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Development of Hybrid Bamboo-Plantain Fibre Composite for Ship Hulls and Submarines

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Abstract: Marine composites require a combination of high strength, low weight, and durability to withstand the harsh environments. In light of the traditional glass and carbon fibre composites present sustainability challenges, hybrid natural fibre composites hold promise for environmental benefits. However, their properties need optimization for maritime applications. This study focuses on developing a hybrid bamboo-plantain fibre-reinforced polyester composite, employing response surface methodology (RSM) to enhance mechanical performance and durability. Alkaline-treated bamboo and plantain fibres were incorporated into unsaturated polyester resin with varying orientations, stress ratios, and volume fractions, following a custom optimal design within RSM. The resulting specimens underwent tests, including tensile, impact, absorption, fatigue, and buckling assessments. Statistical analyses demonstrated that fiber orientation, volume fraction, and stress ratio markedly influence the composite's properties. The RSM findings identified the optimal configurations for fiber orientation (51.22), volume fraction (56.14), stress ratio (0.5), as well as impact testing, ultimate tensile strength, water absorption, oil absorption, fatigue strength, and buckling load, quantified as19.81, 159.93, 2.87, 2.32, 150.46 and 110.49, respectively. Overall, RSM successfully optimised the hybrid composite, highlighting the potential of natural fibre materials in shipbuilding through systematic material design strategies.

Key words: Hybrid natural fibre composite, Bamboo fibre, Plantain fibre, Response surface methodology, Marine composite, Optimization, Marine applications

1. Introduction:

Marine composites have revolutionised shipbuilding and submarine construction over the years due to their superior strength-to-weight ratio, corrosion resistance, and design flexibility (Okuma et al., 2023;Rohith et al., 2019).Traditional marine composites like glass and carbon fibre-reinforced polymers (GFRP/CFRP) face sustainability challenges, prompting research into greener alternatives (Baley et al., 2024). While CFRP offers advantages such as lightweight properties and high strength, its carbon footprint and disposal issues hinder widespread adoption (Chulawala et al., 2020). However, researchers are exploring sustainable options, including natural fibre composites, which show promise despite current performance limitations (Kappenthuler & Seeger, 2021). The marine industry's growing emphasis on sustainability has sparked interest in natural fibre composites as potential alternatives for specific marine applications (El Hawary et al., 2023;Yang et al., 2018). The evolution of marine composites has been driven by stringent requirements including high strength, low weight, excellent water resistance, and durability in harsh marine environments(Rubino et al., 2020).

However, natural fibres have emerged as promising reinforcement materials in composite structures, offering advantages such as biodegradability, low density, competitive specific mechanical properties, and reduced environmental impact(Shireesha & Nandipati, 2019). Among various natural fibres, bamboo and plantain fibres have shown remarkable potential due to their unique characteristics(Afrin et al., 2009;Singh &Samanta, 2014;Adeniyi et al., 2020). The application of natural fibers in marine environments presents unique challenges, primarily concerning water absorption, long-term durability, mechanical properties and performance in marine environments (Yang et al., 2018). However, recent research has explored different natural fibres, polymer matrices, and manufacturing techniques to enhance NFC properties (El Hawary et al., 2023; Midani & Hassanin, 2021) to address these challenges. While their partial renewability makes NFCs promising for long-term marine construction despite currently ranking lower than other fibre-reinforced polymer composites in terms of overall performance (Kappenthuler& Seeger, 2021), challenges persist regarding their mechanical properties and performance in marine environments.

Hybrid combinations of natural fibres offer promising solutions to address the limitations of individual natural fibre composites. These hybrids can enhance mechanical properties, reduce moisture absorption, and improve thermal stability (Neto et al., 2022; Mochane et al., 2019). The hybridization of bamboo and plantain fibers, in particular, offers an interesting avenue for investigation due to their complementary characteristics. Thus, the successful implementation of hybrid natural fibre composites in marine applications requires careful optimization of various parameters. These include fiber ratio, weight fraction, and stacking sequence significantly affect mechanical, physical, and thermal properties (Bichang'a et al., 2022). The complex interactions between these variables make traditional one-factor-at-a-time optimization approaches inadequate for achieving optimal performance characteristics. This necessitates the application of sophisticated optimization techniques that can handle multiple variables simultaneously.

Response Surface Methodology (RSM) has emerged as a powerful tool for optimizing composite materials, offering advantages over conventional optimization methods. RSM enables the understanding of complex interactions between variables while minimizing the number of experimental trials required (Onyenanu et. al., 2024; Chelladurai et al., 2021;Zaid et al., 2022). Recent studies have successfully employed Response Surface Methodology (RSM) to optimize natural fiber composites, achieving significant improvements in mechanical properties. Laouici et al., (2021)used RSM to investigate the effects of fiber type, chemical treatment, volume fraction, and treatment time on tensile strength and Young's modulus of hybrid-natural fiber composites. Mulenga et al., (2021) reviewed various computational techniques, including RSM, for modelling and optimizing natural fiber composites. Haniel et al., (2023) utilized RSM to optimize the fabrication parameters of kenaf and jute fibre-reinforced composites, achieving optimal impact and flexural strengths. In the context of marine composites, RSM has been particularly valuable for various ship components and designs. Nawawi et al., (2011) utilized RSM to optimize underwater composite enclosures, employing finite element analysis and design of experiment techniques. However, the application of RSM to hybrid bamboo-plantain fiber systems remains unexplored, presenting a significant research opportunity. However, this research aims to address these knowledge gaps by developing and characterizing a hybrid bamboo/plantain fiber reinforced polyester composite suitable for ship hull and submarine applications.

2. Literature Review

Due to the growing need for high-performance, environmentally friendly materials for ship hull and submarine construction, marine composites have undergone tremendous development. Because of their exceptional strength-to-weight ratio and resistance to corrosion, traditional marine composites—in particular, glass and carbon fibre-reinforced polymers have dominated the market (Hussnain et al., 2023). Research on more ecologically friendly substitutes is being prompted by the substantial sustainability challenges these materials face, such as their high carbon footprints and disposal problems (Chulawala et al., 2020).With benefits including biodegradability, low density, and less of an influence on the environment, natural fiber composites (NFCs) have become a viable substitute (Shireesha&Nandipati, 2019).Among various natural fibres, bamboo and plantain fibres have shown particular promise. Bamboo fibres demonstrate excellent mechanical properties and have been extensively studied in hybrid compositions with synthetic fibres(Biswas, 2012;Banga et al., 2015). Similarly, plantain fibres have shown potential in automotive applications, with Ihueze & Okafor, (2014)reporting an optimized impact strength of 167.851 KJ/m² in plantain fibre-reinforced polyester composites.

However, natural fiber composites face several challenges in marine applications, particularly concerning water absorption and long-term durability (Yang et al., 2018). Recent research has focused on addressing these limitations through various approaches, including hybridization and optimization of manufacturing parameters. Penjumras et al., (2015)successfully used Response Surface Methodology (RSM) to optimize biocomposite preparation conditions, achieving significant improvements in tensile and impact strength. This demonstrates the potential of systematic optimisation approaches in enhancing NFC properties.The literature reveals a growing trend toward hybrid natural fibre composites as a solution to individual fibre limitations. These hybrids can potentially enhance mechanical properties while maintaining environmental benefits (Neto et al., 2022). Prasad & Rao, (2011)conducted comparative studies between bamboo and other natural fibers, finding that hybrid combinations could achieve comparable or superior mechanical properties to single-fiber composites. Recent advancements in marine applications of NFCs have been significant, though challenges remain. Dąbrowska, (2022)highlighted the potential of plant-oil-based fiber composites for boat hulls while acknowledging the complex interactions between fillers and matrices that need to be addressed. The degradation behaviour of fibre-reinforced composites in marine environments, particularly regarding water absorption and hygrothermal ageing, remains a critical concern (Hussnain et al., 2023).

