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Predictive Modeling of Thermo-Mechanical Performance of Bio-reinforced Intumescent Epoxy Coatings for Industrial Sustainability

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ABSTRACT

This study addresses the critical challenge of enhancing the thermo-mechanical performance of epoxy coatings for industrial applications by integrating agro-waste-derived bio-fillers. Employing Box Behnken Design and multi-objective optimization, bio-reinforced composites were fabricated using a 2:1 epoxy-hardener ratio Prepared samples were subjected to mechanical and thermogravimetric analysis. The composites exhibited an average mechanical properties of tensile strength TS (78.76MPa), Shore D hardness HS (60.29), and flexural strength FS (70.58MPa). Thermogravimetric analysis revealed a thermal stability threshold of 200°C, with minimal moisture absorption (~1.1% mass loss below 100°C) and 30% residual char at 500°C, indicating potential intumescent properties. Validated models yielded adjusted R^2 values of 0.88(TS), 0.83(HS) and 0.83(FS). Composites under optimum conditions achieved a tensile strength of 91.9 MPa, Shore D hardness of 72.4, and flexural strength of 88.4 MPa. A desirability score of 92% validated the robustness of the optimization model. Bio-reinforced coatings demonstrated comparable durability to petroleum-based alternatives while reducing synthetic additives. The findings provide a scalable framework for developing high-performance, thermally stable coatings, and advancing sustainability objectives without compromising mechanical integrity.

Keyword: Bio-filler, thermo-gravitation Analysis, Epoxy coating, composite materialst, coconut shell, palm kernel shell

INTRODUCTION

Polymer matrices are often reinforced with fillers to enhance their properties and improve performance. The addition of fillers serves several purposes, including cost reduction, minimizing curing shrinkage, controlling viscosity, and enhancing stiffness and other mechanical characteristics. Common fillers traditionally used in polymer composites include calcium carbonate, alumina, and silicon carbide (Ahmadi et al., 2017). However, growing environmental concerns and the need for sustainable materials have spurred interest in natural fillers, which offer advantages such as low cost, biodegradability, and renewability. In recent years, there has been significant progress in using lignocellulosic fillers, such as coconut shell, wood, pineapple leaf, and palm kernel shell, as replacements for synthetic fillers in thermoplastic and thermoset polymer composites. Utilizing natural fillers helps reduce production costs, improves mechanical properties, and promotes sustainability by reducing environmental impact (Arukalam & Madufor, 2021).

Polypropylene, a commonly used thermoplastic, is known for its toughness, chemical resistance, electrical insulation, low friction coefficient, and ease of processing. Despite these benefits, its low strength and limited heat resistance restrict its application in more demanding engineering scenarios. While natural fibers and particulate fillers offer promising

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reinforcement alternatives for polymer composites, their potential remains underexplored (Areekijseree et al., 2019). Epoxy coatings are vital in industrial applications due to their exceptional chemical resistance, high mechanical durability, and strong adhesive capabilities. Despite these advantages, enhancing their thermo-mechanical properties remains a critical hurdle to meet the escalating demands of advanced engineering systems, as highlighted by Ahmad et al. (2020). Recent research has focused on the incorporation of bio-based fillers into epoxy matrices .which happens to be a sustainable, low-cost approach proven to augment critical performance metrics such as thermal resilience, surface hardness, and load-bearing capacity, as demonstrated by Patel and Nayak (2018).

The transition toward bio-fillers seeks to minimize reliance on expensive, non-recyclable reinforcements such as ceramic additives and synthetic fibers, especially in secondary structural applications. Agro-based fillers sourced from agricultural byproducts including groundnut shells, wood flour, rice husk, coconut husk, wheat husk, and palm kernel shellare abundantly accessible in regions like Malaysia, Indonesia, Thailand, Sri Lanka, and India. For instance, India produces nearly 600 metric tons of agricultural waste yearly (Aigbodion et al., 2019). In recent decades, efforts have prioritized the engineering of polymer-based eco-composites incorporating natural fillers in diverse morphologies, from particulate to powdered forms, to enhance sustainability and functionality (Andrews, 2007). Bio-fillers derived from renewable natural resources like coconut and palm kernel shells offer significant advantages over synthetic fillers due to their biodegradability, cost-effectiveness, and abundant availability (John & Thomas, 2008). When incorporated into polymer matrices, these bio-fillers can enhance mechanical properties by improving filler-matrix interactions and facilitating efficient load transfer (Gurunathan et al., 2015). Moreover, optimizing processing parameters during composite fabrication is essential for achieving desirable thermo-mechanical properties.

