

Analysis of the Impact and Bending Strength of Coconut Coir Fiber-Reinforced Polyester Resin Composite Material for Automotive Bumper Applications

Lalu Moch Syarif Hidayatullah¹, Anggit Murdani²

^{1,2} Bachelor of Applied Engineering in Production and Maintenance Mechanical Engineering,
Department of Mechanical Engineering, State Polytechnic of Malang, Indonesia

Coressponden Autor Email : Lalu_Moch_Syarif@gmail.com

Abstract

The automotive industry requires lightweight, durable, cost-effective, and environmentally friendly materials to improve vehicle performance and sustainability. This study investigates the effect of coconut coir fiber volume fraction and fiber orientation on the impact and flexural strength of polyester matrix composites intended for automotive bumper applications. Composite specimens were fabricated using the hand lay-up method with three fiber orientations: random, unidirectional, and laminated. Impact and flexural tests were conducted according to ASTM standards, and the experimental data were analyzed using Two-Way ANOVA. The results revealed that fiber volume fraction significantly affected impact strength ($p = 0.043 < 0.05$), indicating that higher fiber content improved the composite's ability to absorb impact energy. In contrast, fiber orientation and the interaction between fiber volume fraction and fiber orientation showed no significant effect on impact strength. Furthermore, neither fiber volume fraction, fiber orientation, nor their interaction significantly influenced flexural strength ($p > 0.05$). These findings demonstrate that fiber volume fraction is the dominant factor affecting the impact performance of coconut coir fiber-reinforced polyester composites. Therefore, the developed composite shows promising potential as a sustainable alternative material for automotive bumper applications.

Keywords: coconut coir fiber, polyester composite, impact strength, flexural strength, automotive bumper.



INTRODUCTION

The rapid development of the automotive industry has increased the demand for materials that are lightweight, possess high strength, offer low production costs, and are environmentally friendly. One approach to meeting these requirements is the development of natural fiber-reinforced composite materials as alternatives to conventional materials such as steel and aluminum alloys. Natural fiber composites offer several advantages, including low density, abundant raw material availability, relatively low manufacturing costs, and better biodegradability compared to synthetic materials. These characteristics have led to the increasing application of natural fiber composites in various automotive components, including interior panels, dashboards, door trims, and vehicle bumpers (Faruk et al., 2012; Pickering et al., 2016; Jawaid & Abdul Khalil, 2011; Koronis et al., 2013).

A bumper is one of the most important components of a vehicle, serving to absorb and dissipate impact energy in order to minimize damage to the vehicle's primary structure. Bumper materials must possess high impact energy absorption capability while maintaining adequate flexural strength to prevent excessive deformation under loading. Therefore, impact and flexural properties are key parameters used to evaluate the suitability of a material for automotive bumper applications. The ability of a material to absorb impact energy is strongly influenced by the mechanical properties of the composite, fiber–matrix interfacial bonding, and fiber orientation (Mallick, 2007; Fiore et al., 2015; Pickering et al., 2016; Al Mahmud et al., 2023).

One natural fiber with significant potential as a composite reinforcement is coconut coir fiber. Indonesia, as one of the world's largest coconut-producing countries, has an abundant supply of coconut husk waste that remains underutilized. Coconut coir fiber contains a relatively high lignin content, which provides resistance to deformation, enhances energy absorption capability, and improves environmental durability. These characteristics make coconut coir fiber a promising reinforcement material for engineering applications, particularly in automotive components that require high impact energy absorption capacity (Faruk et al., 2012; Pickering et al., 2016; Ramesh et al., 2023; Dugvekar & Dixit, 2023).

Previous studies have reported that coconut coir fiber-reinforced polyester composites can improve the mechanical performance of materials. Polyester resin is widely used because of its relatively low cost, simple manufacturing process, and good adhesion to natural fibers. In addition, polyester resin exhibits excellent corrosion resistance and dimensional stability, making it suitable for lightweight structural composite applications. Several studies have shown that the combination of coconut coir fiber and polyester resin can produce impact and flexural properties that are competitive with those of other natural fiber-reinforced composites (Mallick,



2007; Ramesh et al., 2023; Rahman et al., 2024; Adeosun et al., 2022).

