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The Effect of Fiber Orientation and Composition on Mechanical Properties of Coconut Fiber-Reinforced HDPE Waste Polymer Composites

Wahyu Ramadhan[1], Zulnazri[2*] , Andre Yosi[1], Reza Putra[4], Safira Fitri[1], Syariful Maliki[3]

[1] Department of Chemical Engineering, Faculty of Engineering, Universitas Malikussaleh, Lhokseumawe, Aceh, Indonesia
[2] Center of Excellence of Technology Natural Polymer and Recycle Plastics Universitas Malikussaleh, Kampus Bukit Indah, Lhokseumawe, Indonesia
[3] Department of Industrial Chemical Technology, Chemical Engineering, Politeknik Negeri Sriwijaya
[4] Department of Chemical Engineering, Faculty of Engineering, Universitas Malikussaleh, Lhokseumawe, Aceh, Indonesia
[*]E-mail addresses: zulnazri@unimal.ac.id

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ABSTRAK

Penelitian ini mempelajari pengaruh arah serat dan komposisi terhadap sifaat mekanik pada komposit polimer limbah HDPE berpenguat serat serabut kelapa. Diharapkan komposit yang diperkuat dengan serat sabut kelapa akan menunjukkan peningkatan sifat mekanik yang baik dan sebagai produk material alternatif. Penelitian ini terdiri dari empat tahap yaitu persiapan limbah HDPE dan serat serabut kelapa, perendaman menggunakan xylen+MAH (HDPE) dan hexane+BPO (serat), pembuatan komposit menggunakan mesin hot press, dan pengujian mekanik (tarik dan impak) pada komposit. Orientasi serat pada penelitian ini adalah vertikal, horizontal, dan acak dengan masing-masing variasi fraksi volume ialah 90:10, 80:20, 70:30, dan 60:40. pengujian yang dilakukan yaitu uji tarik, uji impak, dan pengamatan mikroskopik. Uji tarik menggunakan standard ASTM D3039, *uji impak menggunakan standard ASTM D256-03. Hasil yang didapat pada penelitian ini ialah nilai kuat tarik tertinggi didapatkan pada orientasi vertikal dengan variasi komposisi 60:40 dengan nilai kuat tarik 27.85 MPa, dan nilai kuat impak tertinggi didapatkan pada orientasi horizontal variasi 90:10 dengan nilai tenaga impak 18.62 Joule. Orientasi dan variasi komposisi sangat mempengaruhi nilai kekuatan pada material komposit dikarenakan serat berfungsi menahan beban pada komposit.*

ABSTRACT

The purpose of research is to study the effect of fiber orientation and composition on the mechanical properties of coconut fiber-reinforced HDPE waste polymer composite. It is expected that composites reinforced with coconut fiber will show good mechanical properties and can be used as alternatif material product. This research consists of four stages, which is preparation of High Density Polyethylene (HDPE) waste and coconut fiber, soaking using xylene + MAH (HDPE) and hexane + BPO (fiber), and making composites using hot press machine, and mechanical testing (tensile and impact) on composites. The fiber orientation in this study is vertical, horizontal, and random with variation of volume fraction 90:10, 80:20, 70:30, and 60:40. The tests carried out tensile tests, impact tests, and microscopic observations. ASTM D3039 is used as standard for tensile tests and ASTM D256-03 for impact test. The result of this study shows the highest tensile strength value is 27.85 MPa for composite with vertical orientation and composition variation 60:40 and the highest impact strength value is 18.62 Joule for composite with horizontal orientation and composition variation 90:10. Orientation and composition variations have significant affect for the tensile strength of the composite material because the fiber functions to withstand the load on the composite.

1. INTRODUCTION

Plastic is a material that is very widely used in human life, resulting in a lot of plastic waste that is very difficult to decompose. According to a report from the United Nations Environment Programme (UNEP), Indonesia produces more than 6 million tons of plastic waste every year. This makes Indonesia one of the largest plastic waste producers in the world, after China. Most of this plastic waste comes from single-use plastic products that are widely used in everyday life, such as plastic bags, plastic bottles, and packaging. More than 6 million tons of plastic are discarded every year, and most of this plastic is HDPE. (UNEP, 2018). Some studies show that HDPE has a higher recycling rate than other plastics, but overall, only a small portion is successfully recycled. According to a report from the World Economic Forum, about 30% of HDPE plastic in developed countries is recycled. (World Economic Forum, 2016).

