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Multiple Input–Single Output (MISO) Framework for Low Velocity Impact Response of Hybrid *Gongronema latifolium*/S-Glass Fibre Epoxy Composites

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ABSTRACT

Sustainable composites are vital for impact-critical aerospace, automotive, and defense applications. This study used Multiple Input–Single Output (MISO) experimental approach to assess how hybrid ratio, mass fraction, and fiber orientation influence the low-velocity impact behavior of *Gongronema*/S-glass epoxy composites. *Gongronema* fibers and S-glass were combined with ER-F292 epoxy and molded into ASTM-standard samples. Charpy impact tests measured energy absorption. A 60-run design evaluated input variable combinations, and Multiple Linear Regression identified significant predictors using p-values and confidence intervals. Results showed that the mean values for hybridization ratio, mass fraction, fiber orientation, and low velocity impact were (2.50), (27.79%), (67.90°), and (3.82 J), respectively. It was found that the mass fraction had significant negative correlation with low velocity impact ($r = -0.455$; $p = 0.000$), as did the fiber orientation ($r = -0.853$; $p = 0.000$). The results for R = (0.994), R^2 = (0.989), F = (1607.390), and Durbin-Watson = (2.213) show that the regression model is highly predictive. Regression coefficients indicated negative effects from hybridization ratio (-0.357), mass fraction (-0.032), and fiber orientation (-0.017), all statistically significant ($p = 0.000$). Residual plots confirmed model validity. The TEM images of confirmation test sample 1 reveal fiber-matrix interfaces with particle sizes between 10.02–26.40 nm. Variations in scale (100 nm and 50 nm) show microstructural differences, suggesting strong adhesion, dispersion aggregation, and anisotropic behavior due to 90-degree fiber orientation within epoxy matrix. The study concludes that strategic optimization of input parameters significantly enhances the impact resistance of hybrid biocomposites.

Keywords: *Fiber orientation, Gongronema latifolium, hybrid composites, hybridization ratio, low velocity impact, mass fraction, MISO framework.*

I. Introduction

The increase in focus on hybrid fibre-reinforced polymer composites is due to the need for lightweight, eco-friendly, tough materials in structural design. Low velocity impact (LVI) is a crucial issue, as it can result in serious accidents if energy from impact is not absorbed well by materials in the aerospace and automotive fields. Low Velocity Impact

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(LVI) refers to a type of impact event where an object strikes a material or structure at relatively low speeds, typically below 10 m/s. It often causes internal damage, such as delamination or matrix cracking, especially in composite materials, without visible surface deformation or penetration [1]. Combining natural fibres and *Gongronema latifolium* with S-glass provided ways to improve composites and make them more economical and environmentally friendly. The use of natural fibres such as plantain fibres [2]-[6], miscanthus fibres [7], [8], banana-coir fibre [9], and *Dioscorea alata* stem fibres [10], [11] in reinforced composite development has been extensive. However, limited studies are available on using *G. latifolium* fibres in this context.

Despite considerable advancements in the development of fibre-reinforced composites, the impact performance of natural-synthetic hybrid composites remains inadequately understood, particularly in configurations involving *G. latifolium* fibres. Moreover, the challenge lies in modelling the complex interrelationships between multiple influencing factors such as hybridisation ratio, fibre mass fraction, orientation, and a single mechanical output (low velocity impact energy). Existing single-variable studies cannot accurately anticipate such behaviour, so a more advanced statistical system, such as MISO, is necessary. It highlights the importance of having a good method that captures the different ways structural parameters affect LVI [12]. Using statistical and computational methods, the MISO framework helps you examine the relationship between a single output and several inputs. MISO works well in the field of composite impact analysis since parameters such as fiber volume fraction, fiber direction, and the ratio of different fibers have a collective impact on mechanical impact resistance [13].