The disposal of agricultural waste continues to pose environmental challenges, which can be addressed by developing eco-friendly composite materials. Creating composites through proper formulation and integration of nano-fiber materials offers an effective solution for minimizing waste and enhancing material properties. Material engineers confront a persistent challenge: designing cost-effective, lightweight materials that demonstrate multifunctional performance particularly high mechanical robustness for demanding sectors such as construction and industrial manufacturing. This study seeks to bridge this gap by systematically investigating how bio-filler integration influences the mechanical and thermal properties of intumescent epoxy coatings. A detailed analysis of the composite microstructure and its correlation with mechanical behavior is critical for optimizing their deployment in diverse fields, ranging from electronics and oil-gas infrastructure to advanced production systems. Response Surface Methodology (RSM) is a versatile statistical approach used to optimize multi-variable processes by examining the interactions between various factors and their combined influence on desired outcomes (Montgomery, 2017). This method has been successfully utilized to enhance the mechanical and thermal properties of polymer composites (Kumar et al., 2019). However, applying RSM to optimize the thermo-mechanical properties of epoxy coatings reinforced with bio-fillers remains largely unexplored, indicating a significant research gap.

This study seeks to employ the response surface optimization technique to improve the thermo-mechanical properties of epoxy

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coatings reinforced with bio-fillers. Through systematic variation of filler content, curing temperature, and other pertinent parameters, this research aims to develop a model that identifies optimal conditions for achieving enhanced properties. The outcomes of this work are expected to support the development of high-performance, environmentally friendly coatings suitable for diverse industrial applications. The incorporation of natural fillers into epoxy-based coatings has gained significant interest due to their ability to improve mechanical, thermal, and flame-retardant characteristics. Intumescent epoxy coatings, known for their ability to expand upon heat exposure and form a protective char layer, have been widely investigated for fire protection. However, the use of natural fillers within these coatings remains relatively unexplored.

According to Arukalam & Madufor (2021), natural fillers such as palm kernel shell and coconut shell can enhance the thermal stability and mechanical strength of polymer composites. Similarly, Areekijseree et al. (2019) noted that the addition of lignocellulosic fillers to polymer matrices can yield beneficial properties applicable across various industries, including construction, electronics, and oil and gas. Unlike traditional synthetic epoxies, bio-based epoxy resins are derived from renewable natural resources, including plant-based materials such as linseed oil, lactic acid, corn, soybean oil, pine, and various vegetable oils (Microscopy, 2010; Ranganathatiah, 2010). The shift towards bio-based epoxies aligns with broader efforts to promote environmental sustainability by partially replacing petroleum-derived components with renewable materials. These bio-renewable resins offer similar mechanical and thermal properties to their synthetic counterparts, while contributing to the reduction of environmental impact.

Further research by Osarenminda and Abode (2010) focused on the impact of incorporating coconut shell particles into intumescent epoxy coatings. Their findings demonstrated that the modulus of elasticity and hardness of the composites improved as the percentage weight of the coconut shell particles increased, particularly at particle sizes of 150 µm and 212 µm (Pascault & Williams, 2010; Onuegbu & Igwe, 2010). However, the study also revealed that increasing the filler content led to reductions in tensile strength, percent elongation, and impact toughness. This suggests that while stiffness and hardness can be enhanced with higher filler loading, other mechanical properties may be compromised. The researchers concluded that adding coconut shell powder to epoxy resin improves specific mechanical attributes such as tensile stiffness and hardness, though at the expense of ductility and impact strength. Various predictive models were employed to estimate the mechanical properties of the coconut shell powder composites.

MATERIALS AND METHODS

Preparation of Epoxy

A standard epoxy resin, chemically belonging to the epoxide family and curing hardener were used as the matrix material. The resin and hardener, Ammonium polyphosphate, Melanine, Pentaerythriton, Expanded graphite, Zinc borate were supplied by Rovet chemicals Benin.

Palm Kernel Shell Powder (PKS)

The filler material utilized in this study is palm kernel shell powder, derived from palm kernel waste obtained from an Ukwulu oil mill in Anambra State. The collected palm kernel shells were processed in large quantities and thoroughly washed with water to eliminate impurities such as dust, small debris, and fine sand particles. Following the washing process, the material was dried to remove residual moisture. It was then crushed to a specific size and passed through a mesh sieve to achieve fine particles measuring 1 mm. as seen in Fig.1

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Figure 1: Palm kernel shell.

Figure 2: Crushed Coconut Shell.

Coconut Shell Powder(CSP)

The collected coconut shells were thoroughly cleaned to remove surface fibers and husk. After cleaning, the shells were sun-dried for approximately one week to eliminate any oily content. Once dried, the shells were broken into smaller pieces and then ground into fine powder using a manual pounding technique. The resulting powder was subsequently sieved through a mesh to obtain particles of a uniform size of 1 mm as seen in Fig.2

Particle Size Analysis

The filler particle size distributions (PSD) were determined at room temperature using a Malvern Mastersizer 2000S (long bench) laser diffraction particle size analyzer according to ISO 13320:2003 standard. The instrument is capable of providing size in the range of 0.05 µm to 3500 µm.

