Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN : 2549-1999 No. : 5 Month : October
p-ISSN : 1693-5462 Volume : 23 Year : 2025

Processing dates: received on 2025-09-25, reviewed on 2025-10-20, accepted on 2025-10-26 and online availability on 2025-10-31

Mechanical and impact performance of oil palm trunk fiber composites for crash box applications

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Abstract

The increasing demand for lightweight and sustainable materials in automotive safety components has driven interest in natural fiber composites. Abundant oil palm trunk waste in South Kalimantan presents a promising, low-cost source for composite reinforcement. This study aims to analyze the crashworthiness performance of crash box structures using oil palm trunk fiber composites as an environmentally friendly alternative material. The research method involved the fabrication of composite specimens with fiber orientations of 30°, 60°, and 90°, using epoxy resin as the matrix. Mechanical testing included tensile tests based on ASTM D638-02 and Charpy impact tests based on ASTM D6110. The tensile test results showed that fiber orientation significantly affects the mechanical properties of the composites. The 60° orientation exhibited the highest tensile strength and elastic modulus, while the 30° orientation demonstrated the highest elongation, indicating better ductility. The 90° orientation showed intermediate performance but tended to be brittle. The impact test results revealed that the 60° fiber orientation had the highest toughness in absorbing impact energy, whereas the 30° and 90° orientations displayed lower toughness. Overall, the 60° fiber orientation of oil palm trunk composites shows potential for crash box applications, as it provides a balance between strength and toughness, although its brittleness still requires further consideration.

Keywords:
Oil palm trunk fiber, natural composites, tensile strength, impact toughness, crash box, sustainable materials.

1 Introduction

Materials for downstream industries play a crucial role in achieving agricultural sector resilience and expanding the sector's economic scale. One of the fastest-growing agricultural sectors is the oil palm plantation in South Kalimantan Province, Indonesia. This region has geographical and climatic conditions that support oil palm

The oil palm trunk, which is considered waste in plantations, can be a potential source of lignocellulosic material. To overcome the scarcity of construction wood, the development of crash boxes made from oil palm trunk fibers is one of the proposed solutions [4].

Energy absorbers play an essential role in crash analysis [5]. Composite materials are suitable for this application due to their high specific modulus, strength, and chemical stability [6]. Based on previous studies, fibers from empty oil palm fruit bunches have good sound absorption properties, but research on their mechanical properties remains relatively limited compared to other natural fibers. In this study, such composites will be tested for impact resistance in crash box structures [7]. Recent trends to improve structural performance include adopting bio-inspired design principles. Biological materials demonstrate superior mechanical performance and multifunctional characteristics related to their surrounding environment [8].

The crash box is a key component of a vehicle's passive safety system that functions to absorb impact energy before it reaches the passenger cabin. The performance of a crash box is determined by three critical characteristics: specific energy absorption (SEA), progressive failure, and controlled deformation. Materials with high SEA can efficiently absorb impact energy while maintaining a low mass, whereas progressive failure ensures that the collapse occurs gradually, resulting in a more stable impact force. Controlled deformation guarantees that the crash box folds along the designed direction without losing its structural integrity [9]-11]. Understanding these principles is essential for evaluating the potential of oil palm stem fiber composite materials as an environmentally friendly alternative for crash box structures, particularly through the analysis of mechanical properties such as tensile strength and impact toughness [12-13].

At present, metals and other metallic materials have not yet undergone significant development. In essence, as technology continues to advance, the demand for higher technological performance increases, thereby requiring the development of materials that are compatible with modern technological progress [14]. Green technology, or environmentally friendly technology, is being increasingly pursued by countries around the world, presenting an ongoing challenge for researchers to support such advancements. One of the key developments in this area is composite technology utilizing natural fibers [15]. Experimental studies on the feasibility analysis of composite panels under axial impact provide a comprehensive review of their crashworthiness [16]. A concrete and feasible example of a multimaterial vehicle body has been demonstrated through the main outcomes of evaluation projects [17]. A basic design of an automotive crash box employing efficient corrugated conical tubes has also been proposed [9]. Furthermore, various multi-cell design concepts have been evaluated for the crashworthiness of thin-walled aluminum tubes [18]. The maximum strength of a material refers to its ability to withstand the highest level of stress before fracture occurs. The maximum strength value is determined by dividing the maximum load by the cross-sectional area. The highest point of the stress–strain curve is known as the ultimate strength [19].

