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Mechanical Testing Analysis of Hybrid Composites of Oil Palm Empty Fruit Bunch Fibre and Sugarcane Bagasse Fibre for Environmentally Friendly Car Body Materials

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ABSTRACT

Indonesia generates large quantities of agro-industrial waste, including oil palm empty fruit bunch (OPEFB) and sugarcane bagasse, which have potential as sustainable reinforcing materials for polymer composites. This study investigated the effect of OPEFB–bagasse fibre composition on the mechanical properties of epoxy-based hybrid composites fabricated using the hand lay-up method. Five composite formulations with a constant epoxy content of 50% and varying OPEFB-to-bagasse ratios were prepared and evaluated through tensile, flexural, impact, and scanning electron microscopy (SEM) analyses. The hybrid composite containing 30% OPEFB, 20% bagasse, and 50% epoxy exhibited the best overall mechanical performance, achieving a tensile strength of 16.78 MPa, a flexural strength of 59.95 MPa, an impact toughness of 3.08 kJ/m², and a Young's modulus of 8.80 GPa. SEM observations revealed good fibre–matrix adhesion and fibre pull-out mechanisms that contributed to improved energy absorption. Statistical analysis showed that fibre composition significantly affected flexural strength ($p = 0.047$), whereas its effects on tensile strength and impact toughness were not statistically significant ($p > 0.05$). The developed hybrid composite exhibited mechanical properties comparable to several previously reported natural fibre-reinforced epoxy composites, indicating its potential for lightweight non-structural automotive body applications.

Keywords: Automotive materials, empty oil palm bunches, hybrid composite, mechanical properties, sugarcane bagasse

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INTRODUCTION

The development of natural fibre-based composite materials has accelerated over the last decade, particularly for automotive applications (Borůvka & Lenfeld, 2018; Skosana et al., 2025). Natural fibre composite materials offer the advantages of being lightweight, environmentally friendly, and having lower production costs compared to synthetic fibres such as carbon and glass (Joshi et al., 2004). Sugarcane bagasse and empty oil palm fruit bunches (*Elaeis guineensis*) (EOPFB) are examples of natural materials that can be processed into composites. In addition to the advantages mentioned above, these materials are abundantly available in Indonesia. According to a 2023 report from the Ministry of Agriculture, Indonesia produces approximately 3.5 million tons per year, with approximately 2.8 million tons of bagasse remaining annually, while oil palm empty fruit bunch (OPEFB) waste reaches 25 million tons per year, opening opportunities to utilise both types of waste as composite raw materials. Utilising this waste as a composite reinforcement can reduce environmental pollution while increasing economic value (Nurfajriani et al., 2022).

Fibres derived from sugarcane bagasse contain between 40-50% cellulose (Mahmud & Anannya, 2021), with a tensile modulus of 2.7 GPa (Devadiga et al., 2020). These characteristics make them a potential and effective composite reinforcement. Meanwhile, OPEFB fibre has a high length-to-diameter ratio (100-150), which improves load distribution in the resin matrix (Rama Rao & Ramakrishna, 2022). The combination of these two fibres is expected to produce a synergistic effect in increasing tensile strength and impact resistance, which are critical for alternative automotive body applications. Epoxy resin was chosen as the matrix in the composite manufacturing because it has a relatively high tensile strength, which is between 35-50 MPa and good chemical resistance. These properties comply with the ASTM D638 standard for automotive applications, making epoxy resin well-suited to improving car performance. Although the potential of natural fibres has been recognised, the main challenge still lies in the low fibre-matrix interfacial compatibility due to the hydrophilic nature of natural fibres and the hydrophobicity of thermoset resins (Behera et al., 2023). Previous research has shown that lignin removal with alkali (5-10% NaOH) and increasing the effective surface area can increase the tensile strength of composites by up to 30% (Holanda et al., 2024). However, further study is needed to determine the optimal fibre percentage, particularly for automotive component applications. Therefore, this study will analyse the effect of fibre percentage (30-70% by weight).

From an environmental perspective, the use of natural fibres can reduce CO_2 emissions by up to 70% compared to synthetic fibres. This is because the natural fibre production process does not require high energy consumption. Life Cycle Assessments (LCAs) show that the production process for natural fibre composites can produce up to 50% lower carbon emissions (Ramachandran et al., 2023). However, their application in the automotive industry remains limited due to a lack of empirical data and standard testing methods specific to natural fibre composites. This research aims to address this gap by generating mechanical property data and technical recommendations for automotive body materials.