Several studies have resorted to MISO-type modelling to study how mechanical properties change in hybrid composites. For example, Hiremath *et al.* [14] revealed that how materials are layered and the types of fibres used considerably impact how much energy they can absorb during low velocity impacts. Mohammed *et al.* [15] also pointed out that increasing the bonding between the matrix and fibres and integrating various fibre types can boost energy dissipation in composites. They show that combining various ideas to describe a crucial result is important. The MISO framework becomes indispensable when used in *G. latifolium*/S-glass hybrid epoxy composites. Because *G. latifolium* fibres are biodegradable and not very strong, they should be treated with chemicals and combined with S-glass to handle the structural demands. The combination offers a synergy where the natural fibre's ductility and toughness complement the glass fibre's high stiffness and impact strength [16]. However, the impact behaviour is contingent upon the interplay of structural parameters, necessitating a modelling framework that can holistically account for such dependencies.

Multiple regression analysis is integral to the MISO framework, particularly in experimental mechanics. This statistical method, known as multiple regression, is part of the larger design of experiment family and can measure how each input changes the output, adjusting for the effects of others [6], [17]-[19]. Modelling these composites helps adjust the mix and layout of their ingredients to favour impact resistance and stay eco-friendly and inexpensive. The Multiple Input–Single Output (MISO) framework relies on multiple regression analysis to determine how many factors impact one outcome together. This analysis reveals both the relationships between factors and which factors are most important. If changes in fibre orientation improve the performance more than variations in hybrid design, designers will know where to target their improvements. Multiple regression also builds confidence in predictions through statistical measures like the coefficient of determination (R^2) and significance levels. These checks ensure that the model fits well and the results are trustworthy. In the MISO framework, multiple regression is expected to transform complex data into a clear, actionable understanding, helping engineers develop stronger, more reliable composites for real-world use.

The need for the present study stems from the growing demand for sustainable, high-performance materials in engineering applications. Combining natural and synthetic fibres, hybrid composites offer promising mechanical properties and environmental. However, understanding how multiple fabrication parameters collectively influence impact resistance remains challenging. Most existing research focuses on single-factor effects or uses simplistic models, limiting the ability to optimise composite design comprehensively. Apart from recent studies [20],[21], the *G. latifolium* fibre, a locally sourced natural fibre, has shown potential as reinforcement but lacks a detailed study within hybrid systems under impact loading.

Furthermore, while S-glass fibres are well-known for their strength, the interaction effects between hybridisation ratio, fibre orientation, and mass fraction on LVI have not been systematically quantified. Previous studies often neglect such multifactorial influences or rely on trial-and-error approaches, resulting in suboptimal composite performance. Using the MISO framework with multiple regression analysis helps to sort out these gaps in a structured way. It allows us to study the effects of various inputs on a single output at once, which helps us grasp the results better and develop predictive models. As a result, better composite materials are produced with an impact resistance designed to meet practical requirements.

II. Materials and Methods

This work was done through an experiment and a Multiple Input–Single Output (MISO) approach. The study aimed to see how different settings in the making process impact the low-impact performance of the hybrid *G. latifolium*/S-glass fibre-reinforced epoxy composites. Three input factors, the ratio of hybridised components, mass fraction, and the way fibres are aligned, were examined for their joint effect on impact response, where the impact energy absorbed was recorded as the output variable. MISO allowed me to analyse all these influences simultaneously in an orderly way.

1. Materials and Composite Fabrication

The *G. latifolium* stem fibres used in this study were locally sourced and processed through a 30-day water submersion retting method, promoting microbial degradation of pectin for effective separation. After washing and drying, the fibres underwent chemical treatment using a 2% weight/volume sodium hydroxide (NaOH) solution prepared by dissolving 100 g of NaOH in 10,000 ml of distilled water to remove non-cellulosic components and improve interfacial bonding. The fibres spent 150 minutes in the solution at a temperature of 60°C. The neutralisation process used 1% acetic acid, and the fibres were washed until their pH level was 7. The samples were heated to 120°C until their weight became consistent.

