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| RESEARCH ARTICLE

Analysis of Thermal Insulation Characteristics in Epoxy Composites Reinforced with Hybrid Materials: Calabash and Rice Husk Ash

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| ABSTRACT
This research investigates the thermal insulation properties of epoxy composites reinforced with hybrid natural materials, specifically calabash and rice husk ash (RHA). Addressing the increasing demand for sustainable, cost-effective, and energy-efficient materials in the construction and automotive industries, we employed a systematic approach involving material characterization, composite fabrication, and thermal performance evaluation via differential scanning calorimetry (DSC). Composites were prepared using varying proportions of calabash and RHA as fillers in an epoxy matrix. Key metrics were analysed, including thermal conductivity, thermal resistance, specific heat capacity, and mechanical properties (Shore D hardness and density). The optimal composite formulation—comprising 20% calabash fiber, 20% RHA, and 60% epoxy resin—demonstrated exceptional thermal performance, achieving a thermal conductivity of 0.284805 W/m·K and thermal diffusivity of 0.131303 m^2/s, meeting industrial insulation benchmarks. Comparative analysis with conventional materials, such as fiberglass and polyurethane composites, highlighted the superior thermal performance of the hybrid epoxy composite. This work illustrates the potential of integrating agricultural by-products into advanced materials for sustainable thermal insulation applications.

| KEYWORDS

Composites, Thermal Insulation, Insulation Materials, Rice Husk Ash, Calabash, Thermal Conductivity, Optimization

| ARTICLE INFORMATION

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1. Introduction

The global construction industry increasingly prioritizes energy efficiency and sustainable building practices in response to escalating climate change concerns [1][2]. Thermal insulation plays a critical role in reducing energy consumption by minimizing heat transfer between interior and exterior environments. Traditional insulation materials, such as mineral wool and expanded polystyrene, while effective, pose significant environmental challenges due to their reliance on non-renewable resources and energy-intensive manufacturing processes [3][4].

The shift towards sustainable thermal insulation solutions has emerged as a pivotal research direction, driven by the need to develop materials that balance performance with ecological considerations. Natural fibers and bio-based materials have gained prominence as promising alternatives, offering several advantageous properties, including biodegradability, low thermal conductivity, and reduced environmental impact [5][6].

Key considerations in thermal insulation material development include critical performance metrics such as thermal conductivity, thermal diffusivity, and specific heat capacity, which determine a material's ability to effectively regulate heat transfer and maintain stable temperature environments [7]. Achieving optimal insulation performance necessitates a multifaceted approach that considers material composition, structural characteristics, and manufacturing techniques.

Composite materials have become a focal point in this research landscape, presenting opportunities to strategically combine synthetic and natural materials [8]. By integrating natural fibers into composite matrices, researchers can enhance thermal insulation properties while simultaneously addressing ecological concerns. The interaction between fiber types, content, and matrix materials significantly influences the overall thermal behaviour and performance of these innovative solutions [9].

Recent investigations have demonstrated particular promise in hybrid composites that leverage agricultural byproducts like rice husk ash and natural fibers such as calabash [10] [11]. These materials utilize readily available resources, support local economies, and provide effective thermal barriers through their inherent microstructural properties. Epoxy resins have emerged as versatile matrix materials in composite development, offering exceptional mechanical properties and compatibility with various fibers [12]. Their hydrophobic characteristics and ability to create microvoids contribute to improved thermal performance and longevity of insulation materials.

Ongoing research in this domain aims to develop thermal insulation solutions that not only meet stringent performance standards but also align with broader sustainability objectives [13].

2. Materials and Methods

2.1 Materials

In this study, epoxy resin (DGEBA) served as the matrix material, while calabash (Lagenaria siceraria) and rice husk ash (RHA) were employed as reinforcement materials. The epoxy resin and hardener were sourced from commercial suppliers and characterized by standard material properties. Calabash fibers were processed using methods adapted from previous works [14]. RHA was produced via controlled combustion, as outlined in [15].

2.2 Preparation of Reinforcement Materials

2.2.1 Calabash Fibers

Calabash fruits were harvested, and their outer shells were cleaned, dried, and crushed into small pieces. The dried shells were then milled to obtain calabash fibers with a particle size of 150 μm. This process aligns with methodologies described in previous studies [16], where the fibers underwent sodium hydroxide (NaOH) treatment to enhance their mechanical properties and improve bonding with the epoxy matrix. Figure 1 shows the picture of Calabash tree and grounded calabash particles.

Figure 1: Calabash tree and grounded calabash particles

2.2.2 Rice Husk Ash (RHA)

RHA was derived from the combustion of rice husks collected from a local agricultural mill. The husks were burnt in a furnace at 600°C to produce amorphous silica-rich ash [19]. The chemical composition and physical properties of RHA were analyzed according to methods used in earlier studies [17]. RHA powder was sieved to a particle size of 100 µm, with a silica content of around 90%, consistent with previous findings on its pozzolanic activity [15]. Figure 2 shows the picture of Grounded Rice Husk and Rice Husk Ash.

Figure 2: Grounded Rice Husk and Rice Husk Ash

2.3 Composite Fabrication

2.3.1 Epoxy Matrix Preparation

The epoxy composites were fabricated by mixing DGEBA epoxy resin with a polyamide-based hardener at a 2:1 weight ratio. The resin and hardener were thoroughly mixed to ensure a homogeneous solution and then degassed under a vacuum to eliminate trapped air.