Although extensive research has been conducted on coconut coir fiber composites, most previous studies have primarily focused on the effect of fiber volume fraction on specific mechanical properties or have evaluated only a single mechanical test separately. Furthermore, many studies have concentrated on material characterization without relating the findings to specific automotive component requirements. In addition, investigations regarding the influence of fiber orientation or fiber arrangement on the combined impact and flexural performance of coconut coir fiber-reinforced polyester composites remain limited, particularly for automotive bumper applications. Nevertheless, fiber orientation plays a crucial role in stress distribution, impact energy absorption mechanisms, and the flexural resistance of composite materials (Fiore et al., 2015; Al Mahmud et al., 2023; Rahman et al., 2024; Ramesh et al., 2023).

No.	Author(s) & Year	Material and Method	Research Findings	Research Gap
1	Hasan et al. (2021)	Multilayer coconut coir fiber composite with fiber surface treatment	Fiber treatment improved the mechanical and thermal properties of the composite.	The effect of fiber orientation on impact and flexural properties for automotive applications was not investigated.
2	Islam et al. (2021)	Review of coconut coir fiber composites reinforced with various polymer matrices	Coconut coir fiber has significant potential to enhance the mechanical performance and sustainability of composite materials.	The study was limited to a literature review and did not perform experimental investigations on the combined effects of fiber orientation and fiber volume fraction.
3	Kumar et al. (2022)	Polyester-coconut coir fiber composite with varying random fiber weight fractions	Increasing fiber content improved the dynamic properties and storage modulus of the composite.	The study focused on dynamic properties and did not simultaneously evaluate impact and flexural strength.
4	Ramesh et al. (2022)	Coconut coir fiber-epoxy composite	NaOH treatment and fiber length	Impact resistance was not investigated, and the

		with variations in fiber length and NaOH treatment	significantly affected the flexural strength of the composite.	study was not directed toward automotive bumper applications.
5	Al Mahmud et al. (2023)	Epoxy composite reinforced with coconut, banana, and ramie fibers	Coconut fiber contributed to improved impact energy absorption capability.	The study employed a hybrid composite system and an epoxy matrix, which does not specifically represent single-fiber coconut coir polyester composites.
6	Ramesh et al. (2023)	Hybrid coconut coir/hemp fiber composite reinforced with a polyester matrix	Fiber fraction influenced both impact and flexural properties, with certain compositions providing optimal performance.	The use of hybrid fibers makes it difficult to determine the specific contribution of coconut coir fiber.
7	Rahman et al. (2024)	Polyester-coconut coir fiber composite with different stacking sequences (0°/0°/0°, 0°/90°/0°, and 0°/+45°/0°)	Fiber orientation significantly influenced the impact and flexural properties of the composite.	The interaction between fiber orientation and fiber volume fraction was not investigated.
8	Singh et al. (2024)	Biodegradable composite reinforced with coconut coir fiber and additional reinforcements	Mechanical properties and microstructural characteristics of the composite were improved.	The study focused on material characterization and was not intended for automotive bumper applications.
9	Adeosun et al. (2022)	Polyester composite reinforced with coconut shell ash	Mechanical properties improved at specific compositions and demonstrated potential for lightweight	The study did not utilize coconut coir fiber and did not evaluate the effect of fiber orientation.



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Based on the state-of-the-art studies on coconut coir fiber-reinforced composites (2021–2025), a significant research gap remains regarding the comprehensive investigation of the combined effects of fiber volume fraction and fiber orientation on the impact and flexural properties of polyester composites intended for automotive bumper applications. Most previous studies have examined these parameters separately, focusing either on fiber content or fiber orientation, making the interaction between these variables insufficiently understood. Furthermore, studies specifically evaluating coconut coir fiber-reinforced polyester composites as potential automotive bumper materials remain limited (Al Mahmud et al., 2023; Rahman et al., 2024; Ramesh et al., 2023; Adeosun et al., 2022).