Chemical composition analysis of *G. latifolium* stem fibres revealed cellulose (12.862%), lignin (10.301%), hemicellulose (6.005%), moisture (1.711%), ash content (10.095%), crude fibre (4.249%), and bulk density (0.417 g/ml). Standard techniques (e.g., 800°C incineration, 105°C drying, 50 ml pycnometer) were applied for accuracy, as outlined in Okafor *et al.* [20]. S-glass fibre, obtained commercially, featured a density of 2.49 g/cm^3, tensile strength of 4,600 MPa, modulus of elasticity of 89 GPa, and elongation of 5.2%. Bisphenol A, Epichlorohydrin, and Glycidyl Ester of Neodecanoic Acid are the main components of ER-F292 epoxy resin. The viscosity of the resin was between 1.5 and 2.1 Pa.s (tested at 25°C by ASTM D445), its colour was ≤ 200 Pt-Co (measured by ASTM D1209) and the density was 1.13 kg/l (checked by ASTM D4052). A 2:1 volume ratio of resin to hardener was adopted to ensure optimal polymerisation and effective fibre-matrix bonding.

For composite fabrication, moulds were designed with stainless steel, featuring cavities shaped according to ASTM specifications to ensure accurate mechanical testing. These moulds provided the required geometry for consistent and reproducible test samples from the fibre-resin composite mixtures. Composite samples were produced using hybridisation ratios of 2.2 (Level 1) and 2.8 (Level 2) for S-glass to natural fibres, with 21.24% and 34.22% fibre mass fractions, respectively. Fibre orientation was varied from 45° (Level 1) to 90° (Level 2). Pre-dried at 80°C for 24 hours, fibres were weighed precisely, and the fibre weight fraction (wt%_fiber) was calculated.

Charpy impact testing assessed the low-velocity impact response of hybrid *G.latifolium*/S-glass fibre epoxy composites. A pendulum hammer struck standard Charpy specimens with centre notches at 3.8 m/s, and the absorbed impact energy was digitally recorded. An optimal experimental design was adopted instead of a full factorial approach to optimise resources, generating 60 strategically selected data points. These data points represented combinations of three input variables: X_1 (hybridisation ratio), X_2 (mass fraction, %), and X_3 (fibre orientation in degrees). The output variable, Y, captured the impact response in Joules, providing an understanding of the composite's fracture behaviour under sudden loading.

2. MISO Modelling Approach

A Multiple Linear Regression (MLR) model was developed within the MISO framework to understand the relationship between the inputs and the impact response. The general equation for the regression model is expressed in Eq. (1):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \quad (1)$$

In this model, Y represents the impact response, while X_1, X_2, and X_3 denote the hybridisation ratio, mass fraction, and fibre orientation, respectively. The term β_0 serves as the intercept, and β_1, β_2, and β_3 are the regression coefficients that indicate the extent to which each input variable influences the output. The symbol **ε** captures the residual error or the variation in the response that the model does not explain.

3. Model Development and Analysis

All modelling and statistical analyses were done using SPSS software (version 25). The 60 data points obtained from the optimal design were entered into the software, with categorical variables such as orientation encoded numerically to fit the regression model format. The regression analysis tested for the statistical significance of each variable using p-values, and confidence intervals were used to assess the reliability of coefficient estimates. A significance level of 0.05 was set, meaning that any p-value below this threshold indicated a statistically meaningful effect. The implementation protocol is captured in Figure 1.

