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Indonesian Journal of
Fundamental and Applied Chemistry

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Development and Characterization of HDPE Waste/Ramie Fiber Composites for Geomembrane Applications in *Litopenaeus vannamei* Shrimp Cultivation

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Abstract

Geomembranes are thin geosynthetic materials composed of polymeric layers that function as barriers in direct contact with soil. The properties of HDPE geomembranes suitable for application as vannamei shrimp (*Litopenaeus vannamei*) aquaculture. HDPE geomembranes applied in vannamei shrimp aquaculture are subjected to thermal loads (UV radiation), oxidative agents, and mechanical force such as interfacial friction and tensile loading in surface wear. This study aims to improve the mechanical properties of the material by incorporating natural fibers as reinforcement into HDPE–ramie fiber biocomposite. The process of making HDPE–ramie fiber biocomposite uses an single screw extruder with a temperature of 170 ºC, a rotation of 20 rpm with a ratio of HDPE waste and ramie fiber of 97.5:2.5, 95:5, and 92.5:7.5. The results of tensile and impact tests show the highest strength and toughness are shown in the HDPE sample and ramie fiber 92.5:7.5 with a value of 5.23 MPa and 96.17 kJ/m^2. The highest material ductility was demonstrated in the HDPE and ramie fiber composite 97.5:2.5 with a value of 1.32%. In addition, the highest stiffness was demonstrated in the HDPE and ramie fiber composite 95:5 with a value of 845.40 MPa. The results of the morphological investigation showed that the bond between the matrix and filler was partially formed and the smallest fiber diameter was 4 µm.

Keywords: HDPE, Ramie, Composite, Geomembrane, Vannamei

Article Info

Received 20 October 2025
Received in revised 17 February 2026
Accepted 18 February 2026
Available Online 28 February 2026

Abstrak (Indonesian)

Geomembran merupakan material geosintetik tipis yang tersusun atas lapisan polimer dan berfungsi sebagai penghalang yang berkontak langsung dengan tanah. Sifat-sifat geomembran HDPE yang sesuai untuk aplikasi budidaya udang vaname (*Litopenaeus vannamei*) harus mampu menahan berbagai kondisi lingkungan. Dalam aplikasi budidaya udang vaname, geomembran HDPE mengalami beban termal (radiasi UV), agen oksidatif, serta gaya mekanik seperti gesekan antarmuka dan beban tarik akibat keausan permukaan. Penelitian ini bertujuan untuk meningkatkan sifat mekanik material dengan menginkorporasikan serat alam sebagai penguat ke dalam biokomposit HDPE–serat rami. Proses pembuatan biokomposit HDPE–serat rami dilakukan menggunakan ekstruder ulir tunggal pada suhu 170 °C, dengan kecepatan putar 20 rpm, serta variasi rasio limbah HDPE dan serat rami sebesar 97,5:2,5; 95:5; dan 92,5:7,5. Hasil pengujian tarik dan impak menunjukkan bahwa kekuatan dan ketangguhan tertinggi diperoleh pada sampel HDPE–serat rami dengan rasio 92,5:7,5, masing-masing sebesar 5,23 MPa dan 96,17 kJ/m². Keuletan material tertinggi ditunjukkan oleh komposit HDPE–serat rami dengan rasio 97,5:2,5 sebesar 1,32%. Selain itu, kekakuan tertinggi diperoleh pada komposit HDPE–serat rami dengan rasio 95:5 sebesar 845,40 MPa. Hasil investigasi morfologi menunjukkan bahwa ikatan antara matriks dan filler terbentuk secara parsial, serta diameter serat terkecil yang teramati adalah 4 µm..

Kata Kunci: HDPE, Rami, Komposit, Geomembran, Vannamei

INTRODUCTION

Geomembranes are thin geosynthetic materials composed of polymeric layers that function as barriers in direct contact with soil. The polymer materials commonly used for geomembrane applications include polyethylene (PE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), and high-density polyethylene (HDPE), with typical thicknesses ranging from approximately 0.2 to 0.8 mm [1]. Currently, geomembranes are widely applied hydropower systems [2], environmental engineering, geotechnical engineering, waterproofing, basal liners [3] , geotextile containment systems [4], and transportation engineering [5,6]. These materials are characterized by high impermeability and good elasticity [3].