Experimental and theoretical studies on axially crushed corrugated metal tubes have been conducted to investigate their deformation and energy absorption behavior [20]. The fabrication of bio-based thermal insulators from oil palm stem fibers has been examined in terms of their thermal, physical, and mechanical properties [21]. Similarly, grooved circular foam-filled tubes under axial compression have been analyzed experimentally to evaluate their crashworthiness [22]. Research on the structural and acoustic performance of thermoplastic polyurethane elastomer composites made from tree bark waste has also demonstrated promising results [12]. Other studies have focused on improving vehicle crashworthiness through the introduction of energy absorbers and the study of their implementation [11], as well as the design feasibility of novel hierarchical hexagonal columns [10]. Furthermore, a numerical design and crashworthiness analysis of an electric vehicle front bumper system using aluminum material for a two-passenger configuration has been carried out [23].

Studies on polyester composites reinforced with wood powder revealed that the size and volume fraction of fillers significantly affect the material's strength and stiffness [24]. Other research reported that chemical treatment of natural fibers can enhance the interfacial bonding between matrix and fiber phases, thereby improving tensile strength and impact toughness [25]. The application of the Vacuum Assisted Resin Infusion (VARI) method has also been proven to improve resin distribution homogeneity and enhance the mechanical properties of natural fiber composites [26]. In addition, research on sandwich composite structures has shown a significant increase in bending strength and weight efficiency, making them suitable for lightweight structural applications [27]. Variations in organic and inorganic filler volume fractions in epoxy composites have also been found to optimize tensile strength and material toughness [28].

The use of natural fibers in composite materials can reduce weight, increase strength, and improve handling and processability. Natural fibers also enhance crack resistance and provide better post-cracking behavior. Natural fibers such as oil palm fibers are considered sustainable construction materials due to their low production cost and environmentally friendly characteristics. Oil palm stem fibers offer advantages as a raw material that is readily available, has low production costs, and comes from a renewable natural resource [13].

To evaluate the potential of oil palm stem fibers, experimental testing is required to determine the strength and stiffness of composite materials reinforced with these fibers and bonded with epoxy as the matrix. Lamination can be performed using either unidirectional or cross-oriented fiber arrangements [29]. It is expected that composites made from oil palm stem fibers with varying fiber orientations will exhibit improved mechanical properties. Therefore, conducting research on the Crashworthiness Performance Analysis of Crash Box Structures Using Oil Palm Stem Fiber Composites is essential.

2 Research methodology

The first step in this study was to prepare all the necessary tools and materials, followed by calculating the composite composition, including the ratio of resin and catalyst. The type of resin used was epoxy resin, with a fiber-to-resin ratio of 5%:95%. The relatively low fiber percentage was due to the reduced fiber mass after the drying process. Oil palm trunk fibers (OPTF) with an average fiber length of 30 mm were used to ensure a uniform fiber distribution within the composite matrix. After confirming that all compositions met the specified requirements, the composite specimens were fabricated with fiber orientations of 30°, 60°, and 90°, and molded according to ASTM D638-02 for tensile testing and ASTM D6110 for impact testing. Once all specimens met the standard dimensions, tensile and impact tests were conducted on each specimen.

2.1 Specimen fabrication

Before obtaining fibers ready for molding, several preparation stages were required in the fabrication of composite specimens, as shown in Figure 1.

Fig. 1. Composite specimen fabrication process

Based on Figure 1, the process of preparing composite test specimens begins with the felling of the tree and the separation of the inner stem section. The stem is then soaked until the fibers can be separated from the natural matrix, followed by a cleaning and alkali treatment using a 5% NaOH solution for several hours to remove lignin and hemicellulose and to enhance the interfacial adhesion between the fibers and the matrix. Afterward, the fibers are washed to a neutral pH and dried at room temperature, making them ready for use as reinforcement in the composite.

The composite fabrication process is carried out by mixing Epoxy Resin type 108 with a hardener, using a composition ratio of 5% oil palm stem fibers and 95% resin–hardener mixture. The molding process is performed at room temperature (±27°C) with a curing time of 24 hours until the composite is fully hardened. To ensure accurate fiber orientation, a custom-designed molding jig equipped with an angular guide is used to position the fibers at 30°, 60°, and 90° orientations relative to the loading direction. Before the resin curing process, the fiber angles are verified using a protractor to ensure proper alignment and repeatability across all specimens. After curing, the hardened composites are cut and shaped into tensile and impact test specimens according to the applicable testing standards.

