

Optimization and multi-objective analysis of tensile, flexural and impact strength in nano-hybrid bio-composites reinforced with *Helicteres isora*, *Holoptelea integrifolia* fibers, and nanographene

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ABSTRACT

Industries worldwide seek sustainable, high-strength bio-composites to reduce carbon footprint and replace synthetic materials. This research enhances natural fiber-based composites, ensuring lightweight, cost-effective, and eco-friendly alternatives. It supports green manufacturing and sustainable engineering, promoting a shift away from fossil-based materials. This study aims to optimize the mechanical properties of nano-hybrid bio-composites reinforced with *Holoptelea integrifolia* fibers, *Helicteres isora* fibers, and graphene nanosheets within a polypropylene matrix. Using the Box-Behnken design and Response Surface Methodology (RSM), the effects of fiber and graphene composition on tensile, flexural and impact strength were analyzed. The Multi-Objective Particle Swarm Optimization (MOPSO) approach was employed to maximize strength while minimizing composite weight. The optimized composition (15.6721 wt% *Holoptelea integrifolia*, 15.7198 wt% *Helicteres isora*, and 0.9307 wt% graphene) achieved a tensile strength of 45.407, flexural strength of 62.0344 MPa and impact strength of 147.119 J/m, demonstrating a significant enhancement. FESEM analysis revealed improved fiber-matrix adhesion, reduced voids, crack path deviation, and fiber bridging mechanisms, which enhanced fracture resistance. These findings support the development of lightweight, high-performance bio-composites, making them ideal for automotive, aerospace, and structural applications where improved strength-to-weight ratios are crucial.

Keywords: *Holoptelea integrifolia* fibers, *Helicteres isora* fibers, flexural strength, Impact strength, Response surface methodology (RSM).

1. INTRODUCTION

There is a significant demand for lightweight materials in several industries to improve the system performance. Composite materials enhance the physical and mechanical properties of lightweight materials and improve its utility [1]. The properties of the hybrid composite were minimized using RSM with the carbon/glass fiber demonstrating a 48% increase in flexural strength and a 76% increase in modulus compared to plain glass fiber composites [2]. The enhanced performance was obtained to optimal composition and efficient filler dispersion, rendering these composites suitable for automotive, aerospace, and construction applications [3]. Composites derived from natural waste and recycled plastic represent a potential domain for researchers and the polymer industry [4]. Acetyl chloride-treated borassus fruit fiber (BFF) composites were analyzed using SEM and FTIR, exhibited higher surface roughness, leading to superior mechanical properties and minimal water absorption [5]. This research examines polypropylene (PP) composites reinforced with lemon leaves (LL) and fig leaves (FL). Lemon leaves enhanced composites exhibited an increase in tensile modulus from 1229 MPa to 1321 MPa at 20 wt.%, and a tensile strength of 43.4 MPa at 30 wt.%, whereas FL reduced tensile characteristics [6]. This study explores the recycling of worn-out abrasive particles from abrasive water jet machining into kenaf fiber-reinforced hybrid polymer composites. Using the hand lay-up method, spent abrasive particles were mixed with epoxy resin in varying percentages to fabricate composites. Experimental results showed improved mechanical properties with the inclusion of spent abrasive particles [7]. Zinc oxide nanoparticles (ZnO NPs)

were synthesized using *Annona squamosa* leaf extract and characterized using PSA, FT-IR, XRD, FE-SEM, and EDX techniques. Adsorption tests demonstrated that ZnO NPs effectively removed methylene blue dye from water, showing strong agreement with the Langmuir isotherm model. The process was exothermic, achieving 99% dye removal efficiency under optimal conditions [8]. Hybrid composites including glass fiber (GF), recycled polypropylene (RPP), and ultrasound-treated oil palm empty fruit bunch (EFB) were synthesized, exhibiting improved mechanical, thermal, and crystallographic properties as well as reduced water absorption attributed to treatment and coupling agents (MAPP) [9]. Bamboo nanofiber reinforced polypropylene composites showed improved tensile strength (10.27–80.12%) and ductility (3–42%) after NaOH treatment, with the optimal composition achieving a tensile strength of 18.9914 MPa and ductility of 181.57% [10]. Nano-composites based on polyvinylidene fluoride (PVDF) incorporating BaTiO₃ and graphene were synthesized using mechanical blending (MB) and chemical-assisted mechanical blending (CAMB) [11]. The Kevlar composites exhibited decreased wear and friction, establishing them as viable materials for automotive components such as brakes and clutches, owing to the efficient dispersion and robust structure of SiO₂ [12].

Asparagus bean stem fiber, derived from agro-waste, offers a sustainable alternative to synthetic fibers for polymer composites. Alkali treatment improved cellulose content (65 wt%) and thermal stability (247°C). Enhanced mechanical properties led to better fiber-matrix interaction and structural strength [13]. Epoxy composites reinforced with raw and alkali-treated *Zanthoxylum* fibers were developed. Alkali treatment enhanced tensile strength (47.3 MPa) but increased water absorption. SEM analysis showed improved fiber bonding and reduced void formation [14]. *Cardiospermum* fiber was extracted and treated with alkali and silane for brake pad applications. Silane-treated fibers improved friction coefficient and wear resistance in brake composites. SEM analysis revealed better surface characteristics, enhancing tribological performance [15]. *Ficus macrocarpa* bark fibers were extracted and chemically treated for polymer reinforcement for light weight structural composite. Cellulose content increased to 59.7 wt%, with improved crystallinity and thermal stability (378.87°C). Surface roughness and structural integrity were enhanced post-treatment [16]. Silane-treated MP fibers were used to enhance brake friction composites. Treated fibers showed higher cellulose content (57.2%) and improved hardness (Rockwell K-95). Lower wear loss and improved surface properties enhanced brake pad performance [17].

The highlights of nano-additives in composites enhanced the properties like thermal conductivity, tensile strength, and fatigue resistance for aerospace, automotive, and biomedical applications. Graphene and MWCNTs improved the vibration behavior and reduced the delamination [18]. Basalt/E-glass fiber epoxy composites with 10% graphite nanoparticles, fabricated by vacuum-assisted lamination shows superior mechanical and surface properties. The flexibility and surface morphology of the composites suit microfluidics and flexible electronics, with high-quality adhesion enhancing their use in structural applications [19]. *Sansevieria Trifasciata* Fiber Polyester (STFP) composites fabricated with varying fiber lengths and weights showed optimal mechanical properties at 40 mm fiber length and below 40% weight. Maximum tensile strength (78.26 MPa), flexural strength (82.6 MPa), and impact strength (8.2 J/cm²) were achieved. Thermal stability reached 200°C with activation energy of 65.48 kJ/mol [20]. Rubber granules (RG) were incorporated into epoxy composites at varying volume fractions to enhance impact toughness and thermal insulation. While impact strength and flexibility improved with increased RG content, tensile strength and stiffness declined. The study suggests RG-reinforced epoxy composites are suitable for energy absorption but require hybrid reinforcements for load-bearing applications [21]. Bamboo-reinforced polymer composites were evaluated for mechanical performance using epoxy and polyurethane matrices. Unidirectional bamboo-epoxy composites significantly improved tensile and flexural strength compared to pure polymer matrices. Microstructural analysis confirmed enhanced fiber-matrix adhesion, demonstrating the potential of bamboo composites as sustainable alternatives to synthetic materials [22].

The p-value was compared at a significance threshold of 0.05 to assess the model's adequacy using Analysis of Variance (ANOVA). The desirability function was employed in Design-Expert 8 to conduct multi-response optimization. Scanning electron microscopy (SEM) was employed to conduct the microscopic characterization [23]. A hybrid PSO-ANN model was used to predict and optimize the mechanical properties of natural fiber composites, enabling faster selection of green fibers by analyzing parameters like cellulose content, microfibrillar angle, and fiber diameter, achieving high accuracy [24]. PSO was applied and other algorithms were used to optimize the thermal buckling temperature in jute fiber composites, showing strong alignment with experimental data and demonstrating PSO's effectiveness in predicting optimal boundary and ply orientation parameters [25]. PSO was utilized to identify the optimal parameters for machining biodegradable hybrid composites, revealing traverse rate as the most influential factor and achieving minimum surface roughness and kerf taper [26]. PSO, among other metaheuristic algorithms, was employed to identify

elastic constants in composite materials by matching experimental and computational data, offering adaptability in property identification [27]. PSO optimized post-curing parameters for Ramie/Carbon fiber composites, determining an optimal post-curing time of 12 hrs and temperature of 60°C to maximize tensile strength [28]. The perforating shear performance of Fiber-Reinforced Polymer (FRP) concrete blocks was studied using machine learning models, including Gradient-Boosted Regression Trees (GBRT), k-nearest Neighbors (KNN), and Lasso Regression. GBRT exhibited the highest predictive accuracy, outperforming KNN and Lasso Regression in training and validation phases. The study highlights GBRT's potential for structural analysis of FRP slabs [29]. RSM was utilized to optimize glass/carbon hybrid composites for tiny wind turbine blades. Advanced mixture design using RSM facilitated the identification of optimal fiber weight percentages, resulting in elevated tensile, flexural, and fatigue strengths, with a peak composite attractiveness of 93.5% [30]. RSM was applied to optimize bamboo fiber and nano-SiO₂ epoxy composites, using a central composite design to analyze mechanical properties. A second-order polynomial model predicted the tensile and flexural strengths, with ANOVA indicating significant effects of fiber and nano-SiO₂ on composite performance [31]. RSM was utilized to develop mathematical models by analyzing the effects of fiber orientation, sequencing, and nanoparticle addition in hybrid composites. Optimal fiber alignment (90° angle) and nanoparticle content (5%) improved the flexural strength by 50% [32].

Response Surface Methodology (RSM) and ANOVA were employed to model the mechanical properties of hybrid natural fiber composites composed of flax, jute, and sisal. The fiber volume fraction exerted the most significant impact on characteristics, yielding optimal results at 80 wt% jute and 20 wt% flax [33]. This study analyzes *Helicteres isora* fibers subjected to alkali, methacryl silane, and potassium permanganate treatment to evaluate their reinforcing capabilities in polymer composites. Alkali-treated fibers exhibited a 4% enhancement in tensile strength and a 30% rise in modulus, whereas silane-treated fibers demonstrated an 18% decrease in water absorption, hence improving their use in composites [34]. Fibers of *Helicteres isora*, reinforced in Polylactic acid composites, were subjected to the treatment with sodium hydroxide, methacryl silane, and KMnO₄ to enhance fiber-matrix compatibility. Silane-treated composites exhibited the reduced water absorption and enhanced tensile strength, however untreated composites displayed superior flexural strength and rendering the silane-treated composites for the optimal selection of applications [35].

This study develops cornstarch (CS) films using fructose (F), glycerol (G), and FG combinations as plasticizers for food packaging. F-plasticized films had higher strength and thermostability, while G-plasticized films showed lower density and water absorption [36]. Residual stresses in prestressed composites were analyzed using theoretical and numerical modeling. A new model estimates stress distribution in unidirectional fibers, validated by numerical simulations for improved accuracy [37]. Fabric prestressing at 50 MPa extended fatigue life by ~43%, but over-prestressing (>100 MPa) reduced effectiveness. The method is useful in low to intermediate-stress regions but unsuitable for high-stress applications [38]. This study explores LDH polymer nanocomposites for aerospace applications, focusing on fabrication, characterization, and mechanical properties using microscopic and spectroscopic techniques [39].

Fibers from *Holoptelea integrifolia* bark were evaluated using chemical analysis, revealing 65.3% cellulose, a density of 1.36 g/cc, and a water content of 14.69%. XRD indicated a CI of 37.42% and a crystallite size of 5.48 nm. Thermal stability was noted up to 235°C, while SEM validated the presence of cellulose fibrils, indicating their potential for reinforcing lightweight polymers [40]. The research created a hybrid composites with *Holoptelea integrifolia* bark fiber (HIBF) reinforced with Ziziphus jujuba seed particles (ZJSP) within bio-based epoxy resin. Using a fuzzy model, the mechanical characteristics of the composites including flexural, tensile, and impact strengths, were accurately predicted (87% accuracy), confirming its viability for robust, sustainable materials [41]. Alkaline-treated *Holoptelea integrifolia* fibers combined with SiC particles in an epoxy matrix increased tensile and flexural properties by up to 40% with a 30% fiber content. FTIR spectroscopy indicated ester carboxyl and OH groups, enhancing the composite's biodegradability and strength, making it suitable for eco-friendly applications [42].