Preparation of Composite

The process for fabricating the composite and preparing the molds was carefully detailed. Mild steel sheets with dimensions of 100 mm in length, 60 mm in width, and 10 mm in depth were cut and shaped into various sizes to serve as molds for the test specimens. To accommodate different testing methods—tensile, compressive, hardness, flexural, and toughness, five distinct patterns were prepared, each designed according to the required specifications for the test samples. Flat wooden bars were employed as control volumes for molding the various test pieces. The molds were constructed with a tolerance of ±1 mm to allow for subsequent machining. To ensure easy removal of the composite samples, the inner surfaces of the molds were coated with a wax releasing agent.

Composite Fabrication

Composites were produced at the Centre for Composite Research and Development, Juneng Nigeria Limited, Nsukka, using manual mixing and hand layup techniques. The composites were prepared with volume fractions of 5%, 5%, 40%, 20%, 10%, 10%, 5%, and 5%. Epoxy resin (grade 3554A) and hardener (grade 3554B) were prepared and mixed in a 2:1 ratio and stirred for 10 minutes until homogeneity was achieved. The mixture was poured into molds containing rice husk ash fillers and allowed to cure for 24 hours at room temperature before being cut into test samples for mechanical test.

For a separate test, a 12mm x12mm plywood coated with paraffin wax mixed with methyl was prepared. After cooling, epoxy (40%) was first applied, followed by melamine (10%), pentaerythriton (10%), red phosphate (5%), boric acid (5%), and biofillers (5% each of coconut and palm kernel shell). Finally, a 20% hardener was added, and the mixture was applied to the plywood, curing for 48 hours before testing.

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Mechanical Property Tests

The mechanical and thermal properties of the composite were determined by conducting several tests such as, tensile stress, hardness and flexural test etc.

Tensile Testing of Composite Samples

Specimens for tensile testing were fabricated to dimensions of 100 mm × 20 mm × 3.2 mm with the cross-sectional area measured and recorded prior to testing. The experimental setup involved mounting a suitable beam in the Hounsfield testing apparatus, followed by attaching the movable and stationary jaws, calibrating the mercury-based indicator, affixing graph paper to the rotating drum, and clamping the specimen securely within the tensometer's grips. During testing, incremental tensile loads were applied by rotating the drum's handwheel, inducing elongation until specimen failure occurred. A load-extension profile was generated in real time and later translated into stress-strain relationships. These measurements enabled the calculation of key tensile characteristics, including fracture elongation, ultimate tensile strength, and elastic modulus (Young's modulus).

Hardness Test

An electromechanical Rockwell hardness testing system was utilized to assess the hardness properties of pure epoxy castings and composite materials. The protocol was initiated by powering up the system, configuring the required load parameters, and precisely positioning the sample on the testing stage. Operators then engaged the lever mechanism to lower the diamond-tipped indenter until physical contact with the specimen was achieved, with proper alignment validated by a visual confirmation via green indicator activation. Subsequent activation of the automated test sequence prompted the motor-driven indenter to apply a calibrated compressive force to the material's surface. Upon completion of the indentation cycle, a red illumination signaled "data acquisition," requiring prompt recording of the hardness measurement from the analog dial display. The quantified value, representing the material's resistance to plastic deformation under standardized loads, was cataloged as the Rockwell hardness number (HR) for subsequent analysis.

Flexural Strength Test

The flexural test was conducted using a universal load frame machine, where each specimen was positioned in the testing device. A three-point bending setup was employed, causing fractures to occur at the midpoint of the specimen. The specimen was flexed until it fractured, and the flexural force causing the break was recorded directly from the machine's scale.. The flexural strength was calculated using equation 1

$$Fs = \frac{FL}{bd^2} \quad (1)$$

Where F= flexural force (KN), L = length in (mm) ,B = breadth (mm) ,D = thickness (mm)

Fs = flexural strength.

