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Article

Taguchi optimization of hybrid agro-aquatic waste-reinforced epoxy composite for enhanced mechanical performance

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ABSTRACT

The choice of engineering materials substantially contributes to the longevity and output–to–input ratio of machines and structures. There is growing interest in sourcing local engineering materials that are more durable than synthetic materials. The mechanical characteristics of these engineering materials must meet acceptable standards. This study examined reinforcing hybrid agro-aquatic waste with epoxy resin as an additive. Since natural materials are biodegradable and renewable, they are an environmentally friendly alternative to conventional materials in engineering applications. This has led to a growing trend in using bio-composites made from natural materials. This study aimed to optimize the strength of hybrid agro-aquatic samples made from bamboo fiber, whelks, clams, periwinkle shells, and palm kernels bonded with resin to improve engineering performance. The composites were made using a hand lay-up technique with varying percentages of shells and fiber (10-30%), mixed with different amounts of epoxy resin. Tensile, impact, flexural, and water absorption tests were performed on the cured samples after 24 hours. The Taguchi L25 (5x5) orthogonal array was used to optimize the experimental trials in Minitab 18, with five design parameters at five levels each. The results showed an average flexural strength of 114.87 MPa, while the unreinforced bio-composite had 72.33 MPa. Turning agricultural waste into engineering materials such as bamboo fiber, clams, palm kernel shells, whelk shells, and periwinkle shells can positively impact the building industry.

Keywords: *Optimization, Bio-composites, Hybrid agro-aquatic, Epoxy, Mechanical performance, Taguchi*

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1. INTRODUCTION

Electric Natural fibers or artificial materials created by combining two or more constituent elements with noticeably different physical or chemical properties are used to create composite materials [1]. Because of their biodegradability and regenerative qualities, these fibers are now regarded as environmentally beneficial materials [2]. It has been demonstrated that natural fibers including sisal, jute, coir, and oil palm fiber make excellent reinforcement [3]. Because it provides a cost-effective and environmentally friendly alternative to conventional inorganic reinforcements and fillers, the usage of natural fiber reinforced composites is becoming more and more common in plastic lumber, automotive, and cosmetic applications [4,5]. The diversity in the pozzolanic characteristics of RHA obtained from various sites was examined by [6]. Their research revealed that the pozzolanic characteristics of RHA vary depending on the site, mostly because of the chemical makeup of the soil formation on which the rice paddies are grown. The strength of the concrete made with them as additives is likewise impacted by this variation in the elemental content of this agricultural waste. There has been an increasing amount of interest in replacing artificially traditional reinforcements in some structural and other technical applications with natural fibers or particles as reinforcements in polymers [7]. This is because, despite the fact that synthetic fiber or particle-reinforced polymer composites, like those made of aramid, glass, or carbon fibers, have a number of advantages over conventional materials like steel and wood concrete- such as high stiffness and a high strength-to-weight ratio- their use is limited by their high initial cost and negative environmental effects [8].

In his early works on composite materials, Ref [9] observed that the development of composites is currently shifting away from synthetic fibers and toward natural fibers. This is because composites containing synthetic fibers, such as glass fibers, are not eco-friendly and create glass waste that cannot break down naturally. Compared with composites made from synthetic fibers, natural fiber composites offer several important advantages [10]. These benefits include: being less expensive, lighter, and non-irritating to the skin; eliminating corrosion and stress corrosion; being available in the form of plants and wastes; being non-toxic; better control over surface contour and smoothness; a higher fatigue endurance limit up to 60% of ultimate tensile stress); being 30–40% lighter than any specific type of aluminum; having a structure designed to meet the same functional requirements; being less noisy when operating and transmitting vibrations less than metals; and being more versatile than metals, able to be tailored to meet complex design requirements and a variety of performance needs [11].

