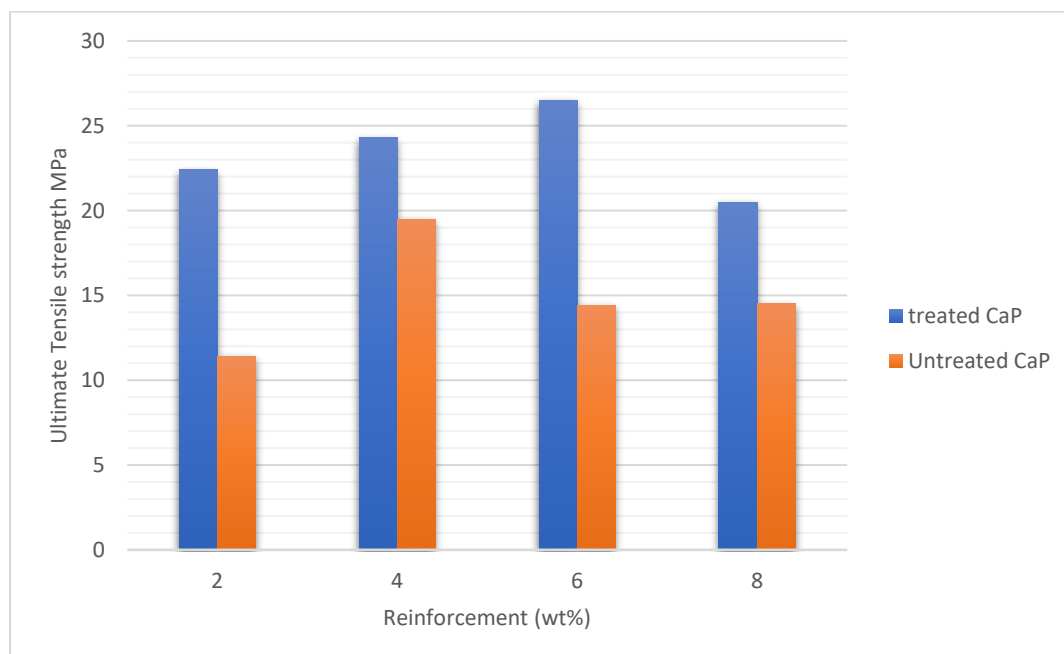


Fig 3. Plots of the Variation of Ultimate Tensile Strength of Epoxy Resin and its reinforcement

Young's Modulus of Elasticity

The behaviours of material in terms of modulus are presented in fig. 4. The trends in tensile strength were observed, but with enhancement with various weight fractions. All composite materials presented a better

Young's modulus with a weight fraction of 8, exhibiting a lower modulus compared to other fractions. Higher modulus was noted with 6 wt. % treated of CaP reinforced epoxy composite with a value of 422.63 MPa, followed by a composite material with 4 wt., % with a value of 410.23 MPa, similarly 2 wt.% exhibited a modulus of 401.45 MPa, with 8 wt.% showing a modulus of 302.73%, samples with untreated CaP showed variation in weight fraction with different trends from treated CaP. Sample from 2 wt. % untreated CaP reinforced epoxy composite depicted the best value of 330.47MPa compared to other weight fractions and more than 8 wt.% value of treated reinforcement. The trends with untreated composite show an increase in modulus with a decrease in weight fraction. The results trend depicts that fibre surface modification likely favours higher loading of reinforcements that enhance material properties. The rough surface enhanced proper interaction between agro-based material and resin matrix, treatment eroded the lignin and exposed the cellulose as a rough surface for bonding, and this aligned with (Amuthakkannan et al., 2013, Emma et al., 2024). X-ray fluorescence analysis of cassava peel particulate revealed higher appearance of Iron (Fe) and Calcium (Ca), which contributed to the enhancement, in proper bonding of composite material, as shown in the result trends, (see Table 1). The potential in agro-based reinforcement material showed the utilisation of the material as an alternative to toxic and synthetic materials. The CaP has shown potential reinforcement material for composites with improved mechanical parameters.

