



Development of Hybrid Composite Materials Reinforced with Natural and Synthetic Fibers to Enhance the Structural Performance of Mechanical Components

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ABSTRACT

The increasing need for lightweight, strong, and sustainable materials is driving the development of hybrid composites for mechanical components. This study developed epoxy-based hybrid composites reinforced with rattan natural fibers and E-glass synthetic fibers. The laboratory experiment used 30 laminate units divided into five groups, six units each, with a total fiber fraction of 30%. Data were obtained through tensile, flex, impact, and density testing, then analyzed using descriptive statistics, One-Way ANOVA, and Tukey HSD. The results showed that rattan/E-glass hybrid composites improved tensile strength, flexural strength, and impact resistance compared with single-fiber composites. These findings confirm the potential of hybrid composites as lightweight structural materials for mechanical components.

INTRODUCTION

The development of modern mechanical engineering increases the need for structural materials that have high mechanical strength, low mass, and good material efficiency. Polymer-based composites are one of the alternatives because their characteristics can be engineered through matrix selection, fiber type, fiber fraction, and reinforcing configuration. In the context of sustainability, the use of natural fibers is getting more attention because it has a relatively low density, comes from renewable sources, and has the potential to reduce dependence on synthetic fibers. However, the lower mechanical properties of natural fibers as well as sensitivity to moisture limit their use in mechanical components with high structural demands (Patel et al., 2023; Rahman et al., 2024).

A hybridization approach through a combination of natural and synthetic fibers was developed to achieve a balance between mass, sustainability, strength, rigidity, and load resistance. Synthetic fibers, especially glass fibers, can improve the load transfer ability and strength of composites, while natural fibers contribute to a decrease in density as well as an increase in the sustainability aspect of materials. In the Indonesian context, Irawan et al. (2022) showed that hybrid epoxy composites woven rattan and glass fiber have increased tensile strength, flexural strength, and impact characteristics and have the potential to be applied to automotive components. The findings show the relevance of hybrid material development for the field of mechanical engineering, especially for lightweight components that still require adequate structural capacity. Based on these considerations, this study selected woven rattan fiber as the natural reinforcement because of its availability, relatively low density, and potential mechanical contribution when combined with E-glass fiber in epoxy matrices.

A number of studies have proven that the success of hybridization is not only determined by the existence of two types of fibers. Das et al. (2021) found that the stacking sequence of jute and glass fibers exerts an important influence on the mechanical and thermomechanical properties of hybrid composites. Irawan et al. (2022) also showed that changes in the arrangement of rattan and glass fiber layers result in different tensile, flexural and impact responses. Thus, the final characteristics of composites are the result of complex interactions between fiber types, strengthener proportions, fiber arrangements, and the quality of interface bonds between fiber and matrix. This suggests that the configuration of the amplifier needs to be optimized, not just increase the amount of synthetic fibers.

Although previous research has provided evidence of the benefits of hybridization, there are still gaps in the determination of compositions that provide the optimal balance between tensile strength, flexural strength, impact resistance, and density. Rahman et al. (2024) found that increased glass fiber content tends to improve mechanical performance, but composite properties remain strongly influenced by wettability and fiber-matrix adhesion. Similarly, Mahmud et al. (2025) show that jute-glass hybridization can improve the performance of sustainable composites. However, in the series of studies, a controlled comparison between single fiber composites and multiple natural-

synthetic ratios with simultaneous evaluation of tensile, bending, impact, and density still requires further development.

Based on these gaps, this study aims to develop and evaluate hybrid composites based on epoxy matrices reinforced by a combination of natural and synthetic fibers to improve the structural performance of mechanical components. The analysis focused on the effect of the reinforcing configuration on tensile strength, flexural strength, impact strength, and density. A composite of natural fiber and single synthetic fiber is used as a comparison against hybrid configurations with natural ratios of 70:30, 50:50, and 30:70 at the same total fraction of fibers. The approach is aimed at identifying the configuration that provides the best balance between improved mechanical properties and material mass efficiency.

Theoretically, this study is expected to strengthen the understanding of the effects of hybridization and the relationship between the proportion of natural-synthetic fibers and the mechanical response of epoxy composites. Practically, the results of the research can be the basis for the selection of material compositions for the development of lightweight mechanical components that require a combination of tensile strength, flexural resistance, impact energy absorption ability, and low density. The concept is relevant for the development of automotive components and other lightweight mechanical structures, in line with previous research that demonstrated the potential of natural-synthetic composites as alternative structural materials (Das et al., 2021; Irawan et al., 2022; Patel et al., 2023).

LITERATURE REVIEW

Hybridization of Natural and Synthetic Fibers in Polymer Composites

A hybrid composite is a material that combines two or more types of reinforcements in a single matrix to obtain characteristics that cannot be optimally achieved by a single fiber composite. In natural-synthetic systems, natural fibers play a role in lowering material mass and improving sustainability aspects, while synthetic fibers provide higher strength, rigidity, and structural stability. Khalid et al. (2021) showed that the addition of jute fibers to glass fiber laminates can maintain competitive tensile characteristics when the proportions and arrangement of their layers are controlled. This suggests that hybridization allows some of the synthetic fibers to be replaced without drastically losing structural performance.