This study introduces a novel approach for nano-hybrid bio-composites by integrating Box-Behnken design, response surface methodology, and Multi-Objective Particle Swarm Optimization (MOPSO) to enhance tensile, flexural and impact strength while reducing weight. The fabricated composites contained *Holoptelea integrifolia* fibers (0–16 wt%), *Helicteres isora* fibers (0–16 wt%), and graphene nanosheets (0–1.6 wt%), with polypropylene forming the remaining composition. It uniquely determines the optimal weight fractions of natural fibers and graphene nanoparticles to maximize performance. FESEM analysis reveals improved fiber-matrix bonding due to nanoparticles, enhancing mechanical properties. Additionally, the study distinguishes the role of *Helicteres isora* fibers in impact strength and *Holoptelea integrifolia* fibers in tensile, flexural strength, providing critical insights for bio-composite development.

2. MATERIALS AND METHODOLOGY

2.1. Materials

Fibers from *Helicteres isora* and *Holoptelea integrifolia* were collected from the bark of the corresponding plant in the coastal areas of Tamil Nadu. The *Helicteres isora* fiber consists of cellulose (64%), hemicellulose (14%), lignin (12%), moisture (9%), and wax (1%), while *Holoptelea integrifolia* fiber contains cellulose (58%), hemicellulose (16%), lignin (17%), moisture (8.2%), and wax (0.8%). These compositions significantly influence the fiber-matrix adhesion and mechanical properties. The bark was cut into little segments, roughly 10 cm in length. The barks were mechanically transformed into short fibers by a paddle mill and sifting procedure. Before alkalization, the isolated fibers were thoroughly washed with pure water and then dehydrated at 50°C for 24 hours. The dehydrated HE/HO fibers were next treated by immersing in a 5% NaOH aqueous solution for 60min [34]. The submerged fibers are maintained in the solution at 60°C for three hours. The fibers are then treated with a 5% acetic acid solution for de-alkalinization. Following de-alkalinization, the fibers are thoroughly washed in distilled water and dehydrated at 70°C in an oven for 12 hours. Polypropylene polymer was procured from Kovai Cheenu Enterprises, Coimbatore, Tamilnadu for the fabrication of composite specimens. Table 1 shows the characteristics of the materials utilized in this study.

Graphene powder supplied by Go Green Enterprises, Chennai was utilized as a nanofiller in this study. Mechanical properties including hardness, strength, and stiffness were enhanced using graphene nanosheets. The production of these nanosheets was accomplished without the use of oxidative processes. Hence, these materials are ideal for uses that demand thermal and electrical conductivity since they contain a NG surface made of carbon particles. Basalt Glass fabrics were reinforced with 0.2 wt.% – 0.8 wt.% graphene using hand layup and compression molding to fabricate laminated plates. While tensile and flexural strengths improved up to 0.6 wt.% graphene due to efficient stress transfer, impact energy increased consistently until 0.8 wt.% graphene owing to reinforcement effects [43]. The carbon bi-directional fabric composite with 0.8 wt% nanographene exhibits superior performance in terms of increased tensile (579 MPa), flexural (547 MPa) and impact (284 J/m) strengths in comparison with other composites [44].

2.2. Fabrication of nanocomposites

The hybrid composite of *Helicteres isora* (HE) and *Holoptelea integrifolia* (HO) fibers with nanographene (NG) filler was produced using compression molding using a steel mold. The surface treatment improves the bonding between the reinforcements and the polymer-based composites. The fibers were cut to a length of 10 mm, and polypropylene (PP) was employed for both the fibers during the fabrications process. The hybrid mixture of *Helicteres isora* (HE) and *Holoptelea integrifolia* (HO) with weight proportions of 0%, 8%, 16%, 24%, and 32% was positioned in the mold for diverse combinations. The nanographene filler (0%, 0.8%, and 1.6%) and polypropylene matrix were combined using a mechanical stirrer for 30 minutes before being placed into the mold. The manufacturing procedure required a consistent temperature of 100°C and a pressure of 10 MPa. A total of 15 combinations were formulated using HE/HO and NG filler with a PP matrix. Figure 1 shows the sequential process for the fabrication of HE/HO and NG and PP matrices.

2.3. Tensile tests

The tensile strength of the composite samples was assessed in accordance with the ASTM D638-22 utilizing a Universal Testing Machine (UTM) equipped with a 5 kN load cell. Figure 2 shows the universal testing machine and the samples used to conduct tensile tests. Specimens were fabricated with dimensions of 165 × 13 × 3 mm and subjected to testing at a crosshead velocity of 5 mm/min. The three samples for each composition were evaluated, and the average tensile strength was recorded.

Table 1: Properties of *Helicteres isora*, *Holoptelea integrifolia* fibers and Graphene.

PROPERTY	HELICTERES ISORA FIBERS	HOLOPTELEA INTEGRIFOLIA FIBERS	GRAPHENE
Color	Brown to light brown	Light brown to gray	Black
Diameter	100 μm	200 μm	0.34 nm
Density	1.2 g/cm ³	1.3 g/cm ³	2.2 g/cm ³
Tensile strength	100 Mpa	140 Mpa	130 GPa
Elongation at break	3%	4%	1.6%

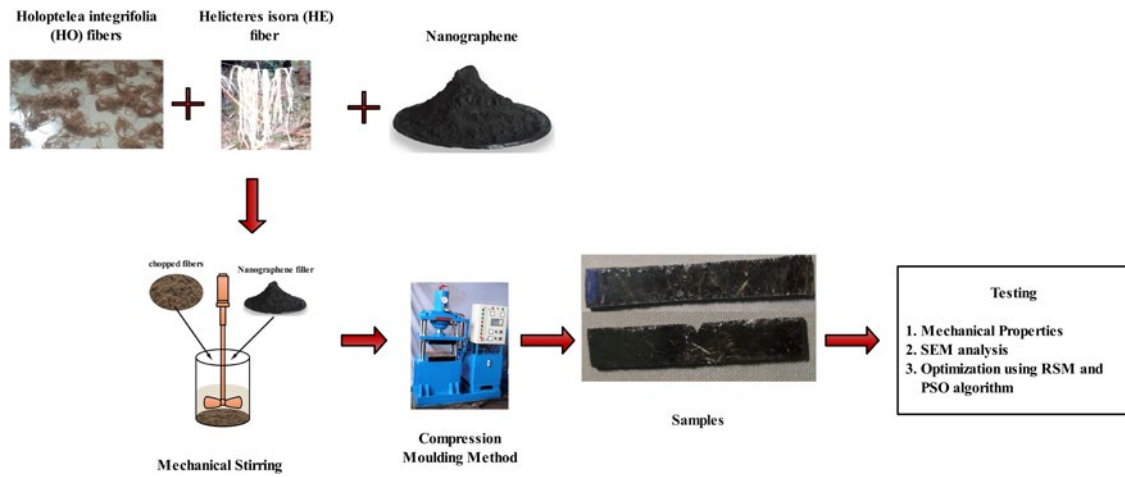


Figure 1: An outline of fabrication process.

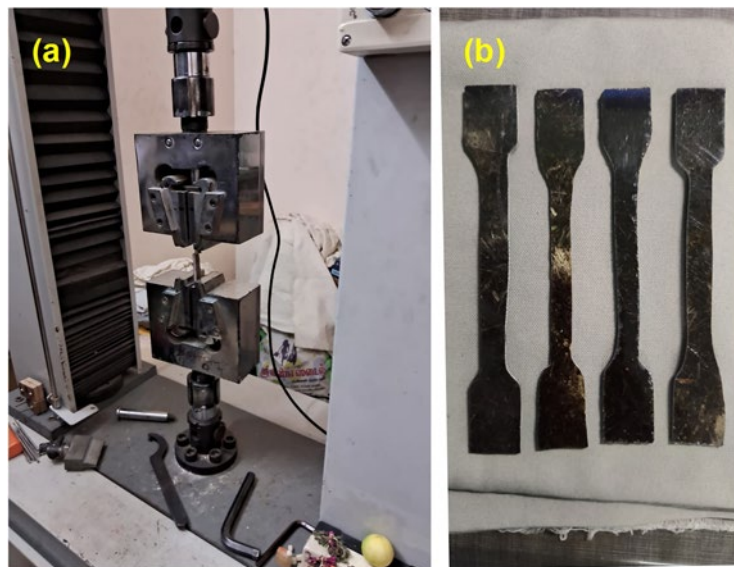


Figure 2: (a) Tensile testing machine, (b) tensile test sample.

2.4. Flexural tests

The flexural strength (FS) of the specimens were measured using a 3-point bending test conducted by Universal Testing machine with 16 tons capacity as per ASTM D790-17. Figure 3 shows the universal testing machine and the samples used to conduct flexural tests. The experiment utilized rectangular specimens of 125 mm length, 12 mm breadth and 3 mm width at 1.6 mm/min cross-sectional speed. Each test was conducted on 5 specimens per condition, following ASTM standards. The allowable error was maintained within $\pm 3\%$. The flexural strength of the specimens was evaluated utilizing Equation 1 [45].

$$\sigma_f = \frac{3fl}{2bh^2} \quad (1)$$

where,

b - breadth of the sample

h - thickness of the sample

l - length of the sample

f - force applied by the machine.



Figure 3: (a) Universal testing machine, (b) flexural test samples.

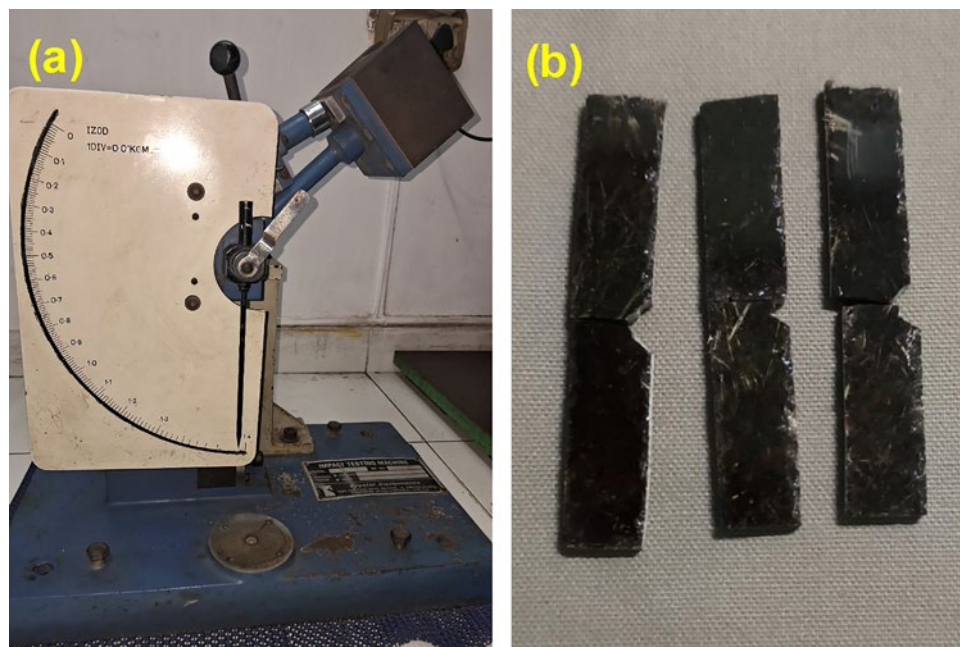


Figure 4: (a) Impact testing machine, (b) impact test sample.

2.5. Impact testing

The strength and fracture resistance of the sample were assessed using an Izod impact test. A specimen with central V notch were fabricated in accordance with the ASTM D256-23^{el} for impact properties. Figure 4 shows the impact test setup and the specimens used to conduct Izod test.