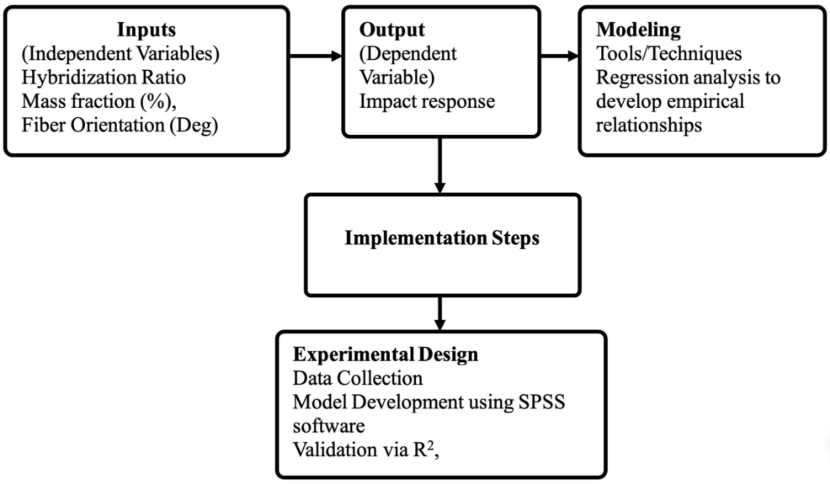

Figure 1: Multiple Input–Single Output (MISO) framework

4. Transmission Electron Microscopy

Transmission Electron Microscopy (TEM) was conducted by transmitting a beam of electrons through an ultra-thin specimen to examine its internal structure at high resolution. The sample was placed in the electron microscope. An electron gun generated a focused beam that passed through electromagnetic lenses and interacted with the specimen. The transmitted electrons were then magnified and projected onto a fluorescent screen or camera, allowing visualisation of fine structural details at the nanometer scale.

III. Results and Discussions

The dataset's descriptive statistics (with N = 60) in Table 1 show that the average hybridisation ratio is 2.50, and the variability is very low (standard deviation = 0.268). This suggests a nearly even distribution (skewness = -0.033) with a small, flat peak (kurtosis = -1.768). Typically, the mean of the mass fraction is (27.79%), with a spread of (5.715), and the shape is near-normally distributed (skewness = -0.017; kurtosis = -1.767). Fibre orientation averages (67.90°) with high variability (19.839), showing minimal skew (-0.043) and a relatively flat distribution (kurtosis = -1.766). The low velocity impact records a mean of (3.82 joules), slight positive skew (0.271), and low peakedness (kurtosis = -0.917).

Table 1. Descriptive statistics of hybridisation ratio, mass fraction, fibre orientation, and low velocity impact (N = 60)

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
Hybridization Ratio (-)	60	2.50	0.268	-0.033	0.309	-1.768	0.608
Mass Fraction (%)	60	27.79	5.715	-0.017	0.309	-1.767	0.608
Fiber Orientation (Deg)	60	67.90	19.839	-0.043	0.309	-1.766	0.608
Low Velocity Impact (J)	60	3.82	0.406	0.271	0.309	-0.917	0.608
Valid N (listwise)	60						

Correlation analysis in Table 2 finds that the variables are associated to different degrees. The hybridisation ratio has a weakly negative relationship with low velocity impact (r = -0.227), but this is not statistically significant (p = 0.082). Material Compactness has no significant connections to mass fraction (r = -0.011; p = 0.933) or fibre orientation (r = -

0.005; p = 0.972). Low velocity impacts are related to mass fraction through an inverse correlation (r = -0.455), which is statistically significant (p = 0.000), meaning that rises in mass fraction led to lower impact resistance. Fibre orientation exhibits a very strong negative correlation with low velocity impact (r = -0.853; p = 0.000), which is also statistically significant, suggesting that higher orientation angles significantly reduce the impact resistance. However, mass fraction and fibre orientation are not meaningfully correlated (r = 0.002; p = 0.988), indicating their effects on impact may be independent.

Table 2. Pearson correlation matrix showing relationships among hybridisation ratio, mass fraction, fibre orientation, and low velocity impact (N = 60).