Therefore, this study aims to investigate the effects of coconut coir fiber volume fraction and fiber orientation, namely random, perpendicular, and cross-ply arrangements, on the impact and flexural strength of polyester matrix composites. The novelty of this research lies in the simultaneous evaluation of the interaction between fiber volume fraction and fiber orientation on both impact and flexural properties, as well as in determining the optimum composite configuration for potential automotive bumper applications. The findings are expected to contribute to the development of lightweight, cost-effective, environmentally friendly, and mechanically reliable natural fiber-reinforced composites for the automotive industry (Faruk et al., 2012; Pickering et al., 2016; Rahman et al., 2024; Al Mahmud et al., 2023). Based on the aforementioned background, the research questions addressed in this study are as follows: (1) How does the coconut coir fiber volume fraction affect the impact and flexural strength of polyester composites (2) How does fiber orientation influence the impact and flexural strength of polyester composites and (3) Which combination of fiber volume fraction and fiber orientation provides the optimum mechanical performance and demonstrates the greatest potential for automotive bumper applications.

LITERATURE REVIEW

Development of Natural Fiber Composites for Automotive Applications

The use of natural fiber-reinforced composite materials in the automotive industry has continued to increase in response to the demand for lightweight, high-strength, cost-effective, and environmentally friendly materials. Natural fibers such as bamboo, kenaf, ramie, hemp, and coconut coir have been extensively investigated as composite reinforcements due to their



favorable strength-to-weight ratio, renewability, and biodegradability. Furthermore, the utilization of natural fibers can reduce dependence on synthetic reinforcements such as fiberglass, which have greater environmental impacts. Several studies have demonstrated that natural fiber composites possess promising mechanical properties for automotive applications while simultaneously reducing vehicle weight and promoting sustainability in manufacturing processes (Faruk et al., 2012; Jawaid & Abdul Khalil, 2011; Koronis et al., 2013; Pickering et al., 2016; Fiore et al., 2015).

Satria et al. (2024) reported that the incorporation of bamboo fiber into hybrid composites improved impact toughness to 0.0986 J/mm^2 and satisfied the requirements for automotive bumper materials. These findings indicate that natural fibers have considerable potential as alternative materials for automotive components that require high energy absorption capability. However, the study still incorporated fiberglass reinforcement, making it difficult to isolate the contribution of natural fibers. Similar findings have been reported by several researchers who concluded that natural fiber composites can provide competitive mechanical performance for lightweight automotive structures (Satria et al., 2024; Faruk et al., 2012; Pickering et al., 2016; Koronis et al., 2013; Jawaid & Abdul Khalil, 2011).

Effect of Fiber Volume Fraction on Composite Mechanical Properties

Fiber volume fraction is one of the most influential parameters affecting the mechanical performance of composite materials. Increasing fiber content generally enhances the load-bearing capability of composites because a larger number of fibers participate in stress transfer. However, excessive fiber loading may result in poor resin distribution, increased void content, and weakened fiber–matrix interfacial bonding, ultimately reducing composite performance. Therefore, determining the optimum fiber volume fraction is essential for achieving balanced mechanical properties (Mallick, 2007; Pickering et al., 2016; Ramesh et al., 2023; Kumar et al., 2022; Fiore et al., 2015).

Several studies have shown that increasing the volume fraction of coconut coir fibers can improve tensile strength, flexural strength, and impact toughness up to an optimum composition. Beyond this optimum level, the mechanical properties tend to decrease because the matrix can no longer effectively bond and support the fibers. These findings indicate that fiber content plays a critical role in determining the overall mechanical behavior of natural fiber composites. Nevertheless, most previous studies have evaluated only one mechanical property at a time and have rarely investigated the simultaneous effects of fiber volume fraction on both impact and flexural performance for automotive bumper applications (Kumar et al., 2022;

Ramesh et al., 2022; Ramesh et al., 2023; Al Mahmud et al., 2023; Rahman et al., 2024).