According to data from the Ministry of Environment and Forestry (KLHK), as reported by Kompas.id, the projected amount of plastic waste in Indonesia has continued to increase over the past decade. This is in line with the projected amount of national general waste, which has also continued to increase over the same period. In 2017, for example, the projected amount of national plastic waste reached 9.2 million tons. This amount is equivalent to 13.98% of the total volume of waste generated in Indonesia. Domestic plastic waste generation is projected to continue increasing from 2017 to 2025. Meanwhile, plastic waste generation in 2025 is projected to reach 9.9 million tons, also equivalent to 13.98% of the total volume of waste generated during that period.

Natural fibers as fillers for polymer composites are increasingly being used in materials engineering. The reasons for using natural fibers as reinforcements for composite materials are their availability, affordability, variety, and wide variety. One natural fiber that can be used as a composite reinforcement is sisal fiber. This type of fiber is derived from the leaf sheaths of the sisal plant after undergoing a fiber separation process. (Zulmiardi, 2022).

Coconut fiber waste (coco fiber) is discarded annually, although the exact amount can vary depending on the location and volume of coconut production in a region. In Indonesia, one of the largest coconut-producing countries, coconut production can reach tens of millions of tons per year. Coconut fiber, also known as "coir," is often produced from the coconut husk removal process, and its fiber is used to make various products such as mats and plant pots, as well as raw materials for the textile and automotive industries.

Composites

Composites are one type of material that exists today, alongside other materials such as metals, polymers, and ceramics. Composite materials are multiphase materials, namely a mixture of two or more types of materials, with the mixing of which no chemical reaction occurs. The properties of composite materials are a combination of the properties of the constituent materials, namely the matrix and reinforcement or filler, where both have different properties. The provisions for reinforcing materials must be able to support/improve the properties of the matrix in forming composite materials. (Tjahjanti, 2018).

Coconut Fiber

Polymer composites with natural fibers such as coconut fiber have advantages when compared to synthetic fibers, coconut fiber composites are cheaper in terms of price compared to synthetic fibers. Coconut fiber is a product derived from the outer skin of coconuts, specifically from the outer part of the coconut. Coconut fiber has a rough and stiff texture, coconut fiber also has advantages compared to other natural fibers. Coconut fiber has quite advantageous properties, where it has a length of 10-20 cm, is resistant to microorganisms, rot, and also mechanical activities such as being hit or rubbed, and is lighter in weight than other fibers. (R. Kaliyan & M. Venkatesan, 2019).

Figure 1. Coconut Fiber

High-Density Polyethylene (HDPE)

HDPE (High-Density Polyethylene) is a type of polyethylene with a high density, due to its more regular and dense molecular structure compared to low-density polyethylene (LDPE). HDPE is a thermoplastic polymer used in a variety of applications due to its strength, chemical resistance, and ability to withstand higher temperatures. HDPE is often used in the manufacture of plastic containers, pipes, toys, and various other consumer products. A breakdown of HDPE plastic can be seen in Figure 2.

Figure 2. Shredded HDPE Plastic

Tensile Testing

A tensile test is the application of tensile force or stress to a material to determine or detect its strength (Salindeho, 2018). This test can determine the mechanical properties of the material, which are essential for engineering design. Tensile strength is the maximum stress that a test specimen can withstand before breaking or being damaged, the maximum load divided by the initial cross-sectional area of the test specimen. The tensile test is based on a damaged specimen under static testing conditions, and the results obtained are in the form of tensile strength. Tensile testing is carried out to determine the tensile strength of the composite material. Testing is carried out using a Universal Testing Machine. Tensile test specimens are formed according to the ASTM D 3039 standard, as shown in Figure 2.4 below:

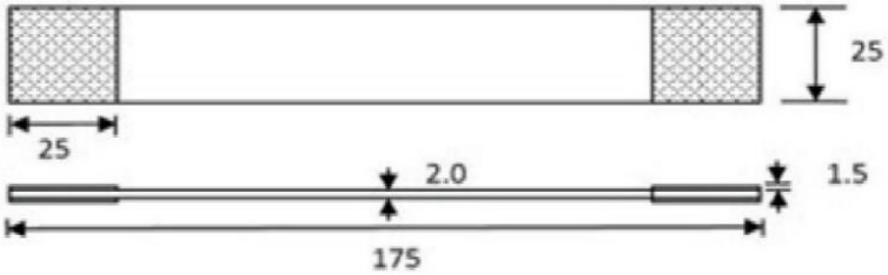


Figure 3. ASTM D 3039 Specimen

Tensile testing is used to assess the strength of composite materials by applying a uniaxial force load. The results obtained from tensile testing are crucial for engineering and product design because they provide data on the material's strength. From this tensile testing, we can determine several mechanical properties of the material, which are essential in engineering design. The linear relationship between stress and strain can be seen in the equation below:

Voltage formula:

$$\sigma = F/A \quad (1)$$

Strain formula:

$$\varepsilon = \Delta L/Lo\ x\ 100\% \quad (2)$$

Modulus of elasticity formula:

$$E = \sigma/\varepsilon \quad (3)$$

Impact Test

The toughness of a composite can be determined using an impact test. This test measures the toughness, or ability of a material to absorb energy before breaking (toughness). Impact testing is performed on standard test bar specimens. The material to be tested is initially formed into a test bar with a specific standard shape. The center of the test bar is the part that receives the stress.