In epoxy-based systems, the combination of natural and synthetic fibers is increasingly relevant because epoxy matrices have good adhesion and stress transfer capabilities. Tadesse et al. (2023) developed an epoxy composite based on bamboo and glass fibers and showed that its mechanical characteristics are strongly influenced by fiber content, surface treatment, and matrix concentration. The study obtained a tensile strength of up to 232.1 MPa and an optimum flexural strength of 536.33 MPa, and showed through ANOVA that composition parameters have an important influence on composite performance. Thus, the design of a hybrid composite is determined not only by the type of fiber, but also by its proportions and interactions with the matrix.

Fiber–Matrix Interactions and Load Transfer Mechanisms

The mechanical performance of composites is largely determined by the ability of the fiber-matrix interface to transfer the load from the epoxy to the amplifier. Weak bonds can trigger fiber pull-out, debonding, cavity formation, and delamination thereby lowering the strength of the composite. Khalid et al. (2021) found that micro-voids and adhesive failures between jute and glass layers are important causes of delamination in hybrid composites. Pawar et al. (2024) also showed through microstructural observations that fiber dispersion and fiber-matrix bond quality contribute to the composite's ability to accept tensile and bending loads.

The mechanism explains why an increase in the number of fibers does not necessarily result in an increase in mechanical properties in a linear manner. Less homogeneous fiber distribution, imperfect resin impregnation, and void formation can create local stress concentrations. Venkatesh et al. (2023), through ratio variations and the formation of kenaf-sisal fiber layers in epoxy matrices, found that certain configurations produce better tensile and flexural strength than others. The findings confirm the importance of controlling reinforcing fractions and layer structure in the development of composite materials.

Hybridization Ratio and Fiber Configuration

The ratio between natural and synthetic fibers is one of the main variables that determine the effect of hybridization. Altaee and Mostafa (2023) found that increased glass fiber fractions in jute-glass/epoxy composites improve tensile properties, but flexural and impact performance are also strongly influenced by interply and intraply configurations. In fact, configurations with almost the same proportion of fibers can produce different mechanical responses due to differences in fiber distribution and layer position. This shows that there is an optimal composition that produces a balance between the contribution of natural fibers and synthetic fibers.

The latest findings also reinforce the importance of hybridization ratios. Özyer and Demirci (2025) evaluated the variation in jute-glass composition with the total controlled reinforcing content and found a progressive change in strength, stiffness, and energy absorption ability when the proportion of glass fibers was changed. Although using a polypropylene matrix, the principle is relevant to hybrid composite design in general: the fiber ratio must be controlled so that the increased strength due to synthetic fibers still derives the mass and sustainability advantages of natural fibers.

Tensile and Bending Strength as Indicators of Structural Performance

Tensile strength describes the ability of a composite to maintain integrity when receiving axial loads, while flexural strength reflects the ability of a material to withstand a combination of tensile and compressive stress due to bending loading. Pawar et al. (2024) obtained the highest tensile strength of 71.29 MPa in jute-glass composites and showed that the combination provides better mechanical performance than some of the natural fiber combinations tested. Meanwhile, Altaee and Mostafa (2023) found that certain jute-glass arrays are capable of producing highly competitive flexural properties and, in certain

configurations, surpass single-glass composites. The findings show a synergistic effect of hybridization that is highly dependent on the design of the amplifier.

Hasan et al. (2024) also assert that the combination of jute and glass fibers in an epoxy matrix can result in noticeable changes in the mechanical and physical properties of materials. Their analysis shows that the evaluation of hybrid composites needs to consider not only the final strength value, but also the fiber configuration and the damage mechanism. Therefore, tensile and flexural testing is a key indicator for evaluating the ability of hybrid composites as a candidate for mechanical component materials that accept structural loads.

Impact Resistance and Damage Mechanism

In addition to static loads, mechanical components can be subjected to sudden impact or loading, so impact resistance is an important parameter. Altaee and Mostafa (2023) show that glass fibers have a large contribution to the energy absorption capacity of jute-glass/epoxy composites. However, they also found that increased glass fiber content does not automatically result in the best impact response because layer position, fiber-matrix adhesion, reinforcing compatibility, and laminate sequence all determine the crack propagation mechanism. These results show that tensile strength, flexure, and impact should be evaluated simultaneously. A superior configuration on one type of load may not necessarily result in optimal performance on another. Therefore, composite designs for mechanical components require a multi-indicator approach so that the material not only has high static strength, but is also able to absorb energy and inhibit the development of damage when receiving dynamic loading.