Effect of Fiber Orientation on Impact and Flexural Strength

In addition to fiber volume fraction, fiber orientation significantly influences the mechanical behavior of composite materials. Fiber orientation affects stress distribution, crack propagation, delamination mechanisms, and the ability of composites to absorb impact energy. Proper fiber alignment can improve load transfer efficiency and enhance the structural integrity of composite materials subjected to mechanical loading (Mallick, 2007; Fiore et al., 2015; Pickering et al., 2016; Rahman et al., 2024; Atiqoh et al., 2023).

Atiqoh et al. (2023) reported that bamboo fiber composites with a 0° orientation exhibited the highest impact strength compared with other fiber orientations. Likewise, Rahman et al. (2024) found that polyester composites reinforced with coconut coir fibers achieved the highest flexural strength at a $0^\circ/0^\circ/0^\circ$ stacking sequence, whereas the $0^\circ/+45^\circ/0^\circ$ configuration provided superior impact performance. These findings demonstrate that fiber orientation can significantly alter the mechanical response of composites under different loading conditions. However, most previous studies have investigated fiber orientation independently without considering its interaction with fiber volume fraction, despite both factors collectively influencing composite performance (Rahman et al., 2024; Atiqoh et al., 2023; Ramesh et al., 2023; Al Mahmud et al., 2023; Fiore et al., 2015).

Potential of Coconut Coir Fiber as a Composite Reinforcement Material

Coconut coir fiber is one of the most promising natural fibers for composite reinforcement applications due to its high lignin content, which contributes to elasticity, toughness, and excellent impact energy absorption capability. In addition, the abundant availability of coconut coir in Indonesia makes it an economical and sustainable alternative to synthetic reinforcement materials. These characteristics have attracted considerable research interest in utilizing coconut coir fibers for engineering and automotive applications (Faruk et al., 2012; Pickering et al., 2016; Ramesh et al., 2023; Dugvekar & Dixit, 2023; Islam et al., 2021).

Previous studies have demonstrated that coconut coir fiber reinforcement can significantly improve the impact and flexural properties of polymer composites while reducing overall material weight. However, the mechanical performance of coconut coir composites remains highly dependent on fiber–matrix adhesion, fiber distribution, fiber orientation, and manufacturing conditions. Consequently, further studies are required to optimize these parameters and maximize composite performance for structural applications (Ramesh et al.,

2022; Ramesh et al., 2023; Al Mahmud et al., 2023; Rahman et al., 2024; Hasan et al., 2021).

Use of Polyester Resin as a Composite Matrix

Polyester resin is among the most widely used thermosetting matrices in composite manufacturing because of its low cost, ease of processing, and favorable adhesion characteristics with natural fibers. In composite systems, polyester resin functions as a binding medium that transfers applied loads from the matrix to the reinforcing fibers. Furthermore, polyester resin exhibits good corrosion resistance, dimensional stability, and environmental durability, making it suitable for lightweight structural and automotive applications (Mallick, 2007; Pickering et al., 2016; Ramesh et al., 2023; Adeosun et al., 2022; Rahman et al., 2024).

Several studies have reported that the combination of coconut coir fibers and polyester resin produces composites with satisfactory mechanical properties for engineering applications. The favorable interaction between the polyester matrix and natural fibers contributes to improved impact resistance, flexural strength, and structural stability. Therefore, polyester resin was selected as the matrix material in this study to evaluate the feasibility of coconut coir fiber composites as automotive bumper materials (Adeosun et al., 2022; Ramesh et al., 2023; Rahman et al., 2024; Kumar et al., 2022; Hasan et al., 2021).