Various recent studies have shown the great potential of bagasse fibre and other agro-industrial waste as reinforcing materials for polymer-based composites (Al Mahmud et al., 2025). studied a hybrid composite of areca nut fibre and bagasse in an epoxy matrix, with a fibre content of 23 wt%, which produced low thermal conductivity (0.163 W/mK) and a tensile strength of 30 MPa, thus having the potential as an environmentally friendly lightweight insulation material. The effect of varying the length of bagasse fibres in unsaturated polyester composites, with longer fibres increasing tensile strength by up to 32.11 MPa and providing a more uniform stress distribution. Furthermore, a hybrid composite based on bagasse, rice husk, and sawdust was studied (Velmurugan et al., 2023), with tensile strength ranging from 16–20 MPa, confirming the potential of multi-agricultural waste for low-cost composites.

Recent research also highlights sustainability aspects and the use of artificial intelligence (AI) technology. One aspect of sustainability is the use of natural fibres in composite materials. Samanth et al. (2025) developed a hybrid composite of bagasse with bio-epoxy, showing a tensile strength of ~62 MPa, a flexural stiffness of ~92 MPa, and a Tg of 92 °C, plus a 45% reduction in carbon footprint due to the use of bio-epoxy. Faruqui et al. (2024) compared alkali-treated and untreated bagasse powder in an epoxy composite, where 20 wt% treated powder resulted in significant improvements in tensile strength, impact strength, and toughness, strengthening the application prospects in the automotive and construction industries (Faruqui et al., 2024).

A comprehensive study was also conducted by Mahmud et al. (2025) on various epoxy-based natural fibre composites (Al Mahmud et al., 2025). This study emphasised that the fibres jute, flax, hemp, sisal, and pineapple nanofibers can increase tensile strength up to 1627 MPa, with various applications in the automotive industry, aerospace, furniture, and construction.

Finally, Aisyah et al. (2024) reviewed hybrid composites of palm oil fibre combined with various other natural fibres. The study results showed significant improvements in mechanical, thermal, and environmental resistance, although they were still hampered by high humidity and fibre-matrix bonding.

Several researchers have investigated natural fibre composites for automotive applications. However, most have focused on the use of single fibres (monofibers) such as hemp or kenaf (Maiti et al., 2022). Research on hybrid composites based on bagasse fibre and empty oil palm fruit bunches remains very limited, particularly regarding the use of epoxy resins, which require complex analysis of intercomponent interactions.

The novelty of the present study lies not only in combining two abundant agro-industrial wastes, namely OPEFB fibre and sugarcane bagasse fibre, but also in systematically investigating the effects of different OPEFB-to-bagasse volume ratios at a constant epoxy matrix content. Unlike previous studies that primarily focused on single natural fibres or hybrid composites for thermal insulation and general engineering applications, this work integrates comprehensive tensile, flexural, impact, and SEM fractography analyses to identify the optimum hybrid composition for lightweight automotive body materials. The findings provide new experimental evidence regarding the synergistic interaction between OPEFB and bagasse fibres and their influence on load transfer, fracture behaviour, and energy absorption, thereby contributing to the development of sustainable natural fibre composites for automotive applications.

Research Gap

From the results of the literature study that has been carried out (Table 1), the following research comparison matrix was obtained:

1. Although hybrid natural fibre composites have been widely investigated, studies specifically examining epoxy-based hybrid composites reinforced with both OPEFB fibre and sugarcane bagasse fibre remain limited.

Table 1
Research gap

No.	Author	Material	Method	Matrix	Variation
1	Mahmud et al., 2025	Areca Nut Fibre and Sugarcane Bagasse	*Vacuum Bag*	Epoxy	NaOH soaking *Purity* 99,9%
2	Velmurugan et al., 2023	Sugarcane Bagasse, Rice Husk and Sawdust	*Hand Lay-Up*	Epoxy	Volume Variation
3	Samanth et al., 2025	Sugarcane Bagasse	*Hand Lay-Up*	Bio-Epoxy and Epoxy	Uses of Bio-Epoxy and Epoxy
4	Faruqui et al., 2024	Sugarcane Bagasse	*Vacuum Bag*	Epoxy	Alkali Treatment
5	Al Mahmud et al., 2025	Sisal fibre, Hamp and pineapple nanofiber	*Vacuum Bag and Hand Lay-Up*	Epoxy	Material Variations
6	Aisyah et al., 2024	Palm Oil Fibre (EFB, OPT, OPF, MF, PKS)	*Vacuum Bag and Hand Lay-Up*	Epoxy and Polyester	Material Variations
7	Present study	Oil Palm Empty Fruit Bunch Fibre and Sugarcane Bagasse Fibre	*Hand Lay-Up*	Epoxy	Volume Variation