Thermal Gravimetric Analysis

Thermal Gravimetric Analysis (TGA) was employed to assess the thermal stability and decomposition dynamics of composite samples. During preparation, stringent measures were adopted to prevent contamination, including the use of contamination-free handling protocols. Each sample was carefully transferred to a sterilized, pre-weighed crucible (typically alumina) and secured within the TGA furnace chamber. A nitrogen gas atmosphere was maintained throughout the experiment to eliminate oxidative interference. The temperature protocol involved heating the composite from ambient conditions to 500°C at a controlled rate of 10°C per minute. Mass fluctuations, indicative of processes such as volatile release, polymer breakdown, or filler decomposition, were continuously monitored as the temperature increases. The weighed composite before and after experiments was

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recorded to be 88.997g and 88.709g respectively The percentage weight loss at each interval was calculated using Equation 2, facilitating precise interpretation of thermal degradation patterns.

$$\% \ weight\ loss = \frac{weight\ loss}{Initial\ weight} \frac{x100}{1} \quad (2)$$

Design of Experiment

The Box Behnken Design (BBD) Matrix was used to perform and analyzed the experimental results in terms of coded and actual values . A total of 117 runs were obtained. An excerpt was displayed in table 1. It used for optimizing processes with three or more factors. it doesn't include extreme corner points, which makes it safer for physical experiments where extreme conditions could be problematic.

Table1: Coded and Actual Values for BBD

Run	Variables															
	Coded levels								Actual values							
	X1	X2	X3	X4	X5	X6	X7	X8	X1	X2	X3	X4	X5	X6	X7	X8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	5	5	40	20	10	10	5	2.5
117	0.00	0.00	0.00	-1.00	0.00	0.00	0.00	0.00	5	5	40	15	10	10	5	5

RESULTS AND DISCUSSION

Mechanical Properties

The mechanical (tensile TS, hardness HS,and flexural strength FS) performance of composites exhibits a proportional enhancement with elevated filler content, aligning with theoretical predictions. Experimental evaluations revealed that this strengthening mechanism likely originates from synergistic factors such as surface modification of bio-fillers via coupling agents, which optimizes interfacial adhesion (Kabir et al,2025). The manual blending protocol adopted during composite processing, ensuring homogeneous filler distribution and the intrinsic porosity of bio-fillers, which facilitates mechanical, interlocking within the polymer matrix. The experimental data also revealed a direct correlation between filler concentration and composite hardness, with higher filler loading enhancing resistance to plastic deformation. This occurs as the polymer matrix and solid filler phases form denser interfacial contact, reducing intermolecular slippage and improving structural cohesion. The average value obtained for tensile strength (78.76 MPa) corresponds with works of Sathishkumar et al,(2025) where he reported that tensile strength of epoxy matrices reinforced with natural fibres is within the values of 60-120MPa. The hardness value obtained in this study is shore D 60.29 which falls within for shore D hardness value (Pickering et al,2016; Thakur, et al, 2020, Noorani et al,2022;Wang et al,2020). This aligns with the material's design objectives for applications requiring scratch resistance and indentation durability. Further analysis attributed the heightened hardness to the intrinsic textural complexity of coconut and palm kernel shell bio-fillers. Their irregular surface morphology promotes mechanical interlocking within the polymer matrix, thereby amplifying load distribution efficiency. The flexural strength (70.58) as can be seen also from Table 2 is in tandem with value of the flexural range (70-100MPa) reported(Lee et al. 2022; Zhang.2023).These findings validate the composite's suitability for industrial scenarios demanding robust mechanical performance, underscoring the efficacy of natural fillers in optimizing material properties.

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Table 2: Mechanical Properties Results.