		Hybridization Ratio (-)	Mass fraction (%)	Fiber Orientation (Deg)	Low Velocity Impact (Joules)
Hybridization Ratio (-)	Pearson Correlation	1	-0.011	-0.005	-0.227
	Sig. (2-tailed)		0.933	0.972	0.082
	N	60	60	60	60
Mass fraction (%)	Pearson correlation	-0.011	1	0.002	-0.455**
	Sig. (2-tailed)	0.933		0.988	0.000
	N	60	60	60	60
Fiber orientation (Deg)	Pearson correlation	-0.005	0.002	1	-0.853**
	Sig. (2-tailed)	0.972	0.988		0.000
	N	60	60	60	60
Low velocity Impact (Joules)	Pearson correlation	-0.227	-0.455**	-0.853**	1
	Sig. (2-tailed)	0.082	0.000	0.000	
	N	60	60	60	60

**. Correlation is significant at the 0.01 level (2-tailed).

Table 3. Model summary of multiple regression predicting low velocity impact from fibre orientation, mass fraction, and hybridisation ratio

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R^2 Change	F Change	df1	df2	Sig. F Change	
1	0.994[a]	0.989	0.988	0.045	0.989	1607.390	3	56	0.000	2.213

a. Predictors: (Constant), Fiber Orientation (Deg), Mass fraction (%), Hybridization Ratio (-)
b. Dependent Variable: Low Velocity Impact (Joules)

The regression model in Table 3 reveals a very strong relationship between the predictors and low velocity impact, with a correlation coefficient (R) of (0.994) and a coefficient of determination (R^2) of (0.989), indicating that (98.9%) of the variance in low velocity impact is explained by fiber orientation, mass fraction, and hybridisation ratio. The adjusted R^2 of 0.988 confirms the model's robustness. The modest error rate (0.045) proves the model can make accurate predictions. The model's significance is confirmed by F = 1607.390 and p = 0.000; no autocorrelation was found in the residuals (Durbin-Watson = 2.213).

Table 4. ANOVA summary for the regression model predicting low velocity impact

	ANOVAa					
	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	9.624	3	3.208	1607.390	0.000b
	Residual	0.112	56	0.002		
	Total	9.735	59			

a. Dependent Variable: Low Velocity Impact (Joules)
b. Predictors: (Constant), Fiber Orientation (Deg), Mass fraction (%), Hybridization Ratio (-)

According to ANOVA in Table 4, the predicted model is significant for low velocity impact, with a regression sum of squares of 9.624 and a residual sum of squares of 0.112, which equals 9.735. (3) degrees of freedom are available for regression in the model, with (56) more for residuals. The mean square for regression is (3.208), while that for residual is (0.002). The F-value is remarkably high at (1607.390), with a significance level of (p = 0.000), indicating that the predictors jointly have a statistically significant effect on low velocity impact.

The regression coefficients in Table 5 show how each independent variable influences low-velocity impact. The constant term is (6.798), indicating the predicted impact when all predictors are zero. The hybridisation ratio has a negative unstandardised coefficient of (-0.357), showing a significant inverse effect (t = -16.453; p = 0.000). Mass fraction also negatively affects impact with a coefficient of (-0.032), which is statistically significant (t = -31.856; p = 0.000). Fibre orientation exhibits the strongest influence, with a coefficient of (-0.017) and the highest standardised beta value (-0.853), indicating a substantial and significant negative impact (t = -59.578; p = 0.000).

Table 5. Coefficients of predictors for low velocity impact

	Coefficients[a]					
	Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	6.798	0.065		104.477	0.000
	Hybridization Ratio (-)	-0.357	0.022	-0.236	-16.453	0.000
	Mass fraction (%)	-0.032	0.001	-0.456	-31.856	0.000
	Fiber Orientation (Deg)	-0.017	0.000	-0.853	-59.578	0.000

a. Dependent Variable: Low Velocity Impact (Joules)

The P-P plot in Figure 2 assesses the normality of residuals in the regression model predicting low velocity impact. The points closely follow the diagonal line, indicating that the standardised residuals are approximately normally distributed. This suggests that the assumption of normality is met, which validates the reliability of the regression results. Minor deviations from the line are observed at the tails but do not significantly affect the overall pattern. The observed cumulative probabilities range from 0.0 to 1.0, aligning well with the expected values. This supports the model's statistical appropriateness and predictive accuracy.