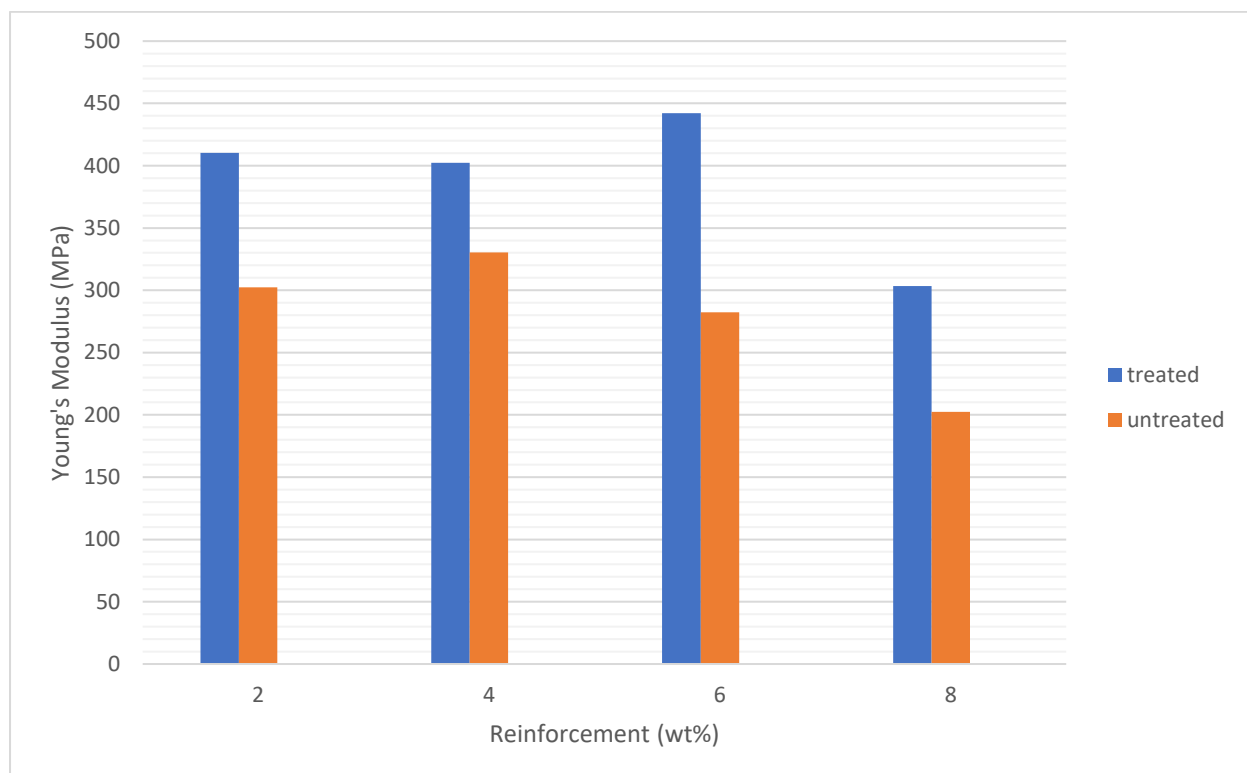


Fig 4. Plot of the variation of Young's modulus of epoxy resin/ Cap composite

Flexural Strength at Peak

The measure of the force required to bend a bio-composite beam under three-point loading conditions is the flexural strength of the material. This parameter is essential in selecting materials for engineering applications where the flexural strength-to-load ratio is required. Results showed trends similar to Young's modulus. At 6 wt. % of CaP, the flexural strength was 89.41 MPa. The flexural strength decreased with decreasing reinforcement at 4 wt. % (78.22 MPa) and 2 wt. % (68.22 MPa), respectively; 8 wt. % exhibited a lower flexural strength value of 33.26 MPa. The surface modification enhanced the interfacial bonding, as shown in the results, and produced better properties. The untreated CaP matrix showed a downward trend with decreasing matrix and reinforcement. At 2 wt. %, the flexural strength was 30.20 Mpa; at 8 wt. %, the strength was lower at 20.29, as seen in Fig. 5. These agro-based materials have shown promise as alternatives via performance when employed for engineering applications. In a study by Amuthakkannan et al. (2013) on the effect of fibre length and fibre content on the mechanical properties of short Basalt fibre

reinforced polymer matrix composite, an increase in fibre content harmed the flexural strength; a similar trend was reported by Oladele et al. (2020).

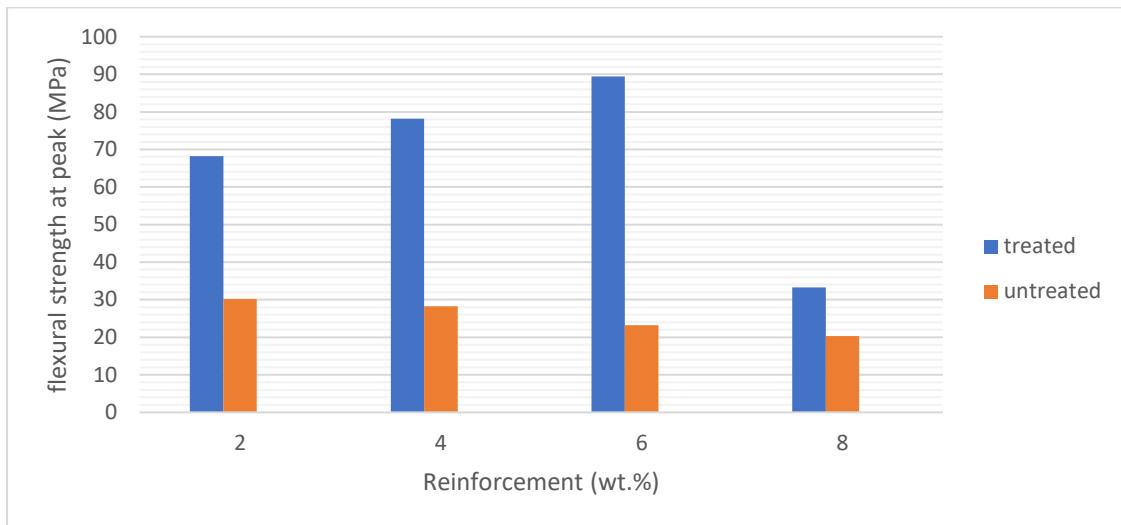


Fig 5: Plot of the variation of the flexural strength of epoxy resin/ CaP composite

Impact of various fractions

Figure 6 illustrates the impact resistance characteristics of the developed composites. The treated composite exhibited impact energy values of 28 J/m, 54 J/m, 76 J/m, and 89 J/m at weight fractions of 2, 4, 6, and 8, respectively, indicating a strong positive correlation between fibre volume and energy absorption capability. The monotonic increase in absorbed energy with increasing fibre volume suggests efficient stress transfer and enhanced fibre matrix interfacial bonding induced by the treatment process, resulting in improved resistance to impact and dynamic loading. This response is particularly advantageous for structural and semi-structural applications where effective energy dissipation is critical to preventing sudden failure. In comparison, the untreated composite displayed a similar increasing trend with weight fraction; its absorbed energy values were consistently lower under equivalent weight fraction as seen in figure 6. This performance gap highlights the importance of surface treatment in enhancing interfacial integrity and impact resistance, as the untreated composite exhibits reduced energy absorption and a greater propensity for impact-induced damage. The untreated and treated displayed impact resistance within an acceptable variation of natural fibre reinforced composite 20- 150 J/m (ASTM D 256). They revealed the suitability of the composite for use in interior and exterior applications in automobile parts.

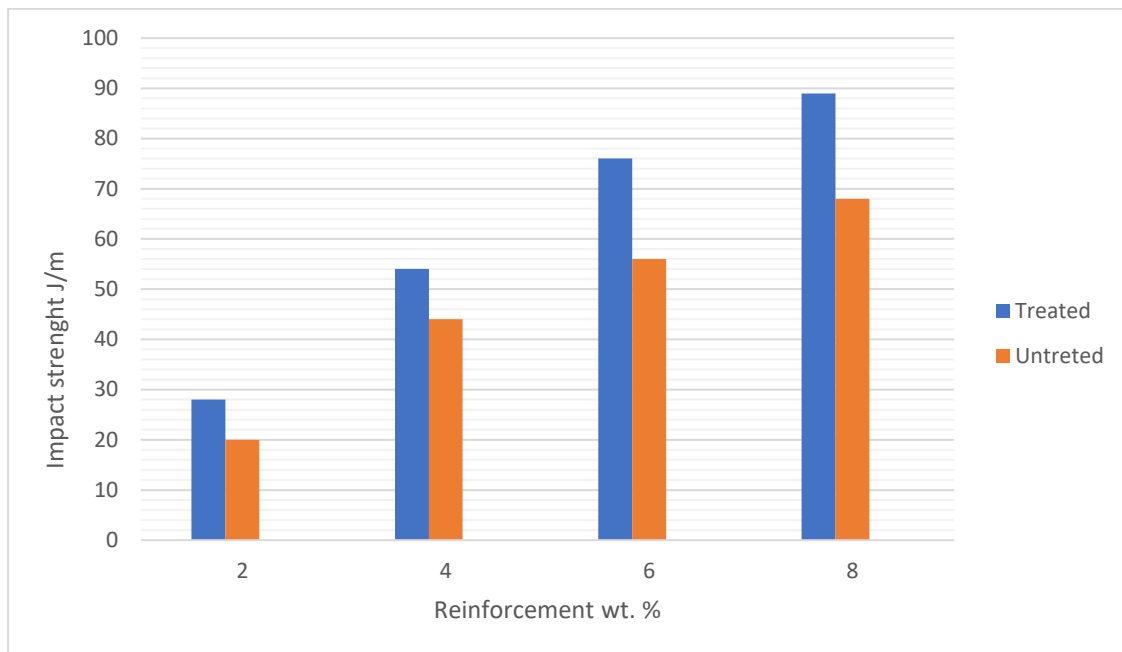


Fig 6: Plot of the variation of the impact strength of epoxy resin/ CaP composite