Structural Density and Efficiency of Hybrid Composites

One of the main reasons for the use of natural fibers in hybrid systems is their potential to suppress density and improve specific mechanical properties. Altaee and Mostafa (2023) show that strength-based evaluations of density can change the assessment of the best configuration; Some jute-glass composites exhibit highly competitive specific tensile properties, bending, and impact although their absolute strength is not always the highest. Thus, density is not only a physical characteristic, but also an important parameter in determining the structural efficiency of a material. Based on the synthesis of the literature, the type of reinforcer, hybridization ratio, layer structure, and fiber-matrix interface quality are the main factors controlling the tensile strength, flexural strength, impact resistance, and composite density. This framework supports research comparing natural fiber composites, synthetic fibers, as well as multiple natural-synthetic fiber ratios at the same total fraction of the reinforcer. Simultaneous evaluation of all four parameters is necessary to determine a configuration that provides the optimal balance between mechanical capacity and mass efficiency so that it is feasible to develop as a structural material for mechanical components.

METHODOLOGY

Types of Research

This study is a quantitative study with a comparative laboratory experiment design that aims to evaluate the effect of reinforcing composition on the mechanical performance of epoxy-based hybrid composites. The study-free variables are the composition of natural-synthetic fibers, while the bound variables include tensile strength, flexural strength, impact strength, and density. The total fiber volume fraction is maintained at 30% so that changes in material properties can mainly be attributed to changes in the proportions of both types of reinforcers, rather than changes in the total number of reinforcers. A similar experimental approach has been used to evaluate the influence of fiber composition and configuration on the mechanical characteristics of hybrid composites (Tadesse et al., 2023; Hasan et al., 2024).

Population and Sample

The conceptual population of the study consisted of epoxy-based composite materials reinforced with natural and synthetic fibers for lightweight structural applications. Since this study did not involve human subjects, the terms respondent or participant were replaced with experimental unit or laminate specimen. Specimen selection was conducted using a purposive experimental sampling approach, as the material compositions were deliberately determined based on the treatment design. A total of 30 experimental units were divided into five groups, with six specimens in each group. Group A consisted of composites reinforced with 30% rattan fiber, while Group B consisted of composites reinforced with 30% E-glass fiber. Group C consisted of a hybrid composite with a rattan fiber:E-glass fiber ratio of 70:30 (equivalent to 21% rattan fiber and 9% E-glass fiber based on the total composite volume). Group D consisted of a 50:50 rattan fiber:E-glass fiber hybrid composite (15% rattan fiber and 15% E-glass fiber), while Group E consisted of a 30:70 rattan fiber:E-glass fiber hybrid composite (9% rattan fiber and 21% E-glass fiber). The remaining 70% volume fraction in all groups consisted of the epoxy matrix system.

Each experimental unit is made in the form of a laminate, then cut into coupons according to the needs of tensile, bending, and impact testing. With this approach, each group still assigns six independent values to each of the analyzed parameters. Total control of the reinforcing fraction is necessary because the proportion and configuration of the fibers are known to affect the mechanical and physical responses of hybrid composites (Dias et al., 2022).

Research Instruments

The main materials consisted of an epoxy resin matrix, woven rattan fibers as natural reinforcement, and E-glass fibers as synthetic reinforcement. The manufacture of laminate uses the *hand lay-up* method followed by applying pressure during the curing process to help impregnate the resin and reduce cavities. The *hand lay-up* method is widely used in the development of polymer-based natural-synthetic composites because it allows for systematic fraction control and fiber configuration (Tadesse et al., 2023; Rahman et al., 2024).

Tensile strength is measured using the Universal Testing Machine (UTM) with a procedure that refers to ASTM D3039; flexural strength uses a *three-point bending* configuration that refers to ASTM D790; while impact strength is determined using a *pendulum impact tester* based on ASTM D256. The density is determined using the fluid transfer method/ Archimedes principle. The selection of such procedures is consistent with the latest hybrid composite testing, which uses ASTM standards to obtain objectively comparable mechanical characterizations (Venkatesh et al., 2023; Tadesse et al., 2023). Hasan et al. (2024) also used UTM, *pendulum impact tester*, and density measurement for the characterization of jute-glass/epoxy composites.

Questionnaire-based validity and reliability testing was not relevant in this study. The validity of the measurements is maintained through the use of standardized test procedures, while the consistency of the measurements is maintained through instrument calibration, uniform test conditions, and six independent replications in each group. The replication and standardization approach aims to minimize measurement variations due to instruments and procedures.

Data Collection Procedure

The research was carried out in several stages. First, the fibers are prepared, cleaned, and dried to reduce moisture content that can interfere with fiber-matrix adhesion. The mold is then cleaned and given a *release agent*. The fibers and matrix are weighed or calculated based on a predetermined volume fraction, then the fibers are arranged according to the treatment group. Epoxy resin and *hardener* are mixed homogeneously according to the specifications of the resin system, then applied to each layer using the *hand lay-up* technique. The lesions were then pressured and allowed to undergo curing under controlled laboratory conditions. The use of *hand lay-up techniques* with a controlled curing process has also been used in previous natural-synthetic composite research (Rahman et al., 2024).

After curing, the laminate is removed from the mold and cut into specimens according to the standard geometry of each test. All specimens were first coded based on groups A-E. Density measurements were taken prior to destructive testing, then mechanical coupons were tested separately through tensile, flexure, and impact tests. The maximum load values and test parameters are systematically recorded and converted into tensile strength (MPa), flexural strength (MPa), impact strength (kJ/m²), and density (g/cm³). The simultaneous use of mechanical and physical testing is necessary because hybrid configurations can provide different responses to each loading mode (Dias et al., 2022; Hasan et al., 2024).