Research Gap and Research Position

The literature review indicates that previous studies have successfully demonstrated the potential of natural fibers as composite reinforcements for automotive applications. However, most investigations have focused on individual parameters such as fiber volume fraction, fiber orientation, chemical treatment, or matrix type. In addition, many studies have evaluated only a single mechanical property, such as tensile, impact, or flexural strength, without considering the interaction among influential parameters (Hasan et al., 2021; Kumar et al., 2022; Ramesh et al., 2022; Ramesh et al., 2023; Singh et al., 2024).

Research on coconut coir fiber-reinforced polyester composites that simultaneously investigates the effects of fiber volume fraction and fiber orientation on both impact and flexural strength remains limited. Furthermore, studies specifically targeting the development of such composites for automotive bumper applications are still scarce. Therefore, this study aims to address this research gap by investigating the effects of varying coconut coir fiber volume fractions and fiber orientations (random, perpendicular, and cross-ply) on the impact and flexural strength of polyester matrix composites intended for automotive bumper applications (Al Mahmud et al., 2023; Rahman et al., 2024; Ramesh et al., 2023; Adeosun et al., 2022; Singh



et al., 2024).

METHOD

This study employed an experimental method to investigate the effects of coconut coir fiber volume fraction and fiber orientation on the impact and flexural strength of polyester matrix composites intended for automotive bumper applications. The research consisted of composite specimen fabrication, mechanical testing, and statistical analysis of the experimental results. The independent variables were fiber volume fraction and fiber orientation, while the dependent variables were impact strength and flexural strength. The experimental design was developed to evaluate the individual and combined effects of these parameters on the mechanical performance of the composites.

The composite materials consisted of coconut coir fibers as reinforcement, polyester resin as the matrix, and a hardener as the curing agent. Prior to fabrication, the coconut coir fibers were cleaned and cut into lengths of 10 mm and 25 mm. Composite specimens were manufactured using the hand lay-up method with three different fiber orientations: random, unidirectional, and laminated. Before molding, the mold surface was coated with a mold release wax to facilitate specimen removal after the curing process. The selected fabrication method was chosen due to its simplicity, low cost, and suitability for producing natural fiber-reinforced composites.

The fiber composition was varied according to the mass of fibers used in each mechanical test. For impact testing, fiber masses of 0.6 g, 0.7 g, and 0.8 g were employed, while for flexural testing, fiber masses of 1.5 g, 2.0 g, and 2.5 g were used. Three specimens were prepared for each combination of fiber mass and orientation, resulting in a total of 27 impact specimens and 27 flexural specimens. The polyester resin and hardener mixture was poured into molds containing the fibers and allowed to cure for several days until the specimens reached testing conditions.

Mechanical characterization was conducted through impact and flexural tests. Impact specimens were prepared with dimensions of 10 mm × 10 mm × 55 mm in accordance with ASTM D5942-96, while flexural specimens measured 10 mm × 10 mm × 200 mm following ASTM D790. The impact test was performed to evaluate the energy absorption capability of the composites before failure, whereas the flexural test was conducted to determine the bending resistance of the material under loading conditions. All experimental testing was carried out at the Mechanical Engineering Materials Laboratory, Institut Teknologi Nasional (ITN) Malang.



The experimental data obtained from the impact and flexural tests were analyzed quantitatively using Minitab statistical software. A Two-Way Analysis of Variance (ANOVA) was employed to determine the significance of the effects of fiber volume fraction, fiber orientation, and their interaction on the mechanical properties of the composites. The results were subsequently used to identify the optimum composite configuration and to evaluate the feasibility of coconut coir fiber-reinforced polyester composites as lightweight, cost-effective, and environmentally sustainable materials for automotive bumper applications.