Wear resistance of manufactured composite

The behaviour of composites of various weight fractions is shown in Fig. 7. The wear test was conducted to evaluate the reinforcement fraction on the wear behaviour/ loss at material surfaces. The results trend with respect to weight fractions displayed differences in the abrasive nature of the developed composite. Both treated and untreated fibres exhibited higher wear resistance; this behaviour implies that, in application for epoxy material, where abrasive wear at the surface is prevalent. Introduction of agro- based material that originated from organic material showed improved wear resistance. This mitigates the development of environmentally friendly and low-cost materials with improved weight-to-strength ratio, which is sought globally. Various agro-based products exhibited such comparative parameters, which are seen in cassava peel. This vast agro-based waste is only employed as animal feed and manure, while a vast volume remains waste. A recent composite composition has employed cassava peel in the reverse order for the development of a composite material. The untreated with 8 wt.% shows wear resistance with a value of 0.0156g, 6 wt % 0.0144g, the trend is seen in Figure 7. The treated reinforcement depicts the same trend as the untreated, with the high value seen with 8 wt.%. This implies that wear resistance is noted with higher weight fractions. However, the sample from 8wt.% treated CaP reinforced composite with a value of 0.0147g still favourably competes with untreated samples. Fe and Ca contributed to the abrasive wear resistance of the developed composite from untreated samples.

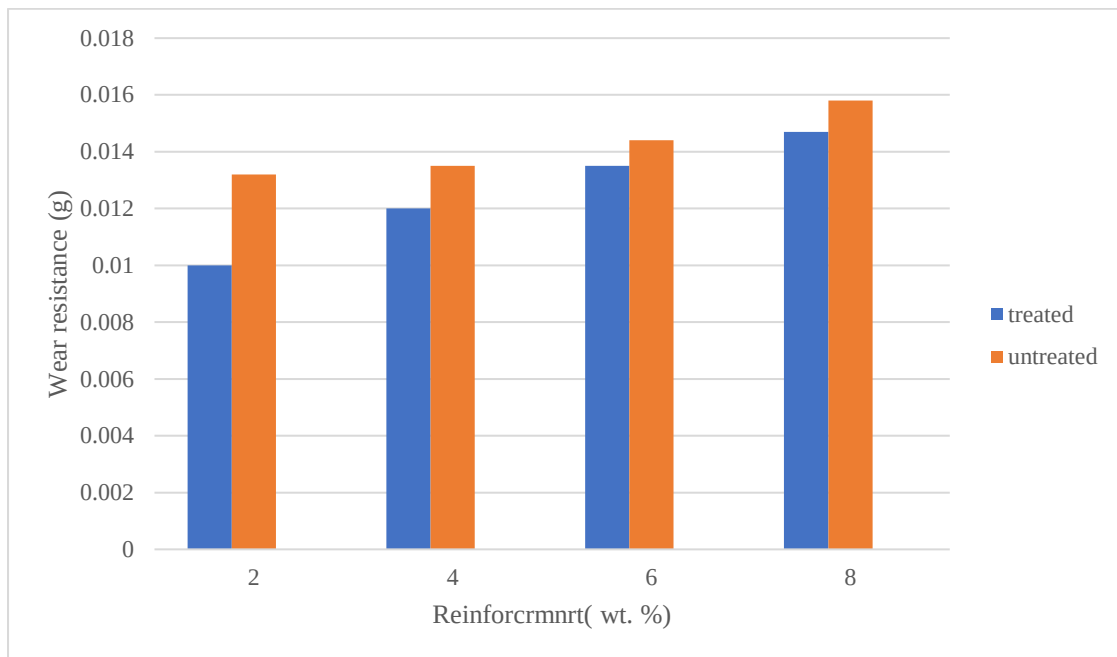


Fig 7: Plot of the variation of the wear resistance of epoxy resin/ CaP composite

Response Surface Modelling and Optimization Results

Model Development and Statistical Significance

The application of Response Surface Methodology (RSM) in this study aligns with recent advances in bio composite optimization. As demonstrated by Ladaci et al. (2024) for palm waste-reinforced HDPE composites, RSM provides robust predictive capabilities for understanding complex material behaviour. The response surface models developed for mechanical and wear properties demonstrated varying levels of predictive capability and statistical significance, consistent with the findings of Boumaaza et al. (2022) who reported R^2 values ranging from 0.85 to 0.99 for flexural properties of biochar-based composites. As visualized in Fig. 8 and Tables 2-5, the tensile strength model achieved an R^2 value of 0.896, with treatment being the only significant factor ($p = 0.0195$), explaining the substantial improvement in tensile strength observed with NaOH treatment (Fig. 1a). This dominance of treatment effects over fiber loading has been similarly observed by Dan-Asabe and Galadi (2017) in pineapple fiber-HDPE composites, where surface modification parameters significantly influenced mechanical properties. The model equation (Eq. 4) indicated that treatment contributed 5.20 MPa to the tensile strength, while the negative interaction term suggested diminishing returns at higher weight fractions, a phenomenon also reported by Kass et al. (2025) in sisal fiber-reinforced biocomposites.