The optimisation of processing parameters has emerged as a crucial factor in achieving desired composite properties. Rasyid et al., (2016) demonstrated the importance of processing conditions on mechanical properties, achieving optimised flexural strength through careful control of moisture content, curing temperature, and time. This highlights the necessity of sophisticated optimisation techniques in composite development. Thus, the Optimisation of a Hybrid Bamboo-Plantain Fiber Reinforced Polyester Composite for Ship Hulls and Submarines represents an unexplored area with potential benefits for marine applications.

3. Methods

3.1 Material Description

The study used bamboo and plantain fibers as reinforcement materials, unsaturated polyester resin, and additives for composite production. Bamboo fibers were sourced from 3-4-year-old Bambusa vulgaris bamboo plants in Abia State, Nigeria. This specific age range was selected as it represents the optimal maturity period for achieving maximum fiber strength characteristics. For the plantain fiber component, fresh Musa paradisiacal pseudostems were harvested from agricultural sites in Uli, Anambra State, Nigeria. These pseudostems were processed immediately post-harvest to maintain optimal fiber properties. The matrix material selected was unsaturated polyester resin (UPR) with the grade designation PIDILITE GP, which was purchased from Main Market Onitsha, Anambra State. This specific grade was chosen for its excellent mechanical properties, good chemical resistance, and proven compatibility with natural fibers. The natural fibers underwent pre-treatment to improve their compatibility with the polymer matrix, including mechanical crushing and alkali treatment using 5% NaOH solution for 4 hours to remove lignin and hemicellulose. Similarly, the plantain pseudostems underwent manual extraction followed by alkali treatment using 4% NaOH solution for 3 hours. Both fiber types were thoroughly washed with distilled water until achieving neutral pH and then it was air dried for 48 hours to reduce the moisture content to less than 10%.

3.2 Samples Production

The hand layup process was used in a controlled laboratory setting to fabricate samples of polyester composite reinforced with hybrid bamboo/plantain fiber. The fibers were alkaline treated (5% NaOH solution) for 4 hours before to production to improve fibre-matrix adhesion and eliminate surface contaminants. To get the desired moisture content, the treated fibers were dried for 24 hours at 80°C. Unsaturated polyester resin with 1.5% by weight of methyl ethyl ketone peroxide (MEKP) catalyst made up the matrix system. Fiber orientations were meticulously regulated by Table 1 experimental design. To ensure consistent fiber distribution, the layup process comprised alternating layers of matrix and fibers with volume fractions ranging from 40% to 60%. Samples were post-cured after being cured for 24 hours at room temperature (25±2°C). Quality control measures included thickness monitoring, void content assessment, and surface finish inspection. The fabrication process yielded test specimens conforming to ASTM standards for mechanical and physical property evaluation.

3.3 Physico-Mechanical Properties

Water and oil absorption tests (ASTM D570) were conducted with sample dimensions 28 mm x 30mm x 3mm by weighing the sample before and after the sample had been immersed in the respective fluids for 7 days and recorded in percentage. Tensile strength (ASTM D638) was evaluated with sample dimensions 60mm x 6mm x 3mm in the universal tensile testing machine (JJ Lloyd London, capacity 1- 20 KN) at a crosshead speed of 10 mm/min and an applied load of 5KN. The impact Charpy test (ASTM D256) was conducted in a Changteh China, model JC-25, pendulum capacity of 4J at a test velocity of 5 m/s with a sample dimension of 75mm x 15mm x 6mm. The fatigue strength (ASTM D3479) was evaluated on sample dimensions 200mm x 25mm x 3mm using the SM1090V (TecQuipment, Nottingham, UK) with a data acquisition system for real-time data capture, monitoring and display. The buckling test (ASTM D695) was performed on sample dimensions 200mm x 13mm x 6mm usingthe Instron 8801 (Instron, Norwood, MA, USA) model machine was used to conduct the buckling test under axial compression.

3.4 Experimental Design Setup

In the present research investigation, the multi-objective experimental design was made through the I-optimal design within the Response Surface Methodology (RSM) framework to optimize the hybrid bamboo/plantain fiber reinforced polyester composite (HBPFC). The design focused on optimizing three critical parameters affecting the composite's performance:

1. Stress Ratio (R): (-1 to 0.5)
2. Fiber Orientation (θ): (0° to 60°)
3. Volume Fraction (V): (40% to 60%)

Design Expert Software 13 was employed to generate a standard random optimal design matrix. The design was enhanced with an axial blend check and overall centroid, without replication of vertices and overall centroid, resulting in 22 experimental blends. This optimization approach specifically targeted impact strength, ultimate tensile strength, water absorption, oil absorption, fatigue strengthand buckling load as the primary response variables.

Table 1: Experimental design for the hybrid bamboo/plantain fibre-reinforced polyester composite

	Factor 1	Factor 2	Factor 3	Response 1	Response 2	Response 3	Response 4	Response 5	Response 6
Run	**A: Orientation**	**B: Vol. Fraction**	**C: Stress Ratio**	**Impact Strength**	**Ultimate Tensile Strength**	**Water Absorption**	**Oil absorption**	**Fatigue Strength (10^7 cycles)**	**Buckling load**
	(Degrees)	(%)		(kJ/m^2)	(MPa)	(%)	(%)	(MPa)	(MPa)
1	60	60	-1	12	152	3.0	2.5	140	110
2	60	40	-0.25	18	160	2.8	2.0	155	130
3	30	50	-1	15	148	4.0	3.5	135	085
4	0	60	-1	20	165	2.5	1.8	165	120
5	60	40	0.5	20	159	2.6	2.0	150	110
6	60	40	-1	16	158	2.7	2.0	145	110
7	30	50	-1	15	148	4.0	3.5	135	085
8	30	40	-0.25	17	149	4.1	3.4	138	080
9	30	60	-0.25	19	150	3.5	2.9	140	090
10	0	50	-0.25	22	166	2.4	1.9	155	100
11	0	40	0.5	20	167	2.3	2.1	160	105
12	30	40	-1	16	146	4.0	3.2	135	080
13	0	40	-0.25	21	164	2.5	2.0	150	115
14	0	40	-1	23	168	2.4	1.8	160	120
15	30	60	0.5	17	153	3.3	2.6	145	090
16	0	50	0.5	19	168	2.4	1.9	160	115
17	60	60	0.5	24	170	2.0	1.5	165	140
18	60	50	-0.25	15	161	2.8	2.0	150	110
19	0	50	0.5	19	168	2.4	1.9	160	115
20	30	50	-1	15	148	4.0	3.5	135	085
21	30	60	-0.25	19	150	3.5	2.9	140	090
22	60	40	0.5	20	159	2.6	2.0	150	110

4. Results

4.1 Optimization of Hybrid Fiber Reinforcement Using Response Surface Methodology

The physico-mechanical properties of a polymer-fibre composite tend to be altered when fiber volume fraction is altered. The same applies to fiber orientation in the composite formulation. An increase in fibre reinforcement volume fraction composition or controlling fiber orientation may cause a rapid change in the physio-mechanical properties of the resulting composite. Increasing the fibre reinforcement volume fraction in most cases enhances most of the physico-mechanical properties apart from moisture absorption capability (Ihueze and Okafor, 2014; Hussnain et al., 2023). Besides fibre reinforcement volume composition and fibre orientation, it is ideal to investigate the outcome of the interaction of these factors under cyclic vibration representing conditions available in the ocean environment. Therefore, the effects of fibre volume fraction, fiber orientation and cyclic stress ratio were investigated in this study to find the optimum combination for a hybrid bamboo/plantain fibre-reinforced polyester composite suitable for ship hull and submarine applications.