Figure 1 illustrates the specimen created in accordance with this regulation. The absorbing energy in the fractured sample can be determined using Equation 2.

$$E = Mg(h_1 - h_2) \quad (2)$$

Where,

E - Absorbed energy

h_1 and h_2 - The initial and final heights of the impactor

g - Acceleration due to gravity

M - Mass of the specimen

Subsequent to the mechanical impact test of the prepared specimens, the results were observed and related using the RSM.

2.6. Multi-objective optimization techniques

In composite material optimization, statistical and computational techniques play a crucial role in identifying the ideal composition for enhanced mechanical properties. Box-Behnken Design (BBD), Response Surface Methodology (RSM), and Multi-Objective Particle Swarm Optimization (MOPSO) are employed in this study to optimize the weight fractions of *Holoptelea integrifolia* fibers, Nano-graphene particles, and *Helicteres isora* fibers in the bio-composite.

2.6.1. Box-Behnken design and response surface methodology

Box-Behnken Design (BBD) is a widely used statistical design of experiments (DOE) method that reduces the number of required experimental trials while efficiently analyzing the interactions between process parameters. The general quadratic regression model used in RSM is given by:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \beta_{ij} X_i X_j + \epsilon$$

where X_i and X_j are the independent variables (fiber and graphene content), Y is the predicted response (tensile, flexural and impact strength), ϵ is the error term, β_i are the linear coefficients, β_{ij} are the interaction coefficients, β_{ii} are the quadratic coefficients, β_0 is the intercept.

By generating a second-order polynomial equation, the design facilitates the prediction of the most effective conditions for optimizing mechanical properties. Following this, the experimental data is analyzed using RSM to identify the most significant factors that influence tensile, flexural and impact strength.

2.6.2. Particle swarm optimization (PSO) and multi-objective optimization

Particle Swarm Optimization (PSO) is a metaheuristic algorithm that is inspired by nature and is based on swarm intelligence. In this algorithm, a group of particles (potential solutions) traverse a search space in order to identify an optimal solution. MOPSO simultaneously optimizes multiple conflicting objectives, including the optimization of tensile flexural and impact strength while minimizing weight.

The following equations regulate the velocity and position updates for each particle in PSO:

$$\begin{aligned} V_i^{t+1} &= wV_i^t + c_1 r_1 (P_{best} - X_i) + c_2 r_2 (G_{best} - X_i) \\ X_i^{t+1} &= X_i^t + V_i^{t+1} \end{aligned}$$

where, W is inertia weight, X_i is the position, c_1, c_2 are acceleration coefficients with random numbers r_1, r_2 between 0 and 1 V_i is the velocity of particle i , G_{best} is the global best solution, P_{best} is the best solution found by the particle.

This study guarantees an efficient, data-driven approach to optimizing the bio-composite formulation by incorporating BBD, RSM, and MOPSO, resulting in an improved weight-to-strength ratio with minimal experimental effort.

2.7. FESEM analysis

The microstructure of hybrid composites including abrasive surfaces was analyzed using a scanning electron microscope (ZEISS, Gemini 1). The specimens were fastened to the supports using silver paste. The abraded specimens were covered with a gold thin layer to lower the electrostatic charge before photomicrographs were taken.

3. RESULTS AND DISCUSSION

Statistical approaches were used to find the impact of nanocomposites and to evaluate the interplay of *Holoptelea integrifolia* fibers, graphene nanosheets, and *Helicteres isora* fibers inside a polypropylene polymer matrix. Graphene nanosheets were added into the polymer matrix at weight percentages between 0 and 1.6%, while *Helicteres isora* and *Holoptelea integrifolia* fibers were added at percentages ranging from 0 to 16% to quantify the selected materials in this study, due to the limitations on the maximum quantity of fibers.

In addition, three representative samples were selected from each test specimen. Table 2 details the combinations and amounts of compounds used in the fabrication of the nanocomposites, following their identification by the response surface methodology and Box-Behnken design. Table 3 displays the mean results of the impact and flexural tests.

Table 2: Combination of composites.

CODE	POLYPROPYLENE (%wt)	HOLOPTELEA INTEGRIFOLIA FIBERS (%wt)	HELICTERES ISORA FIBERS (%wt)	GRAPHENE (wt%)
1	99.2	0	0	0.8
2	83.2	16	0	0.8
3	83.2	0	16	0.8
4	67.2	16	16	0.8
5	92	0	8	0
6	76	16	8	0
7	90.4	0	8	1.6
8	74.4	16	8	1.6
9	92	8	0	0
10	76	8	16	0
11	90.4	8	0	1.6
12	74.4	8	16	1.6
13	83.2	8	8	0.8
14	83.2	8	8	0.8
15	83.2	8	8	0.8

Table 3: Experimental test results.

SPECIMEN CODE	TENSILE STRENGTH (MPa)	FLEXURAL STRENGTH (MPa)	IMPACT STRENGTH (J/m)
1	25.8 ± 0.78	50 ± 0.62	102.30 ± 0
2	35.6 ± 0.83	55 ± 0.80	122.81 ± 1
3	38.2 ± 0.66	57 ± 0.64	112.01 ± 1
4	45.1 ± 0.69	62 ± 0.70	145.58 ± 0
5	28.4 ± 0.85	49 ± 0.99	94.13 ± 0
6	33.7 ± 0.62	54 ± 0.84	112.74 ± 1
7	30.5 ± 0.65	52 ± 0.23	75.47 ± 0
8	40.9 ± 0.71	57 ± 0.37	125.21 ± 0
9	27.3 ± 0.73	46 ± 0.04	90.01 ± 1
10	36.9 ± 0.68	56 ± 0.05	103.11 ± 0
11	29.6 ± 0.72	51 ± 0.56	90.30 ± 0
12	41.8 ± 0.64	57 ± 0.64	123.03 ± 1
13	39.2 ± 0.83	56 ± 0.06	122.39 ± 0
14	38.9 ± 0.81	56 ± 0.87	132.31 ± 0
15	39.0 ± 0.80	57 ± 0.68	120.16 ± 0

Design of Experiment (a statistical measure) was implemented in this investigation to obtain the impact and flexural strength of the composites. The Design-Expert 13 software was used to evaluate the impact of the variables on the result. The design of experiments (DOE) methodology aims to identify optimal parameter values and provide estimated response surfaces that accurately replace the genuine response. RSM with Box-Behnken design modeled and optimized the flexural properties of hybrid natural fiber composites. The study confirmed that fiber type and volume fraction significantly impacted flexural strength, with jute fiber composition enhancing composite performance [46]. *Holoptelea integrifolia* fibers, *Helicteres isora* fibers, and graphene nanosheets were chosen for their superior mechanical properties and compatibility with a polypropylene (PP) matrix. *Holoptelea integrifolia* fibers enhance flexural strength, while *Helicteres isora* fibers improve impact resistance due to their high weight-to-strength ratio. Graphene nanosheets strengthen fiber-matrix bonding, preventing crack propagation.

3.1. Tensile strength

The stress-strain curves of the S1 and S4 composites, depicted in Figure 5, demonstrate distinct mechanical properties. The experimental results shown in Table 3 indicated the highest and lowest performing samples for additional examination through stress-strain curves for tensile and flexural test. S4 exhibits superior tensile strength (45.1 MPa) compared to S1 (25.8 MPa), attributable to enhanced fiber-matrix interactions. S1 demonstrates enhanced ductility with a failure strain of roughly 4.32%, whereas S4 fractures at approximately 3.23%, indicating a compromise between strength and ductility. The findings suggest that S4 is better suitable for applications requiring significant load-bearing capacity, whereas S1 may be advantageous in flexible structural applications.

At 95% confidence level, the researcher found that the interaction between *Holoptelea integrifolia* fibers, *Helicteres isora* fibers, and Graphene was significant (p -value < 0.05), while the interaction between AB, AC, BC, A2, B2 and C2 was also significant (p -value < 0.05), as presented in Table 4. The regression evaluation of the flexural strength response led to the establishment of a second-order model. R^2 and adj. R^2 were determined to be 0.9985 and 0.9958, respectively, indicating that the output model is capable of forecasting the response performance. A robust correlation between the experimental data and the model predictions was evident in the normal probability plots and R^2 values that were obtained (exceeding 0.96 for all results) [47]. Additionally, the addition of the power response of the TS as the equation 2 enhanced the accuracy of the output model. Ultimately, the calculation is as follows.

As a result, equation (2) shows the regression equation for the flexural strength:

$$\begin{aligned} \text{Tensile Strength} = & 21.83 + 0.8604 A + 0.9839 B + 10.089 C - 0.0113 A * B \\ & + 0.1992 A * C + 0.1016 B * C - 0.0264 A^2 - 0.01823 B^2 - 6.198 C^2 \end{aligned} \quad (3)$$

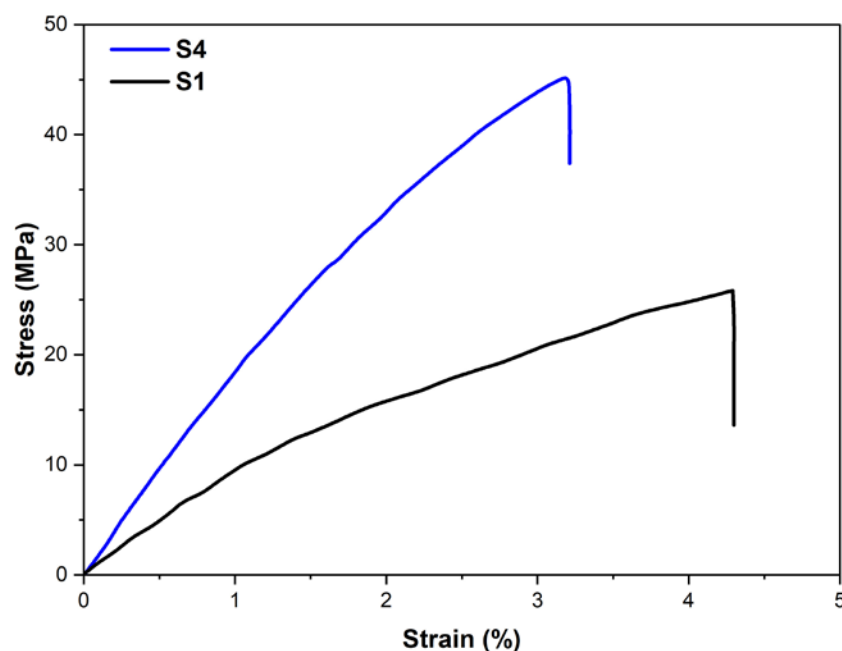


Figure 5: Evaluation of tensile stress versus strain curve of S1 and S4 composite.

Table 4: ANOVA table for tensile strength.