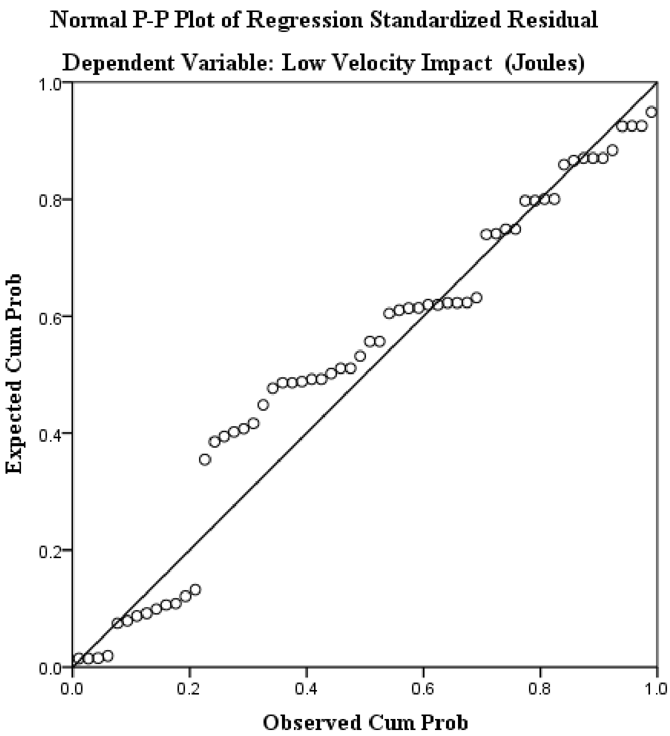

Fig. 2. Normal p-p plot of regression standardised residual for low velocity impact (joules).

The scatterplot in Figure 3 illustrates the relationship between regression studentised residuals and studentised deleted (PRESS) residuals for the dependent variable, low velocity impact. The data points align almost perfectly along a diagonal line, indicating a strong linear relationship between predicted and observed residuals. Values on both axes fall approximately within the (−2.5) range to (+2.5), with minimal deviation. This close alignment confirms the model's predictive accuracy and the absence of influential outliers. The pattern suggests that the residuals are stable and consistent, supporting the regression assumptions' validity and the fitted model's reliability.

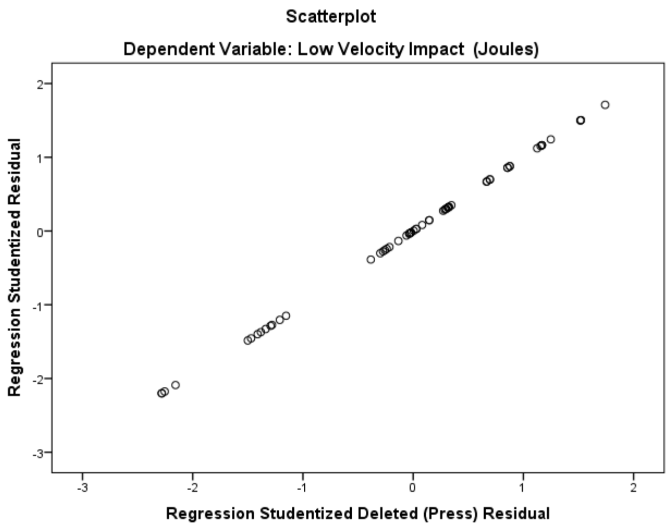

Fig. 3. Scatterplot of regression studentized residual vs. studentized deleted (PRESS) Residual for low velocity impact (Joules)