Analysis of variance (ANOVA) comprises a set of statistical models and corresponding estimate methods, including the assessment of variation within and across groups, utilized to examine the disparities among group means in a sample (Larson, 2008). However, this method was employed to ascertain whether a significant difference exists in the mean of the experiment. Table 2 presents the results of ANOVA related to the impact test, ultimate tensile strength, seawater absorption, crude oil absorption, fatigue strength, and buckling load, obtained from experimental data. These tables elucidate the statistical importance of the pertinent factors and present the coefficients of the corresponding models.A large F-value and a small P-value reveal a significant effect of each term.

The results showed that the variables with the largest to smallest effects ($P \leq 0.05$) on the Impact strength were the single effect of fiber orientation, stress ratio and linear effect of the orientation-stress ratio interaction and volume fraction-stress ratio interaction, while the largest to smallest effects ($P \leq 0.05$) on the Ultimate Tensile strength were the single effect of fiber orientation, stress ratio and linear effect of the orientation-stress ratio interaction, and the linear effect of the interaction between fibre reinforcement weight composition and length. Also, the largest to smallest effects ($P \leq 0.05$) on the Water absorption were the single effect of fiber orientation, volume fraction, stress ratio and linear effect of the orientation-stress ratio interaction, while the largest to smallest effects ($P \leq 0.05$) on the Oil absorption were the single effect of fiber orientation, volume fraction, stress ratio and linear effect of the orientation-stress ratio interaction. Similarly, the largest to smallest effects ($P \leq 0.05$) on the Fatigue strength were the single effect of fiber orientation, volume fraction, stress ratio and linear effect of the orientation-stress ratio interaction. Also, the largest to smallest effects ($P \leq 0.05$) on the Buckling load (critical stress) were the single effect of fibre reinforcement volume fraction.

Generally, the model's high F-values (P<F value) for impact strength, ultimate tensile strength, seawater absorption, oil absorption, fatigue strength and Buckling Load indicated that the linear model was highly efficient for fitting the data under the condition of the experiment and Mean values implied a good agreement between the predicted and the experimental values of the model as shown in Table 2. Also, the high R^2 values indicated that the model was very efficient for fitting the data under the experimental conditions and the adjusted R^2values showed a agreement between the predicted and the experimental values of the model as shown in Table 2. Furthermore, the P values of the model shows a significance of the model.

Table 3 shows the second-order polynomial models and response surface model regression coefficients for impact strength, ultimate tensile strength, seawater absorption, oil absorption, fatigue strength and Buckling Load. The models help in predicting how changes in the composition or processing of the hybrid composite can enhance its mechanical properties, resilience, and overall performance in a maritime environment.

The application of the RSM was suitable for optimizing the hybrid bamboo/plantain fibre polyester composite with desirable responses. The outcome of analysis of experimental data collected from the responses of the independent variables showed that the polynomial equation could be used to illustrate the response surface plots and forecast the impact strength, ultimate tensile strength, seawater absorption, oil absorption, fatigue strength and Buckling Load. Figure 1 shows the 3D response surface and variable interactions plots of the polynomial models that present the effect of independent variables on the impact strength, ultimate tensile strength, seawater absorption, oil absorption, fatigue strength and Buckling Load of the hybrid bamboo/plantain fibre polyester composite. The interactions and surface behaviours are vital for product development and optimization. For the impact strength, Ultimate Tensile Strength, Seawater Absorption, Oil Absorption, fatigue strength and Buckling Load of the Hybrid bamboo/plantain fiber matrix Reinforced with Polyester Composite for the ship hull, by adjusting the fiber orientations and the volume fraction of bamboo and plantain fibres, the mechanical properties and durability of the composites for ship hulls can be tailored ensuring performance stability in marine environments.

Table 2: ANOVA for the selected factorial models of impact strength, Ultimate Tensile Strength, Seawater Absorption, Oil Absorption, fatigue strength and Buckling Load for the Reinforcement of Polyester Composite.

Variables		Main Effect A	B	C	Interaction Effect AB	AC	BC	Model	R^2	Adjusted R^2
Impact Strength	Means quare	35.73	0.0530	12.14	0.0728	24.16	8.24	15.46	0.9125	**0.8164**
	F-value	21.93	0.0325	7.45	0.0447	14.83	5.06	9.49		
	P-value	0.0009	0.8605	0.0104	0.8368	0.0010	0.0304	0.0007		
Tensilestrength	Means quare	154.87	9.84	35.07	1.87	0.5814	0.4634	124.62	0.9771	**0.951**
	F-value	48.27	3.07	10.93	17.92	5.58	0.0235	38.84		
	P-value	< 0.0001	0.1104	0.0030	28.19	8.78	0.0063	< 0.0001		
Water Absorption	Means quare	0.2855	0.2091	0.2250	0.0002	0.0157	0.9027	0.8742	0.9894	**0.9779**
	F-value	27.97	20.48	22.03	0.0266	2.60	0.1229	85.62		
	P-value	0.0004	0.0011	0.0002	0.1420	13.91	0.0013	< 0.0001		
Oil Absorption	Means quare	0.0864	0.1694	0.1389	0.0778	35.89	0.0001	0.8298	0.9976	**0.9950**
	F-value	39.89	78.19	64.12	0.0433	19.96	0.0003	382.96		
	P-value	< 0.0001	< 0.0001	< 0.0001	0.2684	123.87	< 0.0001	< 0.0001		
Fatigue Strength	Means quare	253.86	62.73	64.49	5.97	0.7287	0.4133	196.86	0.9635	**0.9234**
	F-value	30.97	7.65	7.87	89.16	10.88	0.0031	24.02		
	P-value	0.0002	0.0199	0.0199	33.25	4.06	0.0513	< 0.0001		
Buckling Load	Means quare	20.55	206.18	5.19	4.94	0.1042	0.7535	490.05	0.9191	**0.8302**
	F-value	0.4334	4.35	0.1094	134.35	2.83	0.1060	10.33		
	P-value	0.5252	0.0636	0.8974	146.53	3.09	0.0902	0.0005		

Table 3: Second-order polynomial models for the impact strength, Ultimate Tensile Strength, Seawater Absorption, Oil Absorption, fatigue strength and Buckling Load of the Reinforcement of Polyester Composite.