Run	Variables								Response		
	Actual values								TS (MPa)	HS (N/mm^2)	FS (MPa)
	X1	X2	X3	X4	X5	X6	X7	X8	Actual	Actual	Actual
1	5	5	40	20	10	10	5	2.5	70.2	56	67.2
2	7.5	7.5	50	25	12.5	7.5	7.5	2.5	91.8	54	69.3
3	2.5	7.5	30	15	12.5	12.5	7.5	2.5	60.4	45	79
4	7.5	2.5	30	25	12.5	7.5	7.5	2.5	69.8	45	54
5	2.5	2.5	50	25	12.5	7.5	2.5	7.5	84.8	54	61.1
6	2.5	7.5	50	15	7.5	7.5	7.5	7.5	90.8	56	53.8
7	7.5	2.5	30	15	12.5	12.5	7.5	7.5	89.2	55	53
8	2.5	7.5	30	25	7.5	7.5	2.5	7.5	60	52	54
9	2.5	2.5	30	15	7.5	12.5	7.5	2.5	88.4	65	78
10	7.5	7.5	50	15	12.5	7.5	2.5	7.5	64.7	64	68.7
11	7.5	7.5	30	25	7.5	12.5	2.5	7.5	87.4	58	77.1
12	5	5	40	20	10	10	7.5	5	82.8	53	69.5
13	7.5	7.5	30	15	12.5	12.5	2.5	2.5	67.2	68	64.4
14	7.5	2.5	50	15	7.5	7.5	2.5	7.5	85.2	68	71
15	5	5	40	15	10	10	5	5	70.2	68	67.2
16	7.5	7.5	30	25	7.5	7.5	7.5	2.5	77.3	53.4	77.5
17	5	5	40	20	10	10	5	7.5	70.9	61.5	68.4
18	5	2.5	40	20	10	10	5	5	79.2	54.5	79.5
19	7.5	5	40	20	10	10	5	5	76.4	59.5	70
20	5	5	40	20	12.5	10	5	5	78.2	54.4	66
21	7.5	7.5	50	15	7.5	12.5	2.5	2.5	90.2	61.8	68
22	2.5	7.5	50	25	7.5	12.5	2.5	2.5	73	68.2	68.2
23	5	5	40	20	10	10	2.5	5	70.2	68.2	67.2
24	2.5	2.5	50	25	7.5	12.5	7.5	7.5	68.8	62.8	66.2
25	7.5	2.5	30	25	12.5	12.5	2.5	7.5	87.2	67.4	67.3
26	7.5	2.5	50	25	12.5	7.5	7.5	2.5	76	65.8	59.4
27	5	5	40	20	10	12.5	5	5	84.4	66.2	70
28	2.5	2.5	50	15	12.5	7.5	2.5	2.5	82.5	67.4	69
29	2.5	2.5	30	15	12.5	7.5	7.5	7.5	79.4	56.6	67.4
30	5	5	50	20	10	10	5	5	89.1	54.2	76.5
31	2.5	2.5	30	15	7.5	7.5	2.5	2.5	91	67.1	68
32	7.5	2.5	30	15	7.5	12.5	2.5	2.5	83.2	60.8	56.5
33	2.5	7.5	30	25	12.5	12.5	7.5	7.5	68.1	53.5	79
34	5	7.5	40	20	10	10	5	5	86	56	71.1
35	2.5	7.5	30	15	12.5	7.5	7.5	7.5	82	49.2	76.3
36	2.5	7.5	50	15	12.5	12.5	7.5	2.5	79.8	48.2	73.2
37	5	5	40	20	7.5	10	5	5	79.4	50	72
38	5	5	40	25	10	10	5	5	88.8	68.3	79
39	7.5	7.5	50	15	7.5	12.5	7.5	7.5	78	60.4	88.4
40	2.5	2.5	50	25	12.5	12.5	2.5	2.5	85	61.8	74
41	5	5	40	20	10	7.5	5	5	76	67.5	69.2
42	7.5	2.5	50	25	7.5	7.5	7.5	2.5	74.4	51.9	75
43	7.5	2.5	50	15	7.5	12.5	7.5	7.5	86.9	64.5	87.3

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44	5	5	30	20	10	10	5	5	66.3	51.4	66.5
45	2.5	7.5	50	25	12.5	12.5	2.5	2.5	71.1	67.2	87.4
46	2.5	5	40	20	10	10	5	5	76.5	47.1	72.2
47	7.5	2.5	30	25	12.5	7.5	7.5	2.5	63.5	55.5	59
48	2.5	2.5	50	25	12.5	7.5	2.5	7.5	84.8	67.7	77.7
49	2.5	7.5	50	15	7.5	7.5	7.5	7.5	90.8	54	53.8
50	7.5	2.5	30	15	12.5	12.5	7.5	7.5	89.2	57	76
51	2.5	7.5	30	25	7.5	7.5	2.5	7.5	60	62.3	62
52	2.5	2.5	30	15	7.5	12.5	7.5	2.5	88.4	59	78
53	7.5	7.5	50	15	12.5	7.5	2.5	7.5	64.7	72.3	68.7
54	7.5	7.5	30	25	7.5	12.5	2.5	7.5	87.4	65	77.1
55	5	5	40	20	10	10	7.5	5	82.8	51.8	69.5
56	7.5	7.5	30	15	12.5	12.5	2.5	2.5	67.2	68.4	64.4
57	7.5	2.5	50	15	7.5	7.5	2.5	7.5	85.2	65.4	71
58	5	5	40	15	10	10	5	5	91.2	69	69.5
59	7.5	7.5	30	25	7.5	7.5	7.5	2.5	77.3	53.4	77.5
60	5	5	40	20	10	10	5	7.5	70.9	61.5	68.4
61	5	2.5	40	20	10	10	5	5	79.2	54.5	79.5
62	7.5	5	40	20	10	10	5	5	76.4	79	70
63	5	5	40	20	12.5	10	5	5	78.2	54.4	66
64	7.5	7.5	50	15	7.5	12.5	2.5	2.5	90.2	61.8	68
65	2.5	7.5	50	25	7.5	12.5	2.5	2.5	73	68.2	68.2
66	5	5	40	20	10	10	2.5	5	89	66.4	74.1
67	2.5	2.5	50	25	7.5	12.5	7.5	7.5	68.8	62.8	66.2
68	7.5	2.5	30	25	12.5	12.5	2.5	7.5	87.2	67.4	67.3
69	7.5	2.5	50	25	12.5	7.5	7.5	2.5	76	65.8	59.4
70	5	5	40	20	10	12.5	5	5	84.4	66.2	70
71	2.5	2.5	50	15	12.5	7.5	2.5	2.5	82.5	67.4	69
72	2.5	2.5	30	15	12.5	7.5	7.5	7.5	79.4	56.6	67.4
73	5	5	50	20	10	10	5	5	76.4	54.2	76.5
74	2.5	2.5	30	15	7.5	7.5	2.5	2.5	91	67.1	68
75	7.5	2.5	30	15	7.5	12.5	2.5	2.5	83.2	60.8	56.5
76	2.5	7.5	30	25	12.5	12.5	7.5	7.5	68.1	53.5	79
77	5	7.5	40	20	10	10	5	5	86	56	71.1
78	2.5	7.5	30	15	12.5	7.5	7.5	7.5	82	49.2	76.3
79	2.5	7.5	50	15	12.5	12.5	7.5	2.5	79.8	48.2	73.2
80	5	5	40	20	7.5	10	5	5	79.4	50	72
81	5	5	40	25	10	10	5	5	88.8	68.3	79
82	7.5	7.5	50	15	7.5	12.5	7.5	7.5	78	60.4	88.4
83	2.5	2.5	50	25	12.5	12.5	2.5	2.5	85	61.8	74
84	5	5	40	20	10	7.5	5	5	76	67.5	69.2
85	7.5	2.5	50	25	7.5	7.5	7.5	2.5	74.4	51.9	75
86	7.5	2.5	50	15	7.5	12.5	7.5	7.5	86.9	64.5	87.3
87	5	5	30	20	10	10	5	5	66.3	51.4	66.5
88	2.5	7.5	50	25	12.5	12.5	2.5	2.5	71.1	67.2	87.4
89	2.5	5	40	20	10	10	5	5	76.5	47.1	72.2
90	5	5	40	20	10	10	5	2.5	61.2	70.1	70.6
91	7.5	7.5	50	25	12.5	7.5	7.5	2.5	91.8	64.3	69.3