SOURCE	SUM OF SQUARES	Df	MEAN SQUARE	F-VALUE	p-VALUE	
Model	481.67	9	53.52	369.52	< 0.0001	significant
A-Holoptelea integrifolia fibers	131.22	1	131.22	906.01	< 0.0001	
B-Helicteres isora fibers	238.71	1	238.71	1648.18	< 0.0001	
C-Graphene	34.03	1	34.03	234.97	< 0.0001	
AB	2.10	1	2.10	14.52	0.0125	
AC	6.50	1	6.50	44.90	0.0011	
BC	1.69	1	1.69	11.67	0.0189	
A ²	10.57	1	10.57	72.96	0.0004	
B ²	5.03	1	5.03	34.70	0.0020	
C ²	58.10	1	58.10	401.13	< 0.0001	
Residual	0.7242	5	0.1448			
Lack of Fit	0.6775	3	0.2258	9.68	0.0951	not significant
Pure Error	0.0467	2	0.0233			
Cor Total	482.39	14				
Std. Dev.	0.3806		R ²	0.9985		
Mean	35.39		Adj. R ²	0.9958		
C.V. %	1.08		Pred. R ²	0.9773		

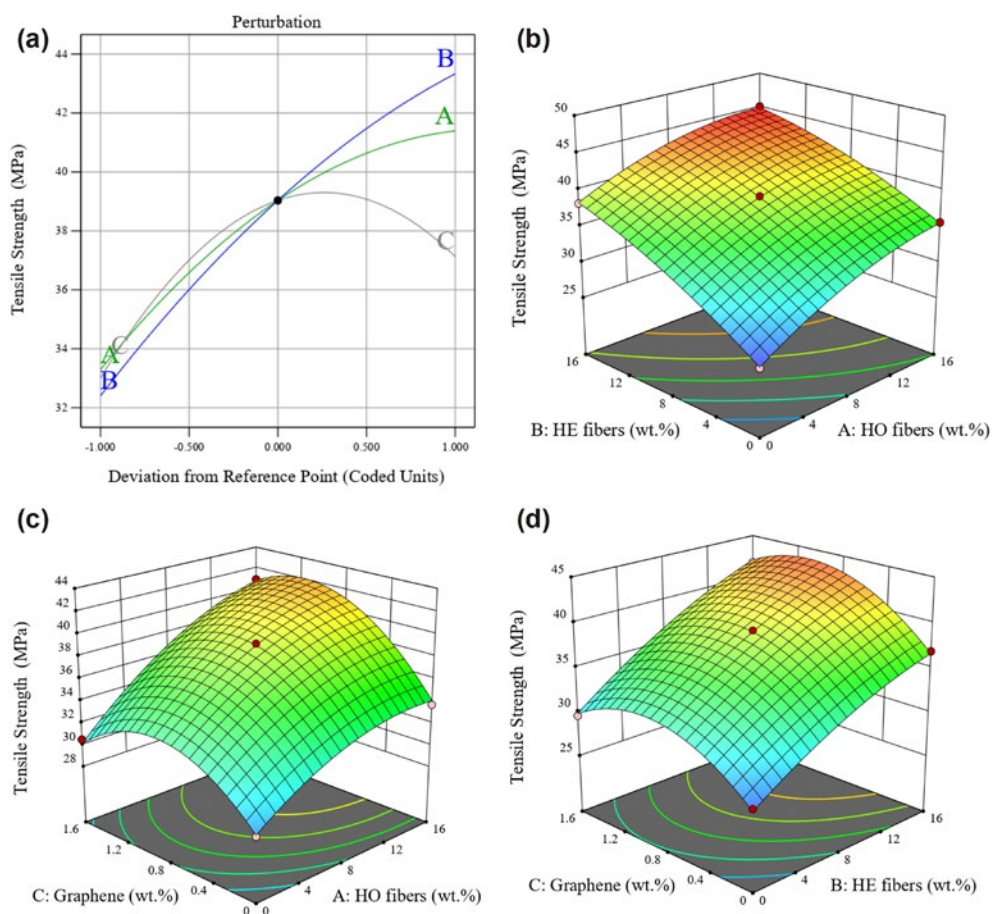
**Figure 6:** Tensile strength of (a) perturbation plot and response plot for (b) HO and HE fibers; (c) HO fibres and NG; (d) HE fibres and NG.

Figure 6 (a–d) demonstrates the variations in tensile strength of the composite material as affected by *Helicteres isora* fibers, *Holoptelea integrifolia* fibers, and graphene nanoparticles. The perturbation plot (Figure 6–a) demonstrates the impact of different reinforcements on tensile strength, with the steeper slope of *Helicteres isora* fibers (B) indicating a more significant effect on tensile properties compared to *Holoptelea integrifolia* fibers (A). The fluctuation in tensile strength demonstrates that increasing the fiber content of *Helicteres isora* results in significant improvements due to its higher tensile modulus and interfacial adhesion with the matrix.

The 3D response surface plots (Figures 6(b), (c), and (d)) clarify the influence of fiber and graphene weight percentages on tensile strength. Figure 6 (b) analyzes the synergistic effects of *Helicteres isora* and *Holoptelea integrifolia* fibers. The tensile strength enhances with the incorporation of fibers up to an optimal ratio, since the fibers increase stress transfer efficiency, aid in fracture bridging, and strengthen the matrix. Excessive fiber loading can lead to fiber agglomeration, which weakens interfacial bonding and somewhat decreases tensile strength.

Figure 6 (c) depicts the interaction between graphene nanosheets and *Holoptelea integrifolia* fibers. The addition of graphene up to 0.8 wt% significantly improves tensile strength by promoting nano-reinforcement, crack deflection, and better load distribution. Above this threshold, tensile strength declines due to the aggregation of graphene, leading to the formation of weak regions and areas of stress concentration inside the matrix. Figure 6 (d) similarly depicts the effect of graphene in combination with *Helicteres isora* fibers. An optimal fiber-to-graphene ratio improves tensile properties by facilitating uniform stress distribution, increasing load-bearing capacity, and postponing fracture initiation.

The current trend suggests that fibers from *Helicteres isora* and *Holoptelea integrifolia* significantly enhance tensile properties, whereas graphene offers supplementary reinforcement at ideal concentrations. The optimal tensile strength is achieved with a precise combination of *Holoptelea integrifolia* (12 wt%), *Helicteres isora* (10 wt%), and graphene (0.8 wt%), illustrating the synergistic effect of fibers and nanoscale fillers in improving the composite structure.

3.2. Flexural strength

This study investigates the flexural properties of two natural fiber-reinforced composites, S4 and S9, through three-point bending experiments. The experimental results reveal that S4 exhibits greater flexural strength (62 MPa) compared to S9 (49 MPa), attributed to improved fiber-matrix adhesion. S9 demonstrates a higher flexural strain at failure (6.22%) than S4 (5.44%), indicating a trade-off between strength and ductility (Figure 7). The results suggest that S4 is more suitable for load-bearing applications, while S9 may be preferred in situations requiring enhanced flexibility under bending loads.

At 95% confidence level, the researcher found that the interaction between *Holoptelea integrifolia* fibers, *Helicteres isora* fibers, and Graphene was significant (p -value < 0.05), while the interaction between *Helicteres*

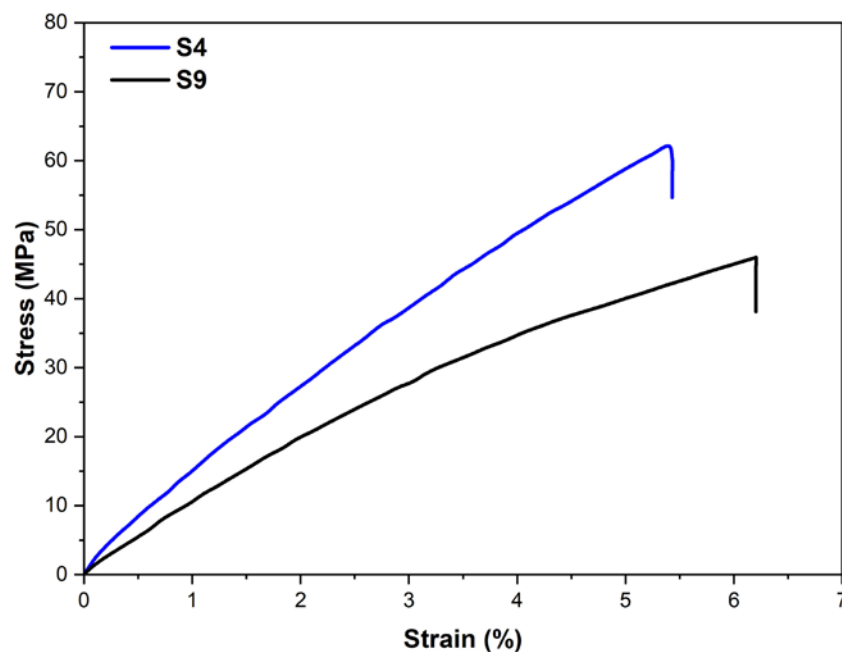


Figure 7: Evaluation of flexural stress versus strain curve of S4 and S9 composite.

isora fibers $\times$ Graphene and Graphene2 was also significant (p -value < 0.05), as presented in Table 5. The p -values in Table 5 show that *Holoptelea integrifolia* fibers, *Helicteres isora* fibers, and graphene significantly influence flexural strength individually ($p < 0.0003$). While fiber-fiber (AB) and fiber-graphene (AC) interactions are non-significant ($p = 1.0000$), the *Helicteres isora* -graphene (BC) interaction ($p = 0.0090$) is significant, indicating that proper graphene dispersion enhances fiber reinforcement. The regression evaluation of the flexural strength response led to the establishment of a second-order model. R^2 and adj. R^2 were determined to be 0.9949 and 0.9858, respectively, indicating that the output model is capable of forecasting the response performance. A robust correlation between the experimental data and the model predictions was evident in the normal probability plots and R^2 values that were obtained (exceeding 0.95 for all results) [47]. Additionally, the addition of the power response of the FS as the equation 2 enhanced the accuracy of the output model. Ultimately, the calculation is as follows.

As a result, equation (3) shows the regression equation for the flexural strength:

$$\text{Flexural Strength} = 43.83 + 0.292 A + 0.698 B + 11.67 C - 1.286 A * B + 1.710 A * C - 0.15625 B * C + 0.0013 A^2 - 0.0065 B^2 - 5.339 C^2 \quad (4)$$

Graphene nanoparticles, *Holoptelea integrifolia* and *Helicteres isora* fibers are represented by its percentage in Figure 8 (a), which demonstrates the flexural strength's sensitivity to these modifications. As demonstrated, the bending strength of the polymer has been enhanced by the addition of *Helicteres isora* fibers and *Holoptelea integrifolia* fibers to its matrix. The flexural strength of these fibers is more sensitive to changes owing to the maximum slope of the *Helicteres isora* fiber. The flexural strength is improved as a result of the *Holoptelea integrifolia* and *Helicteres isora* fibers' impact on the energy waste used in fracture boosting in the flexural test samples. Furthermore, the flexural strength has been improved by the addition of graphene into the composition that has been presented. The graphs clearly demonstrate that the flexural strength of the specimens was enhanced by the combination of only 0.8 wt% of graphene nanosheets into their composition. Enhanced bonding between the substrate and the fibers was the cause of this improvement. Additionally, the absorption of improved energy by nanosheets can impede the expansion of cracks and improve the energy of fracture. Furthermore, they possess the capacity to disrupt the fracture path through a variety of mechanisms, such as the formation of holes, the bridging of fissures, and the deviation from the crack path.

However, the FS of sample with 1.6 wt% NG has reduced relative to those with 0.8 wt% graphene. Lumps are present in specimens with improved nanoparticle content, potentially creating stress concentrations

Table 5: ANOVA table for flexural strength.