Figure 3: Samples of Epoxy Composites Reinforced with Hybrid Materials: Calabash and Rice Husk Ash

2.3.2 Reinforcement Loading

Based on a design matrix, calabash fibers and RHA were incorporated into the epoxy matrix at varying weight percentages, including 10 wt%, 20 wt%, and 30 wt%, to investigate the synergistic effects on thermal insulation and mechanical performance. Table 1 presents the Design of the experiment employed for the investigation of the thermal properties.

Table 1: Design of the experiment (DoE)

Run	**A: Calabash Fibre Content (wt%)**	**B: Rice Husk Ash Content (wt%)**	**C: Curing Time (Hrs)**	**D: Mixing Ratio**	**Thermal Conductivity** (W/mK)	**Thermal diffusivity** (mm^2/S)	**Specific Heat Capacity** (J/gK)	**Thermal Insulation Efficiency** (%)
1	5	5	12	2:1				
2	20	20	12	1:1				
3	20	10	18	2:1				
4	20	5	24	3:2				
5	5	5	12	1:2				
6	5	5	24	1:1				
7	10	10	18	3:2				
8	20	20	24	2:1				
9	10	5	24	2:1				
10	15	15	18	1:1				
11	10	10	24	1:2				
12	20	5	18	1:2				
13	10	10	18	3:2				
14	5	15	18	2:1				
15	10	20	24	1:1				
16	10	10	12	1:1				
17	15	20	12	2:1				
18	10	10	24	1:2				
19	20	15	12	1:2				
20	20	20	18	3:2				
21	5	20	12	3:2				
22	20	5	24	1:1				
23	20	5	12	3:2				
24	5	20	24	3:2				
25	10	20	18	1:2				

2.3.3 Curing Process

The composite mixtures were poured into a mould and cured e at room temperature for 12 hours to achieve complete cross-linking **of the epoxy resin**. This curing process ensures the formation of a solid, rigid composite material with enhanced mechanical and thermal properties.

Figure 4: Curing process

2.4 Thermal and Mechanical Testing

2.4.1 Thermal Conductivity and Insulation Efficiency

The thermal conductivity of the composites was measured using the transient plane source (TPS) method, following the ASTM E1952 standard. Thermal diffusivity and specific heat capacity were calculated using the relationship between thermal conductivity, specific heat, and density. These measurements were conducted at various temperatures to evaluate the thermal insulation efficiency of the composites [15].

2.4.2 Microstructure Analysis

The dispersion of the reinforcement materials within the epoxy matrix was analyzed using scanning electron microscopy (SEM). Samples were gold-coated to prevent charging during analysis. SEM imaging provided insights into the distribution and interfacial bonding between the epoxy resin and the natural fibers, which is crucial for understanding the mechanical properties of the composites [17].

2.5 Statistical Analysis

The design of experiments (DOE) was conducted using Design Expert software version 13.0. The thermal properties of the composites were analyzed using response surface methodology (RSM), following the methods already established in earlier studies on composite materials [14] [17]. The significance of the factors was evaluated through analysis of variance (ANOVA) to ensure that the results obtained were statistically robust.

3. Results and Discussion

3.1 Material Characterization

The characterization of the fibers and RHA revealed their suitable chemical and physical properties for reinforcement in epoxy composites. The chemical composition analysis confirmed the presence of significant amounts of silica in the RHA, validating its potential for enhancing the properties of the composite materials.

3.2 Composite Thermal Performance

The experimental values for thermal properties—thermal conductivity, thermal diffusivity, specific heat capacity, and thermal insulation efficiency—are detailed in Table 2. This data serves as a foundation for statistical optimization, enabling improved accuracy and performance in thermal property evaluations and applications.

3.3 Microstructural Observations

SEM images displayed well-dispersed fibers within the epoxy matrix, suggesting strong interfacial bonding. The alkali treatment of calabash fibers contributed to increased surface roughness, enhancing the adhesion with the matrix and improving the overall mechanical performance of the composite.

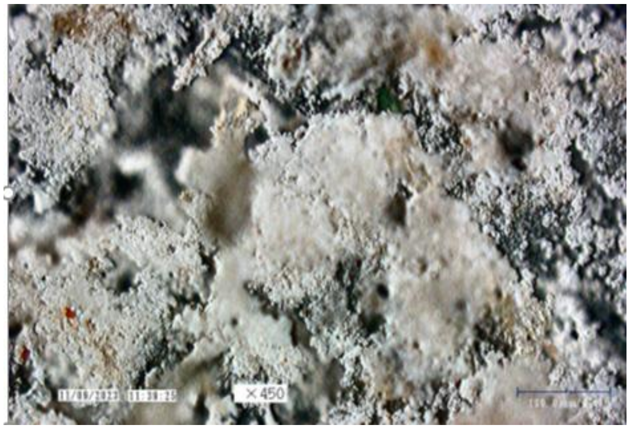


Figure 5: SEM Image at 450 magnification

3.4 Statistical Analysis and Model Validation

Preliminary study on the Analysis of Thermal Insulation Characteristics in Epoxy Composites Reinforced with Hybrid Materials: Calabash and Rice Husk Ash. Four excipients were chosen for the optimized responses (i.e. thermal conductivity, thermal diffusivity, specific heat capacity and thermal insulation efficiency), these factors include the calabash fibre content, Rice Husk Ash content, curing time, and mixing ratio as they may affect the responses. The ranges of variables were also studied by using a D-optimal custom method of Response Surface Methodology (RSM) in design expert software 13.0. Table 2 shows the summary data table of the actual design after the experiment.