Similarly, Ref [12] applied Osadebe's regression model to optimize the structural properties of concrete with RHA added. Although they did not compare their findings with other modeling techniques, the results indicate that this model can be used as a non-saturated model for deriving and predicting concrete strength. The ease of creating composites using natural fibers stems from the materials' easy sourcing from natural or agricultural waste, making the manufacturing process comparatively simple [13]. Natural fiber production can ensure long-term availability. Nevertheless, natural fibers exhibit several shortcomings, including poor flexibility, high water absorption, and short service life [14]. For structures where strength-to-weight is a primary consideration, composites are the preferred material. Natural fiber composites have also been used in non-structural applications.

According to Ref [15], in most poor nations, the high cost of producing concrete is largely due to cement, a primary component of concrete, being expensive. In industrialized nations, mixed cement has become increasingly popular because of its durability and favorable benefit-to-cost ratio. Rice husk ash (RHA) is a residue found in large quantities in rice mills that is created when rice husk is burned. Because of its strong pozzolanic reaction, low energy needs, and reduced GHG emissions throughout the material lifecycle, RHA has been shown to be an effective supplementary cementitious material for concrete production. Environmentally friendly composites are currently used in the production of some vehicle components that were formerly constructed using glass fiber composites. Natural fiber composites offer two key benefits for the automobile industry: they make vehicles lighter, improving fuel efficiency, and they increase production sustainability because natural fibers can be grown [9,16]. In tropical nations like Nigeria, agricultural products such as groundnuts, coconut and palm kernels, periwinkle, whelks, and clams are widely farmed. However, fewer than 10% of the waste produced is used domestically as fuel, and most of it still needs to find a sustainable home elsewhere. Furthermore, research has shown that, compared with identical synthetic fiber composites, burning natural-fiber composite components produced fewer air emissions because they require less energy [17]. The biodegradability of natural fiber-reinforced polymer composites makes them attractive as structural materials [18,19]. Bamboo is one of the natural fibers that has garnered the most attention as a potential reinforcement for various polymer matrices because of its advantageous mechanical characteristics as a hybrid bio composite. A hybrid bio composite uses multiple matrices and/or reinforcement types.

In engineering, hybrid bio composites are used when low cost, a high strength-to-weight ratio, and ease of manufacture are needed. Joint qualities that may be lacking in mono-composite materials are ensured by hybridization, including compressive modulus, tensile strength, and impact strength, among others. As a result, hybrid materials are typically used in designs that require a combination of several fiber qualities. Researchers have been fascinated by hybrid composites since ancient times due to their inventive applications. In light of this, this work aims to investigate the creation and characterization of bio-composites for engineering applications, including clams, bamboo fiber-reinforced epoxy composites, periwinkle shells, palm kernel shells, and whelk shells [20].

Researchers and industry participants have called for adopting natural fibers in reinforced material systems because traditional materials lack the required qualities for polymer matrix composite production in materials science and engineering [21]. Natural fibers from agricultural waste are plentiful in nations where agriculture is the primary industry, but they can also endanger the environment. Using technology to turn waste into value is one strategy to minimize, if not eliminate, ecological contamination. Some easily accessible examples of fibrous agricultural waste are rice husk, bagasse, oil palm fiber, palm kernel shells, whelk shells, clams, and bamboo fiber [22]. Selecting the right engineering materials strongly affects how long structures and machine parts last and how well they perform. As a result, there's growing interest in using locally sourced materials that can compete with synthetic ones in terms of durability. To do that, these local materials must have the mechanical strength needed to handle the environmental and operating conditions they will face. This study therefore aims to bridge this gap.

2. METHODOLOGY

2.1 Materials

Bamboo fibers are made up of a large number of incredibly fine fibers. Bamboo fiber's mechanical qualities are similar to those of other fibers, like carbon and glass fiber. When utilized in composites, it is substantially less brittle and far less expensive than carbon fiber, although not as stiff. Figure 1 (a, b, c, d, e and f) shows the various combinations of the locally sourced biodegradable and environmentally friendly materials used for the purpose of this research. The adhesive use was Epochem 105- Part A, an accelerator-type epoxy resin known for its fast curing and high bonding strength. Bamboo fibers were bonded to the shells using this resin.