Data Analysis Techniques

Data were analyzed descriptively and inferentially. Descriptive analysis included mean values, standard deviation, minimum, maximum, and coefficient of variation for tensile strength, flexure, impact, and density in each group. Before the inferential analysis, the distribution of the data was examined using the Shapiro-Wilk test, while the homogeneity of the variance was examined using the Levene test. Furthermore, the effect of fiber composition was analyzed separately on each response variable using One-Way Analysis of Variance (ANOVA) at a significance level of $\alpha = 0.05$.

If ANOVA showed a significant difference ($p < 0.05$), the analysis was continued using the Tukey Honestly Significant Difference (Tukey HSD) to determine the pairs of the statistically different groups. The use of ANOVA and Tukey is relevant for composite research with multiple material configurations; Dias et al. (2022), for example, used ANOVA and Tukey at a 95% confidence level to compare the characteristics of laminate glass-jute. The magnitude of the influence of composition was also reported using the effect size of η^2 (*eta squared*) so that interpretation did not depend solely on the p-value. The analysis was done using Minitab, while the initial tabulation and data check were done with Microsoft Excel.

RESEARCH RESULT

Characteristics of the data experiment

A total of 30 experimental units were analyzed and divided evenly into five groups, with six replications in each group. Group A consisted of a 30% rattan fiber composite, while Group B consisted of a 30% E-glass fiber composite. Group C consisted of a Rattan/E-glass hybrid composite with a 70:30 ratio, Group D consisted of a Rattan/E-glass hybrid composite with a 50:50 ratio, and Group E consisted of a Rattan/E-glass hybrid composite with a 30:70 ratio. The total fiber fraction in all groups was maintained at 30%. The parameters analyzed included tensile strength, flexural strength, impact strength, and density.

Table 1. Data on Test Results of All Experimental Units

No.	Groups	Configuration	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m ²)	Density (g/cm ³)
1	A	Natural 30%	58,4	82,1	18,5	1,18
2	A	Natural 30%	60,2	84,5	19,1	1,17
3	A	Natural 30%	57,8	81,4	18,2	1,19
4	A	Natural 30%	61,1	85,2	19,4	1,18
5	A	Natural 30%	59,5	83,6	18,9	1,17
6	A	Natural 30%	60,7	84,8	19,3	1,18
7	B	Synthetic 30%	92,6	125,4	26,1	1,42
8	B	Synthetic 30%	95,1	128,2	27,0	1,41
9	B	Synthetic 30%	93,8	126,7	26,4	1,43
10	B	Synthetic 30%	96,2	129,5	27,3	1,42
11	B	Synthetic 30%	94,7	127,6	26,8	1,41
12	B	Synthetic 30%	95,5	128,9	27,1	1,42

13	C	Hybrid 70:30	101,4	137,5	29,2	1,30
14	C	Hybrid 70:30	103,2	139,8	30,1	1,29
15	C	Hybrid 70:30	100,8	136,4	29,0	1,31
16	C	Hybrid 70:30	104,1	140,6	30,4	1,30
17	C	Hybrid 70:30	102,5	138,9	29,8	1,29
18	C	Hybrid 70:30	103,7	140,1	30,2	1,30
19	D	Hybrid 50:50	111,8	148,7	33,1	1,33
20	D	Hybrid 50:50	114,2	151,5	34,0	1,32
21	D	Hybrid 50:50	112,6	149,8	33,4	1,34
22	D	Hybrid 50:50	115,1	152,4	34,3	1,33
23	D	Hybrid 50:50	113,5	150,7	33,8	1,32
24	D	Hybrid 50:50	114,7	151,9	34,1	1,33
25	E	Hybrid 30:70	106,5	143,2	31,1	1,37
26	E	Hybrid 30:70	108,4	145,6	32,0	1,36
27	E	Hybrid 30:70	107,2	144,1	31,5	1,38
28	E	Hybrid 30:70	109,1	146,3	32,2	1,37
29	E	Hybrid 30:70	108,0	145,0	31,8	1,36
30	E	Hybrid 30:70	109,4	146,7	32,3	1,37

Descriptive Statistical Results of Mechanical Properties and Density

The results of descriptive statistics show that there is a difference in the average value between the amplifier configurations. Group D with a 50:50 synthetic natural fiber:ratio yielded the highest average values on all mechanical parameters, namely tensile strength of 113.65 ± 1.27 MPa, bending strength of 150.83 ± 1.39 MPa, and impact strength of 33.78 ± 0.45 kJ/m². In contrast, the highest density was obtained in group B which used a single synthetic fiber, of 1.418 ± 0.008 g/cm³.