2. Limited studies have comprehensively evaluated the mechanical performance, particularly tensile and impact properties, of epoxy-based hybrid natural fibre composites for lightweight and energy-efficient vehicle body applications.
3. Existing studies have provided limited systematic evaluation of the effects of varying OPEFB-to-bagasse fibre ratios in epoxy-based hybrid composites. Comparative investigations of different fibre compositions under a constant epoxy matrix content remain relatively scarce.
4. Although natural fibre-reinforced composites have shown considerable potential for lightweight automotive applications, further experimental evidence is needed to assess the feasibility of epoxy-based OPEFB–bagasse hybrid composites in achieving the mechanical performance required for vehicle body components while supporting lightweight design strategies that may contribute to lower CO_2 emissions.

MATERIALS AND METHODS

Figure 1 shows the flowchart for this study. Oil palm empty fruit bunch (OPEFB) fibres and sugarcane bagasse fibres were used as reinforcing materials, while Eposchon epoxy resin served as the matrix. The fibres were cleaned, cut into a uniform length of 30 mm, and oven-dried at 80°C for 24 h until the moisture content was below 5%, as determined according to ASTM D4442. Untreated fibres were intentionally employed to evaluate the intrinsic reinforcing capability of agricultural waste fibres while minimising processing cost and environmental impact, thereby assessing their feasibility as sustainable reinforcement for low-cost automotive applications.

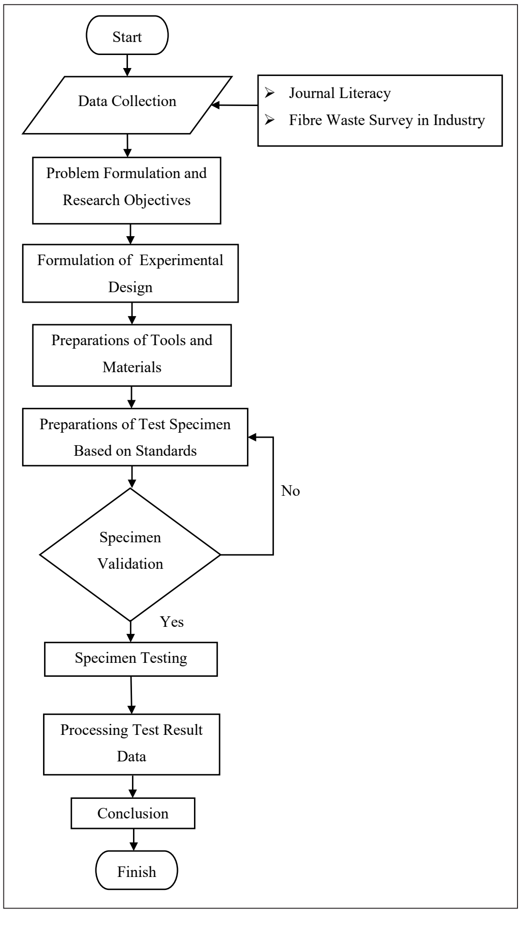

Figure 1. Research flow diagram

Five composite formulations were prepared using the hand lay-up technique: S50 (50% EOPFB/50% epoxy), T50 (50% bagasse-50% epoxy), S20 (20% EOPFB-30% bagasse-50% epoxy), S25 (25% EOPFB-25% bagasse-50% epoxy), and S30 (30% EOPFB-20% bagasse-50%

epoxy). The fibres were randomly oriented within the epoxy matrix to produce hybrid composite laminates.