Impact testing is a method used to determine the strength, hardness, and ductility of a material. Therefore, impact testing is widely used in the field of assessing the mechanical properties of a material (Wardani, 2017).

Impact testing uses the Charpy impact test method. The principle of the Charpy impact test aims to determine the level of resistance or ductility of a material, and the test is performed on a machine according to ASTM D 256-03. This can be seen in Figure 4 below:

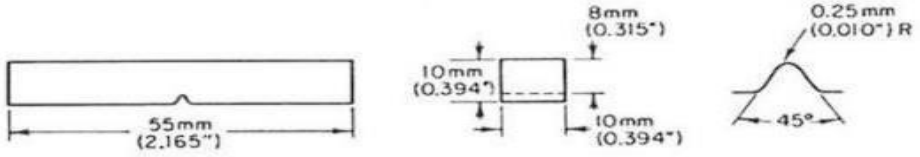


Figure 4. Impact Test Specimen

The breaking force is the pendulum lifted at an angle of less than 150°C, thus generating potential energy. To calculate the energy absorbed by the material, use the following potential energy equation:

Broken power formula:

$(W) = m.\, r\, (\cos \beta - \cos \alpha)$ (4)

Impact Price:

$W/A =$ (5)

Microscopic Observation

Microscopy is the process of viewing and analyzing the structure of a material at a microscopic scale using tools such as an optical microscope, digital microscope, or electron microscope. In the context of composite material testing, microscopy aims to understand the internal characteristics of the material that cannot be seen with the naked eye.

The primary function of microscopy in testing is to evaluate the quality and structural integrity of the material. For example, in the composite manufacturing process, microscopy can be used to ensure that fibers are evenly distributed and that there are no agglomerations or voids that could reduce the material's strength. Furthermore, microscopy also plays a crucial role in failure analysis, namely identifying the type and cause of damage in composites, such as cracks due to mechanical loading or thermal degradation.

Volume fraction

Volume fraction is an important parameter in composite material design. Volume fraction indicates the ratio of the volume of a component to the total volume of the composite. The components whose volume fraction is usually calculated are fiber (Vf) and matrix (Vm). The volume fraction value significantly influences the mechanical and thermal properties of the composite, such as tensile strength, elastic modulus, and resistance to delamination (Daniel & Ishai, 2006).

Determining the volume of the composite mold :

$Vc = (P\ x\ L\ x\ T)$ (6)

Fiberless composite volume :

$Vm = Vc\ x\ \rho m$ (7)

Composite volume without matrix :

$Vs = Vc\ x\ \rho s$ (8)

Determine the volume of the composite :

$Vk = (\%\ serat\ x\ Vs) + (\%\ matrik\ x\ Vm)$ (9)

2. METHOD

The research was conducted at the Materials Engineering Laboratory and the Mechanical Engineering Laboratory at Malikussaleh University. The study consisted of several stages, starting with the preparation of tools and materials, preparation for sample testing, and data collection. The overall study was conducted from April 2025 to June 2025.

Tools in Research

In this study, several tools and equipment were utilized to support the composite fabrication and characterization processes. The equipment included molds with dimensions of 13 × 18 × 0.3 cm and 3.5 × 6 × 1 cm, which were used for sample shaping. A hot press machine was employed for the thermal pressing process under controlled temperature and pressure. A digital scale was used for accurate material weighing. Mechanical testing was conducted using a tensile testing machine and an impact testing machine to evaluate the composite's mechanical properties. In addition, a digital microscope was used for microstructural observation of the samples, and a mini grinder machine was utilized for sample surface preparation prior to testing.

Material in Research

The materials used in this study include shredded high-density polyethylene (HDPE) waste as the polymer matrix, coconut coir fiber as the reinforcing material, and aluminum foil as a mold liner to prevent adhesion between the sample and the mold surface. Distilled water (aquadest) was used as a soaking medium for the fibers. Additionally, 100 ml of xylene was used as a solvent for the initiator, while maleic anhydride (MAH) at a concentration of 2.5% served as a compatibilizing agent to improve interfacial adhesion between the matrix and filler. Hexane (100 ml) was used as the solvent for MAH, and benzoyl peroxide (BPO) at a concentration of 0.25% was utilized as the initiator for the polymerization process.