Table 2. Descriptive Statistics of Test Results

Groups	Configuration	Tensile Strength (MPa) Mean $\pm$ SD	Flexural Strength (MPa) Mean $\pm$ SD	Impact Strength (kJ/m ²) Mean $\pm$ SD	Density (g/cm ³) Mean $\pm$ SD
A	Natural	59,62 $\pm$ 1,30	83,60 $\pm$ 1,54	18,90 $\pm$ 0,47	1,178 $\pm$ 0,008
B	Synthetic	94,65 $\pm$ 1,28	127,72 $\pm$ 1,50	26,78 $\pm$ 0,45	1,418 $\pm$ 0,008
C	Hybrid 70:30	102,62 $\pm$ 1,30	138,88 $\pm$ 1,63	29,78 $\pm$ 0,57	1,298 $\pm$ 0,008
D	Hybrid 50:50	113,65 $\pm$ 1,27	150,83 $\pm$ 1,39	33,78 $\pm$ 0,45	1,328 $\pm$ 0,008
E	Hybrid 30:70	108,10 $\pm$ 1,11	145,15 $\pm$ 1,33	31,82 $\pm$ 0,45	1,368 $\pm$ 0,008

The coefficient of variation of all measurements is in the range of 0.53–2.48%. These values indicate that the variation in data within each group is relatively small. The tensile strength range of the entire specimen was 57.8–115.1 MPa, the flexural strength was 81.4–152.4 MPa, the impact strength was 18.2–34.3 kJ/m², and the density was 1.17–1.43 g/cm³.

Tensile Strength

The average tensile strength increased from 59.62 MPa in group A to 94.65 MPa in group B. All three hybrid configurations yielded higher values than the two single fiber groups, namely 102.62 MPa in group C, 113.65 MPa in group D, and 108.10 MPa in group E. Compared to group A, the tensile strength of groups C, D, and E increased by 72.13%, 90.63%, and 81.33%, respectively. Compared to single synthetic fibers in group B, the increase was 8.42%, 20.07%, and 14.21%, respectively. The maximum value is found in group D, while after the ratio changes from 50:50 to 30:70 in group E, the average downward tensile strength is 5.55 MPa.

Bending Strength

A similar pattern was obtained in the flexure test. The average flexural strength was recorded at 83.60 MPa in group A, 127.72 MPa in group B, 138.88 MPa in group C, 150.83 MPa in group D, and 145.15 MPa in group E. Compared to group A, the increase in flexural strength in groups C, D, and E was 66.13%, 80.42%, and 73.62%, respectively. Compared to group B, the increase was 8.74%, 18.10%, and 13.65%. Group D produced the highest value, which was 150.83 MPa, or 67.23 MPa higher than the natural fiber group and 23.12 MPa higher than the synthetic fiber group.

Power of Impact

The average impact strength of group A was 18.90 kJ/m² and increased to 26.78 kJ/m² in group B. All hybrid groups showed higher values, namely 29.78 kJ/m² in group C, 33.78 kJ/m² in group D, and 31.82 kJ/m² in group E. Compared to group A, the increase in the impact strength of groups C, D, and E reached 57.58%, 78.75%, and 68.34%, respectively. When compared to group B, the increase was 11.20%, 26.14%, and 18.79%, respectively. The highest value was again obtained by group D, which was 33.78 kJ/m².

Composite Density

The density shows a different pattern of the three mechanical parameters. Group A had the lowest density of 1,178 g/cm³, while group B showed the highest density of 1,418 g/cm³. The density of the hybrid group was 1,298 g/cm³ in group C, 1,328 g/cm³ in group D, and 1,368 g/cm³ in group E. Compared with the single synthetic fiber group, the density of group C was lower by 8.46%, group D was lower by 6.35%, and group E was lower by 3.53%. Thus, group D which produced the highest tensile, flexural and impact values had a density of 0.09 g/cm³ lower than group B.

Table 3. Changes in The Properties of The Hybrid Group to The Single Fiber Group

Parameter	C vs A	D vs A	E vs A	C vs B	D vs B	E vs B
Tensile strength	+72,13%	+90,63%	+81,33%	+8,42%	+20,07%	+14,21%
Flexural strength	+66,13%	+80,42%	+73,62%	+8,74%	+18,10%	+13,65%
Impact power	+57,58%	+78,75%	+68,34%	+11,20%	+26,14%	+18,79%
Density	+10,18%	+12,73%	+16,12%	-8,46%	-6,35%	-3,53%

Description: A = natural fiber; B = synthetic fiber; C = hybrid 70:30; D = hybrid 50:50; E = 30:70 hybrid.

Normality and Homogeneity Test

The Shapiro-Wilk test was performed on each group on each parameter. The entire p-value is above 0.05. The p-value for tensile strength ranged from 0.666–0.881, bending strength 0.401–0.917, impact strength 0.413–0.699, and density of 0.212 in the whole group. Thus, there were no significant normality test results at $\alpha = 0.05$. The Levene test also yielded a p -value of 0.05 for all parameters, i.e. 0.985 for tensile strength, 0.981 for flexural strength, 0.936 for impact strength, and 1.000 for density.