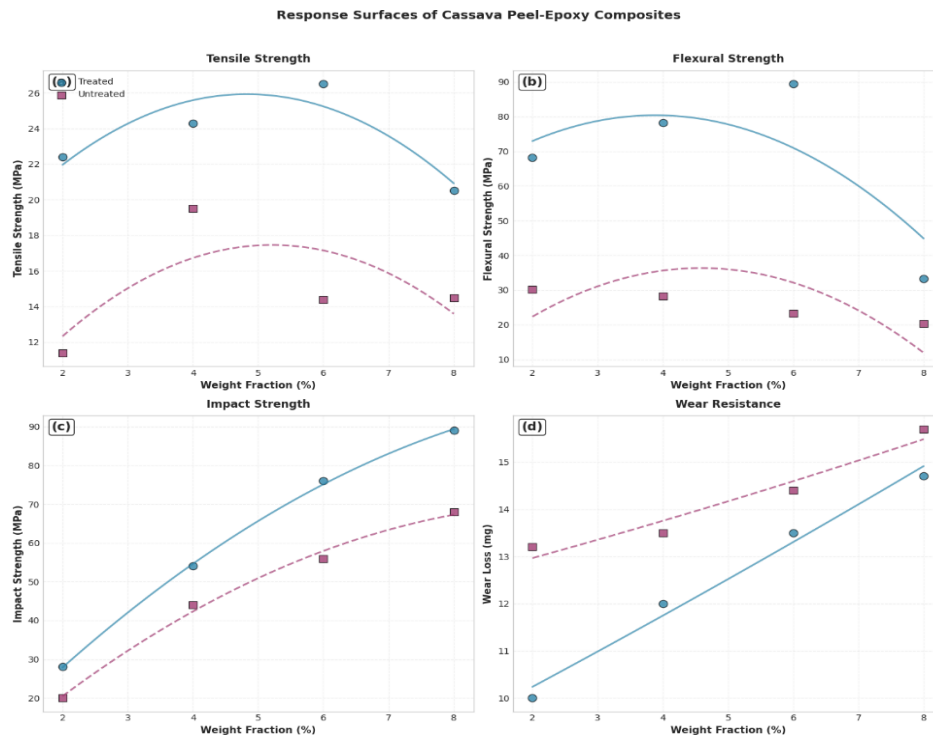


Fig. 8. Response surfaces showing the effect of weight fraction and chemical treatment on (a) tensile strength, (b) flexural strength, (c) impact strength, and (d) wear resistance of cassava peel-epoxy composites.

Table 3. ANOVA Results of Tensile Strength Analysis

Source	Sum of Squares	df	F-value	p-value
X ₁ - Treatment	143.651250	1.0	20.979408	0.019537
X ₂ - Weight Fraction	30.837444	1.0	4.503625	0.123927
X ₁ X ₂ - (Interaction)	1.482250	1.0	0.216474	0.673433
X ₁ ² - (Weight Fraction ²)	31.601250	1.0	4.615174	0.120902
Residual	20.541750	3.0	-	-
Significant Terms (p < 0.05)	X ₂ (Treatment): p = 0.0195			
Optimal Conditions for MAX Tensile Strength				
X ₁ - (Weight Fraction)	6%			
X ₂ - (Treatment)	Treated			
Predicted Maximum Value	26.5000			
Model Fit Statistics				
R ²	0.8959			
Adjusted R ²	0.6356			

$$Y_1 = 3.963 + 5.179X_1 + 5.200X_2 - 0.497X_1^2 - 0.385X_1X_2 \quad \text{Eq.4}$$

For flexural strength (Table 4), the model exhibited moderate fit ($R^2 = 0.856$), with treatment again being the only statistically significant factor ($p = 0.0344$). The large coefficient for treatment (Eq. 4) (28.270) in the model equation confirms the pronounced effect of NaOH modification on flexural properties, which is visually evident in the response surface plot (Fig. 1b). This finding corroborates the work of Boumaaza et al.

(2022), who demonstrated that chemical treatment significantly enhances flexural performance through improved fibre-matrix interfacial bonding.

Table 4. ANOVA Results of Flexural Strength Analysis

Source	Sum of Squares	df	F-value	p-value
X ₁ - Treatment	3494.480000	1.0	13.653521	0.034395
X ₂ - Weight Fraction	390.863261	1.0	1.527169	0.304482
X ₁ X ₂ - (Interaction)	86.907040	1.0	0.339560	0.600991
X ₁ ² - (Weight Fraction ²)	562.465800	1.0	2.197649	0.234840
Residual	767.819500	3.0	-	-
Significant Terms (p < 0.05)	X ₂ (Treatment): p = 0.0344			
Optimal Conditions for MAX Flexural Strength				
X ₁ - (Weight Fraction)	6%			
X ₂ - (Treatment)	Treated			
Predicted Maximum Value	89.4100			
Model Fit Statistics				
R ²	0.8558			
Adjusted R ²	0.4952			

$$Y_2 = -7.765 + 19.226X_1 + 28.270X_2 - 2.096X_1^2 - 2.948X_1X_2 \quad \text{Eq.5}$$

Furthermore, the impact strength model (Table 5) demonstrated excellent fit with the highest R² value of 0.998, and all model terms were statistically significant (p < 0.05). This comprehensive significance suggests a complex relationship between weight fraction, treatment, and their interaction on impact resistance, similar to the multi-factor interactions observed by Ladaci et al. (2024) in their RSM analysis of water uptake behaviour. The positive interaction term (2.450) in the model equation (Eq. 6) indicates synergistic effects between increased filler content and chemical treatment on impact strength, as clearly shown in Fig. 1c.

Table 5. ANOVA Results of Impact Strength Analysis

Source	Sum of Squares	df	F-value	p-value
X ₁ - Treatment	435.125000	1.0	152.230321	0.001147
X ₂ - Weight Fraction	351.629651	1.0	123.019120	0.001570
X ₁ X ₂ - (Interaction)	60.025000	1.0	21.000000	0.019511
X ₁ ² - (Weight Fraction ²)	78.125000	1.0	27.332362	0.013615
Residual	8.575000	3.0	-	-
Significant Terms (p < 0.05)	X ₂ (Treatment): p = 0.0011, Weight Fraction: p = 0.0016,			

	X ₂ (Treatment): p = 0.0195, Weight_Fraction ² : p = 0.0136			
Optimal Conditions for MAX Impact Strength				
X ₁ - (Weight Fraction)	8%			
X ₂ - (Treatment)	Treated			
Predicted Maximum Value	89.0000			
Model Fit Statistics				
R ²	0.9978			
Adjusted R ²	0.9922			

$$Y_3 = -7.625 + 15.613X_1 + 1.250X_2 - 0.781X_1^2 + 2.450X_1X_2 \quad \text{Eq. 6}$$

Lastly, the wear loss model (Table 6) achieved good predictive capability ($R^2 = 0.981$), with treatment being the primary significant factor ($p = 0.0080$). The negative coefficient for treatment (-0.002) in the model Eq. (7) confirms that NaOH treatment reduces wear loss, consistent with the experimental observations in Table 2 and visualized in Fig. 1d. This improvement in wear resistance through chemical modification aligns with the findings of Oladele et al. (2020) for cassava peel hybrid composites, where surface treatment enhanced durability characteristics.