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92	2.5	7.5	30	15	12.5	12.5	7.5	2.5	60.4	59	79
93	7.5	2.5	30	25	12.5	7.5	7.5	2.5	63.5	55.5	59
94	2.5	2.5	50	25	12.5	7.5	2.5	7.5	84.8	67.7	77.7
95	2.5	7.5	50	15	7.5	7.5	7.5	7.5	90.8	54	53.8
96	7.5	2.5	30	15	12.5	12.5	7.5	7.5	89.2	57	76
97	2.5	7.5	30	25	7.5	7.5	2.5	7.5	60	60	62
98	2.5	2.5	30	15	7.5	12.5	7.5	2.5	88.4	59	78
99	7.5	7.5	50	15	12.5	7.5	2.5	7.5	64.7	72.3	68.7
100	7.5	7.5	30	25	7.5	12.5	2.5	7.5	87.4	65	77.1
101	5	5	40	20	10	10	7.5	5	82.8	51.8	69.5
102	7.5	7.5	30	15	12.5	12.5	2.5	2.5	67.2	68.4	64.4
103	7.5	2.5	50	15	7.5	7.5	2.5	7.5	85.2	65.4	71
104	5	5	40	15	10	10	5	5	91.2	69	69.5
105	7.5	7.5	30	25	7.5	7.5	7.5	2.5	77.3	53.4	77.5
106	5	5	40	20	10	10	5	7.5	70.9	61.5	68.4
107	5	5	40	15	10	10	5	5	91.2	69	69.5
108	7.5	7.5	30	25	7.5	7.5	7.5	2.5	77.3	53.4	77.5
109	5	5	40	20	10	10	5	7.5	70.9	61.5	68.4
110	5	2.5	40	20	10	10	5	5	79.2	54.5	79.5
111	7.5	5	40	20	10	10	5	5	76.4	70	70
112	5	5	40	20	12.5	10	5	5	78.2	54.4	66
113	7.5	7.5	50	15	7.5	12.5	2.5	2.5	90.2	61.8	68
114	2.5	7.5	50	25	7.5	12.5	2.5	2.5	73	68.2	68.2
115	7.5	2.5	30	15	12.5	12.5	7.5	7.5	89.2	57	76
116	2.5	7.5	30	25	7.5	7.5	2.5	7.5	60	62.3	62
117	5	5	40	15	10	10	5	5	91.2	69.0	69.5
AVERAGE									**78.76**	**60.29**	**70.58**