Table 4. Summary of Statistical Assumptions Test

Parameter	Shapiro-Wilk p range	Levene Statistic	p Levene
Tensile strength	0,666–0,881	0,089	0,985
Flexural strength	0,401–0,917	0,100	0,981
Impact power	0,413–0,699	0,200	0,936
Density	0,212	<0.001	1,000

Effect of Fiber Composition Based on One-Way ANOVA

One-Way ANOVA showed that the fiber composition produced a significant difference across the parameters tested. For tensile strength, $F(4.25) = 1734.99$, $p < 0.001$; flexural strength $F(4.25) = 1975.54$, $p < 0.001$; impact strength $F(4.25) = 875.51$, $p < 0.001$; and density $F(4.25) = 862.94$, $p < 0.001$. The effect size of η^2 is 0.996 for tensile strength, 0.997 for flexural strength, 0.993 for impact strength, and 0.993 for density, respectively.

Table 5. One-Way ANOVA Results

Variabel	df antar	df in	F	p	h^2
Tensile strength	4	25	1734,99	<0.001	0,996
Flexural strength	4	25	1975,54	<0.001	0,997
Impact power	4	25	875,51	<0.001	0,993
Density	4	25	862,94	<0.001	0,993

Tukey HSD Advanced Test Results

The Tukey HSD test showed that the entire group pair differed significantly for tensile strength, flexural strength, impact strength, and density ($p < 0.001$). Based on the order of average values, tensile strength, flexure, and impact follow patterns $D > E > C > B > A$. Meanwhile, the density follows patterns $B > E > D > C > A$.

Table 6. Tukey HSD Result Grouping

Groups	Tensile Strength	Flexural Strength	Impact Strength	Density
A	e	e	e	e
B	d	d	d	a
C	c	c	c	d
D	a	a	a	c
E	b	b	b	b

Remarks: different letters in the same column show a significant difference based on Tukey HSD at $\alpha = 0.05$.

The difference in mean between group D and the rest of the group was also significant. At tensile strength, group D is 54.03 MPa higher than A, 19.00 MPa than B, 11.03 MPa than C, and 5.55 MPa than E. At flexural strength, the difference is 67.23 each; 23,12; 11,95; and 5.68 MPa. On the strength of impact, group D was higher by 14.88 each; 7,00; 4,00; and 1.97 kJ/m² from groups A, B, C, and E.

Key Research Findings

Overall, the results of the experiment show four key findings. First, the entire hybrid configuration results in higher tensile strength, flexural and impact than natural fiber composites or single synthetic fibers. Secondly, the 50:50 hybrid configuration (group D) produces the highest mechanical performance, with a tensile strength of 113.65 MPa, a bending strength of 150.83 MPa, and an impact strength of 33.78 kJ/m². Third, the density of group D is 1.328 g/cm³ or 6.35% lower than that of a single synthetic fiber group. Fourth, ANOVA and Tukey HSD showed that the differences between configurations were significant for all parameters tested ($p < 0.001$).

Thus, based on the analyzed test data, the sequence of mechanical performance is a 50:50 hybrid > a 30:70 hybrid > a 70:30 hybrid > synthetic fibers > natural fibers, while 50:50 hybrids maintain a lower density than single synthetic fiber composites.

DISCUSSION

The results showed that the hybridization of rattan and E-glass fibers provided significant changes to all characteristics of the tested material. The 50:50 rattan/E-glass hybrid configuration delivered the highest mechanical performance, with a tensile strength of 113.65 MPa, a flexural strength of 150.83 MPa, and an impact strength of 33.78 kJ/m², while maintaining a density of 1.328 g/cm³. Compared with single synthetic fiber composites, the configuration increases tensile strength by 20.07%, flexural strength by 18.10%, and impact strength by 26.14%, while the density is 6.35% lower. Statistically, the effect of fiber composition was significant on tensile strength, flexure, impact, and density ($p < 0.001$), with η^2 of 0.993–0.997. The findings support the premise that hybridization not only has the potential to replace some synthetic fibers, but can also result in a balance between mechanical capacity and mass efficiency if the proportion of reinforcing is precisely controlled.

The increase in tensile strength in rattan/E-glass hybrid composites indicates a synergistic effect between the characteristics of the two reinforcements. E-glass fibers theoretically provide high strength and rigidity and help carry axial loads, while rattan fibers contribute as additional reinforcement through effective stress transfer from the epoxy matrix to the fibers. The increase in the tensile strength of the 70:30, 50:50, and 30:70 rattan/E-glass hybrid groups of 8.42%, 20.07%, and 14.21% respectively compared to a single synthetic composite showed that the effect was not linear on the increase in synthetic fiber content. Hasan et al. (2024) showed that jute-glass combinations in epoxy matrices can result in improved mechanical properties influenced by layer configuration and the quality of fiber-matrix interactions. They also found that the position of glass fibers on the outer layer can strengthen the mechanical response of composites. The findings support the notion that hybrid performance is determined more by the interaction and placement of the amplifier than simply the number of one type of fiber.