Before fabrication, the mould surface was coated with a releasing agent to facilitate specimen removal. After the fibre–resin mixture was placed into the Mold, the laminate was compressed using a steel plate under an applied pressure of approximately 0.5 MPa during curing. The composites were initially cured at room temperature (27 ± 2°C) for 24 h, followed by post-curing at 80°C for 2 h to ensure complete polymerisation. The cured laminates were machined into test specimens according to the dimensions specified by the respective mechanical testing standards.

Tensile, flexural, and impact tests were performed in accordance with ASTM D638, ASTM D7264, and ISO 179, respectively. Five specimens were tested for each composition, and the results are presented as mean ± standard deviation (SD). The coefficient of variation (CV) was calculated to evaluate the repeatability of the fabrication process. One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was used to determine statistically significant differences among the composite formulations. Statistical significance was accepted at $p < 0.05$. Fracture surfaces of the mechanically tested specimens were analysed using scanning electron microscopy (SEM) to evaluate fracture morphology, fibre pull-out behaviour, and fibre–matrix interfacial bonding.

Preparation of Materials

Sugarcane

Sugarcane fibre is obtained from the waste product of sugarcane processing in factories, then washed and dried manually. The fibres, initially measuring 70-150 cm, are cut to a uniform length of 30 mm for use in research is shown in Figure 2.

Palm Oil

Empty oil palm fruit bunch fibre is used as a hybrid material, mixed with bagasse fibre (as shown in Figure 3) to create a composite. The empty oil palm bunches are separated from their thorny stalks and then dried in the sun for 1-3 days. The fibre is then combed with a steel comb to aid decomposition and refined to 30 mm, as required by the research.

Epoxy

The present study used Eposchon Epoxy. The epoxy matrix consisted of epoxy resin and polyamine hardener mixed at a weight ratio of 100:20 according to the manufacturer's recommendation. The mixture was stirred manually for approximately 5 min until homogeneous before impregnation.

Figure 2. Sugarcane bagasse fibre

Figure 3. Empty fruit bunch fibre

Testing

Tensile Test

Tensile testing aims to determine a material's ability to withstand a given tensile force. Tensile testing is destructive because the composite specimen is subjected to continuous tensile force until it elongates and eventually breaks. The tensile test specimen is shown in Figure 4, while tensile specimen printing can be seen in Figure 5.

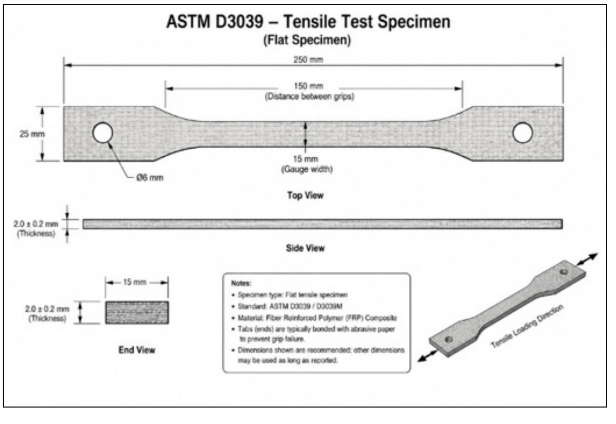

Figure 4. ASTM D3039 – tensile test specimen

Figure 5. Tensile specimen

Flexural (Bending) Test

A bending test aims to determine the strength, durability, and flexibility of a composite specimen under load. Bending testing uses the 3-point method and tests at a speed of 2 mm/min. The flexural test specimen is shown in Figure 6, and the printing specimen is shown in Figure 7.