Figure 1. Various biocomposite materials

The resin and hardener were sourced from the Enugu market. Epochem 205 – Part B, hardener was combined with the epoxy resin for composite encapsulation and coating. The hardener exhibits adequate mechanical strength and good resistance to environmental and chemical attacks. Ancillary materials comprised distilled water, petroleum jelly, rollers, clamps, brushes, pliers, and paper tape, PPE including a nose mask and hand gloves, and standard laboratory apparatus such as measuring cylinders, a weighing balance, test tubes, beakers, and a stopwatch. The schematic diagram in Figure 2 shows the step-by-step development process of the biocomposite.

2.2 Preparation of the biocomposite

All materials were collected from natural sources. All materials were initially washed with tap water to remove surface contaminants. Bamboo fibers underwent additional treatment with sodium hydroxide to remove sap and organic impurities. Subsequently, all specimens were rinsed thoroughly with distilled water until a neutral pH of 7.0 was attained. After drying, we mechanically crushed the shells and sieved them to 300 μm for all samples. Figure 3 (a,b,c,d,e) shows the development processes of the composite from grinding to final development of the composite material.

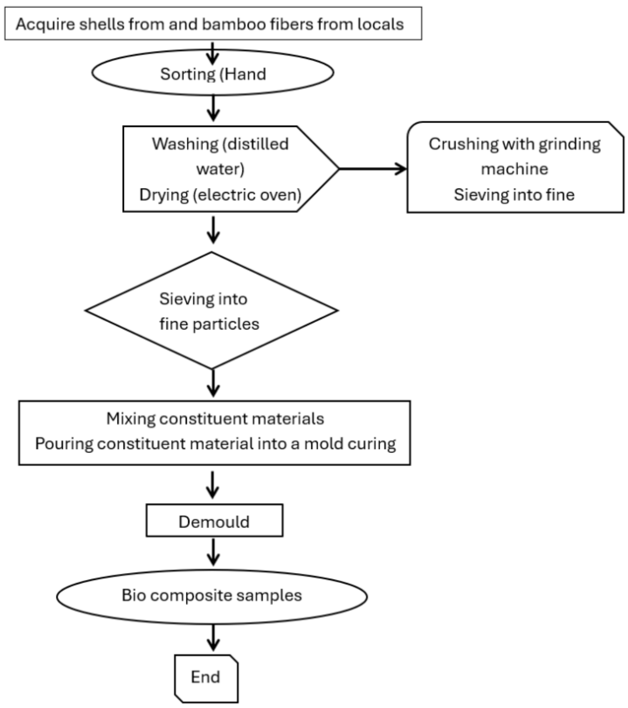

Figure 2. Methodology flowchart

(a) Grinding process of the shell (b) Sintering (c) Mixture and paste making

(d) Sample laid in a mould (e) Final produced bio composite

Figure 3. Process development of the biocomposite

2.3 Composite Fabrication

The epoxy resin was prepared by mixing Part A and Part B in a 2:1 ratio as specified by the manufacturer. Moulds for the test specimens were fabricated according to the flat specimen dimensions and tolerance outlined in ASTM E8. The composite laminates were then produced using the hand lay-up technique. A release agent was applied to prevent adhesion of the sample to the mould and to facilitate demoulding after curing. The composite was fabricated with 30 vol.% fiber content and randomly distributed fiber orientation. The volume fractions of both fiber and shell reinforcement were determined using Eq (1).

$$V_f = \frac{(W_f/\rho_f)}{[(W_f/\rho_f) + (W_m/\rho_m)]} \quad (1)$$

where V_f is the fiber volume fraction (%), W_m and W_f are the weights of the matrix and fiber, respectively, ρ_m and ρ_f are the densities (g/cm^2) of the matrix and fiber, respectively. The reinforced and unreinforced samples with the shells and fiber were prepared and left to cure at room temperature for 24hours before they were removed for cutting and testing.