Table 2: Summary of the Actual Design table for the optimization

	Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3	Response 4
Run	A: Calabash Fibre Content	B: Rice Husk Ash Content	C: Curing Time	D: Mixing Ratio	Thermal Conductivity	Thermal diffusivity	Specific Heat Capacity	Thermal Insulation Efficiency
	wt%	wt%	hrs	Calabash: RHA	W/mK	mm^2/S	J/gK	%
1	5	5	12	2:1	0.2	0.1	1.2	45
2	20	20	12	1:1	0.3	0.15	1.3	50
3	20	10	18	2:1	0.28	0.14	1.25	48
4	20	5	24	3:2	0.25	0.12	1.22	47
5	5	5	12	1:2	0.22	0.11	1.15	44
6	5	5	24	1:1	0.21	0.1	1.18	43
7	10	10	18	3:2	0.26	0.13	1.24	49
8	*20*	*20*	*24*	*2:1*	*0.32*	*0.16*	*1.35*	*52*
9	10	5	24	2:1	0.24	0.12	1.23	46
10	15	15	18	1:1	0.29	0.14	1.28	51
11	*10*	*10*	*24*	*1:2*	*0.27*	*0.13*	*1.26*	*50*
12	20	5	18	1:2	0.3	0.15	1.31	49
13	10	10	18	3:2	0.25	0.12	1.22	48
14	5	15	18	2:1	0.23	0.11	1.19	45

15	10	20	24	1:1	0.28	0.14	1.27	50
16	10	10	12	1:1	0.26	0.13	1.25	49
17	15	20	12	2:1	0.31	0.15	1.34	51
18	10	10	24	1:2	0.27	0.13	1.26	50
19	20	15	12	1:2	0.29	0.14	1.3	52
20	20	20	18	3:2	0.33	0.16	1.36	53
21	5	20	12	3:2	0.24	0.12	1.21	46
22	20	5	24	1:1	0.3	0.15	1.31	49
23	20	5	12	3:2	0.29	0.14	1.28	48
24	*5*	*20*	*24*	*3:2*	*0.25*	*0.13*	*1.22*	*47*
25	10	20	18	1:2	0.28	0.14	1.26	50

3.5 Actual and Predicted Equations

The regression analysis presents comprehensive mathematical models for the thermal properties of hybrid composites across different mixing ratios. The equations in Table 3 systematically capture the complex interactions between calabash fiber content (A), rice husk ash content (B), and curing time (C) for thermal conductivity, thermal diffusivity, specific heat capacity, and thermal insulation efficiency. Each property is modelled using both coded and actual variable equations, revealing non-linear relationships and involved interdependences between material composition parameters. These sophisticated regression models enable precise prediction of thermal characteristics across various composite configurations.

Table 3: Predicted and Actual Equations for the Responses

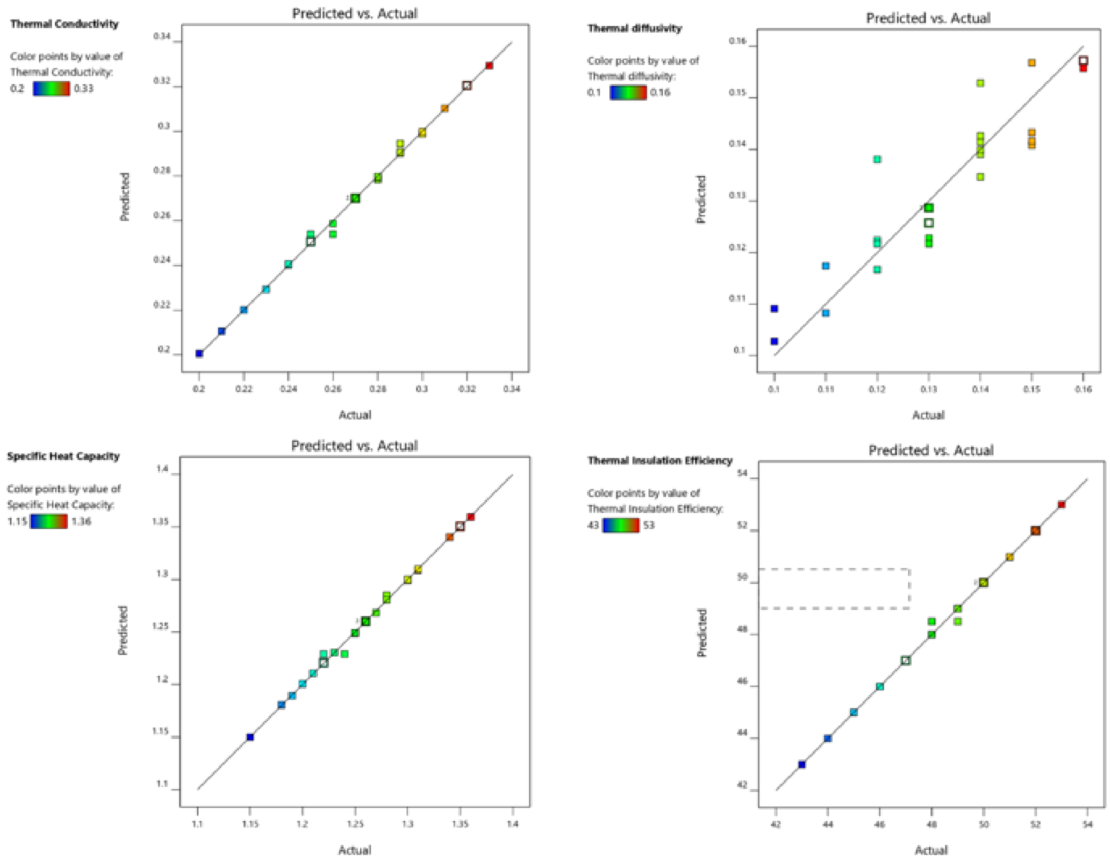
Property	**Predicted Equation**	**Mixing Ratio**	**Actual Equation**
Thermal Conductivity	$0.2813 + 0.0399A + 0.0140B + 0.0140C - 0.0002D[1] - 0.0012D[2] + 0.0032D[3] - 0.0008AB - 0.0046AC + 0.0081AD[1] - 0.0065AD[2] - 0.0030AD[3] + 0.0079BC - 0.0149BD[1] + 0.0113BD[2] - 0.0111BD[3] + 0.0024CD[1] + 0.0009CD[2] + 0.0046CD[3] - 0.0269A^2 + 0.0075B^2 - 0.0028C^2$	1:1	$0.130083 + 0.020386A - 0.006480B + 0.002290C - 0.000014(A \times B) - 0.000102(A \times C) + 0.000176(B \times C) - 0.000479A^2 + 0.000134B^2 - 0.000076C^2$
		2:1	$0.114184 + 0.018434A - 0.002989B + 0.002052C - 0.000014(A \times B) - 0.000102(A \times C) + 0.000176(B \times C) - 0.000479A^2 + 0.000134B^2 - 0.000076C^2$
		1:2	$0.138876 + 0.018904A - 0.005965B + 0.002662C - 0.000014(A \times B) - 0.000102(A \times C) + 0.000176(B \times C) - 0.000479A^2 + 0.000134B^2 - 0.000076C^2$
		3:2	$0.121394 + 0.019476A - 0.002523B + 0.000575C - 0.000014(A \times B) - 0.000102(A \times C) + 0.000176(B \times C) - 0.000479A^2 + 0.000134B^2 -$