Composite Manufacturing

The fabrication of the composite material commenced with the immersion of coconut coir fibers in distilled water for 1 hour to enhance fiber wettability and remove surface impurities. The fibers were then sun-dried for 24 hours to eliminate residual moisture. Subsequently, a curing agent solution was prepared by dissolving 0.1 grams of benzoyl peroxide (BPO) in 100 ml of xylene. From this solution, 20 ml was extracted and mixed with the matrix material based on the predetermined variable composition. In parallel, a compatibilizer solution was prepared by dissolving 2.5 grams of maleic anhydride (MAH) in 100 ml of hexane, from which 20 ml was taken and combined with the filler according to the specified formulation.

After all components were ready, the materials were arranged in a mold following the sandwich method, consisting of a layer of high-density polyethylene (HDPE), a layer of treated coconut coir fiber, and another layer of HDPE. The assembled mold was then subjected to hot pressing at a temperature of 180°C and a pressure of 10 kg for 10 minutes using a hydraulic press machine. Upon completion, the mold was removed from the press and allowed to cool at ambient temperature

Table 1. Research design

No	Fiber Direction	Volume Fraction (%) HDPE: Coconut Fiber
1	Vertical	90 : 10
2		80 : 20
3		70 : 30
4		60 : 40
5	Horizontal	90 : 10
6		80 : 20
7		70 : 30
8		60 : 40
9	Random	90 : 10
10		80 : 20
11		70 : 30
12		60 : 40

3. RESULT AND DISCUSSION

Result

This research conducted several tests including impact testing and tensile strength testing. The composite used was a composite made from High Density Polyethylene (HDPE) waste and coconut fiber, the ratio of each vertical fiber (HDPE: fiber, 90: 10, 80: 20 and 70: 30, 60: 40), horizontal (HDPE: fiber, 90: 10, 80: 20 and 70: 30, 60: 40), and random fiber (HDPE: fiber, 90: 10, 80: 20 and 70: 30, 60: 40).

Table 2. Tensile Test Results on Composites

No	Fiber Direction	Volume Fraction (%) HDPE: Coconut Fiber	Tensile Stress (MPa)	Strain (%)	Modulus of Elasticity (MPa)
1	Vertical	90 : 10	24,124	11,61	2,077
2		80 : 20	27,85	11,62	2,396
3		70 : 30	26,674	8,67	3,076
4		60 : 40	27,85	7.1	3,922
5	Horizontal	90 : 10	10,002	10,2	0,980
6		80 : 20	7,256	6,71	1,081
7		70 : 30	6,864	4,18	0,484
8		60 : 40	2,941	5,97	0,492
9	Random	90 : 10	10,395	4,06	2,560
10		80 : 20	9,806	3,74	2,622
11		70 : 30	18,24	6,57	2,776
12		60 : 40	13,533	3,93	3,443

Table 3. Impact Test Results on Composites

Volume Fraction (%) HDPE: Coconut Fiber	Fiber Direction	Degree		Broken Power (joule)	Impact Price (joule/mm2)
		α	ß		
90 : 10	Vertical	160	143	13,034	0,162
80 : 20		160	141	14,896	0,186
70 : 30		160	146	10,241	0,128
60 : 40		160	145	11,172	0,139

90 : 10	Horizontal	160	138	18,62	0.232
80 : 20		160	141	14,896	0,186
70 : 30		160	139	17,689	0,221
60 : 40		160	141	14.896	0,186
90 : 10	Random	160	143	13,034	0,162
80 : 20		160	141	14,896	0,186
70 : 30		160	146	10,241	0,128
60 : 40		160	145	11,172	0,139

Discussion

Table 2. shows that the tensile strength values obtained ranged from 2.941 MPa to 27.85 MPa. A bar chart for comparing tensile strengths can be seen in Figure 6.