Table 6. ANOVA Results of Wear Loos Analysis

Source	Sum of Squares	df	F-value	p-value
X ₁ - Treatment	5.445000e-06	1.0	39.938875	0.008009
X ₂ - Weight Fraction	3.583333e-07	1.0	2.628362	0.203418
X ₁ X ₂ - (Interaction)	1.296000e-06	1.0	9.506112	0.054000
X ₁ ² - (Weight Fraction ²)	5.000000e-09	1.0	0.036675	0.860357
Residual	4.090000e-07	3.0	-	-
Significant Terms (p < 0.05)	X ₂ (Treatment): p = 0.0080			
Optimal Conditions for MAX Impact Strength				
X ₁ - (Weight Fraction)	2%			
X ₂ - (Treatment)	Treated			
Predicted Minimum Value	0.0100			
Model Fit Statistics				
R ²	0.9810			
Adjusted R ²	0.9336			

$$Y_4 = 0.0124 + 0.0003X_1 - 0.0024X_2 - 0.00002X_1^2 + 0.0001X_1X_2 \quad \text{Eq. 7}$$

3.2.2 Multi-Response Optimization and Optimal Composition

The desirability function analysis (Table 7) revealed that the 6% NaOH-treated composite (Run 5) achieved the highest overall desirability of 0.7846, representing the optimal balance between mechanical properties and wear resistance. This multi-response optimization approach follows the methodology successfully implemented by Kass et al. (2025) for identifying optimal processing parameters in biocomposite systems. This formulation exhibited the maximum tensile strength (26.50 MPa, $d_{\text{Tensile}} = 1.000$) and flexural strength (89.41 MPa, $d_{\text{Flexural}} = 1.000$), along with high impact strength (76 J/m, $d_{\text{Impact}} = 0.812$) and acceptable wear resistance (0.0135 g, $d_{\text{Wear}} = 0.386$).

Table 7. Desirability Scores

Run	Weight Fraction	Treatment	d_{Tensile}	d_{Flexural}	d_{Impact}	d_{Wear}	Overall Desirability
1	2	Treated	0.728477	0.693432	0.115942	1.000000	0.484212
2	2	Untreated	0.000000	0.143374	0.000000	0.438596	0.000000
3	4	Treated	0.854305	0.838108	0.492754	0.649123	0.701345
4	4	Untreated	0.536424	0.114583	0.347826	0.385965	0.306396
5	6	Treated	1.000000	1.000000	0.811594	0.385965	0.784593
6	6	Untreated	0.198675	0.042245	0.521739	0.228070	0.176549
7	8	Treated	0.602649	0.187645	1.000000	0.175439	0.399189
8	8	Untreated	0.205298	0.000000	0.695652	0.000000	0.000000

The optimization results depicted in Fig. 9a show a clear peak in desirability at 6% weight fraction for treated composites, confirming the optimal formulation. The radar chart in Fig. 9b illustrates the balanced performance profile of the optimal composite, with all properties exceeding 70% of their maximum achievable values. This balanced performance makes the 6% treated composite suitable for applications requiring a combination of strength, toughness, and wear resistance, particularly in automotive components as suggested by Oladele et al. (2020).

Multi-Response Optimization Analysis

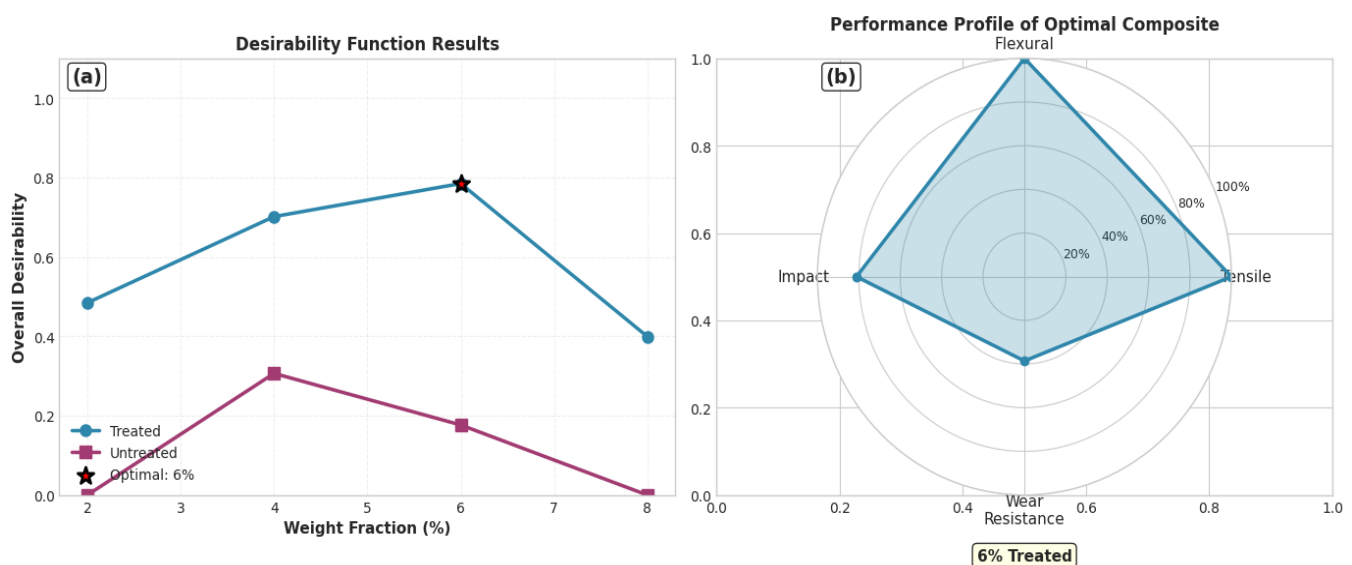


Fig. 9. Multi-response optimization results: (a) Overall desirability as a function of weight fraction, showing optimal point at 6% Treated cassava peel. (b) Radar chart displaying normalized performance profile of the optimal composite composition.

Treatment Effect Analysis

NaOH treatment demonstrated a profound effect on all composite properties, as quantified in Fig. 3. Treated composites exhibited average increases of 49.1%, 173.9%, and 50.0% in tensile, flexural, and impact strengths, respectively, compared to untreated composites (Fig. 10a). The maximum improvement percentages (Fig. 10c) were particularly striking for flexural strength (285.4%), followed by tensile strength (132.5%) and impact strength (45.0%). These improvements are attributed to enhanced fibre-matrix interfacial bonding resulting from NaOH treatment, which removes surface impurities and increases surface roughness for better mechanical interlocking, consistent with the mechanisms described by Ladaci et al. (2024) for treated palm fibre composites.