SOURCE	SUM OF SQUARES	Df	MEAN SQUARE	F-VALUE	p-VALUE	
Model	228.17	9	25.35	108.65	< 0.0001	Significant
A- <i>Holoptelea integrifolia</i> fibers	50.00	1	50.00	214.29	< 0.0001	
B- <i>Helicteres isora</i> fibers	112.50	1	112.50	482.14	< 0.0001	
C-Graphene	18.00	1	18.00	77.14	0.0003	
AB	0.0000	1	0.0000	0.0000	1.0000	
AC	0.0000	1	0.0000	0.0000	1.0000	
BC	4.00	1	4.00	17.14	0.0090	
A ²	0.0256	1	0.0256	0.1099	0.7537	
B ²	0.6410	1	0.6410	2.75	0.1583	
C ²	43.10	1	43.10	184.73	< 0.0001	
Residual	1.17	5	0.2			
Lack of Fit	0.5000	3	0.1667	0.5000	0.7194	not significant
Pure Error	0.6667	2	0.3333			
Cor Total	229.33	14				
Std. Dev.	0.4830		R ²	0.9949		
Mean	54.33		Adj. R ²	0.9858		
C.V. %	0.8890		Pred. R ²	0.9586		

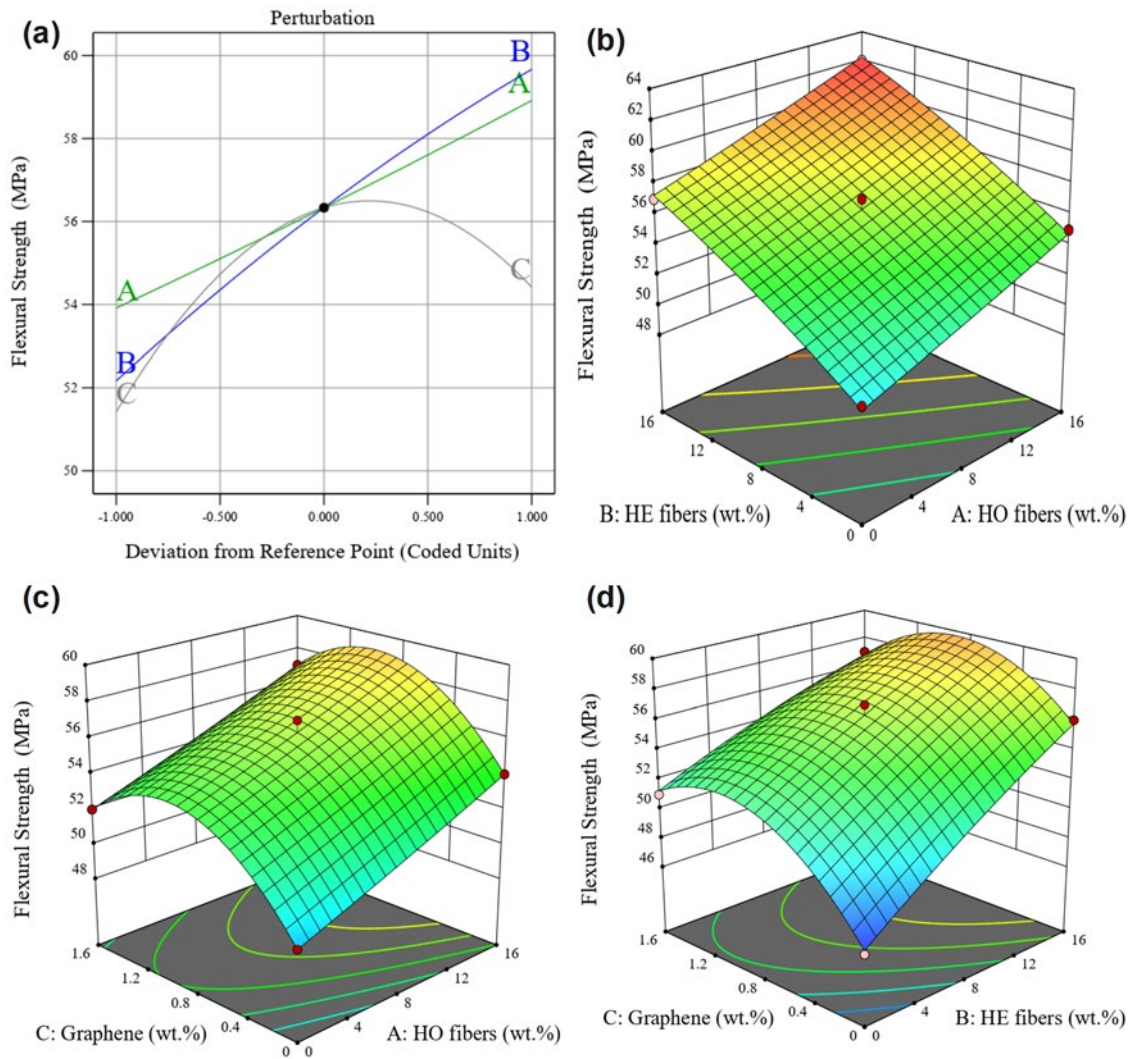


Figure 8: Flexural Strength of (a) perturbation plot and response plot for (b) HO and HE fibres; (c) HO fibres and NG; (d) HE fibres and NG.

and sites for fracture initiation, eventually resulting in a more brittle material. Experimental and numerical analysis showed that 2 wt.% graphene with Timoho fiber (TF) epoxy composites improved tensile (33.17%), flexural (36.48%), and impact (58.02%) [48]. Cementitious Green Hybrid Concrete (CGHC) was analyzed using Response Surface Methodology (RSM) to optimize its compressive and flexural strength. Partial replacements of coarse and fine aggregates with coconut shell, lime powder, and rice husk ash improved strength, except for higher coconut shell content, which reduced performance. The findings support CGHC's use in sustainable road construction [49]. The response approaches are illustrated in Figures 8 (a-d) in accordance with the flexural strength. The flexural strength improved because to the stable graphene weight percentage and the improved weight percentage of *Holoptelea integrifolia* and *Helicteres isora* fibers, as evidenced in procedure.

In addition, the uniformity of the weight percentage of *Helicteres isora* fibers and the increase in the weight percentage of *Holoptelea integrifolia* fibers are both significant contributors to the flexural strength, as can be inferred from Figure 8 (c). Uniformly distributed *Helicteres isora* fibers create a stable reinforcement network, improving stress distribution and reducing deformation. Balanced fiber ratios prevent weak spots, optimize load transfer efficiency, and enhance flexural performance. Furthermore, the bending strength is improved by the addition of graphene at a concentration of up to 0.8 wt%, while it is reduced above 0.8wt %. Additionally, it is inferred from Figure 8 (c) that the bending strength is improved by maintaining a constant weight proportion of *Helicteres isora* fibers and rising the weight percentage of *Holoptelea integrifolia* fibers. Furthermore, this strength is improved by increasing the graphene content to 0.8% weight, whereas a decrease in flexural strength is observed at larger weight percentages.

Figure 8 (d) demonstrates that the constancy of *Holoptelea integrifolia* fiber weight percentage, along with the enhancement of *Helicteres isora* fiber weight percentage, contributes to an increase in flexural strength. Furthermore, the incorporation of graphene weight percentage first enhanced the flexural strength and subsequently leading to a decline in the flexural strength.

3.3. Energy response for impact test

The regression test results for the impact strength response suggest that the percentage parameters of *Holoptelea integrifolia*, *Helicteres isora* fibers, and graphene nanoparticles are linear. The R^2 and adj. R^2 values of 0.9700 and 0.9160, correspondingly, illustrated the predictive capacity of the output models with respect to reaction performance. At a 95% confidence level, the researcher found that the interaction among *Holoptelea integrifolia* fibers and *Helicteres isora* fibers was significant (p-value < 0.05), though the interaction involving Graphene2 was also significant (p-value < 0.05), as indicated in Table 6.

The p-value for graphene (p = 0.0541) in Table 6 is close to the 0.05 significance threshold, indicating a moderate effect on impact strength but with variability. This suggests that graphene's influence depends on dispersion and interaction with fibers, requiring further optimization. Future studies should explore higher precision in graphene dispersion, alternative functionalization methods, or hybrid nanofillers to enhance its role in impact resistance.

The regression equation offers the most conclusive evidence regarding the impact strength as given in equation (5).

$$\text{Impact Strength} = 86.22 + 0.720 A + 1.396 B + 42.11 C + 0.051 A * B + 0.4348 A * C + 0.7668 B * C + 0.0078 A^2 - 0.0746 B^2 - 29.007 C^2 \quad (5)$$

The impact strength was improved by the addition of fibers from *Helicteres isora* and *Holoptelea integrifolia* into the polymer matrix, as demonstrated in Figure 9 (a). The impact strength was improved by the impact of *Holoptelea integrifolia* and *Helicteres isora* fibers on energy waste during fracture propagation in grooved specimens in the impact test. Furthermore, augmenting the graphene content in the composition initially improves the impact strength. As the nanographene quantity continues to rise, the impact strength of the specimens reduces. Figure 9 (a) illustrates that the addition of 0.8 wt% NG in the sample improves the impact strength, attributable to the improved bonding between the substrate and the fibers.

The presence of nanosheets, through phenomena such as bridging, perforation, and deviation from the fracture trajectory impede the crack propagation. Furthermore, the absorption of improved energy enhances

Table 6: ANOVA table for impact strength.

SOURCE	SUM OF SQUARES	df	MEAN SQUARE	F-VALUE	p-VALUE	
Model	3724.29	9	413.81	17.97	0.0027	significant
A- <i>Holoptelea integrifolia</i> fibers	1311.49	1	1311.49	56.94	0.0006	
B- <i>Helicteres isora</i> fibers	766.56	1	766.56	33.28	0.0022	
C-Graphene	144.67	1	144.67	6.28	0.0541	
AB	42.64	1	42.64	1.85	0.2318	
AC	30.97	1	30.97	1.34	0.2986	
BC	96.33	1	96.33	4.18	0.0962	
A ²	0.9169	1	0.9169	0.0398	0.8497	
B ²	84.25	1	84.25	3.66	0.1140	
C ²	1272.47	1	1272.47	55.24	0.0007	
Residual	115.17	5	23.03			
Lack of Fit	31.50	3	10.50	0.2510	0.8569	Not significant
Pure Error	83.67	2	41.83			
Cor Total	3839.46	14				
Std. Dev.	4.80		R ²	0.9700		
Mean	112.77		Adj. R ²	0.9160		
C.V. %	4.26		Pred. R ²	0.8197		

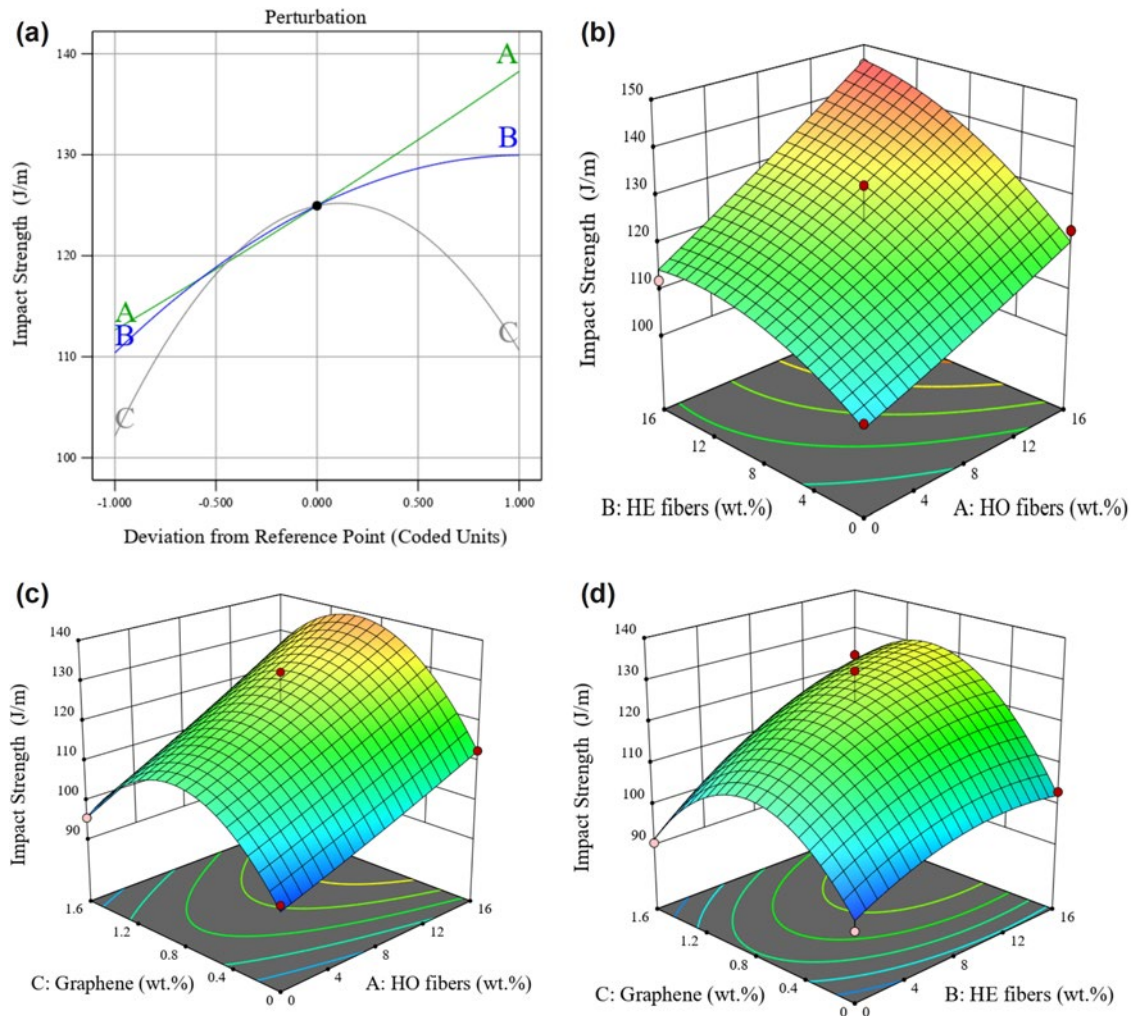


Figure 9: Impact strength of (a) perturbation plot and response plot for (b) HO and HE fibres; (c) HO fibres and NG; (d) HE fibres and NG.

the fracture energy. Nevertheless, the impact strength of the sample containing 1.6 wt% NG has decreased in comparison to those containing 0.8 wt% graphene. Aggregates are formed in specimens with a high concentration of nanoparticles, which may induce stress concentration, thereby facilitating fracture propagation and ultimately resulting in increased brittleness of the material. The response mechanisms associated with impact intensity are illustrated in Figures 9 (b-d). The impact strength was improved by maintaining a constant weight percentage of graphene and increasing the weight percentage of *Holoptelea integrifolia* fibers and *Helicteres isora* fibers in a linear fashion, as illustrated in Process (b). RSM identified optimal fiber/matrix ratios and fiber length, improving tensile, compressive, impact, and flexural properties, confirmed by ANOVA [50].