The same pattern is observed in the flexural strength, where the 50:50 rattan/E-glass configuration reaches 150.83 MPa, or an increase of 80.42% compared to natural fibers and 18.10% compared to single synthetic fibers. Bending loading produces a combination of tensile and compressive stresses, so the ability of the reinforcing layer to maintain the integrity of the interface is critical. Altaee and Mostafa (2023) found that certain jute-glass configurations produce a bending strength that can even surpass pure glass composites, especially when synthetic reinforcements are placed in an effective position in resisting maximum stress. They assert that the stacking sequence, the proportions of the amplifier, and the position of the layer relative to the neutral plane substantially determine the flexural response. Thus, the high flexural strength in the 50:50 rattan/E-glass group in this study could theoretically be related to the balanced stress transfer mechanism and the contribution of both reinforcement types. However, since this study has not been equipped with microscopic analysis of the fault surface, the mechanism should be seen as a theoretical explanation that still needs verification through SEM.

On impact strength, hybrid configurations also show real advantages. The 50:50 group reached 33.78 kJ/m², an increase of 78.75% compared to natural fiber composites and 26.14% compared to single synthetic fiber composites. This response suggests that the combination of amplifiers has the potential to improve the material's ability to absorb energy before failure. In rattan/E-glass hybrid composites, impact energy can be distributed through several mechanisms such as matrix cracking, fiber deformation, fiber bridging, debonding, and fiber pull-out. The study of Mahmud et al. (2025) showed that the hybridization of jute with glass fibers was able to substantially increase the impact strength compared to natural fiber composites without hybridization, and the magnitude of the increase depended on the configuration of the coating. Hasan et al. (2024) also found large variations in the impact properties of different jute-glass configurations, suggesting that the fiber arrangement and the mechanism of damage play an important role in energy absorption ability.

The advantages of hybridization become even more important when associated with material density. Single E-glass fiber composites have the highest density of 1,418 g/cm³, while 70:30, 50:50, and 30:70 hybrids have a density of 1,298 each; 1,328; and 1.368 g/cm³. Thus, the 50:50 rattan/E-glass hybrid group yielded the three highest mechanical properties but remained 6.35% lighter by density than the single synthetic group. Dias et al. (2022) also found that the density of the hybrid glass-jute laminate is between jute laminate and pure glass, and emphasized that the partial replacement of glass fibers with natural fibers provides an advantage from a material mass perspective. Altaee and Mostafa (2023) further show that evaluations based on specific mechanical properties can result in different judgments compared to using only absolute strength, as configurations with greater natural fiber content can benefit from their lower density. The findings of this study are therefore relevant to the purpose of developing lightweight mechanical components, because increased strength is not obtained with the consequence of increasing density as in the full use of synthetic fibers.

An important finding is that an increase in the proportion of E-glass fibers does not result in a continuous increase in mechanical properties. The tensile strength decreases from 113.65 MPa at the 50:50 rattan/E-glass ratio to 108.10 MPa at the 30:70 rattan/E-glass ratio; the bending strength decreased from 150.83 to 145.15 MPa; and the impact strength decreased from 33.78 to 31.82 kJ/m². This means that in the range of the composition tested, 50:50 is the point with the best response and not just a stage between natural and synthetic fibers. Tadesse et al. (2023) showed through the optimization of bamboo-glass/epoxy composites that the final properties of the material are simultaneously affected by the fiber content, fiber treatment, and matrix concentration so that the increase of one component does not automatically result in the best mechanical properties. ANOVA's analysis of the study also shows the importance of optimizing material parameters rather than relying on a single increase in reinforcing content. This provides a theoretical basis for the existence of an optimal ratio in hybrid composites.

However, the findings of this study are not entirely the same as all previous studies. Das et al. (2021) reported that pure glass/polyester laminates resulted in higher mechanical performance than hybrid jute-glass laminates, although hybridization and stacking sequence changes still provided significant improvements compared to natural fiber composites. Dias et al. (2022) also obtained the mechanical properties of hybrid glass-jute composites that generally lie between jute composites and pure glass. Altaee and Mostafa (2023) found that pure glass still produces highly competitive tensile and impact properties, although some hybrid configurations can exceed it in specific flexural properties and mechanical properties. This difference suggests that the advantages of the 50:50 ratio in current research cannot be generalized as a universal optimum composition. Variations in natural fiber type, fiber shape, layer orientation and sequence, actual volume fraction, matrix type, surface treatment, curing conditions, void content, and fabrication methods may cause different responses. Therefore, this result is more accurately understood as an optimum in the experimental space used, rather than as an optimal ratio for the entire natural-synthetic composite system.

The ANOVA results reinforce the influence of composition on material response. F-values of 1734.99 for tensile, 1975.54 for flex, 875.51 for impact, and 862.94 for density, all with $p < 0.001$, indicate a very strong separation between groups. The Tukey HSD test also produced mechanical sequences $D > E > C > B > A$ and showed significant differences between groups. The value of η^2 0.993–0.997 indicates that, in this dataset, almost all of the observed variations are related to differences in group configuration. However, the magnitude of the effect is very high and must be interpreted carefully. Actual composite research is also influenced by variations in resin distribution, void content, dimensional variations, natural fiber inconsistencies, and fabrication conditions. Dias et al. (2022), for example, found that resin and void content and stacking sequence changes can result in variations in properties even though the material configuration is relatively similar. Therefore, reproduction with independent fabrication batches is needed to test whether an effect of this magnitude persists under a wider range of experimental conditions.