2.2 Tensile test

The tensile test is conducted to determine the response of the composite material when subjected to axial tensile loading until fracture occurs. This method aims to obtain the tensile strength of the composite, as shown in Figure 2.

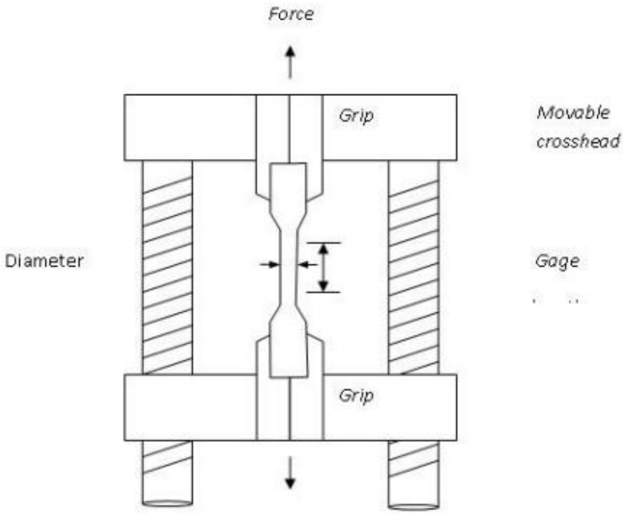

Fig. 2. Tensile test sketch

In this study, tensile test specimens were prepared with dimensions based on ASTM D638-02 (Standard Test Method for Tensile Properties of Plastics), as shown in Figure 3-4.

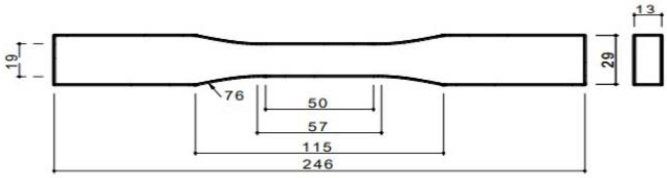

Fig. 3. Specimen dimensions

Fig. 4. Tensile test specimen

After the specimens were fabricated, tensile testing of the oil palm trunk fiber composites was performed, as shown in Figure 5.

Fig. 5. Tensile test of composites

Figure 5 shows the universal testing machine (UTM) Tensilon RTF-2410 used for tensile testing of composite specimens. The specimens were mounted vertically between two grips at the top and bottom of the machine. During testing, the grips moved apart, applying an axial tensile force to the specimen. The machine was equipped with a load cell to measure the applied force and a displacement sensor to record elongation. The test results were presented in the form of stress–strain curves, which were used to determine the mechanical properties of the composites, including ultimate tensile strength, elastic modulus, and fracture strain. The tensile test also revealed the failure mechanisms of the composites, such as fiber fracture, matrix cracking, and interlayer delamination.

2.3 Impact Test

The impact test was conducted to determine the toughness of the composite material against sudden shock or impact loads. This test requires a single force application to fracture the specimen, using the apparatus shown in Figure 6.

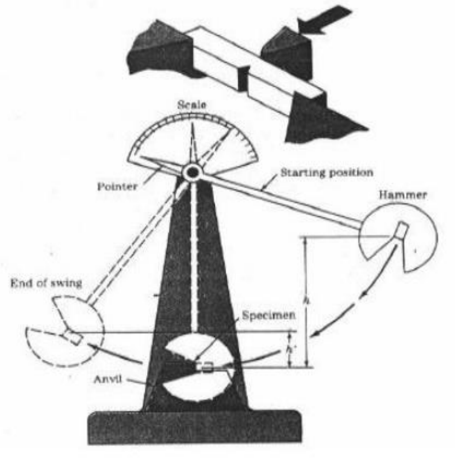

Fig. 6. Charpy impact test

In this study, the fabricated specimens were tested using the Charpy method to determine their ductility or brittleness. The Charpy method was selected because it provides more accurate impact resistance data.

The impact test specimens were prepared with dimensions based on ASTM D6110 (Standard Test Method for Determining the Charpy Impact Resistance of Notched Specimens of Plastics), as shown in Figure 7.