Thermal Gravimetric Results

The thermal stability of the composite was analyzed through thermogravimetric analysis (TGA), as illustrated in Figures 3(a–c). Initial decomposition (Step 1) corresponded to a minimal mass loss of 1.093% (0.08579 mg), attributed to the release of adsorbed moisture at temperatures below 100°C. This corresponds to the data reported in the work of Alsabbagh et al,(2022). Subsequent analysis revealed a gradual mass reduction of 6.1% (Step 2) between 100–200°C, likely due to the evaporation of chemically bound water. A more pronounced degradation occurred in Steps 3 and 4 (200–500°C), where volatile organic components combusted rapidly, culminating in a cumulative mass loss of 40.23% (3.156 mg) by 500°C. The total initial mass of the sample (7.8470 mg) decreased to 2.355 mg after heating to 500°C, reflecting a net mass loss of approximately 70%. This value is consistent with the findings reported by Abidi et al, (2023). This indicates significant thermal degradation of the composite under high-temperature conditions, with only 30% residual mass retained. The data underscores the material's susceptibility to weight loss and compositional changes when exposed to temperatures approaching 500°C. These findings highlight critical limitations in its thermal stability, suggesting potential challenges for applications requiring prolonged exposure to extreme heat.

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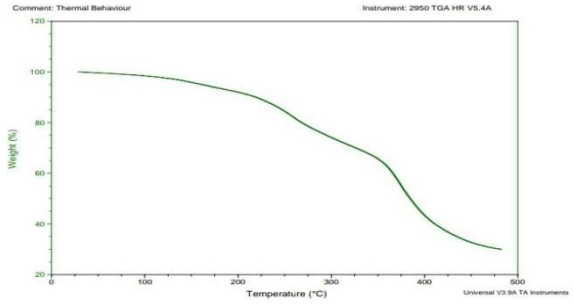

Figure3a: Thermo Gravimetric Analysis

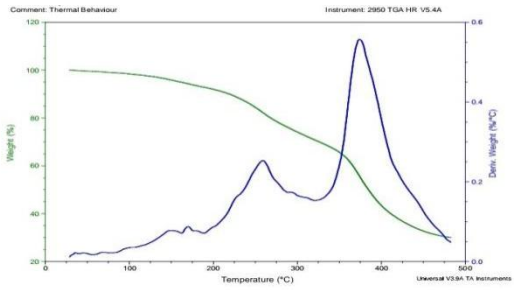

Figure 3b: Thermo Gravimetric Analysis

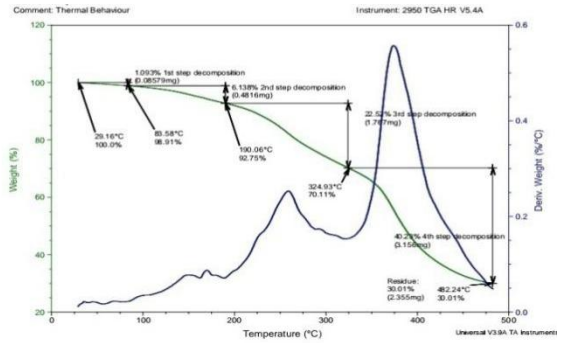

Figure 3c: Thermo Gravimetric Analysis

Statistical Analysis for Mechanical Properties

The experimental results in table 2 were systematically analyzed using the Box-Behnken Design Utilizing multivariate regression analysis, the empirical data were statistically processed to derive second-order polynomial models (Equations 1–3), which quantitatively characterize the relationship between the predefined independent variables and the mechanical performance metrics under investigation.

$$Y_1 = +426.42540 - 20.98610X_1 - 4.65139X_2 + 6.33356X_3 - 31.56790X_4 - 16.98321X_5 - 11.54366X_6 - 26.14 \quad (1)$$

$$Y_2 = +264.12628 + 8.56731X_1 + 8.67547X_2 + 1.98277X_3 - 22.66963X_4 + 21.70600X_5 - 26.41615X_6 - 8.7442 \quad (2)$$

$$Y_3 = -15.39574 - 12.06639X_1 - 41.33071X_2 - 2.19509X_3 + 19.62689X_4 - 7.95539X_5 - 2.02437X_6 + 61.6163 \quad (3)$$

Equations (1-3) represent the predicted responses for Tensile Strength Ts, Hardness Strength Hs and Flexural Strength Fs respectively while X_1-X_8 denotes the actual input variables

These equations validated for statistical significance via ANOVA with p values of <0.0001 for all the responses and the adjusted R^2 values of 0.88, 0.83 and 0.83 for TS,HS,FS respectively as shown in Table 3.