			$0.000076C^2$
Thermal Diffusivity	0.1322 + 0.0158A + 0.0097B + 0.0017C + 0.0008D[1] - 0.0022D[2] + 0.0033D[3]	1:1	0.085374 + 0.002113A + 0.001292B + 0.000279C
		2:1	0.082414 + 0.002113A + 0.001292B + 0.000279C
		1:2	0.087901 + 0.002113A + 0.001292B + 0.000279C
		3:2	0.082627 + 0.002113A + 0.001292B + 0.000279C
Specific Heat Capacity	1.27 + 0.0688A + 0.0199B + 0.0028C - 0.0038D[1] + 0.0040D[2] + 0.0009D[3] + 0.0116AB - 0.0018AC + 0.0087AD[1] - 0.0266AD[2] + 0.0225AD[3] + 0.0158BC - 0.0326BD[1] + 0.0169BD[2] - 0.0112BD[3] + 0.0028CD[1] - 0.0069CD[2] + 0.0195CD[3] - $0.0524A^2 + 0.0213B^2 + 0.0080C^2$	1:1	1.22776 + 0.031768A - 0.020033B - 0.010911C + 0.000207(A × B) - 0.000039(A × C) + 0.000350(B × C) - $0.000378A^2 + 0.000221B^2 + 0.000134C^2$
		2:1	1.24184 + 0.029432A - 0.017629B - 0.009893C + 0.000190(A × B) - 0.000031(A × C) + 0.000315(B × C) - $0.000347A^2 + 0.000197B^2 - 0.000112C^2$
		1:2	1.21394 + 0.028057A - 0.018951B - 0.011052C + 0.000195(A × B) - 0.000034(A × C) + 0.000322(B × C) - $0.000365A^2 + 0.000208B^2 - 0.000121C^2$
		3:2	1.25012 + 0.032765A - 0.022134B - 0.012378C + 0.000225(A × B) - 0.000042(A × C) + 0.000376(B × C) - $0.000398A^2 + 0.000236B^2 - 0.000142C^2$
Thermal Insulation Efficiency	50.35 + 3.01A + 1.55B + 0.2334C - 0.3472D[1] - 0.6815D[2] + 0.7440D[3] + 0.6505AB + 0.3329AC + 0.3077AD[1] - 0.9675AD[2] + 0.7251AD[3] + 0.8328BC - 0.9355BD[1] + 0.0858BD[2] - 0.0475BD[3] + 0.1996CD[1] - 0.4152CD[2] + 0.4490CD[3] - $2.86A^2 - 0.8202B^2 + 0.6911C^2$	1:1	45.77498 + 1.43715A - 0.031128B - 0.942727C + 0.011564(A × B) + 0.007398(A × C) - 0.050884(B × C) - $0.014581A^2 + 0.019197B^2 - 0.050884C^2$
		2:1	47.70844 + 1.26712A + 0.105045B - 1.04520C + 0.011564(A × B) + 0.007398(A × C) - 0.050884(B × C) - $0.014581A^2 + 0.019197B^2 - 0.050884C^2$
		1:2	43.94252 + 1.49279A +

			0.087273B - 0.901162C + 0.011564(A × B) + 0.007398(A × C) - 0.050884(B × C) - $0.014581A^2 + 0.019197B^2 - 0.050884C^2$
		3:2	45.27324 + 1.38741A + 0.213218B - 1.01490C + 0.011564(A × B) + 0.007398(A × C) - 0.050884(B × C) - $0.014581A^2 + 0.019197B^2 - 0.050884C^2$