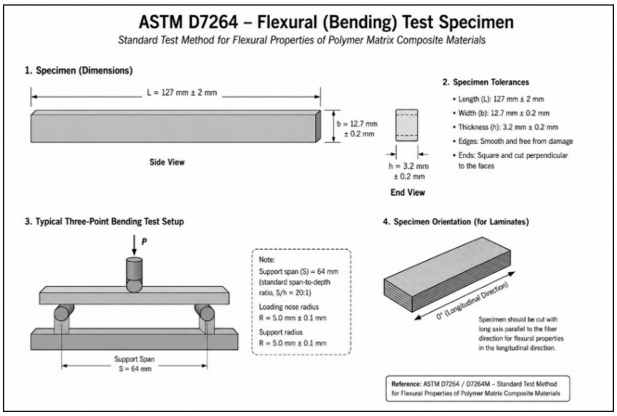

Figure 6. ASTM – flexural (bending) test specimen

*Figure 7.*Flexural (bending) specimen

Impact Test

The Charpy impact test was selected because it is widely used to evaluate the impact toughness of fibre-reinforced polymer composites under dynamic loading conditions. This method provides quantitative information on the composite's energy absorption capacity before fracture, an important performance parameter for lightweight automotive body materials subjected to accidental impacts. Furthermore, the Charpy test enables correlation between impact energy absorption and fracture mechanisms observed through SEM fractography, such as fibre pull-out, matrix cracking, and interfacial debonding. The speed applied for the testing was 2 mm/min. The Charpy impact test specimen (unnotched) is shown in Figure 8, and the printing specimen is shown in Figure 9.

SEM Test

Scanning Electron Microscopy (SEM) is a material characterisation method that uses an electron beam to produce images of a material's surface at very high magnifications. SEM testing is used to observe the morphology, topography, and microstructure of a material that cannot be observed with a conventional optical microscope.

RESULTS AND DISCUSSIONS

Tensile Strength Test Result

Based on the tensile strength test results in Table 2 and Figure 10, the specimen with the S50 code has an average maximum stress of 12.64 MPa. The specimen with the T50 code

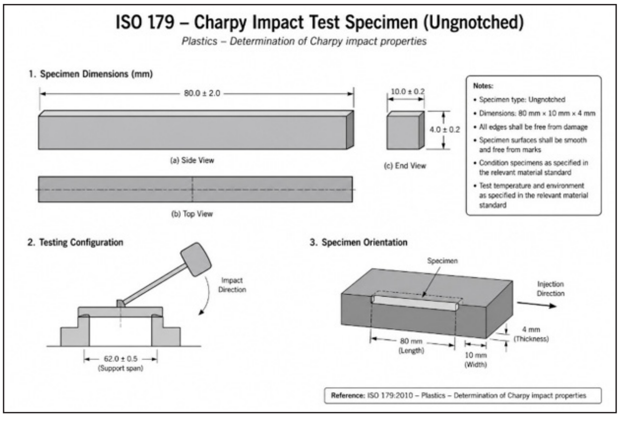

Figure 8. ISO 179 – Charpy impact test specimen (unnotched)

Figure 9. Impact specimen

Table 2
Test result

Tensile Strength (MPa)					
Statistical Parameter	**S50**	**T50**	**S30**	**S25**	**S20**
Average	12.50	11.96	16.78	16.42	15.48
St Dev	4.42	3.86	1.46	4.08	1.47
CV	35%	32%	9%	25%	9%
Flexural Strength (MPa)					
Statistical Parameter	**S50**	**T50**	**S30**	**S25**	**S20**
Average	49.00	51.04	59.95	39.07	48.31
St Dev	8.36	4.95	10.82	13.92	8.34
CV	17%	10%	18%	36%	17%
Impact Toughness (kJ/m²)					
Statistical Parameter	**S50**	**T50**	**S30**	**S25**	**S20**
Average	2.84	1.75	3.19	2.72	2.44
St Dev	1.43	0.52	1.51	0.35	0.32
CV	50%	30%	47%	13%	13%

has an average maximum stress of 11.96 MPa, while the specimen with the S30 code has an average maximum stress of 16.78 MPa. The specimen with the S25 code has an average maximum stress of 16.42 N/mm², and the specimen with the S20 code has an average maximum stress of 15.48 N/mm². It can be concluded that the highest average maximum stress value is found in the specimen with code S30, and the lowest one is found in the specimen with code T50.

The S30 hybrid composite exhibited the highest tensile strength, indicating that the selected OPEFB-to-bagasse fibre ratio provided the most efficient stress transfer from the