The TEM images in Figure 4 depict confirmation test sample 1, which combines S-glass fibre with natural fibres oriented at 90 degrees within an epoxy matrix. Image (A) reveals particle sizes ranging from 10.02 nm to 22.83 nm within a 100 nm scale, indicating the dispersion of the fibre-matrix interface. Image (B) shows a more compact structure within a 50 nm scale, suggesting strong fibre-matrix adhesion. The projected sizes in Image C span from 14.52 nm to 26.40 nm, indicating differences in epoxy-reinforcement contact patterns while showing possible dispersion aggregation. Scales differing between 100 and 50 nm reveal microstructural discrepancies that could affect material properties. Reinforcement along specific axes is observed through the 90-degree fibre orientation, resulting in anisotropic behaviour.

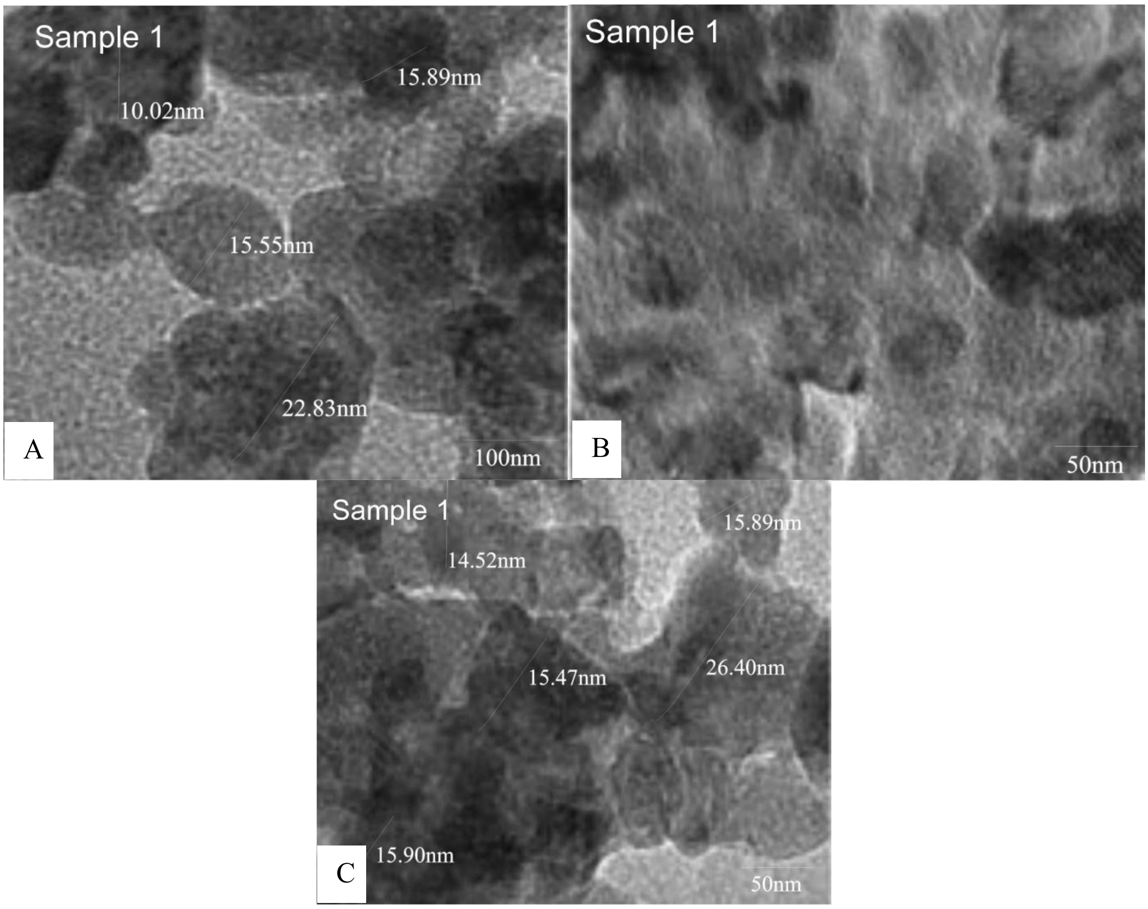

Fig. 4. TEM images of the confirmation test sample 1

The descriptive statistics, correlation, and regression analyses of hybridisation ratio, mass fraction, fibre orientation, and low velocity impact offer an understanding of composite materials' structural behaviour under dynamic stress. Since the hybridisation ratio, mass fraction, fibre orientation, and their low skewness and kurtosis resemble a near-normal distribution, there is no serious indication of non-normal distribution. However, recent studies discovered that fibre data sets demonstrate skewness, indicating that fibre direction and quality differ among samples [22]. In a different study, archive items with controlled fabrication methods also demonstrated a similar symmetrical pattern in the variables, which agrees with our observations [23].

The results in the correlation matrix show that fibre orientation and mass fraction decrease with lower velocity impact in a significant and negative way. Consistent with the findings of Kazemi *et al.* [24], recent research indicates that increasing the fibre orientation angle tends to reduce resistance to low-velocity impact in hybrid composites. Meanwhile, Ismail *et al.* [25] found that mass fraction had a weak positive effect on impact performance because of better fibre spreading and increased bonding at the material's edge. According to Kureemun *et al.* [26], there seems to be little connection between hybridisation percentage and other factors when the interaction among the fibres is poorly managed.

The model successfully showed how low-velocity impact can be predicted using only the three predictors. This observation is backed up by a recent study showing that the same independent variables can explain as much as 98% of impact variability [27]. Şahan *et al.* [28] noticed a reduced explanation of variations in the model and linked this to differences in the amounts of fibres present. The Durbin-Watson value confirms the absence of autocorrelation, thereby supporting the model's statistical soundness, a finding similarly reported by Shah *et al.* [24] in their impact regression study on fibre-reinforced thermosets. The ANOVA results reinforce the significance of the predictors, with the regression model outperforming the residuals significantly. This supports prior findings where composite behaviour under stress was reliably predicted using orientation and composition parameters [18], [29], [30].