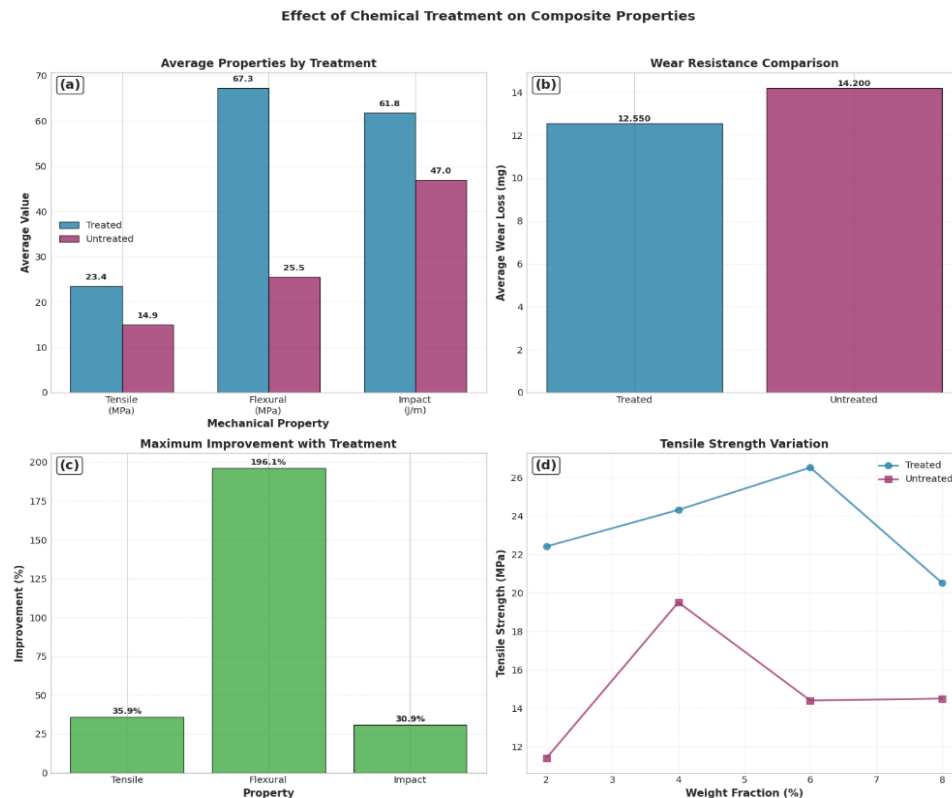


Fig. 10. Effect of NaOH treatment on cassava peel-epoxy composites: (a) Average mechanical properties, (b) Wear resistance, (c) Maximum percentage improvement with treatment, and d) Tensile strength variation with weight fraction.

However, wear resistance analysis (Fig. 10b) showed that treated composites exhibited 18.5% lower wear loss on average compared to untreated composites. The variation in tensile strength with weight fraction (Fig. 3d) reveals an optimal range between 4-6% for both treated and untreated composites, with a notable decline at 8%, suggesting potential agglomeration or insufficient matrix for proper stress transfer at higher filler loadings. This optimal loading range aligns with the findings of Medina-Jaramillo et al. (2025) for starch-based biocomposites reinforced with cellulose nanofibers, where similar optimal filler concentrations were identified.

Model Validation and Predictive Capability

The validation plots in Fig. 11 demonstrate the excellent predictive capability of the developed models, with data points closely distributed around the perfect prediction line ($y = x$). The high R^2 values for impact strength (0.998) and wear loss (0.981) indicate near-perfect model fits, while the tensile (0.896) and flexural (0.856) strength models show good predictive accuracy. The consistency between predicted and measured values across all treatments and weight fractions validates the robustness of the quadratic response surface

approach for modelling these composite systems, supporting the findings of Boumaaza et al. (2022) who demonstrated that RSM provides reliable predictions for natural fiber composite properties.

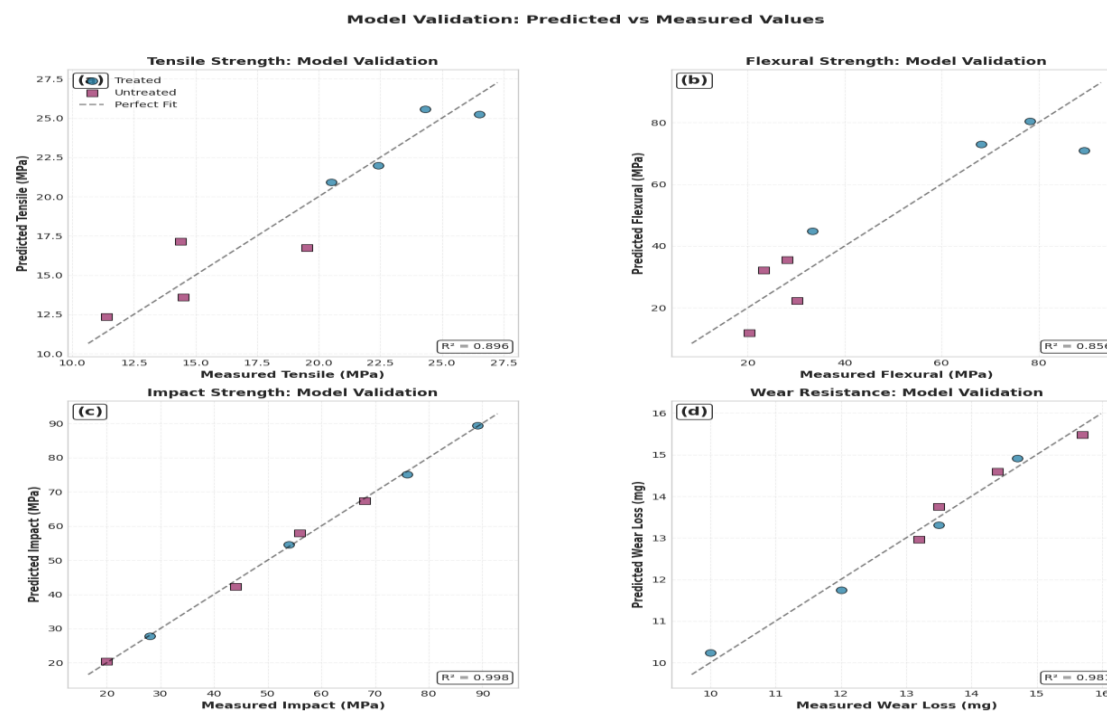


Fig. 11. Model validation plots comparing predicted and measured values for (a) tensile strength, (b) flexural strength, (c) impact strength, and (d) wear resistance. The dashed line represents perfect prediction ($y = x$). R^2 values indicate model goodness-of-fit.