Research Variables

Independent Variables

- X_1 : Coconut coir fiber volume fraction (fiber mass)
- X_2 : Fiber orientation (random, unidirectional, and laminated)

Dependent Variables

- Y_1 : Impact strength
- Y_2 : Flexural strength

Controlled Variables

- Type of reinforcement fiber (coconut coir fiber)
- Matrix material (polyester resin)
- Hardener content
- Specimen dimensions
- Fabrication method (hand lay-up)
- Testing standards (ASTM D5942-96 and ASTM D790)

RESULTS AND DISCUSSION

Effect of Fiber Volume Fraction and Fiber Orientation on Impact Strength

The effect of fiber volume fraction and fiber orientation on the impact strength of coconut coir fiber-reinforced polyester composites was analyzed using a Two-Way ANOVA at a significance level of 5%. The results are presented in Table 1.

Table 1. Two-Way ANOVA Results for Impact Strength

Source of Variation	DF	Adj SS	Adj MS	F-Value	P-Value
Fiber Orientation	2	0.0156	0.00778	0.01	0.995
Fiber Volume Fraction	2	116.360	58.180	3.75	0.043*
Orientation $\times$ Volume Fraction	4	0.1472	0.03681	0.02	0.999

Significant at $\alpha = 0.05$

As shown in Table 1, only the fiber volume fraction significantly affected the impact strength of the composite, with a p-value of 0.043 (< 0.05). In contrast, fiber orientation ($p = 0.995$) and the interaction between fiber orientation and fiber volume fraction ($p = 0.999$) did not show a significant effect. These results indicate that increasing the amount of coconut coir fiber within the polyester matrix contributes more substantially to impact energy absorption than the fiber arrangement pattern.

Mechanically, a higher fiber volume fraction increases the number of fibers available to transfer and distribute stresses throughout the composite structure. During impact loading, the absorbed energy is dissipated through mechanisms such as fiber pull-out, crack deflection, and fiber bridging, thereby enhancing the toughness of the composite. These findings are consistent with those reported by Ramesh et al. (2023), who found that increasing the coconut coir fiber content improved the impact energy absorption capability of polyester-based composites.

The insignificant effect of fiber orientation suggests that the short fibers used in this study were unable to generate sufficiently different crack propagation paths among the orientation configurations. Consequently, the impact behavior of the composite was governed primarily by fiber content rather than fiber alignment. Similar observations have been reported in studies of short-fiber composites, where fiber volume fraction exerted a greater influence on impact performance than fiber orientation.

Effect of Fiber Volume Fraction and Fiber Orientation on Flexural Strength

The influence of fiber volume fraction and fiber orientation on flexural strength was also evaluated using Two-Way ANOVA. The results are summarized in Table 2.

Table 2. Two-Way ANOVA Results for Flexural Strength

Source of Variation	DF	Adj SS	Adj MS	F-Value	P-Value
Fiber Orientation	2	56.66	28.33	0.46	0.639
Fiber Volume Fraction	2	45.31	22.66	0.37	0.698
Orientation $\times$ Volume Fraction	4	443.44	110.86	1.80	0.174

Table 2 shows that all investigated factors produced p-values greater than 0.05. Therefore, neither fiber orientation, fiber volume fraction, nor their interaction significantly affected the flexural strength of the composite. These findings indicate that the variations in

fiber content employed in this study were insufficient to produce statistically significant differences in flexural performance.

The lack of significance may be attributed to the relatively uniform stress distribution among the specimens. In addition, the hand lay-up manufacturing process may have introduced voids and non-uniform resin distribution, reducing the efficiency of stress transfer from the polyester matrix to the reinforcing fibers. As a result, increasing fiber content did not necessarily lead to a proportional increase in flexural strength.

These results differ from those reported by Rahman et al. (2024), who observed a significant effect of fiber orientation on the flexural properties of coconut coir fiber-reinforced polyester composites. Such differences may be attributed to variations in fiber configuration, fiber length, manufacturing techniques, and sample size. In the present study, the selected fiber orientations did not produce sufficiently distinct stress distributions to significantly influence flexural strength.