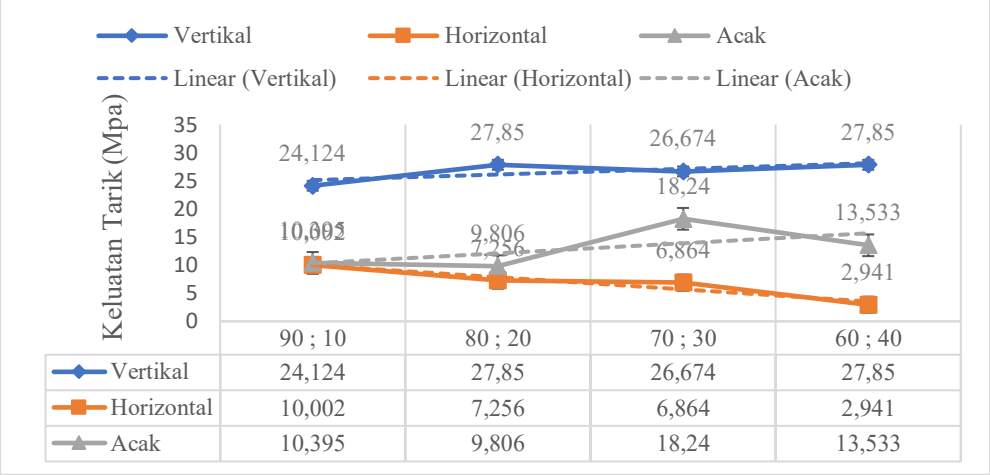


Figure 6. Comparison Line Diagram of Tensile Strength from Tensile Test Results

Based on Figure 4.1, the highest tensile strength was obtained in the vertical fiber orientation with an HDPE-to-fiber composition of 80:20, reaching 27.85 MPa, while the lowest in this orientation was 24.124 MPa at a 90:10 composition. In the random fiber orientation, the highest tensile strength was observed at the 70:30 composition with a value of 18.24 MPa, and the lowest was at 80:20, reaching 9.806 MPa. The horizontal fiber orientation exhibited the lowest performance overall, with the highest tensile strength recorded at 90:10 (10.002 MPa) and the lowest at 60:40 (2.941 MPa). Overall, vertical fiber orientation produced the highest tensile strength, while horizontal orientation resulted in the lowest. These findings indicate that fiber orientation significantly influences tensile strength, with aligned (vertical) fibers providing better load resistance due to their longer effective fiber length (Agus Sabarudin, 2019).

Table 2. shows that the strain/elongation values obtained ranged from 3,74% to 14,18%. The bar chart for the strain/elongation comparison can be seen in Figure 7.

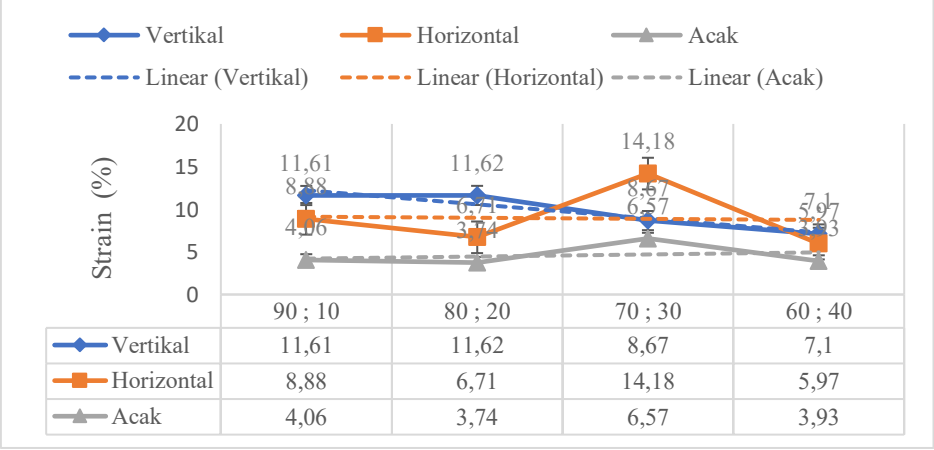


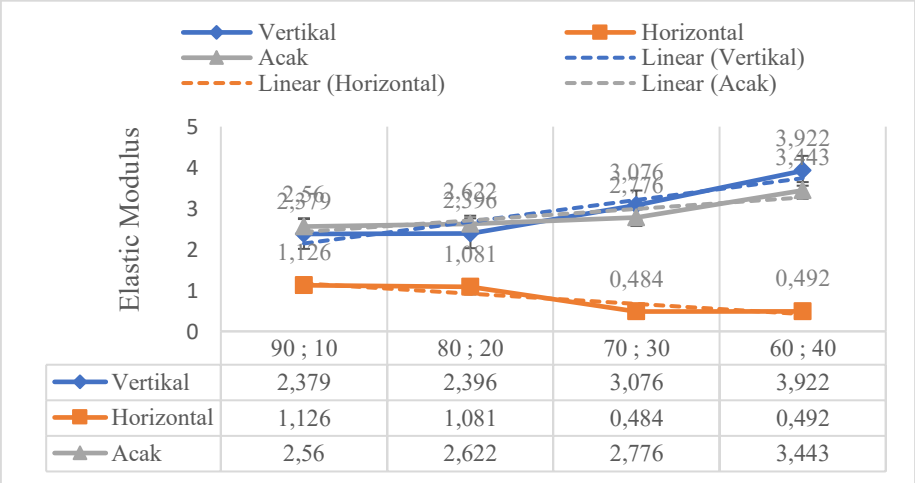
Figure 7. Strain Comparison Line Diagram from Tensile Test Results