2.4 Taguchi design

Genichi Taguchi developed the Taguchi method by introducing the loss function and using an outer orthogonal array to extend experimental trials. This design approach was adopted to reduce the total number of experiments while maximizing the influence of uncontrollable factors within the experimental domain. For each treatment level, the signal-to-noise (SN) ratio was computed using Taguchi's SN ratio formula derived from the loss function. To optimize the process parameters, the study employed the "larger-the-better" quality criterion expressed in Eq (2); the "smaller-is-better" criterion in Eq (3); and the "Nominal-is-best" criterion in Eq (4).

$$S/N = -10log_{10}\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{\mu^2}\right) \quad (2)$$

$$S/N = -10log_{10}\frac{1}{n}\left(\sum\frac{\mu^2}{n}\right) \quad (3)$$

$$S/N = -10log_{10}\frac{1}{n}\left(\sum\frac{\mu^2}{S^2}\right) \quad (4)$$

where μ is the response at each factor level combination, n is the number of replications, and *s* is the standard deviation. The experiments were designed using a Taguchi L_{25} orthogonal array and analyzed with Minitab 18 software. Table 1 shows the percentage weight values of the shells and fiber used in the experiment. Each experimental run was completed three times, and the analysis used the average value obtained.

Table 1. Experimental factors and levels

S/N	Factors	Level				
A	Periwinkle Shells	05%	10%	15%	20%	25%
B	Clam Shells	05%	10%	15%	20%	25%
C	Whelk shells	05%	10%	15%	20%	25%
D	Bamboo fibres	05%	10%	15%	20%	25%
E	Palm Kernel shells	05%	10%	15%	20%	25%

2.5 Determination of the flexural strength

Flexural test specimens measuring 200mm x 30mm x 4mm were fabricated in compliance with standard specifications, and tests were carried out using a Universal Testing Machine (UTM), model M500-25CT, following the procedures outlined in ASTM D7264M-15. A force of 50N was applied to them until failure. Three samples were used for each test, and the average was used as the outcome. For this research, the maximum bending strength was measured and recorded. The experimental configuration for flexural testing of the specimens is presented in Figure 4.

Figure 4. Experimental setup for flexural testing

3. RESULTS

Five-level differences in the mass fractions of the samples were designed using a Taguchi L25 orthogonal array. Twenty-five experiments were performed to assess the effect of these parameters on the mechanical behavior of the shell/fiber-reinforced epoxy composite. Impact strength, Tensile strength, Flexural strength, and water absorption were subsequently measured for each specimen. Each experiment was conducted three times, and the results were averaged. The statistical program Minitab 18 was used to examine experimental data.

3.1 ANOVA of flexural strength

The influence of treatment parameters on flexural strength was statistically examined using analysis of variance (ANOVA). A significance threshold of $\alpha = 0.05$ was adopted for all tests. Parameter significance was determined based on the magnitude of the F-ratio, which denotes a greater effect of the treatment parameter on flexural strength at the 5% significance level. Furthermore, periwinkle shell had the most significant effect on flexural strength, with a 44.90% contribution, followed by palm kernel shell at 28.13%. Clam shell was not significant at the 5% level, contributing only 3.45%. The model R^2 of 92.24% indicates that periwinkle shell, palm kernel shell, clam shell, whelk shell, and bamboo fiber explained 92.24% of the variation in flexural strength. Residual plots in Figure 5 confirmed normality, independence, and constant variance of residuals, thus validating the ANOVA assumption.

3.2 Regression modeling of the flexural strength behavior

A predictive model was developed to determine the flexural strength of the samples contents wherein the multiple linear and quadratic models were fitted in Minitab 18. The resulting equations are presented as Eqs. 5 and 6, respectively.