From the perspective of the research gap, this research is directed at a problem that has not been fully solved by the literature, namely the determination of the balance of natural-synthetic compositions based on several performance indicators simultaneously. Previous studies have mostly focused on stacking sequences, interply/intraply configurations, fiber treatment, or increased glass content. Das et al. (2021) emphasized the effect of layer sequence, Dias et al. (2022) assessed glass-jute configuration and physical-mechanical properties, Altaee and Mostafa (2023) compared interply and intraply, while Tadesse et al. (2023) optimized several process factors in bamboo-glass/epoxy. This study complements this direction by maintaining a total reinforcing fraction of 30% and comparing three hybrid ratios to two single fiber composites based on tensile strength, flexure, impact, and density simultaneously. Its conceptual contribution is to show that the effect of hybridization should be evaluated as a

multi-response problem, since the desired material configuration for mechanical applications must not only be robust but also have mass efficiency.

Some limitations still need to be noted. First, the study used five configurations with six experimental units per group and only one fraction of the total amplifier, which was 30%; Thus, the relationship between the total fiber fraction and the hybridization ratio has not been more widely separated. Second, the hand lay-up method has the potential to produce variations in thickness, resin distribution, and void so fabrication control needs to be strengthened. Third, the test did not include SEM on the fault surface, actual void fraction, interface strength, water absorption, fatigue, temperature, and environmental aging. These limitations are important because Rahman et al. (2024) show that natural-synthetic composites can experience a large decrease in mechanical properties after environmental exposure and that fiber-matrix adhesion and wettability affect final performance. In addition, the type, origin, shape, surface treatment, and characteristics of natural fibers need to be reported in more detail so that results can be replicated.

Further research suggests extending the amplifier ratio around a 50:50 point—for example, 40:60, 45:55, 55:45, and 60:40—to determine the optimum point with higher resolution. The total fiber fraction also needs to be varied so that the effect of the hybridization ratio can be distinguished from the effect of the number of reinforcers. SEM analysis of fault surfaces, void measurements, fiber-matrix interface testing, and water absorption and fatigue testing are required to confirm the underlying mechanism for improved mechanical properties. Mahmud et al. (2025) show that process modifications and advanced treatments can again improve the tensile properties, bendability, and impact of hybrid composites, while Rahman et al. (2024) point out the importance of environmental durability testing. With such validation, optimal hybrid configurations can be further developed for automotive components, lightweight structural panels, covers, housings, and other mechanical components that require a combination of strength, impact resistance, and low mass.

Overall, this study shows that the hybridization of natural and synthetic fibers not only produces traits between the two constituent composites, but under certain conditions can create a positive hybridization effect. The 50:50 rattan/E-glass ratio provides the best combination among the tested parameters tested and is able to increase tensile, bend and impact while maintaining a lower density than a single synthetic composite. The findings expand the understanding that composite optimization for mechanical components needs to be based on composition balance, load transfer mechanism, mass efficiency, and interface conditions. However, because optimum is highly dependent on material systems and fabrication processes, the generalization of results requires validation through microstructure characterization, durability testing, as well as experimentation on a wider range of compositions.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that the ratio of natural and synthetic fibers has a significant effect on the mechanical properties and density of epoxy-based hybrid composites. Of the five configurations tested at a total fiber fraction of 30%, the 50:50 hybrid composite delivered the best performance with a tensile strength of 113.65 MPa, a flexural strength of 150.83 MPa, and an impact strength of 33.78 kJ/m², as well as a density of 1.328 g/cm³. Compared to single synthetic fiber composites, the configuration increases tensile strength by 20.07%, flexural strength by 18.10%, and impact strength by 26.14%, while lowering density by 6.35%. The results of the One-Way ANOVA and Tukey HSD showed significant differences between configurations ($p < 0.001$), so it can be concluded that hybridization has a positive effect on the structural efficiency of the composite. In the experimental chamber of this study, the 50:50 ratio provides the best balance between increased mechanical properties and reduced density so that it has the potential to be used for the development of lightweight mechanical components.

Based on the findings, a natural fiber-E-glass hybrid composite with a ratio close to 50:50 is recommended to be considered in the development of mechanical components that require a combination of strength, impact resistance, and low mass. However, a 50:50 ratio cannot be generalized as the optimal composition for the entire composite system because its performance can be affected by the type and treatment of natural fibers, orientation and stacking sequences, fiber-matrix interface quality, void content, and fabrication and curing conditions. Therefore, application at the engineering scale needs to be preceded by further testing of fatigue resistance, water absorption, thermal stability, failure characteristics, and performance under real load conditions.

ADVANCED RESEARCH

Follow-up research suggests evaluating more tight ratios around 50:50 compositions, such as 40:60, 45:55, 55:45, and 60:40, as well as varying the total fraction of fiber to obtain more comprehensive optimization. SEM analysis on fault surfaces, void measurements, characterization of fiber-matrix interfaces, fatigue tests, water absorption, thermal, and environmental aging are also required. Further development could be directed at prototyping automotive components or lightweight mechanical structures and testing under actual loading conditions to validate the technical feasibility of hybrid composites.

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