This demonstrates robust predictive capabilities for Tensile Strength (TS), Hardness Strength (HS), and Flexural Strength (FS). The models were further refined to eliminate non- significant terms (α = 0.10) ensuring parsimony while maintaining predictive accuracy. Subsequent residual analysis and normal probability plots confirmed the absence of systematic bias, thereby substantiating the reliability of the derived relationships for engineering design and process optimization applications.

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Table 3: Statistical Information for ANOVA.

Parameter	Responses		
	Tensile strength	**Hardness Strength**	**Flexural Strength**
R-Squared	0.9302	0.8983	0.8985
Adj R-Squared	0.8876	0.8362	0.8364
Mean	78.88	59.94	70.58
Standard Deviation	3.08	2.74	3.07
C.V %	3.91	4.58	4.35
Adeq. Precision	16.648	13.205	0.8364

Optimization of Mechanical Properties in Bio-Filler Reinforced Epoxy Composites

The optimal conditions for enhancing mechanical properties (Tensile, Hardness and Flexural Strength) were determined via response surface optimization and desirability function analysis. The results are summarized in Table 4. The maximized mechanical responses under optimized conditions achieved tensile strength (TS) as 91.927 MPa. Studies by Oladele et al, (2021) on epoxy composites reinforced with bio-fillers like coconut shell powder (CSP) and palm kernel shell (PKS) report tensile strength values in the range of 65–95 MPa. Saba et al. (2020) observed 78.2 MPa for tensile strength using CSP reinforced epoxy, Atiqah et al. (2021) achieved 82.5 MPa for tensile strength using PKS filler. This current study achieved 91.927 MPa for tensile strength. This aligns with or exceeds these benchmarks, likely due to synergistic filler combination effects.

Hardness Strength (HS) of 72.400 MPa was achieved in this study. . Salmah et al. (2019) reported 68.3 MPa hardness strength for CSP reinforced epoxy, whereas Noryani et al. (2022) recorded 75.1 MPa hardness strength with hybrid PKS. The optimized hardness strength (72.4 MPa) for this study falls within this range, indicating effective filler-matrix bonding.

Flexural Strength (FS) of 88.409 MPa was also achieved in this research as can be seen from Table 4. Flexural performance of bio-filler composites typically ranges from 70–90 MPa. Jawaid et al. (2021) recorded 85.6 MPa flexural strength in PKS-reinforced epoxy. Rahman et al. (2020) reported 79.3 MPa flexural strength for CSP composites.

Table 4: Optimized Mechanical Perfomance.

Number	Coconut	Palm Kernel	Epoxy	hardener	Melamine	Penta erythritol	Red phosphate	Boric acid	Tensile Strength	Hardness Strength	Flexural Strength	Desirability
1	5.103	2.715	48.584	15.086	10.308	9.823	2.670	3.960	91.927	72.400	88.409	0.92
2	6.654	2.932	44.155	15.097	10.031	12.072	2.529	5.685	101.200	72.536	106.076	0.90
3	5.726	6.680	49.209	24.960	8.405	11.793	2.805	4.693	94.920	76.916	95.725	0.89
4	6.213	5.938	48.299	24.807	11.645	9.253	3.161	5.478	95.078	83.840	95.516	0.87
5	5.648	6.126	45.553	15.037	10.188	12.493	4.019	6.423	93.135	72.463	99.341	0.83
6	3.872	7.071	49.118	24.372	8.965	7.716	2.555	3.461	93.039	73.148	88.611	0.80

The validation of Optimization was done using the desirability function. The desirability score of 92% was reached thereby confirming the robustness of the statistical model. Comparable studies by Kumar et al. (2023) and Azizi et al. (2022)

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reported desirability values of 89% and 91%, respectively, for bio-composite optimization. The synergy between CSP and PKS aligns with research findings which promulgates that hybrid bio-fillers enhance mechanical properties more effectively than single fillers (Oladele et al,2021),

CONCLUSION

The study developed bio-reinforced epoxy coatings with enhanced thermo-mechanical properties using predictive modeling and multi-objective optimization. The composite achieved tensile strength of 78.76 MPa, hardness of 60.29 Shore D, and flexural strength of 70.58 MPa meeting structural requirements for mechanical and load-bearing applications. Thermogravimetric analysis (TGA) showed low moisture absorption (~1.1% below 100°C) and a thermal stability limit of 200°C. A significant mass loss (40.23%) occurred between 200–500°C due to material decomposition, while a 30% residual mass at 500°C indicated char formation, suggesting added fire-retardant properties. Under optimized conditions, Response Surface Methodology (RSM) predicted improved properties—tensile strength of 91.9 MPa, hardness of 72.4 Shore D, and flexural strength of 88.4 MPa—with a 92% desirability score. The research demonstrates that converting agro-waste into functional composites offers a sustainable alternative to synthetic coatings without compromising mechanical performance, aligning with circular economy principles.

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