Responses	Polynomial Models
Impact Strength	Coded: Impact Strength = $16.13-1.82A + 0.0715B - 1.65C [1] + 0.6307C [2] + 0.0998AB - 1.93AC [1] - 0.6298AC [2] - 1.60BC [1] + 0.8811BC [2] + 2.56A^2 + 0.8821B^2$ Actual: Stress Ratio (-1) = 50.981 + -0.312447 * A + -1.04488 * B + 0.000332675 * AB + 0.00284688 * A^2 + 0.00882075 * B^2 Stress Ratio (-0.25) = 39.5567 + -0.269116 * A + -0.796802 * B + 0.000332675 * AB + 0.00284688 * A^2 + 0.00882075 * B^2 Stress Ratio (0.5) = 37.567 + -0.162805 * A + -0.813042 * B + 0.000332675 * AB + 0.00284688 * A^2 + 0.00882075 * B^2
Tensile strength	Coded: Ultimate Tensile Strength = $149.69-3.27A + 0.8728B - 2.45C [1] - 0.0418C [2] + 0.5052AB - 2.48AC [1] + 1.27AC [2] - 2.59BC [1] + 0.0427BC [2] + 14.38A^2 - 0.8263B^2$ Actual: Stress Ratio (-1) = 157.823 -1.2344 * A + 0.603985 * B + 0.00168388 * AB + 0.0159756 * A^2 -0.00826273 * B^2 Stress Ratio (-0.25) = 143.315 -1.10931 * A + 0.86731 * B + 0.00168388 * AB + 0.0159756 * A^2 -0.00826273 * B^2 Stress Ratio (0.5) = 133.384 -1.11127 * A + 1.11781 * B + 0.00168388 * AB + 0.0159756 * A^2 + -0.00826273 * B^2
Water Absorption	Coded: Water Absorption = $3.88 + 0.1431A - 0.1430B + 0.1857C [1] + 0.0066C [2] - 0.0047AB + 0.0569AC [1] + 0.0296AC [2] + 0.2107BC [1] - 0.1064BC [2] - 1.30A^2 - 0.1246B^2$ Actual: Stress Ratio (-1) = -0.915799 + 0.0943179 * A + 0.131789 * B -1.56177e-05 * AB -0.00144784 * A^2 -0.00124555 * B^2 Stress Ratio (-0.25) = 0.517654 + 0.0934065 * A + 0.100083 * B-1.56177e-05 * AB -0.00144784 * A^2 -0.00124555 * B^2

$$\text{Stress Ratio } (0.5) = 0.424317 + 0.0895387 * A + 0.100294 * B - 1.56177e{-}05 * AB - 0.00144784 * A^2 - 0.00124555 * B^2$$

Oil Absorption

Coded: Oil absorption =

$$3.33 + 0.1096A - 0.1530B + 0.1759C[1] - 0.0442C[2] + 0.1032AB + 0.1154AC[1] - 0.0330AC[2] + 0.2791BC[1] - 0.0702BC[2] - 1.31A^2 - 0.1785B^2$$

Actual:

$$\text{Stress Ratio } (-1) = -2.60609 + 0.077856 * A + 0.180778 * B + 0.000343834 * AB - 0.00145913 * A^2 - 0.00178484 * B^2$$

$$\text{Stress Ratio } (-0.25) = -0.93123 + 0.0729085 * A + 0.145848 * B + 0.000343834 * AB - 0.00145913 * A^2 - 0.00178484 * B^2$$

$$\text{Stress Ratio } (0.5) = -0.275565 + 0.0712631 * A + 0.131973 * B + 0.000343834 * AB - 0.00145913 * A^2 - 0.00178484 * B^2$$

Fatigue Strength

Coded: Fatigue Strength =

$$137.02 - 4.64A + 2.51B - 2.85C[1] - 0.8993C[2] - 0.9039AB - 5.36AC[1] + 4.19AC[2] - 2.27BC[1] - 0.8092BC[2] + 16.68A^2 + 2.02B^2$$

Actual:

$$\text{Stress Ratio } (-1) = 205.637 + -1.29493 * A + -1.90539 * B + -0.00301304 * AB + 0.0185375 * A^2 + 0.0201969 * B^2$$

$$\text{Stress Ratio } (-0.25) = 190.721 + -0.976666 * A + -1.75907 * B + -0.00301304 * AB + 0.0185375 * A^2 + 0.0201969 * B^2$$

$$\text{Stress Ratio } (0.5) = 178.936 + -1.07742 * A + -1.36999 * B + -0.00301304 * AB + 0.0185375 * A^2 + 0.0201969 * B^2$$

Buckling Load

Coded: Buckling Value (Critical Stress) =

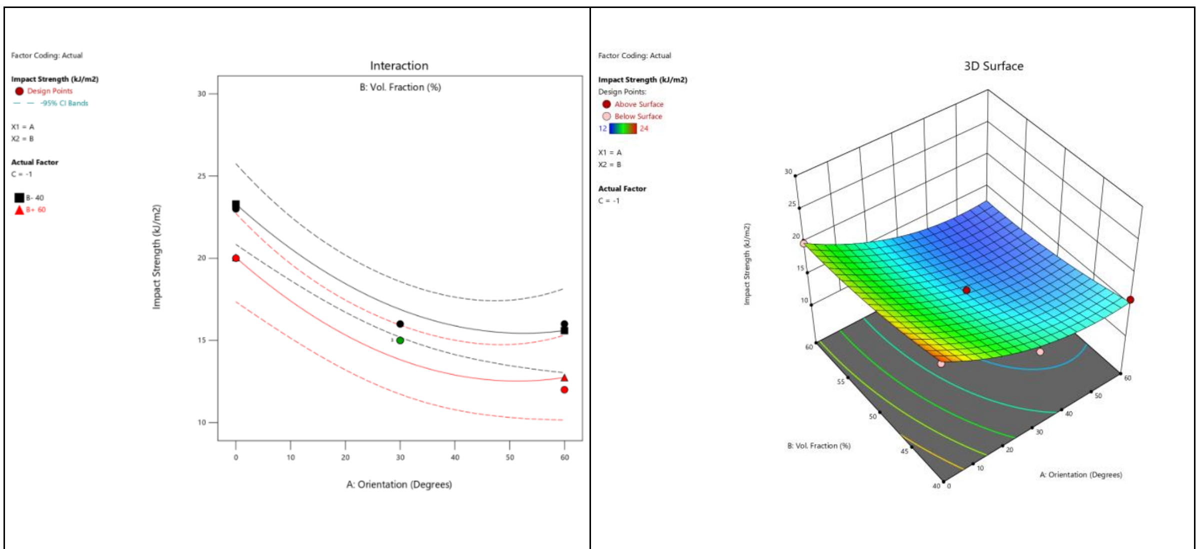
$$82.55 + 1.62A + 4.12B - 0.9570C[1] - 0.8039C[2] + 0.8222AB - 6.62AC[1] + 5.05AC[2] - 3.05BC[1] - 3.57BC[2] + 31.12A^2 + 3.77B^2$$

Actual:

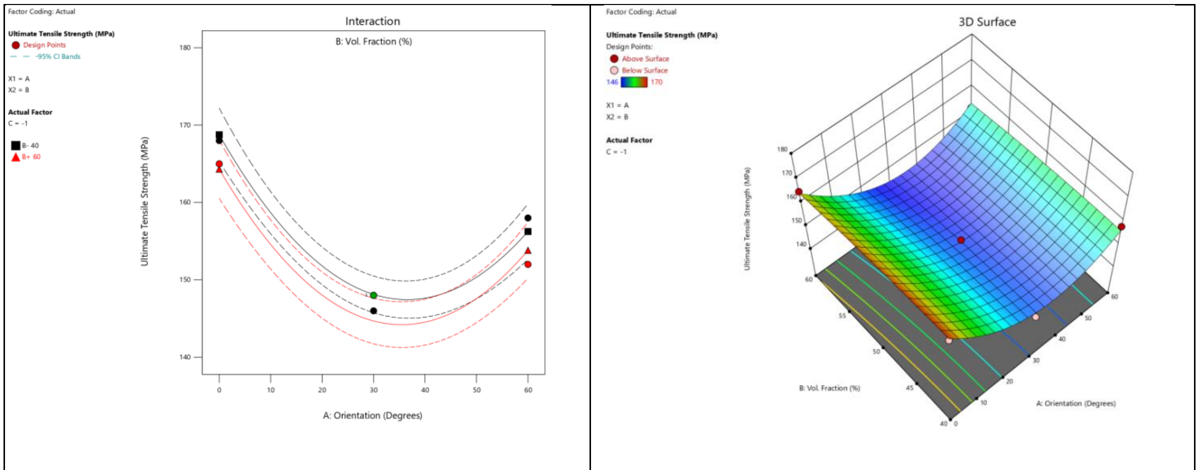
$$\text{Stress Ratio } (-1) = 210.717 + -2.37805 * A + -3.74536 * B + 0.00274079 * AB + 0.0345725 * A^2 + 0.0377045 * B^2$$

$$\text{Stress Ratio } (-0.25) = 201.826 + -1.98935 * A + -3.79769 * B + 0.00274079 * AB + 0.0345725 * A^2 + 0.0377045 * B^2$$