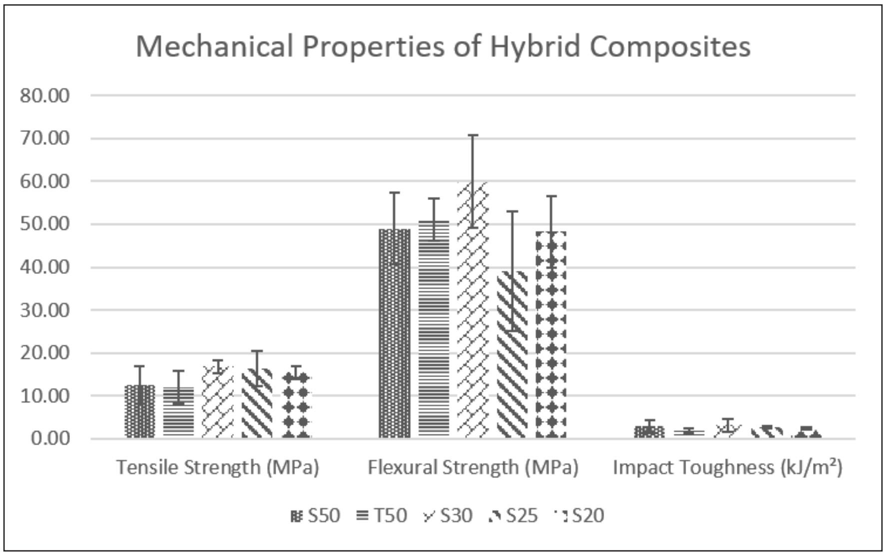

Figure 10. Mechanical properties of hybrid composites

epoxy matrix to the reinforcing fibres. Under tensile loading, effective interfacial adhesion allows the applied load to be transferred from the relatively ductile epoxy matrix to the stiffer natural fibres, thereby delaying crack initiation and propagation. The balanced proportion of OPEFB and bagasse fibres in the S30 formulation likely promoted a more homogeneous fibre distribution and reduced stress concentration sites compared with the other formulations. Consequently, the composite sustained higher tensile loads before failure.

Although the S25 composite contained a comparable amount of reinforcement, its lower tensile strength may be attributed to less uniform fibre distribution and localised resin- or fibre-rich regions. Such heterogeneity can reduce the efficiency of load transfer and promote premature interfacial debonding during tensile loading.

One-way ANOVA indicated that the effect of fibre volume fraction on tensile strength was not statistically significant ($F = 2.28$, $p = 0.096$). Although the S30 formulation exhibited the highest average tensile strength, the observed differences among formulations may be attributed to specimen variability and the inherent heterogeneity of natural fibre composites.

Flexural Strength Test Result

Based on the bending strength test results below, the specimen with code S50 has an average maximum load of 43,394 N, and the specimen with code T50 has an average maximum load of 45,292 N. Furthermore, the specimen with code S30 has an average maximum load of 53,202 N, while the specimen with code S25 produces an average maximum load of 58,625 N. The specimen with code S20 has an average maximum load of 42,867 N and an average maximum stress of 48,307 MPa. It can be concluded that the highest average flexural strength is observed in specimen S25, and the lowest in specimen S20.

During flexural loading, the upper surface of the specimen experiences compressive stress, whereas the lower surface is subjected to tensile stress. Therefore, the quality of fibre–matrix bonding becomes particularly important in resisting crack initiation on the tensile side of the specimen. The superior flexural performance of the S30 composite suggests stronger interfacial bonding, allowing the applied bending load to be more effectively distributed throughout the hybrid reinforcement.

One-way ANOVA revealed a statistically significant effect of fibre volume fraction on flexural strength ($F = 2.92$, $p = 0.047$), indicating that the hybrid fibre composition significantly influenced the bending performance of the composites. This result suggests that optimising the OPEFB-to-bagasse fibre ratio enhances stress distribution and load-bearing capability under flexural loading.

Impact Test Result

Based on the impact test results below, the S50 specimen has an average maximum impact toughness of 2,840 kJ/m². While the T50 specimen test results have an average maximum impact toughness of 1,746 kJ/m². The S30 specimen test results show an average maximum impact toughness of 3,084 kJ/m². Then, the S25 specimen test results produce an average maximum impact toughness of 2,716 kJ/m². While the S20 specimen has an average maximum impact toughness of 2,442 kJ/m². It can be concluded that the highest average maximum impact toughness is observed in S30.

Unlike tensile loading, impact loading involves rapid energy absorption within a very short time. Therefore, the impact toughness of hybrid composites depends not only on fibre strength but also on the ability of the fibre–matrix interface to dissipate fracture energy through mechanisms such as fibre pull-out, matrix deformation, crack deflection, and interfacial debonding. The higher impact toughness observed for the S30 composite indicates that these energy absorption mechanisms were more effectively activated than in the other formulations.