Interaction Effect Between Fiber Volume Fraction and Fiber Orientation

In addition to evaluating the main effects of each factor, this study examined the interaction between fiber volume fraction and fiber orientation. Based on the ANOVA results presented in Tables 1 and 2, the interaction effect was not significant for either impact strength ($p = 0.999$) or flexural strength ($p = 0.174$).

The absence of a significant interaction indicates that the effect of increasing fiber volume fraction occurred independently of fiber orientation. In other words, changes in fiber orientation did not alter the trend of the fiber volume fraction effect on the mechanical properties of the composite. This finding suggests that fiber content was the dominant factor influencing composite performance, while the orientation variations used in this study were insufficient to generate a significant synergistic effect.

From a materials engineering perspective, this outcome may be attributed to the relatively narrow range of fiber volume fraction and the use of short fibers, which limited the ability of fiber orientation to control stress distribution during loading. Furthermore, the inherent variability associated with the hand lay-up process may have increased internal material variability, making the interaction effect difficult to detect statistically.

Implications for Automotive Bumper Applications

The results indicate that coconut coir fiber-reinforced polyester composites have considerable potential as alternative automotive bumper materials, particularly because their

impact performance was significantly influenced by fiber content. Impact energy absorption is one of the most critical requirements for bumper materials, as bumpers are designed to protect vehicle structures during low- to medium-speed collisions.

Although the flexural test results did not reveal significant effects of the investigated variables, the relatively stable flexural performance across all treatment combinations suggests that the developed composite possesses satisfactory mechanical stability. Considering the abundance of coconut coir waste, its low production cost, and its environmentally friendly nature, coconut coir fiber-reinforced polyester composites offer a sustainable alternative material for the automotive industry.

Overall, the findings demonstrate that fiber volume fraction is the primary factor influencing the impact resistance of coconut coir fiber–polyester composites, whereas fiber orientation and the interaction between the two variables do not significantly affect either impact or flexural properties. These results further support the novelty of this study, which simultaneously evaluates the effects of fiber volume fraction and fiber orientation on the mechanical performance of composites for automotive bumper applications.

DISCUSSION

The results of this study indicate that the coconut coir fiber volume fraction significantly affects the impact strength of polyester matrix composites, whereas fiber orientation and the interaction between these two factors do not exhibit a significant effect. These findings suggest that the impact energy absorption capability of the composite is influenced more by the amount of fiber incorporated into the material than by the fiber arrangement pattern. As the fiber content increases, the amount of energy absorbed before failure also increases. This phenomenon occurs because a higher fiber content enlarges the stress transfer area between the matrix and the reinforcement, allowing impact energy to be distributed more effectively throughout the composite structure. Furthermore, coconut coir fiber contains a relatively high lignin content, which contributes to improved toughness through mechanisms such as fiber pull-out, crack bridging, and longer crack propagation paths before fracture occurs.

These findings are consistent with those reported by Ramesh et al. (2023), who observed that increasing the coconut coir fiber content in polyester composites enhanced impact resistance up to an optimum composition. Similar results were reported by Al Mahmud et al. (2023), who demonstrated that coconut fibers effectively improve impact energy absorption compared with composites without fiber reinforcement. The agreement between the present findings and previous studies confirms the potential of coconut coir fiber as a reinforcement

material for composite structures requiring high toughness, particularly in automotive applications subjected to dynamic loading conditions.

In contrast to the impact test results, statistical analysis of the flexural test revealed that fiber volume fraction, fiber orientation, and their interaction did not significantly influence the flexural strength of the composites. This outcome suggests that the fiber mass variations employed in this study were insufficient to generate statistically significant differences in flexural stress distribution. Moreover, the hand lay-up manufacturing process may have resulted in non-uniform fiber distribution and the formation of voids within the composite structure. The presence of voids can reduce the efficiency of stress transfer from the matrix to the reinforcement fibers, meaning that an increase in fiber content does not necessarily lead to a corresponding increase in flexural strength.