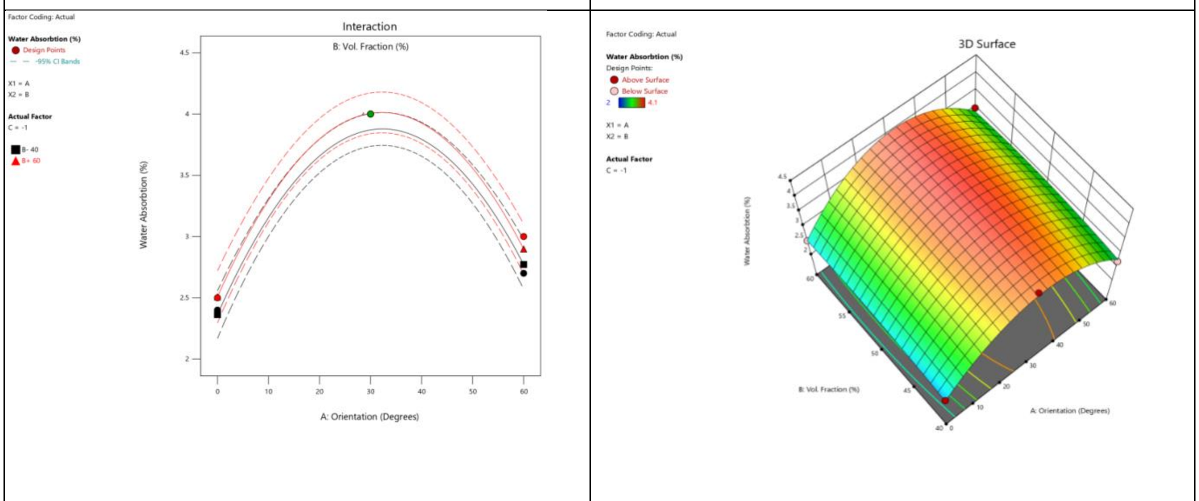
$$\text{Stress Ratio } (0.5) = 156.947 + -2.10526 * A + -2.77929 * B + 0.00274079 * AB + 0.0345725 * A^2 + 0.0377045 * B^2$$



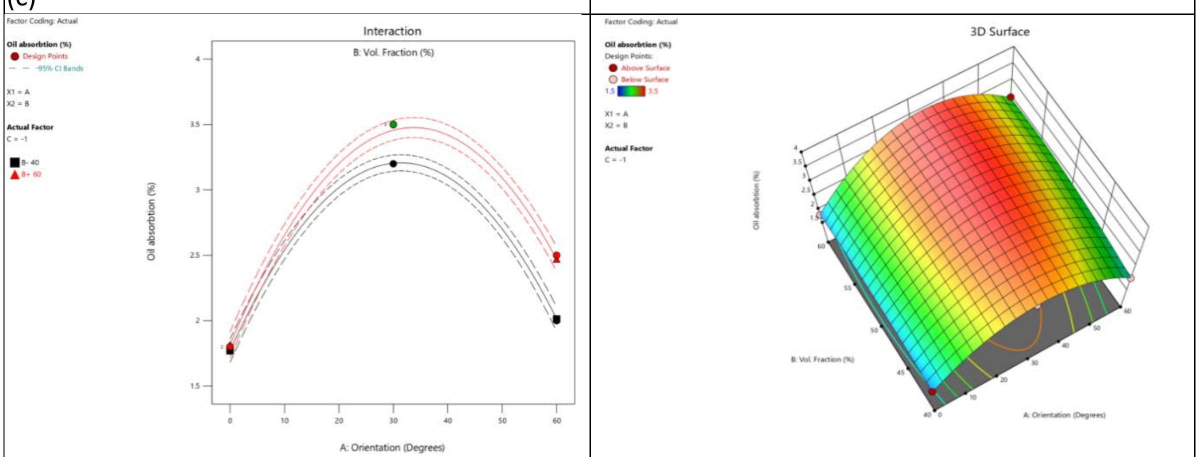
(a)


Factor Coding: Actual
Ultimate Tensile Strength (MPa)
Design Points
-95% CI Bands
X1 = A
X2 = B
Actual Factor
C = -1
B- 40
B+ 60
Interaction
B: Vol. Fraction (%)
Ultimate Tensile Strength (MPa)
A: Orientation (Degrees)
3D Surface
Above Surface
Below Surface
146
170
B: Vol. Fraction (%)

(b)


Factor Coding: Actual
Water Absorbtion (%)
Design Points
-95% CI Bands
X1 = A
X2 = B
Actual Factor
C = -1
B- 40
B+ 60
Interaction
B: Vol. Fraction (%)
Water Absorbtion (%)
A: Orientation (Degrees)
3D Surface
Above Surface
Below Surface
2
4.1
B: Vol. Fraction (%)

(c)


Factor Coding: Actual
Oil absorbtion (%)
Design Points
-95% CI Bands
X1 = A
X2 = B
Actual Factor
C = -1
B- 40
B+ 60
Interaction
B: Vol. Fraction (%)
Oil absorbtion (%)
A: Orientation (Degrees)
3D Surface
Above Surface
Below Surface
1.5
3.5
B: Vol. Fraction (%)

(d)