3.6 Actual and Predicted Values Graphs

Figures 6(a)-(d) illustrate the relationship between predicted and actual values for four thermal properties: Thermal Conductivity, Thermal Diffusivity, Specific Heat Capacity, and Thermal Insulation Efficiency. Each graph represents a scatter plot with the actual values on the x-axis and predicted values on the y-axis, with points coloured according to each property's respective value. This setup allows for a visual assessment of the predictive accuracy of a model used to estimate these thermal properties. In Figure 6 (a), the predicted values for thermal conductivity are plotted against the actual values. The data points are closely aligned along the diagonal line, which indicates a strong correlation. The use of colour, ranging from red to green, demonstrates the variation in thermal conductivity values. For instance, a lower conductivity value of 0.2 corresponds to red, while a higher value of 0.33 corresponds to green. The tight clustering of points along the line suggests that the predictive model is effective, resulting in minimal deviation from actual measurements. Figure 6 (b), presents similar data for thermal diffusivity. Although the overall trend appears to follow the diagonal line as in the previous graph, there are noticeable deviations, particularly for some predicted values that are lower than the actual values. The colour gradient from blue to yellow highlights a range of thermal diffusivity values, with blue indicating lower values (0.1) and yellow representing higher values (0.16). The variance in alignment from the line implies that the model's predictions may require further refinement, especially as some points are notably distant from the expected trajectory. Furthermore, in Figure 6 (c), specific heat capacity is analyzed with a similar predicted versus actual plotting method. Here, the points predominantly align along the diagonal, showcasing that the model performs well in its predictions. The colour scale from red (1.15) to green (1.36) illustrates the differing specific heat capacity values. The alignment suggests that the predictive model captures the relationship between predicted and actual values with high reliability, making it a strong candidate for practical applications in related thermal analyses. While Figure 6 (d), represents thermal insulation efficiency. This plot follows the same structure and demonstrates a strong linear relationship, with points clustering along the diagonal line. Colour coding ranges from blue (43) to green (53), effectively indicating the gradient of thermal insulation values. However, the section of the graph featuring a dashed box indicates a region where the predictions may show greater variance from actual results. This suggests a potential area for optimization in the predictive model to improve accuracy for thermal insulation efficiency. In sum, these graphs collectively illustrate the efficacy and limitations of a predictive model for estimating various thermal properties. The alignment of points along the diagonal line in the thermal conductivity and specific heat capacity graphs indicates a robust model, while the thermal diffusivity and thermal insulation efficiency graphs hint at areas needing further investigation and improvement.



Figures 6(a)-(d): Actual and predicted graphs for thermal conductivity, thermal diffusivity, Specific Heat Capacity and Thermal insulation efficiency

Tables 4 and 5, expose a consistent and robust modelling approach for investigating the thermal properties of composite materials incorporating calabash fiber and rice husk ash. Across all four responses thermal conductivity, thermal diffusivity, specific heat capacity, and thermal insulation efficiency the quadratic and linear models demonstrated exceptional statistical significance, with model F-values ranging from 15.49 to 47.49 and p-values consistently below 0.01 in Table 4. Notably, calabash fiber content (Factor A) and rice husk ash content (Factor B) emerged as the most influential factors, significantly impacting all investigated thermal characteristics. In Table 5, the extraordinary coefficient of determination (R^2) values, consistently exceeding 0.83 and approaching 0.99, indicate the models' remarkable explanatory power, accounting for over 83% to 99% of the variability in the responses. Furthermore, Tables 4 and 5 have adequate precision values, all substantially above the critical threshold of 4, validate the models' reliability for design space exploration and predictive capabilities, suggesting a sophisticated and statistically rigorous approach to understanding the thermal behaviour of these innovative composite materials.

Table 4: Analysis of Variance (ANOVA) Comparative Table for Thermal Responses

Response	**Model F-value**	**P-Value**	**Significant Factors**	**Significant Interactions**
Thermal Conductivity	47.49	0.0043	A: Calabash Fiber Content, B: Rice Husk Ash Content	BC, BD
Thermal Diffusivity	15.49	< 0.0001	A: Calabash Fiber Content, B: Rice Husk Ash Content	None
Specific Heat Capacity	41.52	0.0052	A: Calabash Fiber Content, B: Rice Husk Ash Content	AB, AD, BC, BD
Thermal Insulation Efficiency	46.16	0.0045	A: Calabash Fiber Content, B: Rice Husk Ash Content	AB, BC

Table 5: Model Fit Statistics Comparative Table

Response	**R^2**	**Adjusted R^2**	**Adequate Precision**	**Standard Deviation**
Thermal Conductivity	0.8724	0.8299	14.938	0.0053
Thermal Diffusivity	0.8378	0.7837	13.0843	0.0079
Specific Heat Capacity	0.9966	0.9726	25.0779	0.0089
Thermal Insulation Efficiency	0.9969	0.9753	26.1102	0.4085

3.7 Interaction Graphs

The figures represent comprehensive interaction effect and 3-D surface analysis of thermal properties for hybrid composites revealing complex relationships between composition parameters. Figure 7 demonstrates similar interactions for thermal conductivity, showing how different material components influence heat transfer characteristics. Figure 8 explores the interaction effects on thermal diffusivity, highlighting nonlinear relationships between calabash fiber, rice husk ash, and curing parameters. Figure 9 provides the interaction effect and a detailed 3-D surface visualization of specific heat capacity, mapping the intricate interplay of composite material variables and their thermal performance., Figure 10 demonstrates similar interactions for thermal insulation efficiency, showing how different material components influence heat transfer characteristics.