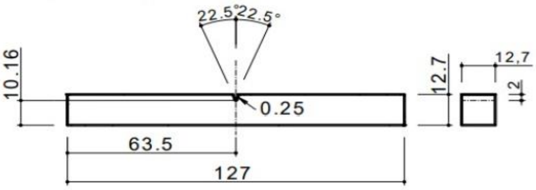

Fig. 7. Dimensions of charpy specimen

Fig. 8. Impact test specimen

After specimen preparation, impact testing was performed on the oil palm trunk fiber composites, as shown in Figure 9.

Fig. 9. Impact test of composites

Figure 9 shows the impact testing machine used to evaluate the toughness of the composite materials against sudden impacts. In this test, the composite specimen was clamped into a special fixture located at the center of the machine. A pendulum hammer was then released from a certain height to strike the specimen with a specific amount of energy. The energy absorbed by the specimen upon fracture was displayed on the monitor in Joules. This absorbed energy value represents the impact toughness of the composite and serves as an indicator of the material's resistance to damage from impact. The test also revealed composite failure mechanisms such as delamination, matrix cracking, and fiber breakage.

3 Results and discussion

Tensile and impact tests were carried out using 15 samples for each variable, with the test results taken from the average values of the specimens. The data obtained from the tensile tests included stress, strain, maximum load, and elastic modulus. Meanwhile, the data obtained from the impact tests consisted of fracture energy and impact strength. These results were then used to determine which oil palm trunk fiber composite exhibited the best performance. The test results were presented in the form of graphs to make the findings more concise and easier to understand. Additional detailed test data are provided in the appendix.

3.1Tensile test results

After completing the tensile testing of the composite specimens (Fig. 10), the final data were processed to compare which fiber orientation demonstrated the highest strength according to ASTM D638-02 standards. The test results are presented in the form of Tables 1 and Figure 11-14.

Fig. 10. Tensile test result

The test results showed that all specimens fractured at the middle section (gauge length), which is the area with the smallest cross-section. The observed failure pattern was dominated by fibrous fracture, with indications of failure mechanisms including fiber breakage and fiber pull-out from the matrix.

Table 1. Tensile test results.

No	Variable	Fiber Orientation (°)	Initial Angle (°	Final Angle (°)	Energy (J)	Impact (J/m)
1	D1	30	130	124,7	0,2364	18,612
2	D2		130	121,2	0,4012	31,589
3	D3		130	123,7	0,2828	22,267
4	D4		130	124,5	0,2456	19,340
5	D5		130	124,4	0,2502	19,704
6	E1	60	130	124,8	0,2318	18,249
7	E2		130	124,5	0,2456	19,340
8	E3		130	122,0	0,4591	36,150
9	E4		130	121,0	0,5593	55,993
10	E5		130	123,0	0,3550	28,000
11	F1	90	130	123,7	0,2828	22,267
12	F2		130	124,7	0,2364	18,612
13	F3		130	124,0	0,2692	21,190
14	F4		130	123,5	0,2646	20,800
15	F5		130	122,0	0,3487	27,457

Table 1 presents the tensile test results of oil palm trunk fiber composites with fiber orientations of 30°, 60°, and 90°. The measured parameters include maximum stress, representing the highest tensile strength the material can withstand; strain, describing the material's ability to elongate before fracture; maximum load carried by the specimen; and elastic modulus, indicating the stiffness of the material. These data provide an overview of how fiber orientation affects the mechanical properties of the composites in terms of strength, ductility, and stiffness.

Based on the tensile test results shown in the table, fiber Based on the tensile test results presented in the table above, fiber orientation has a significant influence on the mechanical properties of oil palm stem composites. For variable A (fiber orientation 30°), the maximum stress ranges from 11.9 to 25 MPa, with a relatively high strain value of 2.44%–3.66%. The average elastic modulus of approximately 440.5 MPa indicates that the material with this orientation tends to be more ductile, although its tensile strength is lower compared to other orientations. Meanwhile, variable B (fiber orientation 60°) shows a significant improvement in tensile performance, with a maximum stress reaching 42 MPa and a maximum load of 19.523 kN. The highest elastic modulus of 1395.2 MPa indicates that the material at this orientation exhibits the greatest tensile strength and stiffness, although the strain is relatively low (1.63%–2.44%), suggesting that it is strong but less ductile.For variable C (fiber orientation 90°), the maximum stress reaches 39.6 MPa with a maximum load of 17.792 kN. The average elastic modulus of approximately 997.4 MPa shows that the material has a relatively high tensile strength, but with low strain (around 1.63%), making it more brittle in nature. Overall, the results indicate that the 60° fiber orientation provides the best combination of strength and stiffness, while the 30° orientation yields a more ductile behavior, and the 90° orientation tends to be brittle yet strong.