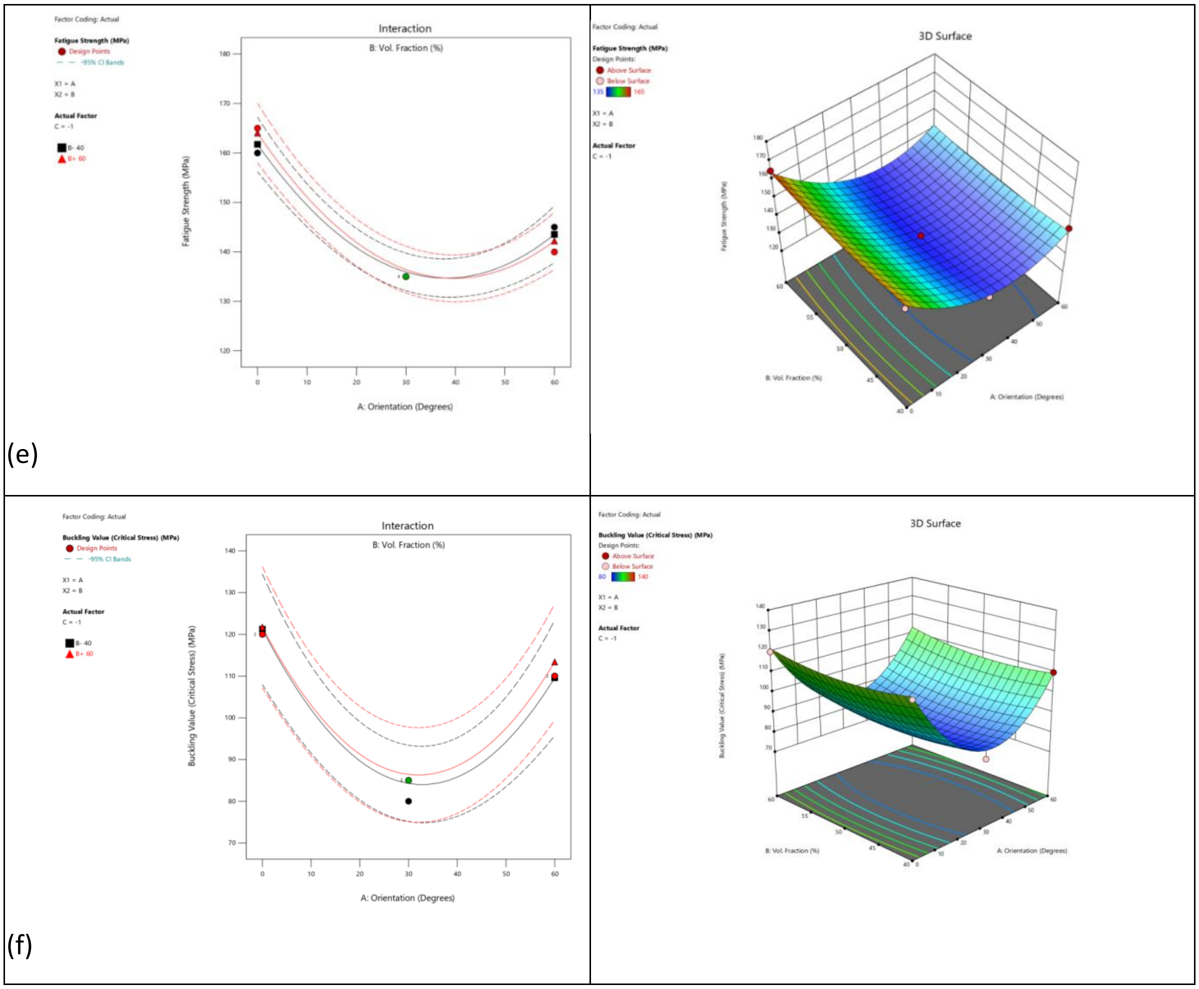
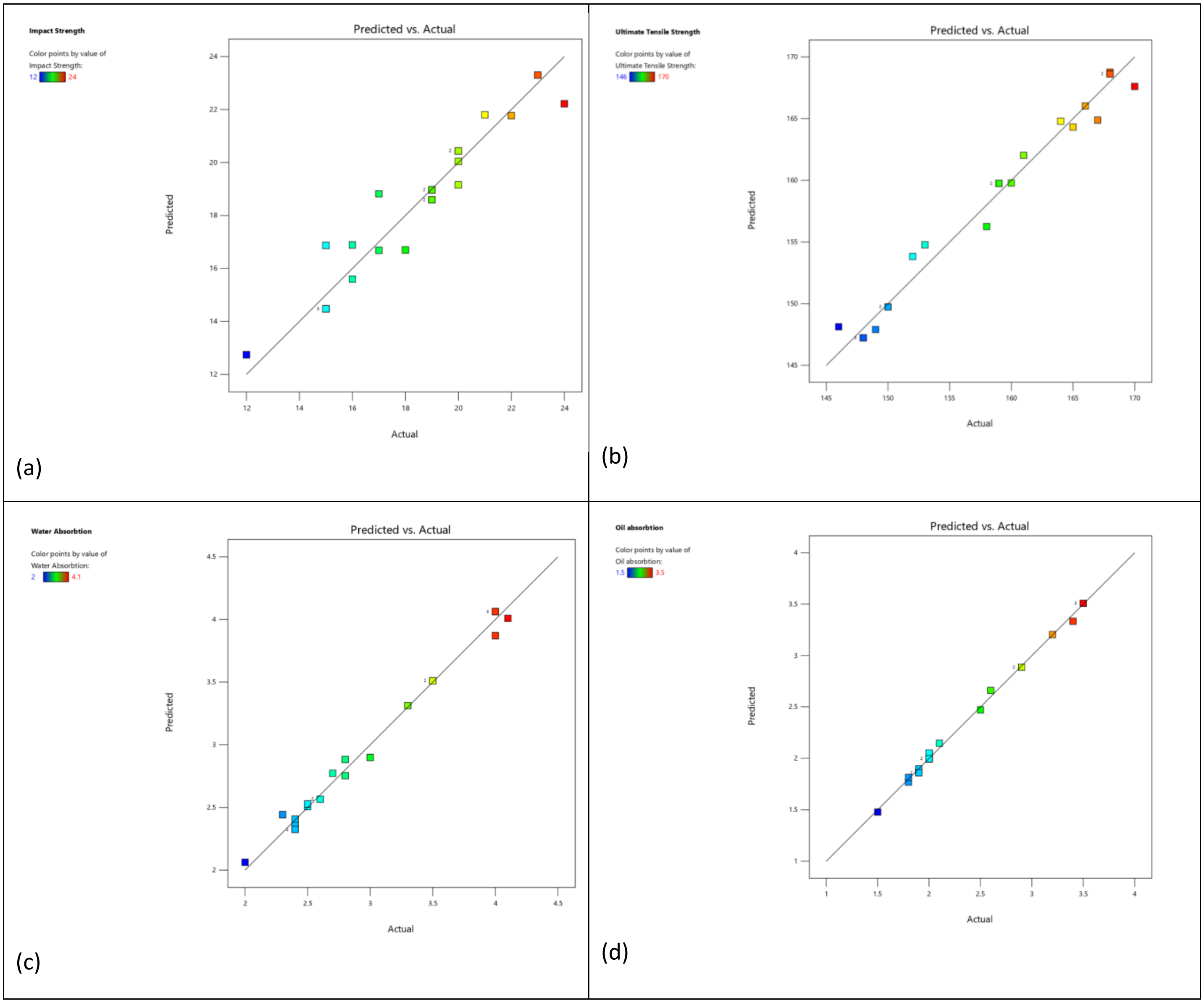


Figure 1: Interaction Plots and 3-D Response Surface showing the interaction between the variables on (a) Impact Strength, (b) Ultimate Tensile Strength, (c) Seawater Absorption, (d) Oil Absorption, (e) fatigue strength and (f) Buckling Load.