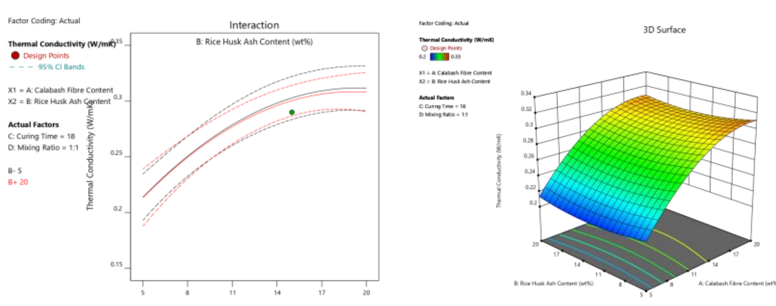


Figure 7: [A] Interaction Effect [B] 3-D Surface Showing the Interaction Between the Variable and Thermal Conductivity

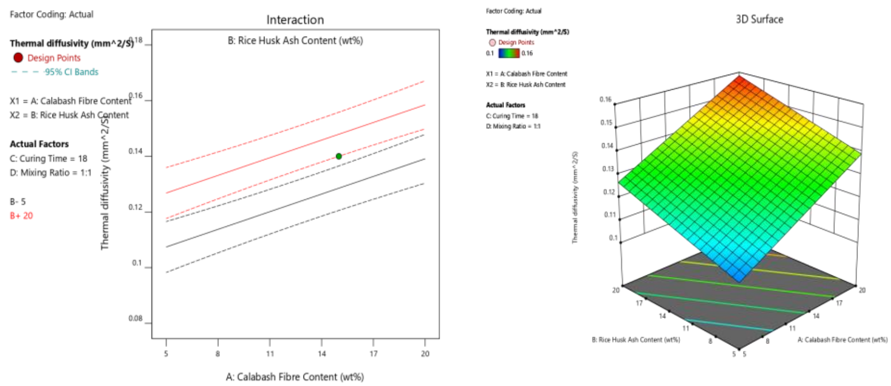


Figure 8: [A] Interaction Effect [B] 3-D Surface Showing the Interaction Between the Variable and Thermal Diffusivity

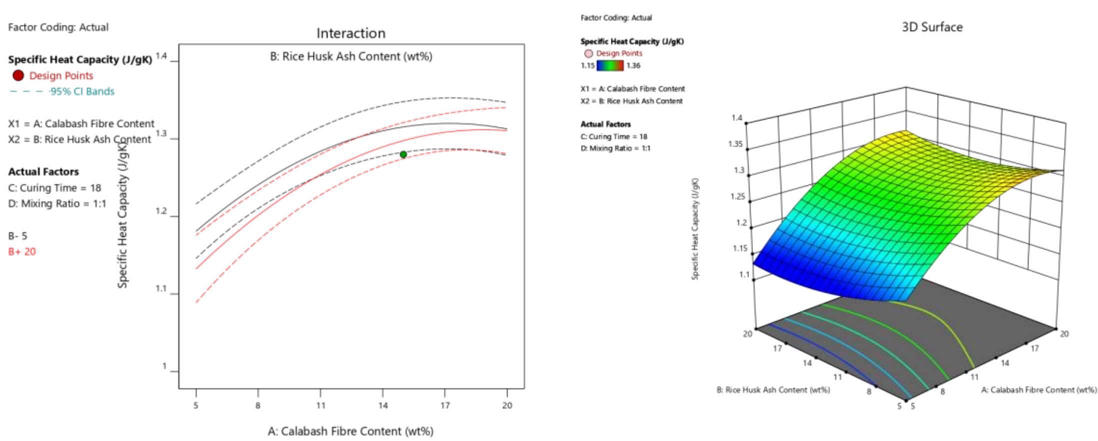


Figure 9: [A] Interaction Effect [B] 3-D Surface Showing the Interaction Between the Variable and Specific Heat Capacity

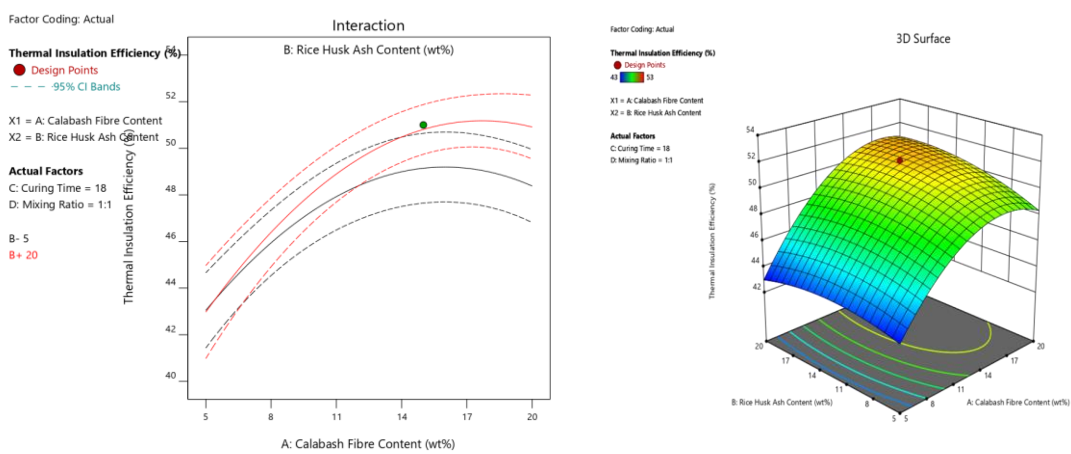


Figure 10: [A] Interaction Effect [B] 3-D Surface Showing the Interaction Between the Variable and Thermal Insulation

4.0 Comparative Analysis and Validation of Thermal Properties with Other Materials

The data is further contextualized by comparing the thermal properties of the developed hybrid composites with those of conventional materials, as summarized in Table 6. The comparative analysis highlights the competitive performance of the hybrid composites relative to polyurethane, fiberglass, and other polymer matrix composites.