Let:

Y = Flexural strength (Mpa)

X1 = Palm kernel shell (g)

X2 = Periwinkle shell (g)

X3 = Clam shell (g)

X4 = Whelk shell (g)

X5 = Bamboo fiber (g)

Multiple Linear Regression model:

$$Y = 123.52 - 0.357X1 - 0.366X2 - 0.043X3 + 0.158X4 - 0.283\ 3X5$$

$$R^2 = 38.78\%,\ R^2_{adj} = 22.66\% \qquad (5)$$

Multiple Linear Regression Model:

$$Y = 100.8 - 0.400X1 + 0.667X2 + 1.173X3 + 0.500X4 - 0.283X5 - 0.047721 + 0.043822 - 0.0608\ 423$$

$$R^2 = 77.30\%,\ R^2\ adj = 23.54\% \qquad (6)$$

The linear model in Eq. (5) indicates that increasing palm kernel shell, periwinkle shell, and whelk shell content negatively affects flexural strength, while clam shell content has a positive effect. However, with R2 = 38.78%, the linear model explains only a limited portion of the variation. The quadratic model in Eq. (6) provides a better fit with R^2 = 77.30%, suggesting that the correlation between the process parameters and flexural strength is nonlinear. The positive coefficients for periwinkle shell, clam shell, and bamboo fiber, and the square terms, imply that optimal dosages of these materials exist for maximizing flexural strength, though the low R^2adj = 23.54% indicates possible overfitting and warrants caution in extrapolation. Thus, while the quadratic model improves prediction accuracy, the linear model may be more robust for practical mix design due to its simplicity and fewer parameters. Figure 6 and Figure 7 compare the experimental and predicted flexural strength values for the linear and quadratic models used to determine the correlation coefficient.

The Pearson correlation between the experimental results and the linear regression predictions was 0.623 with a p-value of 0.001. For the quadratic regression model, the correlation with experimental data improved to 0.879 with a p-value < 0.000. The quadratic model also generated more refined predictions and exhibited a higher adjusted R2 than the linear model. Consequently, the quadratic regression model better estimates the influence of reinforcement parameters on the composite's flexural strength. With a correlation coefficient of 0.879, the developed quadratic model demonstrates strong agreement with experimental results.