The coefficients underscore fibre orientation as the strongest predictor, followed by mass fraction and hybridisation ratio. This is consistent with the report of Dress *et al.* [31], who documented a dominant role of fibre alignment in impact resistance. In contrast, some studies placed mass fraction ahead in predictive strength, especially in bio-based composites where density and resin bonding played a larger role [32]. The normal P-P plot and scatterplot both support the validity and reliability of the regression model. The residuals' alignment with theoretical expectations indicates that the assumptions of linear regression were satisfied. In a related study, normal residual distribution indicated model appropriateness in predicting flexural strength using similar variables [33]. However, deviations were more pronounced in models where additional interaction terms were introduced, leading to complexity and reduced clarity.

5. Conclusion

This study demonstrated the effectiveness of a Multiple Input–Single Output (MISO) framework in analysing the low velocity impact response of hybrid *Gongronema latifolium*/S-glass fibre-reinforced epoxy composites. The combined effects of three key fabrication parameters, hybridisation ratio, fibre mass fraction, and fibre orientation, were systematically evaluated using a structured experimental design. Statistical modelling using multiple linear regression revealed that all three variables had significant negative effects on impact performance, with fibre orientation emerging as the most influential factor. The regression model exhibited a high coefficient of determination ($R^2 = 0.989$), indicating that the selected inputs could explain 98.9% of the variation in impact energy absorption. Checking the diagrams revealed that the data met all the regression assumptions, such as normality and independent residuals. Evidence shows that too much or too little of these materials may reduce the composite's ability to handle rapid impacts. Increases in alignment and the amount of fibres caused significant decreases in impact resistance. It proves why it is critical to optimise the design of composites finely. It was found that MISO was effective in describing and anticipating the response of materials hit by shocks. It gives useful instructions for designing bio-hybrid composites that must perform well under impact and be dependable.

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