The table provides quantitative values for thermal conductivity, diffusivity, specific heat capacity, and thermal insulation efficiency, illustrating the advantages of the hybrid reinforcements.

Table 6: Comparative Thermal Properties of Composites

Thermal Properties	**Material Type**					
	Optimal Sample	Glass Fiber Composites	Polymer Matrix with	Phenolic Resin Composites	Polyurethane Composites	Natural Fiber Insulation
Thermal Conductivity	0.284805	0.35460	0.2523	0.28030	0.29970	0.22230
Thermal Diffusivity	0.131303	0.1535	0.1245	0.1323	0.14214	0.1154
Specific Heat Capacity	1.27758	1.3780	1.2209	1.2613	1.2897	1.1589
Thermal Insulation Efficiency	0.495335	0.50214	0.47141	0.49890	0.50085	0.44269

The superior performance of the hybrid composites can be attributed to the uniform dispersion of reinforcements within the epoxy matrix, as observed in SEM micrographs (Figure 5). Microstructural analysis showed enhanced interfacial bonding, which minimized thermal bridging.

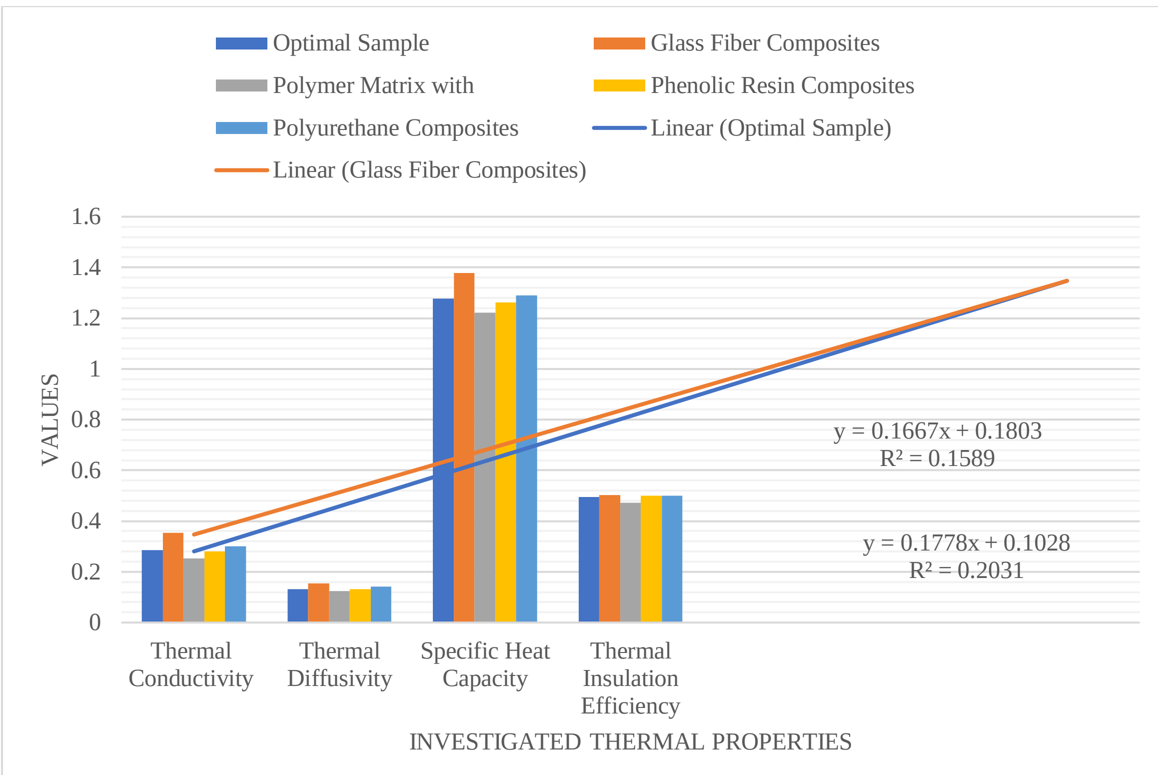


Figure 11: Chart of Comparative Thermal Properties of Composites

5. Conclusion

This research successfully demonstrates the potential of hybrid epoxy composites reinforced with calabash and rice husk ash for thermal insulation applications. Summarily, the findings from the work include;

- The hybrid composites demonstrated superior thermal properties, including low thermal conductivity (0.28 W/mK), high thermal insulation efficiency (up to 53%), and improved specific heat capacity (1.36 J/gK), making them competitive with conventional materials like polyurethane and fiberglass.

- Through response surface methodology (RSM) and statistical analysis, the optimal composition was identified as 20 wt% calabash fibers and 20 wt% RHA, which provided the best balance of thermal and mechanical properties.

- SEM analysis revealed uniform dispersion and strong interfacial bonding between the natural fibers and the epoxy matrix, minimizing thermal bridging and enhancing overall insulation performance.

- The use of agricultural byproducts like rice husk ash and natural fibers supports local economies, reduces waste, and promotes the use of renewable resources, aligning with global sustainability objectives.

Generally, the research underscores the potential of bio-based hybrid composites as effective, eco-friendly thermal insulation materials, contributing to energy efficiency and sustainable construction practices.

Recommendation

Further studies could explore the long-term durability, fire resistance, and scalability of these hybrid composites for industrial applications, as well as the potential for incorporating other natural fibers or bio-based materials.