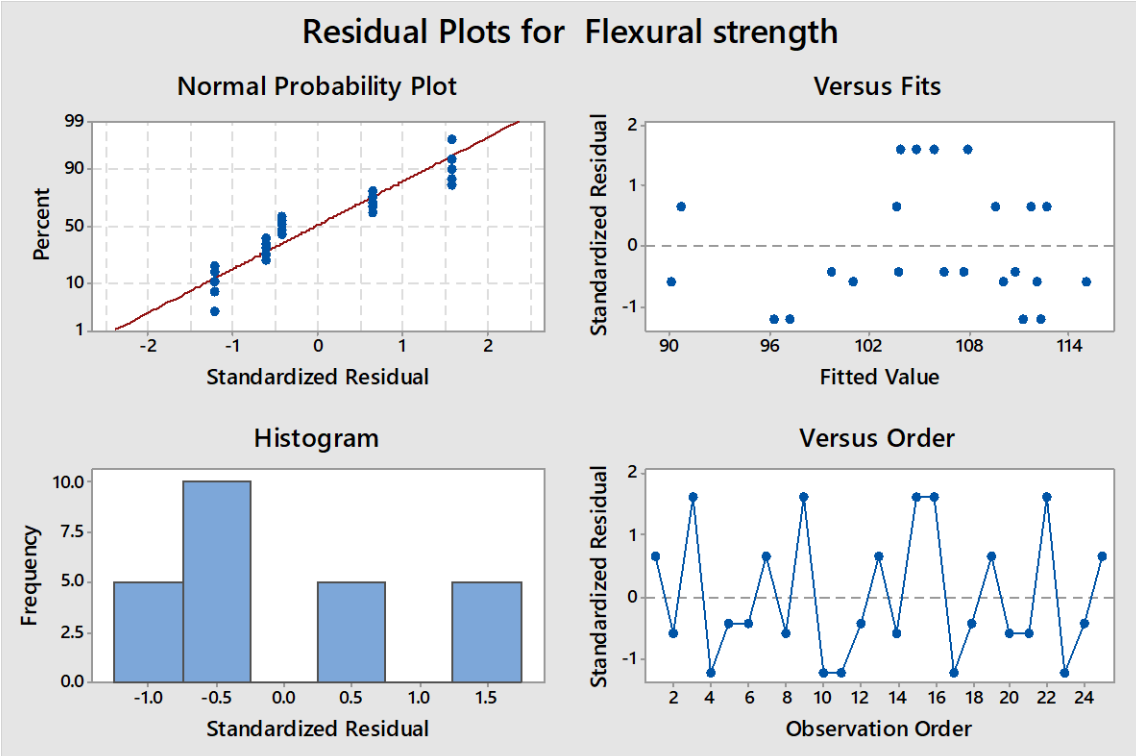

Figure 5. Residual plot of flexural strength

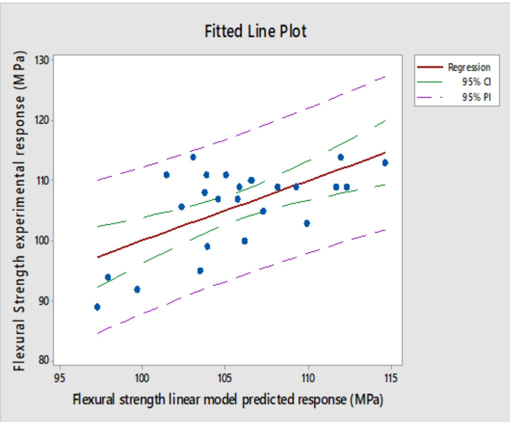

Figure 6. Linear predicted response

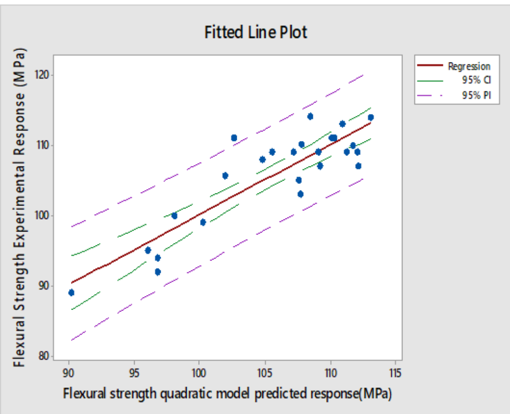

Figure 7. Quadratic predicted model

3.3 Experimental validation of flexural strength

Taguchi optimization identifies the optimal reinforcement combination for the flexural strength of periwinkle shell as 25wt%, palm kernel shell as 20wt%, whelk shell as 15wt%, clam shell as 10wt%, and bamboo fiber as 10wt% in the epoxy composite. A confirmation test was conducted by fabricating new samples under the predicted conditions. The average flexural strength from four specimens was 114.87MPa, representing a 58.81% increase over the unreinforced epoxy (72.33 MPa). This confirms a significant improvement in the matrix flexural strength following reinforcement.

3.4 Impact strength

The impact strength of specimens from each Taguchi orthogonal array experiment was measured with a universal testing machine and reported as energy at break per unit cross-sectional area in J/m^2. Table 2 summarizes the ANOVA results for impact strength. According to the F-values, periwinkle was the most significant element in the composite, contributing 38.63 percent, followed by palm kernel at 31.50 percent. The clam shell contributed 3.45 percent, as shown by the P-value, which is also significant. The hybrid agro-aquatic materials account for 89.17 percent of the total variation in the composite's impact strength response, according to the R-sq value in the model summary. This suggests that 10.83 percent of the variance is related to factors not accounted for in the study, such as shell particle size. Figure 8 depicts the residual plots of impact strength. The residuals are normally distributed, as evidenced by the normal probability plot of the residuals at the top left, which follows a nearly straight line. As a result, the ANOVA assumptions are not violated.