In the vertical fiber orientation, strain decreases as the fiber volume fraction increases, with the highest strain recorded at 11,62% for the 80:20 HDPE-to-fiber ratio and the lowest at 7,1% for the 60:40

ratio. This indicates that adding fibers aligned with the load direction increases the stiffness of the composite and reduces deformation. Conversely, in the horizontal orientation, the highest strain value of 14,18% was observed at the 70:30 ratio, suggesting that fibers positioned perpendicular to the tensile load are less effective in resisting deformation, resulting in a more flexible material. For randomly oriented fibers, strain values were generally lower than those in the horizontal orientation, with the highest value of 6,57% at the 70:30 ratio and the lowest of 3,74% at the 80:20 ratio, indicate a moderate level of stiffness.

Overall, increasing the fiber volume fraction leads to greater stiffness and reduced strain. This is because fibers serve as the main load-bearing component in the composite, and the tensile strength improves with better load distribution across the fiber surface and strong interfacial bonding between fiber and matrix. These findings are consistent with previous research by Wicaksono et al. (2021), which stated that increasing fiber content enhances the composite's ability to withstand tensile loads.

Table 2. Shows that the elastic modulus values obtained ranged from 0,484 MPa to 3,922 MPa. The bar chart for the comparison of elastic modulus can be seen in Figure 8.



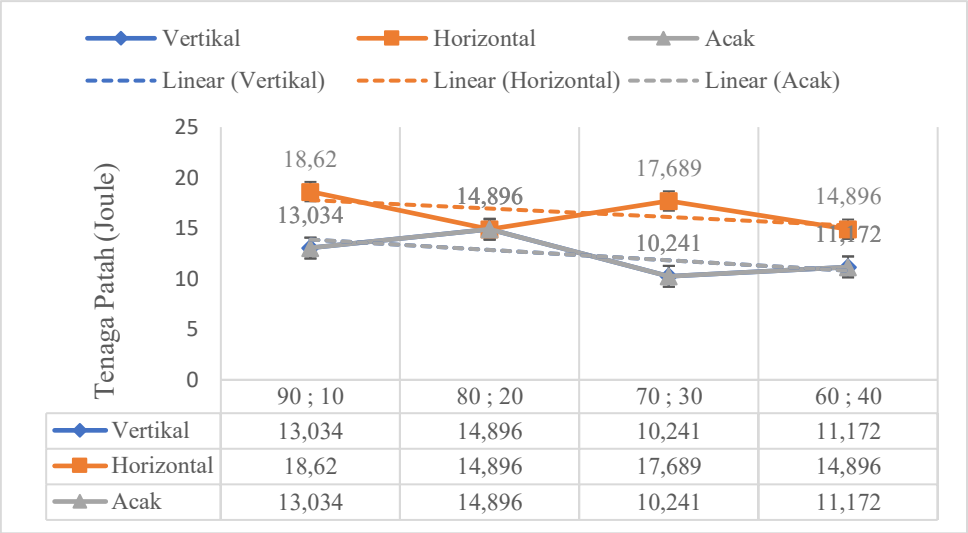
	90 ; 10	80 ; 20	70 ; 30	60 ; 40
Vertikal	2,379	2,396	3,076	3,922
Horizontal	1,126	1,081	0,484	0,492
Acak	2,56	2,622	2,776	3,443

Figure 8. Line Diagram of Comparison of Elastic Modulus of Tensile Test Results

The figure presents the elastic modulus (MPa) of composite materials with varying fiber orientations (vertical, horizontal, and random) and HDPE-to-fiber ratios (90:10, 80:20, 70:30, and 60:40). The results indicate that both fiber orientation and volume fraction significantly influence the stiffness of the material. In the vertical orientation, the elastic modulus increased consistently with higher fiber content, reaching a maximum value of 3,922 MPa at the 60:40 ratio. This is attributed to the alignment of fibers with the load direction, allowing for more effective stress transfer. In contrast, the horizontal orientation where fibers are perpendicular to the load resulted in much lower modulus values, with the lowest value of 0,484 MPa observed at the 70:30 ratio. This suggests that fibers in this orientation are less efficient at bearing load. The random orientation showed moderate increases in modulus due to the multidirectional contribution of fiber distribution, despite its irregularity.