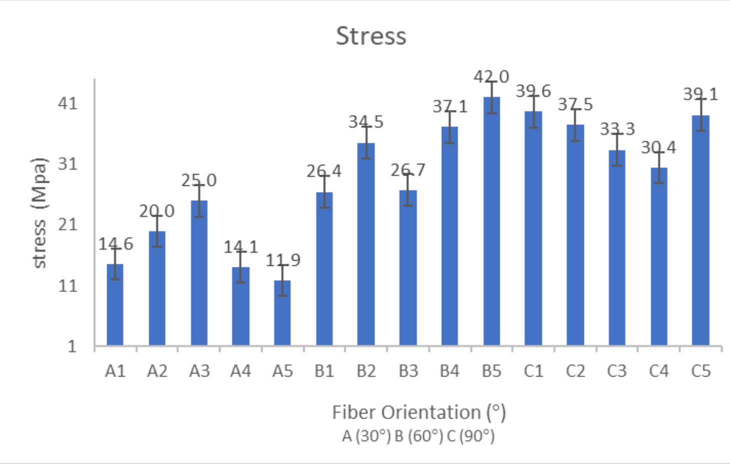

Fig. 11. Stress graph

Figure 11 shows the fiber orientation of 60° exhibited the highest average tensile stress, approximately 32.94 MPa, indicating that this orientation provides the greatest tensile strength of the composite material. The 90° orientation ranked second, with an average tensile stress of about 35.98 MPa, showing a high tensile strength but slightly lower than that of the 60° orientation. Meanwhile, the 30° fiber orientation produced the lowest average tensile stress, around 17.52 MPa, suggesting that the material with this orientation has lower tensile strength but tends to exhibit greater ductility compared to the other orientations.

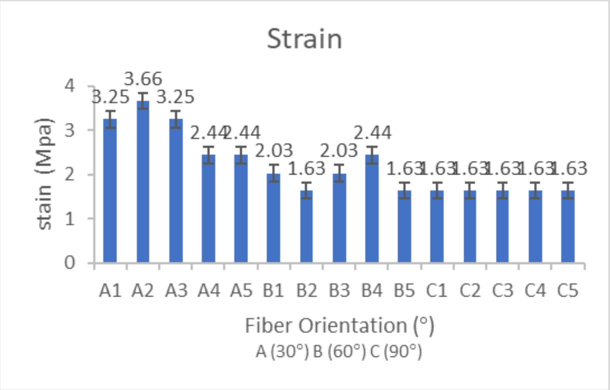

Fig. 12. Strain graph

The 30° fiber orientation exhibited the highest average strain of 3.01%, indicating greater ductility of the material. The 60° orientation produced a strain of only 1.95%, while the 90° orientation was even lower at 1.63%, showing that these two orientations are more brittle compared to the 30° orientation.

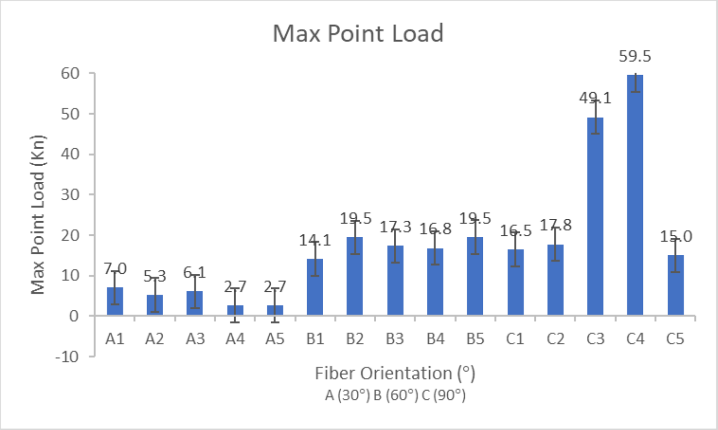

Fig. 13. Maximum load graph

The highest average maximum load was observed at the 60° fiber orientation with 17.45 kN. The 90° orientation ranked second with 12.03 kN, while the 30° orientation was much lower at only 4.755 kN, indicating the lowest load-bearing capacity.