Table 2. ANOVA results for Impact strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Palm Kernel shell	4	281.90	31.50%	281.90	70.475	2.91	0.163
Periwinkle shell	4	345.80	38.63%	345.80	86.449	3.57	0.123
Clam shell	4	13.11	1.47%	13.11	3.278	0.14	0.961
Whelk shell	4	17.13	1.91%	17.13	4.282	0.18	0.939
Bamboo fiber	4	140.20	15.66%	140.20	35.050	1.45	0.365
Error	4	96.90	10.83%	96.90	24.226		
Total	24	895.04	100.00%				

Table 3. ANOVA results for tensile strength

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Palm Kernel(wt%)	4	86.652	23.38%	86.652	21.663	11.34	0.019
Periwinkle(wt%)	4	178.307	48.12%	178.307	44.577	23.33	0.005
CLam Shell(wt	4	55.356	14.94%	55.356	13.839	7.24	0.041
Whelk Shell(wt%)	4	16.258	4.39%	16.258	4.064	2.13	0.241
Bamboo fibre(wt	4	26.336	7.11%	26.336	6.584	3.45	0.129
Error	4	7.643	2.06%	7.643	1.911		
Total	24	370.552	100.00%				

Table 4. Model Summary

S	R-sq	R-sq(adj)
1.38234	97.94%	87.62%

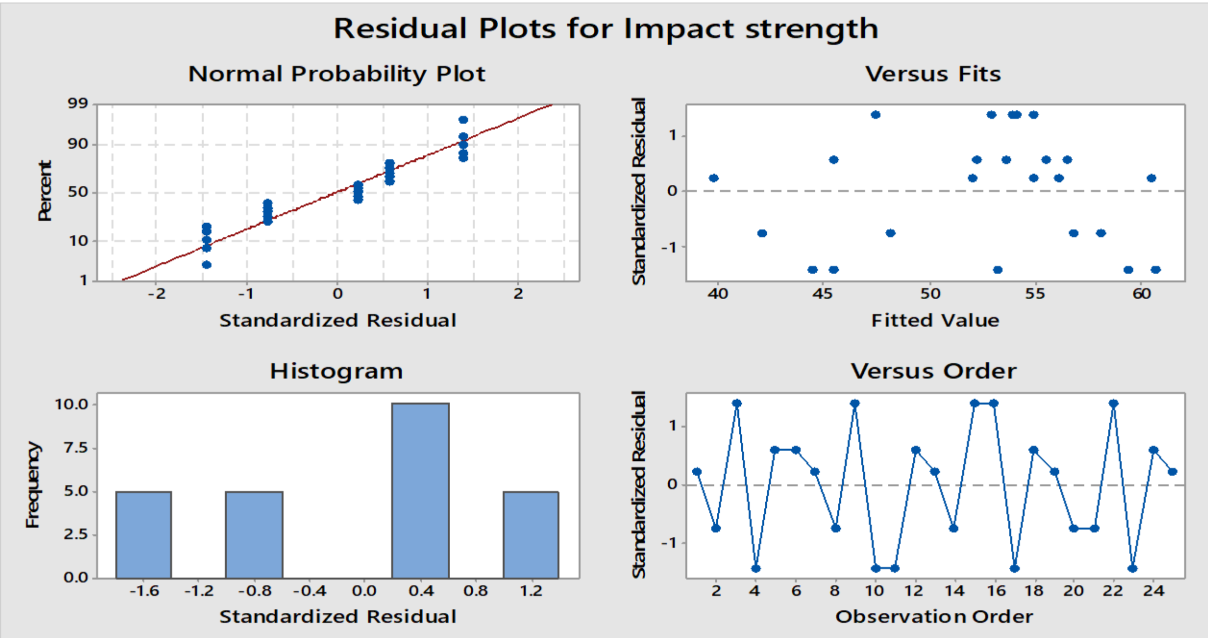

Figure 8. Residual plots for impact strength

3.5 Tensile strength

Each experimental run in the Taguchi L_{25} orthogonal array underwent tensile strength testing on a universal testing machine. The machine grips held each specimen, and a 50 N load was applied until failure. Table 3 shows the analysis of variance results for tensile strength. According to the F-values, periwinkle was the most significant element in the composite, contributing 48.12 percent, followed by palm kernel at 23.38 percent.

Whelk shell contributed 4.39 percent, and its P-value was also insignificant. The hybrid agro-aquatic materials account for 97.94 percent of the variation in the composite's tensile strength response, according to the R-sq value in the model summary. This suggests that 2.06 percent of the variance is related to factors not accounted for in the study, such as shell particle size. Table 4 summarizes the model. Figure 9 depicts the residual plots of the tensile strength.