Impact Strength
Color points by value of
Impact Strength:
12
24
Predicted vs. Actual
Predicted
Actual
(a)
Ultimate Tensile Strength
Color points by value of
Ultimate Tensile Strength:
146
170
Predicted vs. Actual
Predicted
Actual
(b)
Water Absorbtion
Color points by value of
Water Absorbtion:
2
4.1
Predicted vs. Actual
Predicted
Actual
(c)
Oil absorbtion
Color points by value of
Oil absorbtion:
1.5
3.5
Predicted vs. Actual
Predicted
Actual
(d)

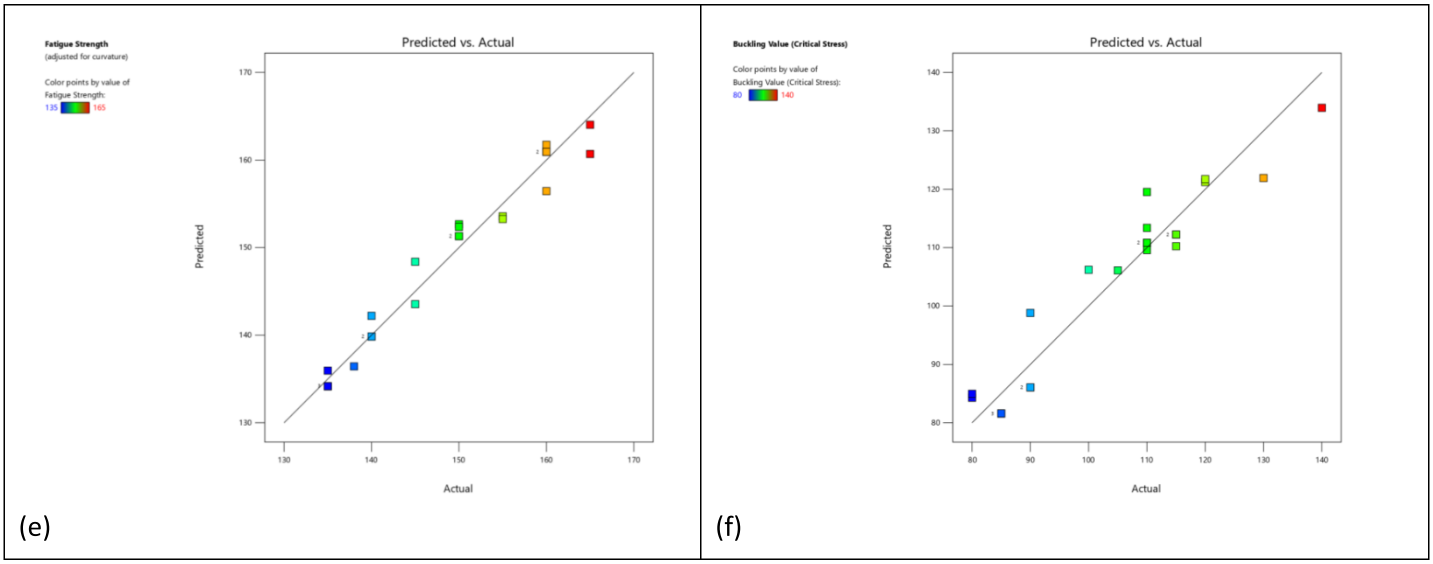


Figure 2: Showing the predicted and actual values for the (a) Impact test, (b) Ultimate tensile strength, (c) Seawater absorption, (d) Crude oil absorption, (e) Fatigue strength and (f) Buckling load.

4.2 Comparison of Some of the Properties of Materials for Ship and Submarine Hull

Table 3 elucidates that HY-80 manifests superior tensile strength among all materials, thereby signifying its superior capability to endure tensile or stretching forces. CGFRP ranks next, demonstrating commendable strength, albeit not reaching the levels of HY-80. HBPFC is positioned between GFRP and BF-EP, suggesting its potential for application but necessitating optimization to approach the performance metrics of steel.

Table 3: Summary of Some Material Properties for Ship and Submarine Hull

Material type	Density (g/cm^3)	Water Absorption (%)	Oil Absorption (%)	Impact strength (KJ/m^2)	Tensile strength (MPa)	Fatigue Strength (MPa)	Buckling Strength (MPa)	Reference
HY-80	7.85	–	–	270	620	275	380	Reddy and Swamidas, (2013)
CGFRP	1.9	0.3	0.1	30	800	200	300	Reddy and Swamidas, (2013)
GFRP	1.8	0.5	0.1	20	400	150	200	Reddy and Swamidas, (2013)
BE-EP	1.2	1.0	1.8	20	150	50	50	Khalil et al., 2012
HBPFC	0.76	2.9	2.3	20	160	111	160	Present Study

Moreover, HY-80 consistently exhibits predominant buckling strength, which is critical for structural elements subjected to compressive forces. CGFRP displays favourable performance relative to GFRP, indicating enhanced applicability for maintaining structural integrity. Furthermore, HY-80 preserves its advantageous position, with HBPFC presenting properties that are comparable to those of GFRP and BF-EP, implying that it may perform adequately under cyclic loading conditions. In terms of impact resistance, both CGFRP and HBPFC exhibit moderate levels of impact resistance, which is essential for ensuring durability in marine environments. In contrast, HY-80 leads in this domain, providing resilience against abrupt forces.

There is little or no water absorption concerns with HY-80, which is advantageous in marine applications. HBPFC demonstrates moderate adsorption characteristics, which may warrant further treatment to enhance durability. The oil absorption values are similarly lower for HY-80, indicating a reduced susceptibility to oil penetration, a factor that is particularly salient in marine contexts. The density of composite materials is significantly lower, rendering them attractive for applications where weight is a critical consideration. Nonetheless, the density of HY-80 confers substantial strength, which is vital for structural applications. Table 3 illustrates that while conventional materials such as HY-80 excel in essential mechanical properties making it suitable for high-performance, load-bearing, and impact-resisting applications, particularly in military and marine environments. On the other hand, the newly formulated HBPFC exhibits promise, offers superior strength-to-density ratio, sustainable alternative with moderate strength, impact resistance, buckling resistance and fatigue performance. They are more suitable for applications where eco-friendliness, manoeuvrability, weight reduction, and renewable resources are prioritized, such as in military submarine, lightweight ship hull, construction and automotive industries. The choice between these materials depends heavily on the specific requirements of the application, balancing strength, weight, sustainability, and performance.

5. Conclusion

In conclusion, this study developed and optimized hybrid bamboo-plantain fibre-reinforced polyester composite for potential applications in ship hulls and submarines through the application of response surface methodology. Statistical analysis revealed that fiber orientation, volume fraction, and stress ratio significantly influence mechanical properties and absorption behaviour. The optimized composite formulation achieved improved impact strength, tensile properties, and durability compared to conventional materials (Hussnain et al., 2023; Yang et al., 2018). While further degradation studies under continuous marine exposure are required, initial results are promising for sustainable marine composites. However, challenges around moisture sensitivity and long-term performance in harsh environments still need to be addressed (Dąbrowska, 2022). Overall, the research demonstrates the viability of RSM in developing high-performance hybrid natural fibre composites.

References

Adeniyi, A. G., Onifade, D. V., Ighalo, J. O., Abdulkareem, S. A., & Amosa, M. K. (2020). Extraction and characterization of natural fibres from plantain (Musa paradisiaca) stalk wastes. *Iranica Journal of Energy & Environment*, *11*(2), 116–121.

Afrin, T., Tsuzuki, T., & Wang, X. (2009). *Bamboo fibres and their unique properties*. https://dro.deakin.edu.au/articles/journal_contribution/Bamboo_fibres_and_their_unique_properties/21047254/1/files/37357111.pdf

Baley, C., Davies, P., Troalen, W., Chamley, A., Dinham-Price, I., Marchandise, A., & Keryvin, V. (2024). Sustainable polymer composite marine structures: Developments and challenges. *Progress in Materials Science*, 101307.

Banga, H., Singh, V. K., & Choudhary, S. K. (2015). Fabrication and study of mechanical properties of bamboo fibre reinforced bio-composites. *Innovative Systems Design and Engineering*, *6*(1), 84–98.