The ANOVA results showed that the differences in impact toughness among the composite formulations were not statistically significant ($F = 1.52$, $p = 0.233$). Although S30 exhibited the highest average impact toughness, the relatively large variability among specimens reduced the statistical evidence for differences between formulations.

Young's Modulus Results

The Young's modulus of the hybrid OPEFB–bagasse epoxy composites as shown in Table 3 ranged from 7.55 to 9.95 GPa, with the highest value obtained by the S20 composite, followed by S25 (9.70 GPa) and S30 (8.80 GPa). The increase in Young's modulus indicates that the hybridisation of OPEFB and bagasse fibres improved the stiffness of the composite through more efficient stress transfer and stronger fibre–matrix interfacial bonding. Conversely, the lower S50 modulus may be attributed to less effective resin impregnation and localised defects associated with the higher OPEFB fibre content. The obtained modulus values are comparable to those reported for natural fibre-reinforced epoxy composites, while the low coefficient of variation (7-23%) indicates good measurement repeatability and composite consistency.

Table 3
Young's modulus calculation

Number	**Young's Modulus (GPa)**				
	Code				
	S50	T50	S30	S25	S20
1	7.36	8.05	9.62	9.42	10.73
2	9.51	7.23	9.17	10.60	10.27
3	5.03	8.05	9.29	9.24	9.09
4	6.97	6.85	7.30	8.99	9.41
5	8.90	8.90	8.63	10.25	10.27
Total	**37.77**	**39.08**	**44.00**	**48.49**	**49.75**
Average	**7.55**	**7.82**	**8.80**	**9.70**	**9.95**
St Dev	**1.76**	**0.80**	0.91	0.69	0.68
CV	23%	10%	10%	7%	7%

SEM Results

SEM observations of the fracture surface of the S30 specimen revealed a rough and irregular morphology. This indicates a complex fracture mechanism involving matrix cracking, fibre pullout, and fibre-matrix debonding. Several voids observed on the fracture surface were related to fibre pullout, indicating that a significant amount of tensile energy was lost during fibre extraction from the epoxy matrix. In addition, residual epoxy on the fibre surface indicated adequate interfacial bonding between the fibre and the matrix, thereby promoting effective stress transfer. Although a small number of voids were observed, they were not sufficient to significantly reduce mechanical performance. The relatively homogeneous fibre distribution and balanced fibre-matrix composition contributed to enhanced energy absorption and resistance to crack propagation, consistent with the superior tensile strength (16.78 MPa) and impact toughness (3,084 kJ/m²) of the S30 specimen.

Comparison to the Previous Studies

As shown in Table 4, the mechanical properties obtained in this work are comparable to those reported for natural fibre composites intended for lightweight automotive body panels. Overall, the developed hybrid composite exhibited mechanical properties comparable to or superior to those of several natural fibre-reinforced epoxy composites proposed for automotive applications.

For tensile strength, the present study achieved values ranging from 11.96 to 16.78 MPa, which are comparable to those reported by Marichelvam et al. (2021) (6.45-19.80 MPa) but higher than those reported by Dattatreya et al. (2023) (4.76-9.18 MPa). However,

Table 4
Comparison to the previous studies

Mechanical Property	Present Study	Ref A (Marichelvam et al., 2021)	Ref B (Dattatreya et al., 2023)	Ref C (Venkatesh et al., 2023)
Tensile Strength (MPa)	11.96-16.78	6.45-19.8	4.76-9.18	43.39-48.23
Flexural Strength (MPa)	39.07-59.95	8.99-28.79	1.52-9.6	59.58-67.48
Impact Toughness (kJ/m²)	1.75-3.19	1.35-2	1.2-2	11.91-15.32

the tensile strength remained lower than that reported by Venkatesh et al. (2023) (43.39-48.23 MPa). The superior tensile performance reported is likely associated with differences in fibre type, fibre architecture, interfacial bonding, and fabrication process, all of which strongly influence stress transfer from the epoxy matrix to the reinforcing fibres (Venkatesh et al., 2023). Improved fibre alignment and stronger interfacial adhesion generally enhance tensile strength by promoting more efficient load transfer.