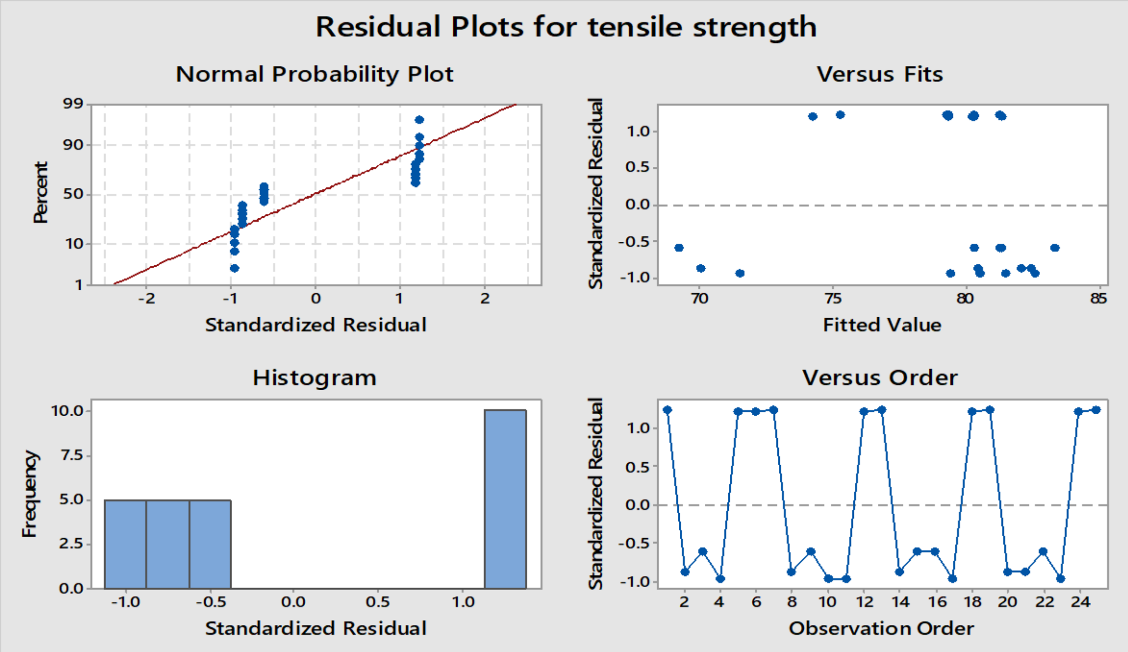

Figure 9. Residual plots for tensile strength

4. Conclusion

It is concluded that optimizing the engineering properties and performance characteristics of bio composite materials by incorporating epoxy resin as an additive offers a promising approach to enhancing their mechanical and durability attributes. Epoxy resin, known for its excellent bonding, strength, and resistance to environmental factors, can significantly improve the biocomposite matrix, making it more competitive with conventional synthetic composites. By fine-tuning resin content, curing conditions, and reinforcement materials, bio composites can be tailored to specific applications, reducing limitations and expanding their use in industries such as automotive, construction, and aerospace. This research emphasizes the potential for sustainable, high-performance materials that maintain the environmental benefits of biocomposites while achieving superior structural integrity and long-term functionality. Future studies should focus on refining these processes and exploring new biocomposite formulations to support widespread commercial adoption. In conclusion, the following research findings and results were established: Taguchi Optimization identified 20wt% palm kernel shell, 25wt% periwinkle shell, 10wt% clam shell, 15wt% whelk shell, and 10wt% bamboo fiber as optimal reinforcement for maximum flexural strength of the epoxy composite. ANOVA and F-value analysis showed that periwinkle shell was the most significant factor, contributing 44.90%, followed by palm kernel at 28.13%. The developed bio-composite is cost-effective, biodegradable, and exhibits improved engineering properties, demonstrating the potential of converting agricultural waste into value- added engineering materials and is thus recommended for industrial applications.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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