Bichang'a, D., Aramide, F., Oladele, I., & Alabi, O. (2022). A Review on the Parameters Affecting the Mechanical, Physical, and Thermal Properties of Natural/Synthetic Fibre Hybrid Reinforced Polymer Composites. *Advances in Materials Science and Engineering*, *2022*, 1–28. https://doi.org/10.1155/2022/7024099

Biswas, S. (2012). Mechanical properties of bamboo-epoxy composites a structural application. *Advances in Materials Research*, *1*(3), 221.

Chelladurai, S. J. S., Murugan, K., Ray, A. P., Upadhyaya, M., Narasimharaj, V., & Gnanasekaran, S. (2021). Optimization of process parameters using response surface methodology: A review. *Materials Today: Proceedings*, *37*, 1301–1304.

Chulawala, A. M., Crasta, F., & Kottur, V. K. N. (2020). A Review on Carbon Fibre Reinforced Polymer Composites and the Methods of Their Manufacture, Disposal and Reclamation. In H. Vasudevan, V. K. N. Kottur, & A. A. Raina (Eds.), *Proceedings of International Conference on Intelligent Manufacturing and Automation* (pp. 475–481). Springer Singapore. https://doi.org/10.1007/978-981-15-4485-9_49

Dąbrowska, A. (2022). Plant-oil-based fibre composites for boat hulls. *Materials*, *15*(5), 1699.

El Hawary, O., Boccarusso, L., Ansell, M. P., Durante, M., & Pinto, F. (2023). An overview of natural fiber composites for marine applications. *Journal of Marine Science and Engineering*, *11*(5), 1076.

Haniel, Bawono, B., & Anggoro, P. W. (2023). Optimization of Characteristics Polymer Composite Reinforced Kenaf and Jute Fiber Using Taguchi-Response Surface Methodology Approach. *Journal of Natural Fibers*, *20*(2), 2204453. https://doi.org/10.1080/15440478.2023.2204453

Hussnain, S. M., Shah, S. Z. H., Megat-Yusoff, P. S. M., & Hussain, M. Z. (2023). Degradation and mechanical performance of fibre-reinforced polymer composites under marine environments:–A review of recent advancements. *Polymer Degradation and Stability*, 110452.

Ihueze, C. C., & Okafor, E. C. (2014). Response surface optimization of the impact strength of plantain fiber reinforced polyester for application in auto body works. *Journal of Innovative Research in Engineering and Sciences*, *4*(4), 505–520.

Kappenthuler, S., & Seeger, S. (2021). Assessing the long-term potential of fiber reinforced polymer composites for sustainable marine construction. *Journal of Ocean Engineering and Marine Energy*, *7*(2), 129–144. https://doi.org/10.1007/s40722-021-00187-x.

Khalil, H. A., Bhat, I. U. H., Jawaid, M., Zaidon, A., Hermawan, D., & Hadi, Y. S. (2012). Bamboo fibre reinforced biocomposites: A review. *Materials & Design*, *42*, 353-368.

Laouici, H., Benkhelladi, A., & Bouchoucha, A. (2021). *Tensile Mechanical Properties of Natural Fibre Composites–A Statistical Approach*. https://www.researchsquare.com/article/rs-369937/latest

Larson, M. G. (2008). Analysis of Variance. *Circulation*, *117*(1), 115–121. https://doi.org/10.1161/CIRCULATIONAHA.107.654335

Midani, M., & Hassanin, A. H. (2021). Green, Natural Fibre and Hybrid Composites. In I. Shyha & D. Huo (Eds.), *Advances in Machining of Composite Materials* (pp. 395–420). Springer International Publishing. https://doi.org/10.1007/978-3-030-71438-3_15

Mochane, M. J., Mokhena, T. C., Mokhothu, T. H., Mtibe, A., Sadiku, E. R., Ray, S. S., Ibrahim, I. D., & Daramola, O. O. (2019). *Recent progress on natural fiber hybrid composites for advanced applications: A review*. http://researchspace.csir.co.za/dspace/handle/10204/10871

Mulenga, T. K., Ude, A. U., & Vivekanandhan, C. (2021). Techniques for modelling and optimizing the mechanical properties of natural fiber composites: A review. *Fibers*, *9*(1), 6.

Nawawi, A. M., Husaini, M., Arshad, M. R., & Samad, Z. (2011). Optimization of underwater composite enclosure design using response surface methodology. *Indian Journal of Geo-Marine Sciences*, *40*(2), 222-226.

Neto, J., Queiroz, H., Aguiar, R., Lima, R., Cavalcanti, D., & Banea, M. D. (2022). A review of recent advances in hybrid natural fiber reinforced polymer composites. *Journal of Renewable Materials*, *10*(3), 561.

Okuma, S. O., Obaseki, M., Ofuyekpone, D. O., & Ashibudike, O. E. (2023). A Review Assessment of Fiber-Reinforced Polymers for Maritime Applications. *Journal of Advanced Industrial Technology and Application*, *4*(1), 17–28.

Onyenanu, I. U., Ogbogu, M. C., & Nwadiuto, C. J. Performance Optimization of an Improved Biomass Gasifier Charcoal Stove using Response Surface Method (RSM).

Penjumras, P., Abdul Rahman, R., Talib, R. A., & Abdan, K. (2015). Response Surface Methodology for the Optimization of Preparation of Biocomposites Based on Poly(lactic acid) and Durian Peel Cellulose. *The Scientific World Journal*, *2015*(1), 293609. https://doi.org/10.1155/2015/293609

Prasad, A. R., & Rao, K. M. (2011). Mechanical properties of natural fibre-reinforced polyester composites: Jowar, sisal and bamboo. *Materials & Design*, *32*(8–9), 4658–4663.

Rasyid, M. A., Salim, M. S., Akil, H. M., & Ishak, Z. A. M. (2016). Optimization of processing conditions via response surface methodology (RSM) of nonwoven flax fibre-reinforcedacrodurbiocomposites. *Procedia Chemistry*, *19*, 469–476.

Reddy, D. V., & Swamidas, A. S. J. (2013). *Essentials of offshore structures: framed and gravity platforms*. CRC press.

Rohith, K., Shreyas, S., Vishnu Appaiah, K. B., Sheshank, R. V., Ganesha, B. B., & Vinod, B. (2019). Recent Material Advancement for Marine Application. *Materials Today: Proceedings*, *18*, 4854–4859. https://doi.org/10.1016/j.matpr.2019.07.476

Rubino, F., Nisticò, A., Tucci, F., & Carlone, P. (2020). Marine application of fiber reinforced composites: A review. *Journal of Marine Science and Engineering*, *8*(1), 26.

Shireesha, Y., & Nandipati, G. (2019). State of art review on natural fibers. *Materials Today: Proceedings*, *18*, 15–24.

Singh, T. J., & Samanta, S. (2014). Characterization of natural fiber reinforced composites-bamboo and sisal: A review. *Int J Res Eng Technol*, *3*(7), 187–195.

Yang, M. F. M., Hamid, H., & Abdullah, A. M. (2018). Potential Use of Cellulose Fibre Composites in Marine Environment—A Review. In A. Öchsner (Ed.), *Engineering Applications for New Materials and Technologies* (Vol. 85, pp. 25–55). Springer International Publishing. https://doi.org/10.1007/978-3-319-72697-7_3

Zaid, H., Al-sharify, Z., Hamzah, M. H., & Rushdi, S. (2022). Optimization of different chemical processes using response surface methodology-a review: Response surface methodology. *Journal of Engineering and Sustainable Development*, *26*(6), 1–12.