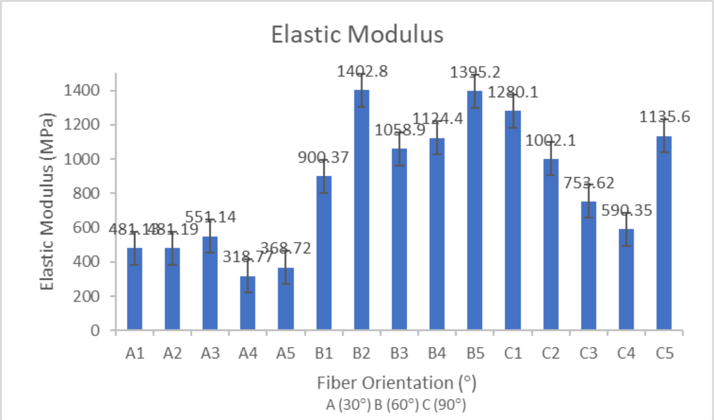

Fig. 14. Elastic modulus graph

The 60° fiber orientation recorded the highest elastic modulus of 1176.33 MPa, indicating the stiffest material with the greatest resistance to deformation. The 90° orientation had a value of 952.35 MPa, while the 30° orientation was the lowest at 440.19 MPa, reflecting a more flexible behavior.

3.2 Charpy impact test results

This test aims to determine the mechanical property of impact strength on specimens with specified shapes and dimensions according to ASTM 6110 standards. The following are the impact test results of oil palm stem fiber composites, as shown in Figure 15-17 anda Table 2.

Fig. 15. Impact Test Result

Figure 15. shown the test results showed that all specimens fractured in the middle section, specifically in the area directly subjected to the pendulum impact load. The observed damage pattern indicated a combination of several failure mechanisms. Most specimens exhibited a dominant fiber pull-out, where fibers detached from the matrix, leaving the fiber surfaces clearly visible after fracture. This indicates that part of the impact energy was absorbed through the debonding mechanism between the fibers and the matrix.

Table 2. Impact test results.

No	Variable	Fiber Orientation (°)	Initial Angle (°)	Final Angle (°)	Energy (J)	Impact (J/m)
1	D1	30	130	124,7	0,2364	18,612
2	D2		130	121,2	0,4012	31,589
3	D3		130	123,7	0,2828	22,267
4	D4		130	124,5	0,2456	19,340
5	D5		130	124,4	0,2502	19,704
6	E1	60	130	124,8	0,2318	18,249
7	E2		130	124,5	0,2456	19,340
8	E3		130	122,0	0,4591	36,150
9	E4		130	121,0	0,5593	55,993
10	E5		130	123,0	0,3550	28,000
11	F1	90	130	123,7	0,2828	22,267
12	F2		130	124,7	0,2364	18,612
13	F3		130	124,0	0,2692	21,190
14	F4		130	123,5	0,2646	20,800
15	F5		130	122,0	0,3487	27,457

The impact test Table 2 presents the test data for three composite specimen variables, namely D, E, and F, each consisting of five specimens with V-notches. The tests were carried out using a pendulum load of 5.5 Joules with an initial angle of 130°. The results recorded the final angle after impact, the absorbed energy in Joules, and the impact strength in J/m. Variations in the final angle of each specimen resulted in differences in absorbed energy and impact strength, reflecting the composite's ability to withstand impact loads.

For Variable D (D1–D5), the absorbed energy ranged from 0.2364 to 0.2828 Joules, with impact strength values between 18.612 and 22.267 J/m, indicating that this variable exhibited relatively low to moderate toughness. For Variable E (E1–E5), the absorbed energy ranged from 0.2318 to 0.4591 Joules, with impact strength values between 18.249 and 36.150 J/m, where the highest value was recorded by specimen E4 at 36.150 J/m, making this variable the toughest. Meanwhile, for Variable F (F1–F5), the absorbed energy ranged from 0.2364 to 0.3487 Joules, with impact strength values between 18.612 and 27.457 J/m, placing it at a moderate toughness level, between variables D and E.