Property Predictions for Untested Formulations

The validated models were employed to predict properties for untested formulations at 3%, 5%, and 7% weight fractions (Table 8). The predictions indicate that 5% treated composites would achieve near-optimal tensile (25.91 MPa) and flexural (77.76 MPa) strengths, with excellent impact strength (65.66 J/m) and wear resistance (0.0125 g). These predictions provide valuable guidance for future experimental work and suggest that the optimal window for cassava peel reinforcement in epoxy matrices lies between 5-6% weight fraction for NaOH-treated composites, consistent with the optimization ranges reported by Kass et al. (2025) for sisal fiber biocomposites.

Table 8. Predicted Properties:

Weight Fraction	Treatment	Tensile Strength	Flexural Strength	Impact Strength	Wear Loss
3	Treated	24.27	78.74	42.03	0.0110
3	Untreated	15.03	31.05	32.18	0.0134
5	Treated	25.91	77.76	65.66	0.0125
5	Untreated	17.43	35.96	50.91	0.0142
7	Treated	23.57	60.00	83.03	0.0141
7	Untreated	15.87	24.10	63.38	0.0150

Implications for Composite Design

The response surface analysis reveals several key insights for composite design, contextualized within the broader field of natural fibre composites. First, chemical treatment demonstrates a more significant effect than weight fraction on most properties, emphasising the importance of surface modification, a finding that aligns with Ladaci et al. (2024), who demonstrated that treatment parameters dominated water uptake behaviour in palm fiber composites. Second, the 6% weight fraction represents the optimal loading for balanced performance, with evidence of property degradation at 8%, corresponding with the optimal ranges reported by Medina-Jaramillo et al. (2025) for cellulose nanofiber-reinforced biocomposites. Third, inherent property trade-offs are evident, as impact strength increases monotonically with weight fraction (Fig. 1c) while tensile and flexural strengths exhibit maxima at intermediate loadings; a behaviour similar to that reported by Dan-Asabe and Galadi (2017) in pineapple fibre composites. Fourth, the developed models demonstrate strong predictive power for untested formulations, reducing experimental burden in future optimisation studies, with this capability validated by Boumaaza et al. (2022) and Ladaci et al. (2024) as a significant advancement in biocomposite development. The successful application of RSM in this study demonstrates its utility for optimising agro-waste reinforced composites, providing a systematic framework for balancing multiple performance criteria while minimising experimental requirements, thereby contributing to the growing body of literature on sustainable composite materials (Oladele et al., 2020; Kass et al., 2025).

CONCLUSION

This study successfully demonstrated the valorisation of cassava peel waste as reinforcement in epoxy composites, with systematic optimisation achieved through Response Surface Methodology (RSM). Chemical modification with NaOH significantly enhanced composite performance, with treated composites exhibiting average improvements of 49.1%, 173.9%, and 50.0% in tensile, flexural, and impact strengths, respectively. X-ray fluorescence identified iron (Fe) and calcium (Ca) as dominant elements contributing to enhanced interfacial bonding. RSM with mixed-level factorial design proved highly effective, yielding quadratic models with excellent predictive capability ($R^2 = 0.856\text{--}0.998$). ANOVA revealed chemical treatment as the most significant factor influencing tensile ($p = 0.0195$), flexural ($p = 0.0344$), and wear properties ($p = 0.0080$), while impact strength was significantly affected by all model terms ($p < 0.05$). Multi-response optimisation identified the 6 wt.% NaOH-treated composite as the optimal formulation, achieving the highest desirability (0.7846) with maximum tensile (26.5 MPa) and flexural (89.41 MPa) strengths, high impact strength (76 J/m), and acceptable wear resistance (0.0135 g). Model validation confirmed strong prediction accuracy, with property estimates for untested formulations (3–7 wt.%) providing guidance for future development. This study contributes to sustainable composite literature by: (i) demonstrating cassava peel valorisation as eco-friendly reinforcement, (ii) establishing RSM as a robust optimization framework for agro-waste composites, (iii) providing quantitative evidence of treatment effects through ANOVA, (iv) identifying optimal formulations via multi-response optimization, and (v) delivering validated predictive models for future material design. Future work should explore additional factors (NaOH concentration, treatment temperature, particle size) using full factorial designs, with morphological (SEM) and thermal (TGA/DSC) characterization to further elucidate structure-property relationships. The findings support development of biodegradable, cost-effective alternatives to synthetic composites for engineering applications, aligning with circular economy principles.

REFERENCE

1. Adeniyi AG, Abdulkareem SA, Adeyanju CA, Ighalo JO (2022) Recycling of Delonix regia Pods Biochar and Aluminium Filings in the Development of Thermally Conducting Hybrid Polystyrene Composites. *Journal of Polymers and the Environment*. doi:10.1007/s10924-022-02413-5
2. Aisien FA, Aisien ET (2020). Biogas from cassava peel waste. *Detritus* 10:100
3. Alamry Ali, Md Saiful Islam, Sinin Hamdan, Masuk Abdullah(2025) Enhancing the performance of hybrid bio-composites reinforced with natural fibres by using coupling agents, *Materials Research Express*, 10.1088/2053-1591/ad92f4, 12, 3, (035504), (2025).