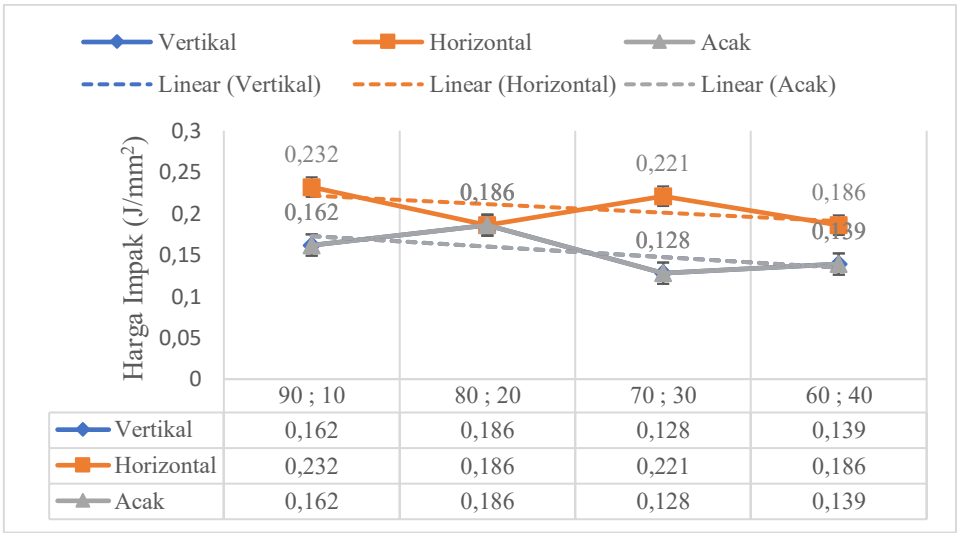
Overall, a higher fiber volume fraction and proper fiber alignment relative to the load direction lead to increased elastic modulus. These findings align with composite material theory as described by Gibson (2016) and Mallick (2007), which states that composite stiffness strongly depends on fiber orientation and volume proportion. Additionally, elastic modulus is generally proportional to tensile strength and inversely related to strain. Materials with higher modulus values are stiffer and more brittle, while those with lower modulus are more flexible and less prone to fracture. However, these properties can vary depending on processing conditions, fiber orientation, and volume fraction.

The toughness of a composite can be determined using an impact test, which measures the toughness or ability of a composite material to absorb energy before breaking (toughness). A visualization of the comparison of fracture strength values from the impact test results on 12 samples is presented in Figure 9. while a comparison of ductility values from the impact test results is presented in Figure 10.



	90 ; 10	80 ; 20	70 ; 30	60 ; 40
Vertikal	13,034	14,896	10,241	11,172
Horizontal	18,62	14,896	17,689	14,896
Acak	13,034	14,896	10,241	11,172

Figure 9. Line Chart Comparison of Impact Energy from Impact Test Results



	90 ; 10	80 ; 20	70 ; 30	60 ; 40
Vertikal	0,162	0,186	0,128	0,139
Horizontal	0,232	0,186	0,221	0,186
Acak	0,162	0,186	0,128	0,139

Figure 10. Line Chart of Impact Value Comparison from Impact Test Results

Figures 9. and 10. illustrate that fiber orientation and composition significantly influence the mechanical strength of HDPE composites. Horizontal fiber orientation result the highest fracture energy and impact strength, particularly at a 90:10 composition, with a fracture energy of 18.62 Joule and an impact value of 0.232 J/mm^2. This is attributed to the alignment of the fibers with the load direction, allowing more effective stress transfer. In contrast, vertical orientation shows moderate performance, with peak values observed at an 80:20 composition (14.896 Joules and 0.186 J/mm^2). Random fiber orientation results in the lowest mechanical performance due to the non-directional fiber distribution, which limits effective stress dispersion. Overall, increasing fiber content up to 20% enhances strength, but exceeding 30% can reduce performance due to uneven distribution or weak interfacial bonding. Therefore, a horizontal fiber orientation combined with a 90:10 or 80:20 composition is identified as the optimal configuration for improving the fracture resistance of HDPE composites.

In this study, microscopic observations were conducted using a digital microscope with a 30-degree field of view (SPF). The best composite specimens of HDPE waste and coconut fiber waste were selected, which had undergone tensile and impact tests. The following are images of the results of microscopic observations on the best tensile and impact test specimens.