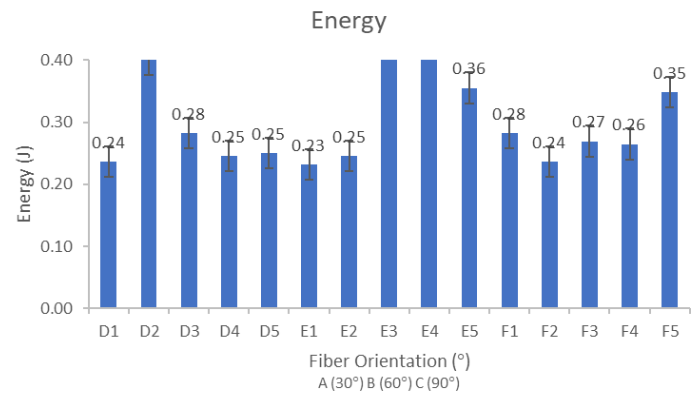

Fig. 16. Energy graph

Figure 16 shows the average energy absorbed during the impact test, indicating that variable D has an average energy of 0.2832 Joules, variable E recorded the highest average energy of 0.3702 Joules, while variable F showed an average energy of 0.2803 Joules. This indicates that the composite specimens of variable E were able to absorb more impact energy compared to variables D and F, thus exhibiting better toughness against impact loads.

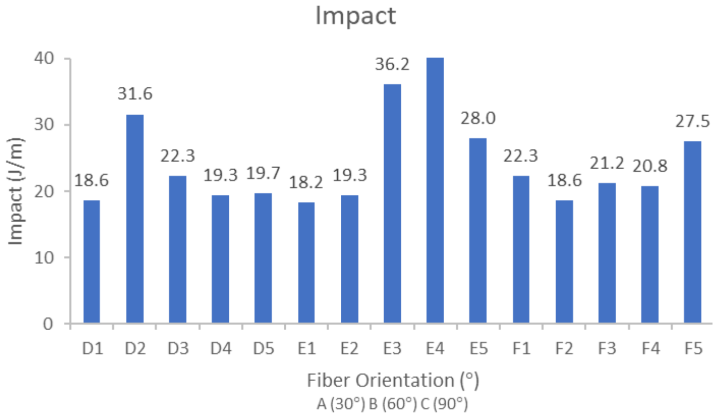

Fig. 17. Impact strength graph

Figure 17 shows the average impact strength results, that variable D has an average value of 22.302 J/m, variable E recorded the highest average of 29.946 J/m, while variable F has an average of 22.465 J/m. These results indicate that the composite in variable E exhibited the highest toughness against impact loads, whereas variables D and F showed relatively similar toughness, both lower than variable E.

There was no clear correlation between the tensile and impact data, indicating a trade-off between strength and toughness that affects the crashworthiness behavior. The 60° fiber orientation exhibited the highest tensile strength and stiffness but was relatively brittle, while the 30° orientation showed greater ductility and energy absorption capacity despite lower strength. Meanwhile, the 90° orientation had moderate strength but low toughness due to inefficient stress transfer. This trade-off suggests that combining different fiber orientations could optimize both structural strength and energy absorption. Therefore, the composite made from oil palm trunk fibers is considered feasible for crash box applications, especially when using hybrid or layered orientations to balance strength and toughness.

4. Conclusion

Based on the tensile and impact test results, fiber orientation significantly affects the mechanical behavior of oil palm trunk fiber composites. The 60° orientation exhibited the highest tensile strength, stiffness, and impact toughness, while the 30° orientation showed greater ductility but lower strength. The 90° orientation displayed intermediate properties yet remained relatively brittle. Although the 60° configuration demonstrated superior overall performance, its brittleness suggests that hybrid or multi-layer designs may be required for crash box applications. From a practical perspective, the results indicate that composites with 60° fiber orientation offer promising potential for lightweight, energy-absorbing structures, particularly when combined with design strategies that enhance ductility. Therefore, the 60° orientation shows potential for use, particularly as part of a material combination for crash boxes, as it provides a balance between strength and toughness.

Acknowledgment

The authors would like to express their deepest gratitude to the Directorate of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology, through the BIMA – Kemdikti Saintek program, for their financial support and facilitation in the implementation of this research.

Thanks are also extended to LLDIKTI Region XI and Politeknik Batulicin for their support, motivation, and collaboration throughout the research process.

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