4. Amuthakkannan, P. Manikandan, V. Winowlin, J. T. Uthayakumar, M. (2013) Effect of fibre length and fibre content on the mechanical properties of short Basalt fibre reinforced polymer matrix composite. *Material. Phys mech.* 16(107-117)
5. ASTM D790-17, Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials, ASTM International, West Conshohocken, PA, 2017. www.astm.org.
6. Barbalho, G. H. A., Nascimento, J. J. S., Silva, L. B., Delgado, J. M. P. Q., Vilela, A. F., Pereira, J. F., Santos, I. B., Luiz, M. R., Pinheiro, L. S. S., Silva, A. G. S (2025). Moisture absorption and its effects on the mechanical properties of biopolymers reinforced by curauá fiber and montmorillonite clay: A transient experimental evaluation. *Journal of Composites Science*, 9, 248. <https://doi.org/10.3390/jcs9050248>
7. Boumaaza, M., A. Belaadi, M. Bourchak, M. Jawaid, and S. Hamid. (2022). "Comparative Study of Flexural Properties Prediction of Washingtonia Filibera Rachis Biochar Bio-Mortar by ANN and RSM Models." *Construction and Building Materials* 318:125985.
8. Dan-Asabe, B., and Galadi. A. A. (2017). "Mathematical Modeling of the Flexural Strength, Impact Energy and Water Absorption of a Pineapple Fibre-HDPE Composite Using RSM Technique." *Journal of Polymer & Composites* 5 (2): 42-49.
9. Dos Santos AL, Castro ALS, Salomon KR, de Souza TS, Vich DV (2022). Global research trends on anaerobic digestion and biogas production from cassava wastewater: a bibliometric analysis. *Journal of Chemical Technology & Biotechnology*
10. Emma Martinaud, Carmen Hierro Iglesias, James Hammerton, Bawan Hadad, Rob Evans(2024)Valorising Cassava Peel Waste Into Plasticised Polyhydroxyalkanoates Blended with Polycaprolactone with Controllable Thermal and Mechanical Properties.Experimental Evaluation. *J. Compos. Sci.* 2025, 9, 248. <https://doi.org/10.3390/jcs9050248>
11. Garba B, Balogun R, Kalejaiye–Matti R, Maku B (2020). Ensuring Sustainable Development in the Cassava Value Chain and Value Addition in Nigeria. *International Journal of Economic Development Research and Investment* 11 (1):50-68
12. Howeler RH (2001). Proceedings of the Validation Forum on the Global Cassava Development Strategy,Rome, 26-28 April 2000. In: Validation Forum on the Global Cassava Development Strategy 2000:Rome, Italy, 2001. FAO
13. Ismanto AE, Wang S, Soetaredjo FE, Ismadji S (2010). Preparation of a capacitor's electrode from cassava peel waste. *Bioresource Technology* 101 (10):3534-3540
14. Kass, M. Y., Mekonone, S. T., Ayaliew, T. G., & Demisie, L. F. (2025). "Optimization of process parameters for sisal fiber-reinforced cornstarch biocomposites in sustainable packaging applications." *Discover Applied Sciences*, 7, 1119.
15. Kayiwa R, Kasedde H, Lubwama M, Kirabira J (2021). The potential for commercial-scale production and application of activated carbon from cassava peels in Africa: A review. *Bioresource Technology Reports* 15:100772
16. Kongkiattikajorn J and Sornvoraweat B (2011). Comparative study of bioethanol production from cassava peels by monoculture and co-culture of yeast. *Agriculture and Natural Resources* 45 (2):268274
17. Ladaci, N., Saadia, A., Belaadi, A., Boumaaza, M., Chai, B. X., Abdullah, M. M. S., Al-Khawlani, A., & Ghernaout, D. (2024). ANN and RSM prediction of water uptake of recycled HDPE biocomposite reinforced with treated palm waste *W. filifera*. *Journal of Natural Fibers*, 21, 2356697.
18. Medina-Jaramillo, C., Coelho-Leandro, G., Ayala-Valencia, G., et al. (2025). "Starch-based biocomposites reinforced with cellulose nanofibers from potato peel byproducts." *Scientific Reports*, 15, 38412.
19. Odetoye TE, Adeniyi AG, Akande O (2020). Valorisation of post-consumer polythene water sachet and Parinari polyandra shell residue for composites production. *SN Applied Sciences* 2 (11):1828. [doi:10.1007/s42452-020-03641-x](https://doi.org/10.1007/s42452-020-03641-x)
20. Ofem, M.I. and Ubi, P.A (2020) Properties of cassava peels reinforced High-density polyethylene. *Indian journal of Engineering*, 17(48), 450-461.

21. Ofuyatan O., Ede A., Olofinnade R., Oyeibisi S., Alayande T. & Ogundipe J. (2018). Assessment of Strength Properties of Cassava Peel Ash-Concrete, *International Journal of Civil Engineering and Technology*, 9(1), pp. 965–974.
22. Oladele, I. O., Akinwekomi, A D., Agbabiaka, O. G. and Oladejo, M. O. (2019). Influence of Biodegradation on the tensile and wear resistance properties of bio-derived CaCO₃/Epoxy composite. *J. Polym Res.*(26) 1-9
23. Oladele, I. O., Ibrahim, I. O., Adediran, A. A., Akinwekomi, A. D., Adetula, Y. V., & Olayanju, T. M. A. (2020). "Modified palm kernel shell fiber/particulate cassava peel hybrid reinforced epoxy composites." *Results in Materials*, 5, 100053.
24. Oladele, I.O and Agbabiaka, O.G.(2015) investigated the influence of mercerisation treatment of sisal fibre on the mechanical properties of reinforced polypropylene composite and modelling of the properties. *Fibres polymer*.16(3)650-656
25. Osuide E. E., Ukeme U., Osuide, M. O. (2021). An Assessment of the Compressive Strength of Concrete Made with Cement Partially Replaced with Cassava Peel Ash; P - ISSN: 2536 – 6866 e - ISSN: 2659 – 1529, *SAU Sci-Tech. J.*, 6(1).
26. Pradiza RR, Dwilaksana D, Mahardika M, Amanda P, Ilyas RA, Asyraf MRM and Asrofi M (2025). Morphology and tensile properties of biocomposite based on polyvinyl alcohol and cassava starch reinforced by lemon peel fibre. *International Journal of Agriculture and Biosciences* 14(4): 549–555. <https://doi.org/10.47278/journal.ijab/2025.051> A Publication of Unique Scientific Publishers
27. Rangappa SM, Siengchin S & Dhakal HN (2020). Green composites: eco-friendly and sustainable. *Appl Sci EngProg*; 13(3): 182–183.
28. Saliu O, Adeniyi A, Mamo M, Ndungu P, Ramontja J (2022). Microwave exfoliation of a biochar obtained from updraft retort carbonisation for supercapacitor fabrication. *Electrochemistry Communications*:107308
29. Sanjay MR, Madhu P, Jawaid M (2018). Characterisation and properties of natural fibre polymer composites: a comprehensive review. *J Clean Prod* 2018; 172: 566–581.
30. Vinod A, Sanjay MR, Suchart S (2020). Renewable and sustainable biobased materials: an assessment on biofibers, biofilms, biopolymers and biocomposites. *J Clean Prod*: 258: 120978. International Energy Agency. *World Energy Outlook (2023)* IEA, 2023, <https://www.iea.org/reports/world-energy-outlook-2023>
31. Zhang, Y.; Yuan, Z.; Xu, C.C. (2017) Bio-based resins for fibre-reinforced polymer composites. In *Natural Fibre-Reinforced Biodegradable and Bioresorbable Polymer Composites*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 137–162.
32. Zhenhao Liao, Yiyun Hu, Yan Shen, Ke Chen, Cheng Qiu, Jinglei Yang, Lei Yang(2024) Investigation into the Reinforcement Modification of Natural Plant Fibres and the Sustainable Development of Thermoplastic Natural Plant Fibre Composites, *Polymers*, 10.3390/polym16243568, 16, 24, (3568).