According to figure 9 (c), the impact strength was improved by maintaining a consistent weight percentage of *Helicteres isora* fibers and increasing the weight percentage of *Holoptelea integrifolia* fibers and the amount of NG to 0.8 wt%. Nevertheless, the impact strength was reduced as the graphene weight percentage increased. From figure 9(d), the weight proportion of *Holoptelea integrifolia* fibers remains constant, while the weight percentage of *Helicteres isora* fibers increases, resulting in enhanced impact strength. Initially, the addition of graphene weight percentage enhanced the impact strength, subsequently leading to a decline. The optimization results from Design-Expert software indicated that the optimal values for flexural strength (49.21 MPa), flexural modulus (1659.04 MPa), and impact strength (58.24 J/m), at a PALF content of 16.84 wt.%, fiber length of 13.67 mm, and MAPE load of 2.95 wt.% [51]. Enhancing *Helicteres isora* fiber-graphene interaction can be achieved through fiber surface modification (e.g., NaOH, silane), and graphene functionalization (-COOH, -OH). Hybrid reinforcements and compatibilizers can further improve bonding. These strategies ensure better load transfer, preventing aggregation, and enhancing composite strength.

3.4. Microstructural analysis

A Scanning Electron Microscope (FESEM) with X-ray energy dispersive spectroscopy (EDS) was used to examine the morphological surface and structural behavior of the fracture in flexural and impact specimens at the Bannari Amman Institute of Technology, Sathyamangalam, Tamilnadu. To prevent electron accumulation and improve electrical conductivity, the sample surfaces were treated with a layer of gold plating apparatus. The structural performance of nano-hybrid composites and the relationship between fibers, nanoparticles, and the matrix are evaluated by the surface morphology, which is a critical parameter.

Figure 10 illustrates the fracture surface of the pure polypropylene polymer specimen subjected to impact test. The fracture surface exhibits characteristics of a brittle fracture, displaying a leaf-like morphology. SEM investigation demonstrated enhanced interfacial adhesion in ramie composites, resulting in superior mechanical performance [52].

FESEM analysis was conducted to evaluate the fracture behavior, fiber-matrix adhesion, and graphene distribution in tensile-tested composites. The graphene nanosheets exhibited brittle failure, marked by minimal plastic deformation and rapid crack propagation, as depicted in Figure 11(a). In contrast, Sample 13 (8 wt% *Holoptelea integrifolia* fibers, 0.8 wt% graphene nanosheets, and 8 wt% *Helicteres isora* fibers) demonstrated strong fiber-matrix adhesion, reduced fiber pullout, and improved stress transfer, leading to elevated tensile strength (Figure 11(b)).

Graphene nanoparticles at 0.8 wt% demonstrated homogeneous dispersion, enhancing load distribution and preventing crack formation, as depicted in Figure 11(c). The SEM examination confirmed that the enhanced hybrid composite formulation had greater mechanical performance, hence validating the experimental results. This study highlights the synergistic effect of *Holoptelea integrifolia* and *Helicteres isora* fibers, in conjunction with graphene nanofillers, on improving the properties of bio-composites.

Figure 12 shows the fracture surface of specimens (specimen number 13) subjected to impact loading, which have 8 wt% *Holoptelea integrifolia* fibers, 0.8 wt% graphene nanosheets, and 8 wt% *Helicteres isora* fibers. Furthermore, it illustrates the effective dispersion of nanoparticles throughout the substrate and the lack of nanoparticle aggregation within the matrix. This distribution has resulted in a notable improvement in the adhesion of *Helicteres isora* and *Holoptelea integrifolia* fibers to the polymer matrix.

The fracture of *Holoptelea integrifolia* and *Helicteres isora* fibers significantly contributes to the improvement of impact strength. Additionally, the extraction of *Holoptelea integrifolia* and *Helicteres isora* fibers from polypropylene under impact loading, which results in substrate fracturing is regarded as an alternative method for energy absorption during impact.

Figure 13 distinctly illustrates the bonding between the graphene nanosheets and the fibers of *Helicteres isora* and *Holoptelea integrifolia*. Additional researchers have documented the existence of graphene nanosheets within polymer nanocomposites [38].

Figure 14 depicts the fractured surface of the sample, comprising 0.8 wt% NG and, 16 wt% HO fibers. The significance of fiber fracture in the extraction of fibers from the substrate under flexural load and the enhancement of strength is frequently overlooked. However, this protrusion is infrequently observed, particularly

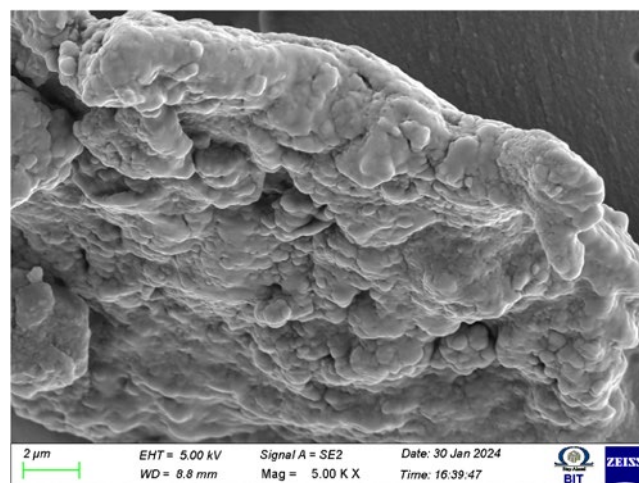


Figure 10: SEM image of pure polypropylene specimen.

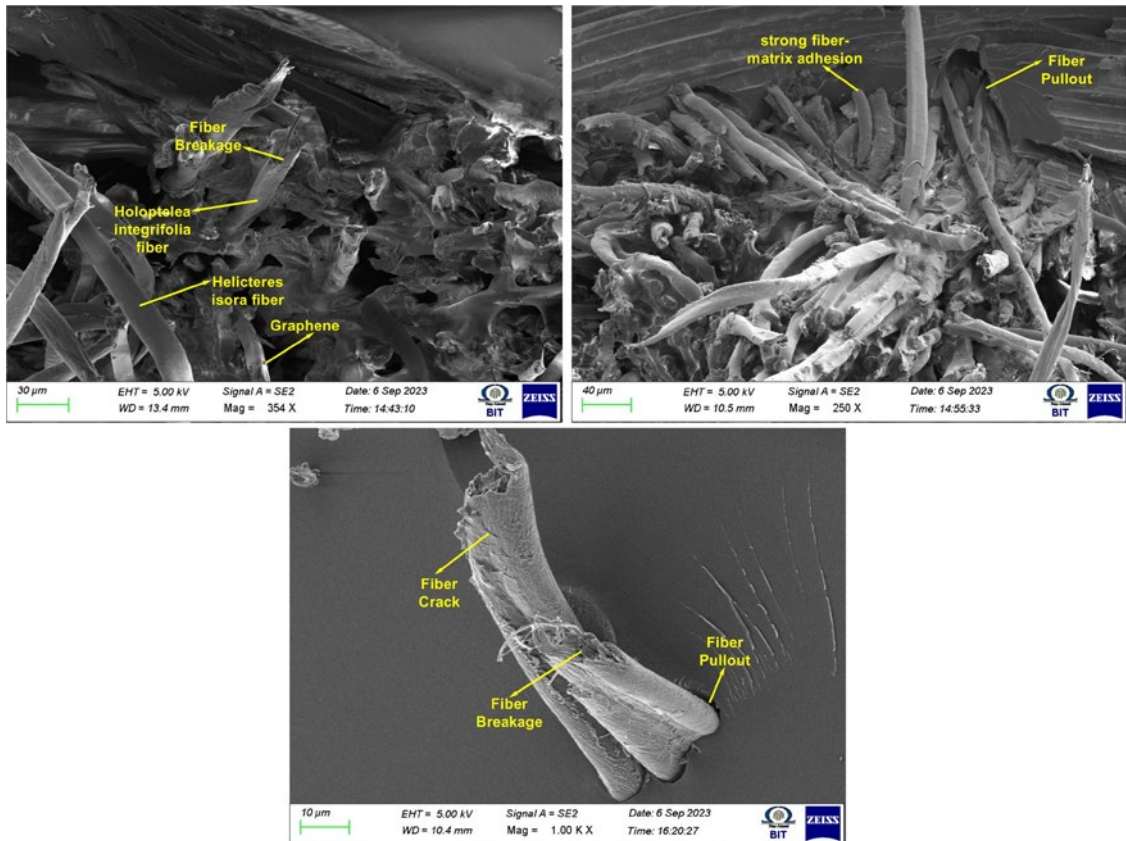


Figure 11: SEM image of tensile test fractured S13 sample.

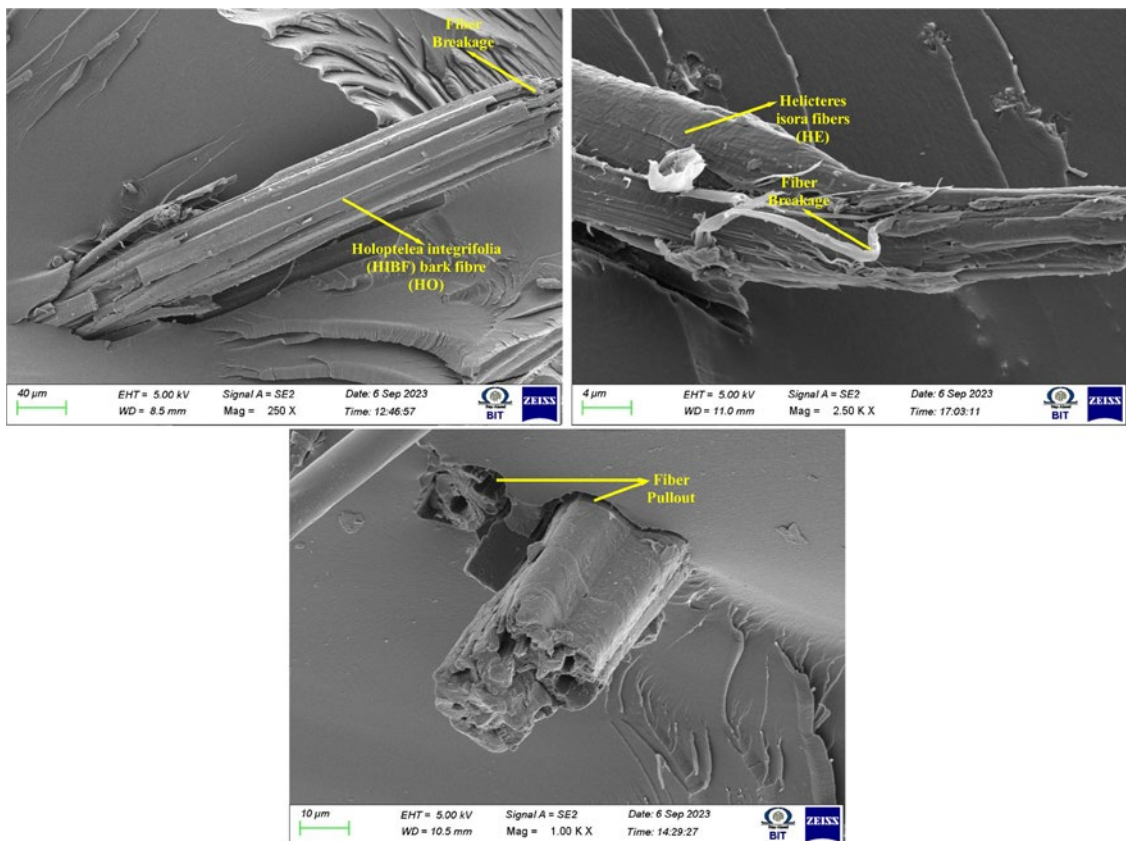


Figure 12: SEM image of the fractures sample in S13 through impact test.