In terms of flexural strength, the present study produced values of 39.07-59.95 MPa, exceeding those reported by Marichelvam et al. (2021) (8.99-28.79 MPa) and Dattatreya et al. (2023) (1.52-9.60 MPa), while approaching the performance reported by Venkatesh et al. (2023) (59.58-67.48 MPa). The higher flexural strength indicates that the selected hybridisation ratio between OPEFB and bagasse fibres provided effective resistance against bending loads. Under flexural loading, compressive and tensile stresses act simultaneously; therefore, uniform fibre distribution and adequate resin impregnation significantly delay crack initiation and propagation.

Regarding impact toughness, the present study achieved 1.75-3.19 kJ/m², which is higher than those reported by Marichelvam et al. (2021) (1.35-2.00 kJ/m²) and Dattatreya et al. (2023) (1.20-2.00 kJ/m²). This suggests that the hybridisation of OPEFB and bagasse fibres enhanced the composite's energy absorption capability. The presence of two distinct natural fibres may promote multiple energy-dissipation mechanisms, including fibre pull-out (as shown in Figure 11), crack deflection, matrix deformation, and progressive fibre fracture, thereby increasing resistance to sudden impact loading. These mechanisms are commonly observed in hybrid natural fibre composites and contribute to improved impact performance.

Overall, the comparison demonstrates that the proposed hybrid composite offers a balanced combination of tensile, flexural, and impact properties as shown in Table 4. Although its tensile strength is lower than that of the composite developed by Venkatesh et al. (2023), the present material exhibits superior flexural strength and impact toughness compared with several previously reported natural fibre composites. These findings indicate that the developed hybrid composite has promising potential for lightweight, non-structural automotive body components where bending resistance and impact energy absorption are critical performance requirements.

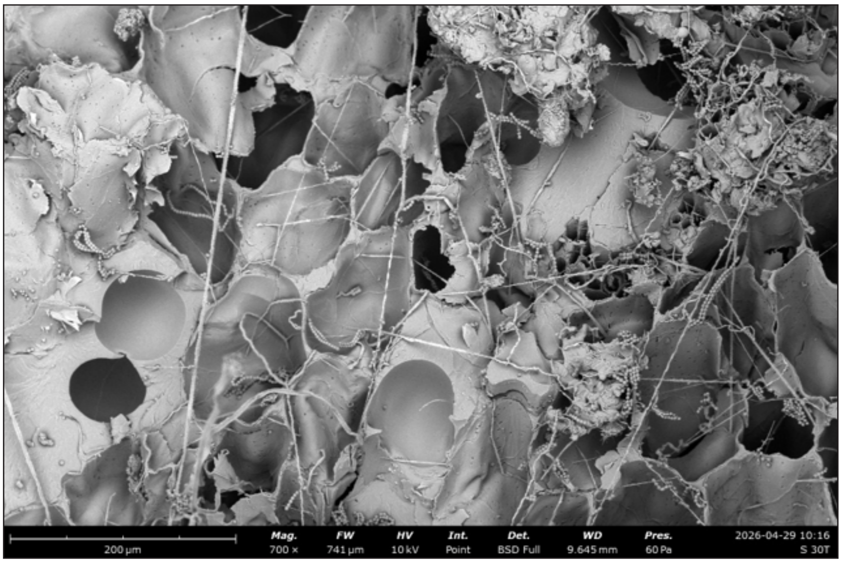

Figure 11. SEM micrograph of the S30 fracture surface

CONCLUSION

The hybrid composite containing 30% OPEFB, 20% bagasse, and 50% epoxy exhibited the best overall mechanical performance, achieving a tensile strength of 16.78 MPa, a flexural strength of 59.95 MPa, an impact toughness of 3.08 kJ/m², and a Young's modulus of 8.80 GPa. SEM analysis revealed good fibre–matrix adhesion and fibre pull-out mechanisms that enhanced energy absorption. Statistical analysis indicated that fibre composition significantly influenced flexural strength ($p = 0.047$), whereas its effects on tensile strength and impact toughness were not statistically significant ($p > 0.05$). Compared with previous studies, the developed hybrid composite demonstrated competitive mechanical properties, particularly in flexural strength and impact toughness, indicating its potential as a sustainable material for lightweight non-structural automotive body applications.

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AUTHOR CONTRIBUTION

AS: Conceptualisation, Methodology, Supervision, Validation, Writing-review & editing, Corresponding author; AM: Methodology, Validation, Formal analysis, Writing -review

& editing; SF: Investigation, Data curation, Software, Formal analysis, Visualisation, Writing-original draft.

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