The insignificant effect of fiber orientation on both impact and flexural properties is also noteworthy. Theoretically, fiber orientation influences stress distribution and crack propagation paths in composite materials. However, the fibers used in this study were relatively short, with lengths of 10 mm and 25 mm, and therefore the differences among random, unidirectional, and laminated orientations were insufficient to produce significant variations in mechanical behavior. In addition, the relatively small specimen dimensions used in the impact test allowed the impact energy to be distributed almost uniformly throughout the specimen, reducing the influence of fiber orientation compared with that of fiber content.

The present findings differ from those reported by Rahman et al. (2024), who found that fiber orientation significantly affected both the impact and flexural properties of coconut coir fiber-reinforced polyester composites. These discrepancies may be attributed to differences in orientation configurations, manufacturing methods, fiber lengths, and the degree of fiber distribution homogeneity within the matrix. In Rahman et al.'s study, the fibers were arranged more systematically, resulting in a clearer relationship between the loading direction and fiber alignment. In contrast, some of the fiber arrangements used in the present study may still have allowed non-uniform fiber distribution, thereby reducing the observable differences in mechanical properties among treatment groups.

The interaction analysis between fiber volume fraction and fiber orientation showed that these two factors did not significantly influence each other in either the impact or flexural tests. This result indicates that changes in fiber orientation did not alter the effect of fiber volume fraction on the mechanical properties of the composites. In other words, the effect of increasing fiber content occurred independently of the fiber arrangement used. The absence of a significant interaction effect may also suggest that the range of fiber volume fractions investigated was

relatively narrow and therefore insufficient to generate a synergistic effect between the two factors. Future studies should consider wider variations in fiber content or apply surface treatments to improve fiber–matrix interfacial bonding and better reveal potential interaction effects.

From an application perspective, the results demonstrate that coconut coir fiber-reinforced polyester composites have potential as alternative materials for automotive bumpers. The improvement in impact energy absorption with increasing fiber content represents a critical characteristic required for bumper components. In addition to providing satisfactory mechanical performance, coconut coir fiber offers several advantages, including low production cost, abundant availability, and reduced environmental impact compared with synthetic reinforcement materials. Therefore, the development of coconut coir fiber composites represents a promising sustainable material solution for the future automotive industry.

Overall, the findings indicate that fiber volume fraction is the dominant factor affecting the impact resistance of coconut coir fiber–polyester composites, while fiber orientation does not significantly influence either impact or flexural properties under the conditions investigated. These findings reinforce the novelty of this study, which evaluates the simultaneous effects of fiber volume fraction and fiber orientation on the mechanical performance of composites intended for automotive bumper applications, and provide a scientific basis for the further development of lightweight and environmentally friendly natural fiber composite materials.

CONCLUSION

This study investigated the effects of coconut coir fiber volume fraction and fiber orientation on the impact and flexural strength of polyester matrix composites for automotive bumper applications. The Two-Way ANOVA results revealed that fiber volume fraction significantly affected impact strength, with a p-value of 0.043 (< 0.05), whereas fiber orientation and the interaction between the two factors showed no significant influence. The increase in fiber content enhanced the composite's ability to absorb impact energy due to the greater number of fibers participating in stress distribution and crack propagation resistance. However, for flexural performance, neither fiber volume fraction, fiber orientation, nor their interaction exhibited a statistically significant effect on the flexural strength of the composite.

Overall, the findings demonstrate that coconut coir fiber-reinforced polyester composites have considerable potential as alternative automotive bumper materials due to their good impact energy absorption capability, abundant raw material availability, relatively low production cost, and environmentally friendly characteristics. The main contribution of this

study is the identification of fiber volume fraction as the dominant factor influencing the impact resistance of coconut coir fiber–polyester composites. These findings provide valuable insight for the development of sustainable natural fiber-reinforced composites and support their future application in the automotive industry.

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