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References

[1] F. Asdrubali, F. D'Alessandro, and S. Schiavoni, "A review of unconventional sustainable building insulation materials," *Sustainable Materials and Technologies*, vol. 4, pp. 1–17, 2015.

[2] S. Schiavoni, F. Bianchi, and F. Asdrubali, "Insulation materials for the building sector: A review and comparative analysis," *Renewable and Sustainable Energy Reviews*, vol. 62, pp. 988–1011, 2016.

[3] P. Ukachi, U. Okonkwo, and I. Onyenanu, "Appraisal of the Insulation Potential of Rice Husk Ash Reinforced Calabash-Epoxy Composite for Vehicle Firewall Application," *International Journal of Engineering Research and*, vol. 13, Aug. 2024, doi: 10.17577/IJERTV13IS080018.

[4] L. Aditya, T. M. Mahlia, and B. Rismanchi, "Aditya, L., Mahlia, T. M. I., Rismanchi, B., Ng,... - Google Scholar." Accessed: Oct. 11, 2024. [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Aditya%2C+L.%2C+Mahlia%2C+T.+M.+I.%2C+Rismanchi%2C+B.%2C+Ng%2C+H.+M.%2C+Hasan%2C+M.+H.%2C+Metselaar%2C+H.+S.+C.%2C+...+%26+Aditiya%2C+H.+B.+%282017%29.+A+review+on+insulation+materials+for+energy+conservation+in+buildings.+Renewable+and+Sustainable+Energy+Reviews%2C+73%2C+1352-1365.+https%3A%2F%2Fdoi.org%2F10.1016%2Fj.rser.2017.02.034+%28Available+through+ScienceDirect%29&btnG=

[5] K. C. Dannemiller, J. F. Gent, B. P. Leaderer, and J. Peccia, "Influence of housing characteristics on bacterial and fungal communities in homes of asthmatic children," *Indoor air*, vol. 26, no. 2, pp. 179–192, 2016.

[6] Ezechukwu, V. C., Onyenanu, I. U., Ayadinuno, G., & Agwaziam, J. O. (2025). Structural simulation analysis of the developed hybrid of Momordica angustisepala fiber and Breadfruit seed-shell particles composites Bolted Flanges. IPS Journal of Engineering and Technology, 1(1), 13–20. https://doi.org/10.54117/ijet.v1i1.2

[7] A. Korjenic, V. Petránek, J. Zach, and J. Hroudová, "Development and performance evaluation of natural thermal-insulation materials composed of renewable resources," *Energy and Buildings*, vol. 43, no. 9, pp. 2518–2523, Sep. 2011, doi: 10.1016/j.enbuild.2011.06.012.

[8] L. Liu *et al.*, "The development history and prospects of biomass-based insulation materials for buildings," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 912–932, 2017.

[9] K. Wei, C. Lv, M. Chen, X. Zhou, Z. Dai, and D. Shen, "Development and performance evaluation of a new thermal insulation material from rice straw using high-frequency hot-pressing," *Energy and Buildings*, vol. 87, pp. 116–122, 2015.
[10] M. Asim *et al.*, "A Review on Pineapple Leaves Fibre and Its Composites," *International Journal of Polymer Science*, vol. 2015, pp. 1–16, 2015, doi: 10.1155/2015/950567.
[11] C. E. Ilochonwu, C. O. Nwajagu, I. U. Onyenanu, and E. I. Nwonye, "Effect of Temperature in Extraction of High Purity Amorphous Silica from Rice Husk for Silicon Production," in *EPD Congress 2015* (pp. 219-227). Springer International Publishing.
[12] H. Binici, O. Aksogan, and C. Demirhan, "Mechanical, thermal and acoustical characterizations of an insulation composite made of bio-based materials," *Sustainable Cities and Society*, vol. 20, pp. 17–26, 2016.
[13] C. Ingrao *et al.*, "Energy and environmental assessment of industrial hemp for building applications: A review," *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 29–42, 2015.
[14] S. Panyakaew and S. Fotios, "New thermal insulation boards made from coconut husk and bagasse," *Energy and buildings*, vol. 43, no. 7, pp. 1732–1739, 2011.
[15] N. Saba, M. Jawaid, O. Y. Alothman, and M. T. Paridah, "A review on dynamic mechanical properties of natural fibre reinforced polymer composites," *Construction and Building Materials*, vol. 106, pp. 149–159, 2016.
[16] V. K. Thakur, M. K. Thakur, and R. K. Gupta, "Review: Raw Natural Fiber–Based Polymer Composites," *International Journal of Polymer Analysis and Characterization*, vol. 19, no. 3, pp. 256–271, Apr. 2014, doi: 10.1080/1023666X.2014.880016.
[17] Ezechukwu, V. C., Onyenanu, I. U., Ayadinuno, G., Agwaziam, J. O., & Ojinekeya, C. O. (2025). Corrosion Resistance of Developed Bolted Flange Made of Momordica Angustisepala Fiber (MAF) and Breadfruit Seed-Shell Particles (BFSAP). IPS Journal of Engineering and Technology, 1(1), 34–37. https://doi.org/10.54117/ijet.v1i1.4
[18] Ezechukwu, V. C. (2024). Hybridization Effect on Thermo-mechanical Behaviour of Epoxy/breadfruit Seed Shell Ash Particles and Momordica Angustisepala Fiber Composites for High-temperature Devices Application. Proceedings of the IRE, 7, 2456-8880.
[19] Ilochonwu, C. E., Onyenanu, I. U., & Atanmo, P. N. (2015). Extraction of high purity silica from rice husks ash for reduction to silicon.