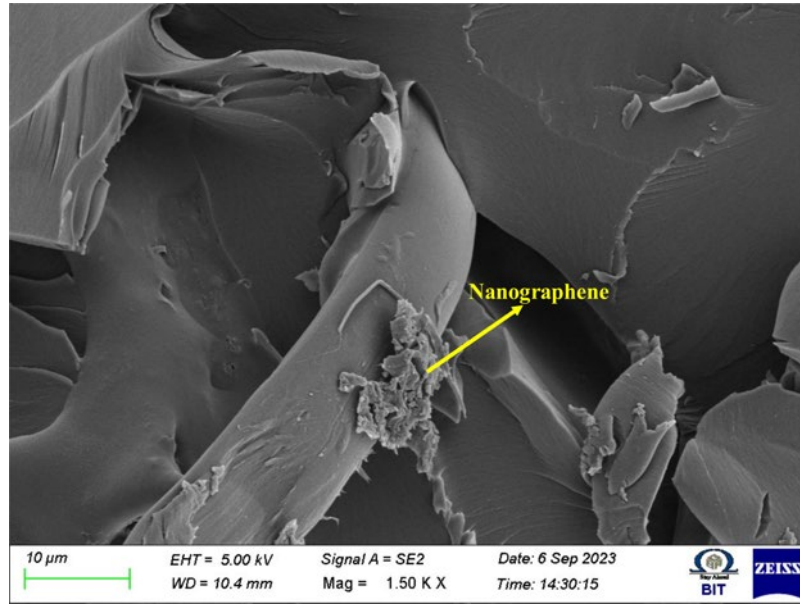


Figure 13: SEM image of the graphene in S13 through impact test.

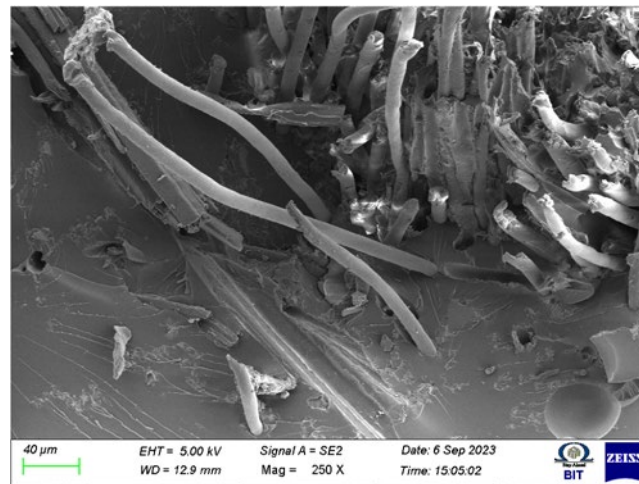


Figure 14: SEM image of the fractures sample in S2 through flexural test.

in *Holoptelea integrifolia* fibers, which exhibited the most significant protrusion of polypropylene after impact loading, despite the addition of 0.8 wt% nanographene.

4. OPTIMIZATION RESULTS

The critical factors for design in this study are the simultaneous reduction of composite weight and the improvement of tensile, flexural and impact strength through experimental analysis. Consequently, the elements evaluated for the multi-objective optimization include maximizing tensile, flexural and impact strength while concurrently minimizing weight. This article implemented the multi-objective particle swarm optimization technique. Equations 6 and 7 characterize the parameters and the multi-objective optimization approach.

$$\left\{ \begin{array}{l} \text{Minimize } [- \text{ Tensile strength, Weight}] \\ \text{s.t.} \\ 0\% \leq \text{Helicteres isora fiber} \leq 16\% \\ 0\% \leq \text{Holoptelea integrifolia fiber} \leq 16\% \\ 0\% \leq \text{NG} \leq 1.6\% \end{array} \right. \quad (6)$$

$$\begin{cases} \text{Minimize } [- \text{Flexural strength, Weight}] \\ \text{s.t.} \\ 0\% \leq \text{Helicteres isora fiber} \leq 16\% \\ 0\% \leq \text{Holoptelea integrifolia fiber} \leq 16\% \\ 0\% \leq \text{NG} \leq 1.6\% \end{cases} \quad (7)$$

$$\begin{cases} \text{Minimize } [- \text{Impact strength, Weight}] \\ \text{s.t.} \\ 0\% \leq \text{Helicteres isora fiber} \leq 16\% \\ 0\% \leq \text{Holoptelea integrifolia fiber} \leq 16\% \\ 0\% \leq \text{NG} \leq 1.6\% \end{cases} \quad (8)$$

4.1. Utility function

This study employed the Utility function approach because of its user-friendliness, the accessibility of Design-Expert software, the flexibility in adjusting weight percentages, and its capacity to discern the relevance of qualities for each individual response. Design-Expert may address multi-objective optimization issues by amalgamating replies into a dimensionless metric referred to as the utility function, accomplished by the utility technique.

The utility technique entails normalizing each assessed response to a dimensionless range of $0 < di < 1$; thus, a larger value of di signifies greater efficacy of the response. The optimization utilized for each tensile, flexural and impact strength result is depicted in Table 7.

4.2. Particle swarm optimization (PSO)

This research employed multi-objective particle swarm optimization to obtain an optimal state of tensile, flexural and impact strength in addition to optimizing with the utility function, as indicated by the output equations derived from the experimental design results. Based on population dynamics, the PSO is a technique that is predominantly inspired by the collective behavior of fish or birds. It was Eberhard et al. who first introduced this technique. Compared to other random optimization techniques, the PSO method is user-friendly and generates efficient results, resulting in superior outcomes. Due to its swift convergence and superior distribution compared to other multi-objective optimization (MCDM) methods like as PEAS and NSGA, Particle Swarm Optimization (PSO) has become a topic of contemporary interest.

Based on the optimization conducted using Design-Expert software, as referenced in table 3, and the PSO method, together with the criteria established in equations 5 and 6, Pareto diagrams demonstrated the multi-objective optimization for tensile, impact and flexural strength. Figure 15 illustrates the graphs of the optimal points for tensile, flexural and impact strength. The cumulative points shown in Fig. 15 for both optimization methods include the optimal points derived from the stipulations of equations 6 and 7. Each individual point is considered an optimal point.

The optimal points derived from equations 5 and 6 are represented by the cumulative points in Figure 15 for both optimization methods. Each point is regarded as optimal. An integrated PSO, GA, and DE approach optimized natural fiber reinforcement conditions, accurately enhances the mechanical performance with B-Spline function for predicting optimal fiber length, loading, and treatment time [53].

Table 7: Effects of parameter values on optimization.

MAXIMUM LIMIT	MINIMUM LIMIT	GOAL	UNIT	PARAMETERS	OPTIMUM LEVEL
16	0	In Range	wt%	<i>Helicteres isora</i> fiber	15.6721
16	0	In Range	wt%	<i>Holoptelea integrifolia</i> fiber	15.7198
1.6	0	In Range	wt%	Graphene	0.9307
25.8	45.1	Maximum	MPa	Tensile strength	45.4087
62	46	Maximize	MPa	Flexural strength	62.0344
145.58	90.01	Maximize	MPa	Impact strength	147.119

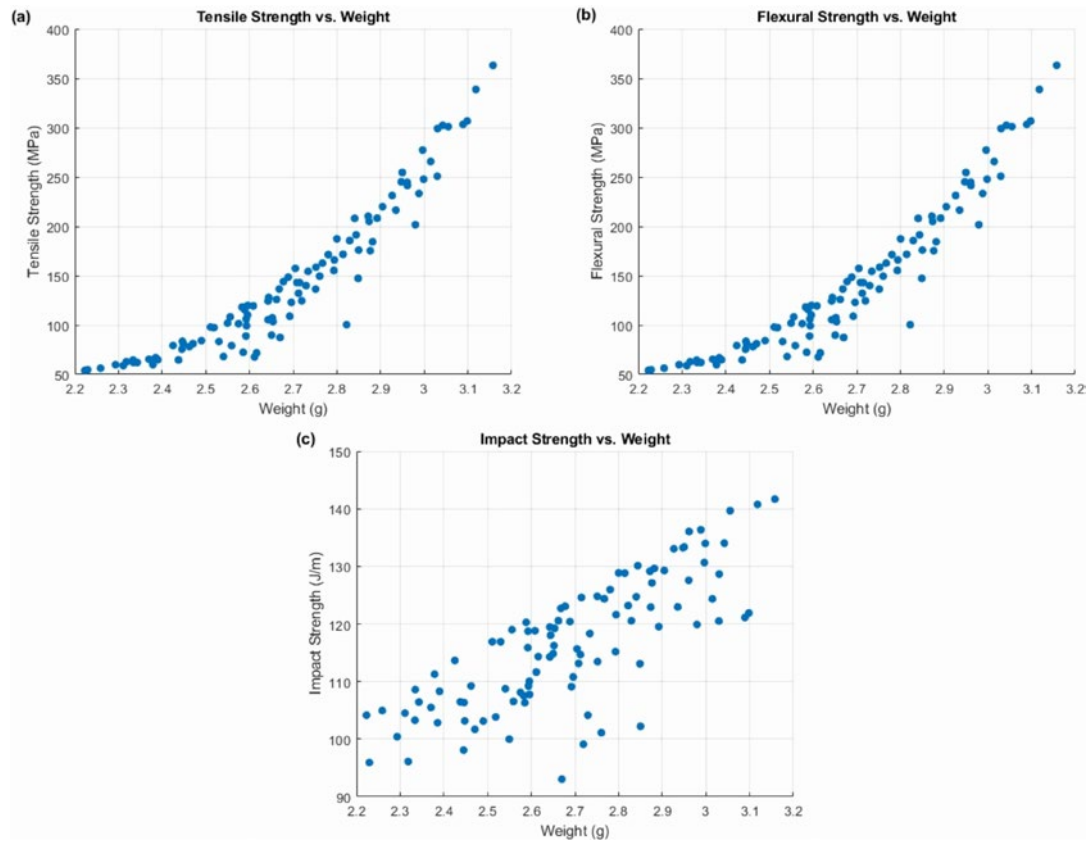


Figure 15: Chart showing the best spots for (a) tensile strength (b) flexural strength and (c) impact strength as determined by PSO.