Micro Observation Image of Tensile Test

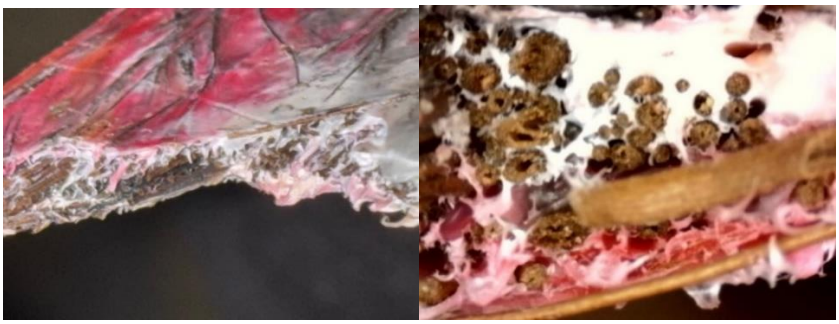


Figure 11. Micro Observation of Tensile Test Specimen with the Highest Stress Value in the Vertical Fiber Direction (60:40).

Figure 12. Micro Observation of Tensile Test Specimen with the Highest Strain Value in the Horizontal Fiber Direction (70:30).

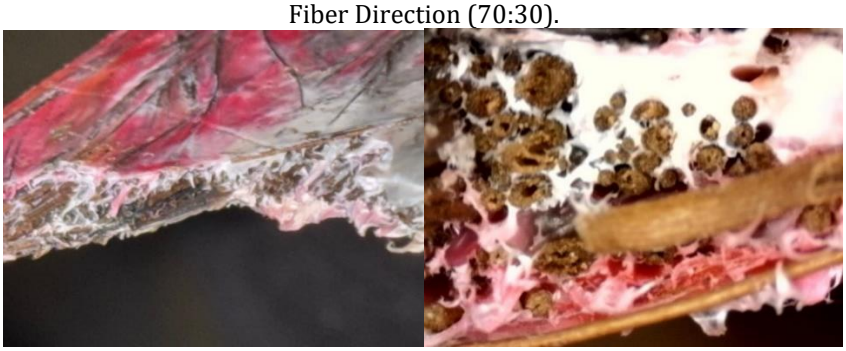


Figure 13. Micro Observation of Tensile Test Specimens with the Highest Elastic Modulus Value in the Vertical Fiber Direction (60:40).

Micro Observation Image of Impact Test

Figure 14. Micro Observation of Impact Test Specimens with the Highest Fracture Strength and Impact Price Values in the Horizontal Fiber Direction (90:10).

The primary function of microstructural analysis in material testing is to evaluate the quality and integrity of the material's internal structure. In composite manufacturing, this analysis ensures uniform fiber distribution and detects defects such as voids or agglomerations, which can compromise mechanical properties. Microstructural evaluation is also critical in failure analysis to identify damage mechanisms, such as crack initiation due to mechanical loading or thermal degradation.

Based on microstructural observations of the tensile test specimens (Figures 11. and 13), the HDPE waste–coconut fiber composites exhibit good interfacial bonding between the matrix and filler, contributing to high tensile strength and elastic modulus. However, the presence of voids was noted, likely due to

inadequate wetting or uneven distribution of HDPE in the fiber interspaces, which may reduce the overall strength of the composite.

Observations from Figure 12. which represents specimens with horizontally aligned fibers, show improved interfacial bonding and fiber alignment, resulting in higher strain capacity. This suggests that fiber orientation significantly influences the mechanical behavior.

In contrast, microstructural analysis of the impact test specimen in Figure 14. revealed poor bonding between the matrix and filler in composites with horizontal fiber orientation. This weak interfacial adhesion negatively affects the impact strength and energy absorption capacity of the material.

4. CONCLUSION

A series of mechanical tests conducted on composite materials made from recycled HDPE waste and coconut fiber revealed promising results, indicating potential as an environmentally friendly alternative material. Tensile testing showed that the composite had a tensile strength range of 2.941–27.85 MPa, strain values between 3,74%–14,18%, and an elastic modulus ranging from 0,484 to 3,922 MPa. Meanwhile, impact testing results indicated fracture energy values of 10.241–18.62 Joules and toughness values between 0.128–0.232 J/mm^2. The fiber orientation significantly influenced the mechanical performance of the composite; in tensile testing, composites with vertically aligned fibers performed better than those with horizontal or random fiber orientations, as the fibers aligned with the tensile load direction, enhancing strength. Conversely, in impact testing, composites with horizontally oriented fibers exhibited superior performance due to their ability to resist and distribute impact energy more effectively. Microstructural observations further supported these findings, where tensile test specimens showed good bonding between the HDPE matrix and coconut fibers, contributing to higher mechanical strength. In contrast, impact test specimens displayed weaker bonding, as the HDPE did not fully encapsulate the fibers, negatively affecting the composite's strength.

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