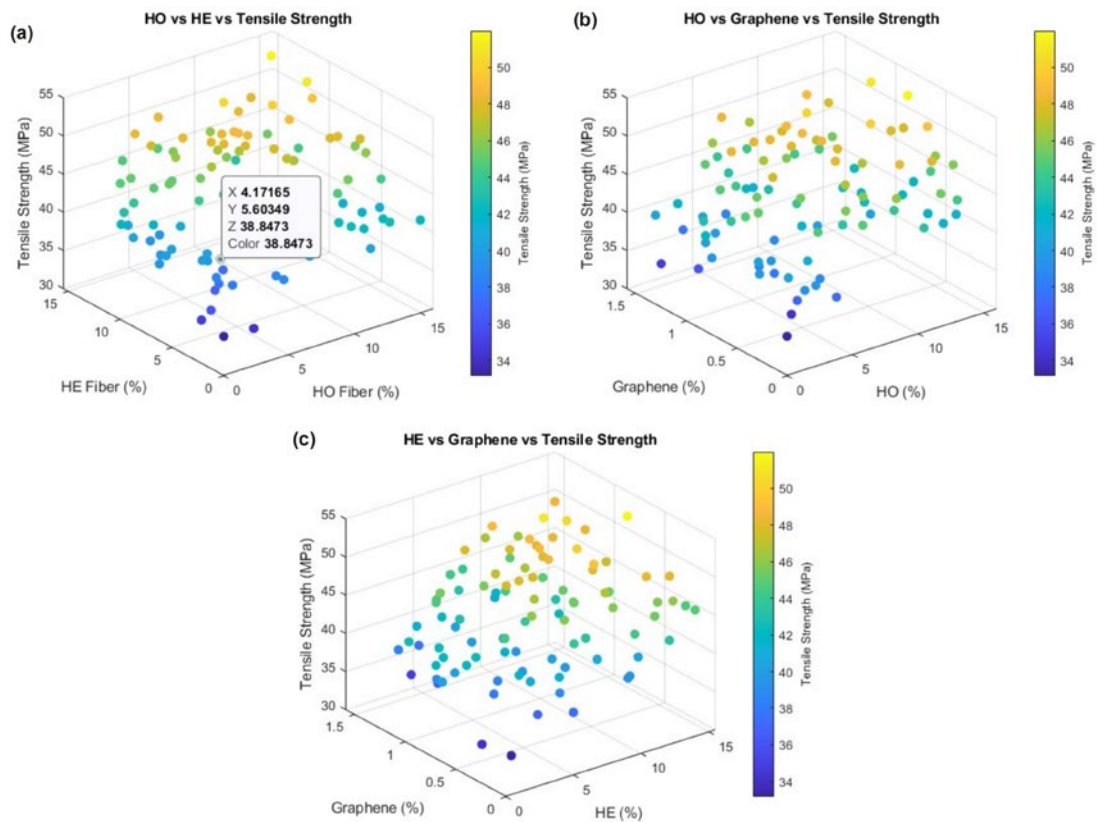


Figure 16: Distribution plot of (a) HO vs HE fibers; (b) HO fibers vs NG; (c) HE fibers vs NG in the optimum state to enhance the tensile strength.

Furthermore, Figure 16 illustrates the properties of *Helicteres isora* fibers, *Holoptelea integrifolia* fibers, and NG distributions, together with differences in tensile strength results. Additionally, Figure 17 displays the parameters of *Helicteres isora* fibers, *Holoptelea integrifolia* fibers, and NG distributions, and variations in flexural strength results. In conjunction with the variations in impact strength responses, Figure 18 illustrates the parameters of *Helicteres isora* fibers, *Holoptelea integrifolia* fibers, and nanographene distributions.

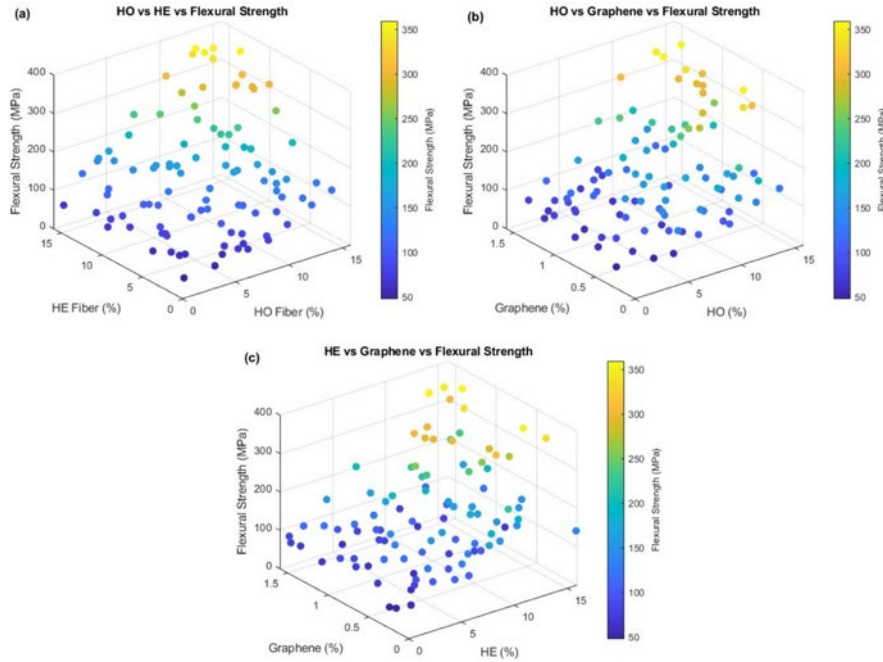


Figure 17: Distribution plot of (a) HO vs HE fibers; (b) HO fibers vs NG; (c) HE fibers vs NG in the optimum state to enhance the FS.

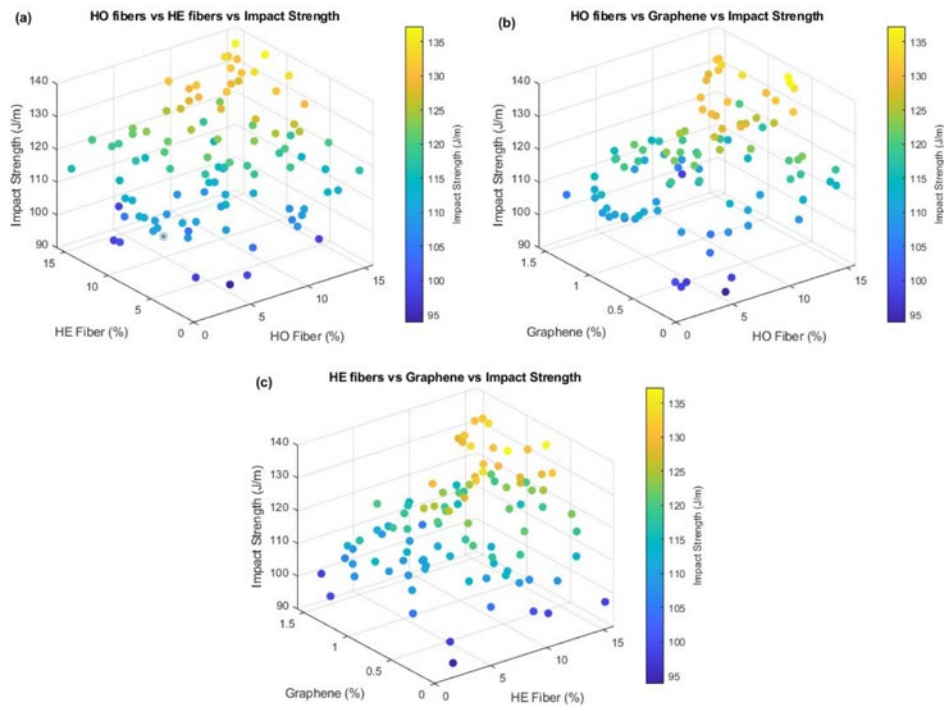


Figure 18: Distribution plot of (a) HO vs HE fibers; (b) HO fibers vs NG; (c) HE fibers vs NG in the optimum state to enhance the impact strength.

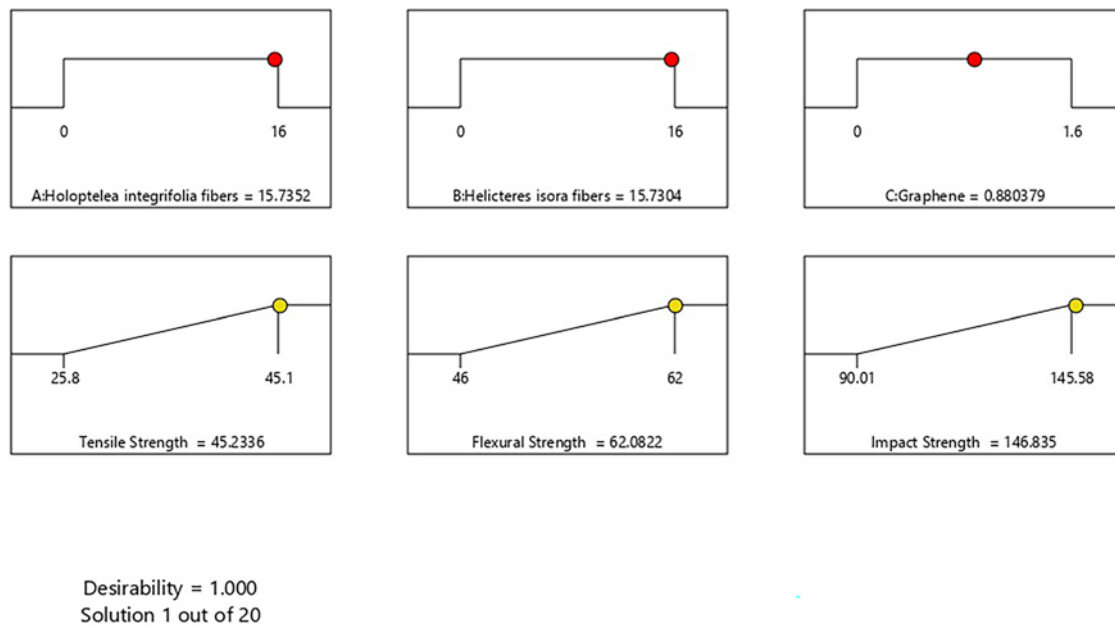


Figure 19: Optimize factor and design results to minimize weight while enhancing tensile, flexural and impact strength.

Figure 19 illustrates the peak tensile, flexural strength alongside the weight of the composite specimen. Additionally, it highlights the advantages of *Helicteres isora* fibers, *Holoptelea integrifolia*, NG proportion, and the optimum benefits of desirable results and their contextual placement within the framework of modifications using the efficiency function technique. Additionally, these positions are illustrative of one of the Pareto front's ideals, as demonstrated by the light weight composite specimen, which exhibits the maximal impact resistance and the lightest composite sample.

5. CONCLUSIONS

This work studied the influence of the weight percentage of *Holoptelea integrifolia* fibers, Nano-graphene particles, and *Helicteres isora* fibers on the tensile, flexural and impact strength of HO/PP/HE/NG bio-composites using Box Behnken and response surface methodologies. Moreover, the MOPSO (Multi objective particle swarm optimization) approach was employed to conduct multi-objective optimization in order to reduce the weight of the bio-composite introduced and improve its tensile, flexural and impact strength. *Helicteres isora* fibers, with a maximal content of 16 wt%, are optimum sample for enhancing tensile, flexural and impact strength due to its high weight-to-strength ratio. FESEM images indicate that the fracture surface of the matrix exhibits brittleness during impact strength, and the addition of nanoparticles enhances the attachment of fibers to the PP. Tensile, flexural strength is primarily improved through the fragmentation of the substrate and fibers, while impact strength is significantly increased by fiber fracture and protrusion from the poly-propylene matrix. The ideal weight percentages of graphene nanoparticles in the proposed bio-composite for enhancing tensile, flexural and impact strength are 0.265%, 0.7712% and 0.8124% respectively. The impact is substantially influenced by the content of *Helicteres isora* fibers, while the tensile, and flexural strength is predominantly influenced by *Holoptelea integrifolia* fibers of the three independent characteristics that were examined. The optimized composition (15.6721 wt% *Holoptelea integrifolia*, 15.7198 wt% *Helicteres isora*, and 0.9307 wt% graphene) offers high tensile (45.407 MPa), flexural (62.0344 MPa) and impact strength (147.119 J/m), making it suitable for practical applications in industries requiring strong yet lightweight materials. In automotive and aerospace applications, these composites enhances impact-resistant components like bumpers and aircraft panels.

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