HDPE geomembranes has been widely used as hydraulic seals, waste containment facilities, and hydraulic structures in dams and reservoirs [7,8]. In addition, HDPE geomembranes are used to prevent environmental degradation, such as acting as barriers to leachate and contaminants from infiltrating soil, water ponds, fishery ponds, canals, mining [9], reservoirs, artificial beaches, gases and energy storage facilites [8,10], as well as to control water seepage [7]. HDPE geomembranes exhibit elastic material characteristics with low viscoelastic behavior [11]. HDPE geomembranes may be exposed to environmental conditions over extended periods.

Service life of HDPE geomembranes is relatively long life ranging from approximately 20 to 100 years [8,9]. Degradation of HDPE geomembranes is caused by several factors, including the depletion of antioxidant agents on the HDPE surface leads to physical extraction processes [12]. High temperatures such as exposure to hot water, as well as ultraviolet (UV) radiation in contact with HDPE geomembranes, also contribute significantly to material degradation [3,9,10,13]. In addition, localized stresses on the membrane surface can induce crack formation lead to material failure [12].

The properties of HDPE geomembranes suitable for application as vannamei shrimp (*Litopenaeus vannamei*) farming [14-16]. HDPE geomembranes are used as waterproof and a barrier separating the aquaculture system from the soil [17]. Vannamei shrimp farming is a food-security–oriented aquaculture practice that has attracted significant interest since 1931. This cultivation system is typically conducted in rectangular ponds with surface areas ranging from approximately 2,500 to 4,000 m² and water depths of 1.8 to 3.0 m. The ponds are lined with HDPE geomembranes and supporting systems such as central drainage channels, continuous 24-hour aeration, and paddle-wheel aerators arranged diagonally along the pond walls. This system is designed to regulate stagnant zones, control sludge accumulation, and generate a circular water flow pattern within the shrimp ponds. Stocking densities in this system commonly range from 120 to 300 shrimp/m^2, yielding harvests of approximately 25 tons/ha/production. In intensive culture practices, complete and balanced nutrition is provided to enhance the productivity of vannamei shrimp [18].

HDPE geomembranes applied in vannamei shrimp aquaculture are subjected to thermal loads (UV radiation), oxidative agents, and mechanical force [19] . Mechanical force is the most common factor contributing to damage in HDPE geomembranes. Damage to HDPE geomembranes typically occurs due to interfacial friction and tensile forces during installation and operation. Such interfacial friction and tensile loading lead to surface wear as well as internal degradation within the HDPE geomembrane material. These phenomena result in dimensional changes within the geomembrane structure, increased stress may induce material instability and failure [4]. Biocomposite materials are formed through the combination of two or more materials to enhance material properties, such as mechanical strength, by incorporating natural fibers as reinforcement. Ramie fiber is a natural polymer material that has recently attracted considerable interest for application in biocomposites. This study aims to improve the mechanical strength of HDPE geomembrane biocomposites through the incorporation of ramie fibers using an extrusion process.

MATERIALS AND METHODS

Materials

The materials used HDPE waste of packaging as bottles, pipes, household was copped into 5 - 8 mm and washed using distilled water. Ramie fibers from the farmers in Bantul, Yogyakarta, have initial length of 1 m washed by distilled water and copped into lengths of 3 mm. An alkali treatment was then conducted in ramie fiber to remove impurities from the fiber surface using a 5% NaOH until 45 minutes with the MERCK brand.

Synthesis of HDPE–ramie fiber biocomposite

HDPE and ramie fibers were mixed before extrusion according to compositions and then fed into the hopper of a single-screw extrusion machine at 170 ºC with a srew rotation of 20 rpm then molded according to standards. The mixture of HDPE waste and ramie fiber used was 97.5:2.5 (HR 2.5%), 95:5 (HR 5%), and 92.5:7.5 (HR 7.5%). After extrusion process the material was in a pliable state and insert into a mold with the standard specifications and allowed to cooling temperature at 27 - 30 °C for 1 hour. The characterization on this HDPE–ramie fiber biocomposite was a tensile test using the ASTM D 3038, an Impact test using the Charphy method with ASTM D 256, and a scanning electron microscope. The results of the Impact test were subjected to material failure analysis.

RESULTS AND DISCUSSION

Tensile Strength Analysis

The material strength of the HDPE–ramie fiber biocomposite is presented in **Figure** 1. The tensile strength results indicate an improvement in the HR 2.5%, HR 5%, and HR 7.5% samples. The tensile strength of the HDPE–ramie fiber biocomposite increased from 2.2 MPa for the HR 2.5% sample to 3.12 MPa for the HR 5% sample. The highest tensile strength was observed in the HR 7.5% sample, reaching a value of 5.23 MPa.

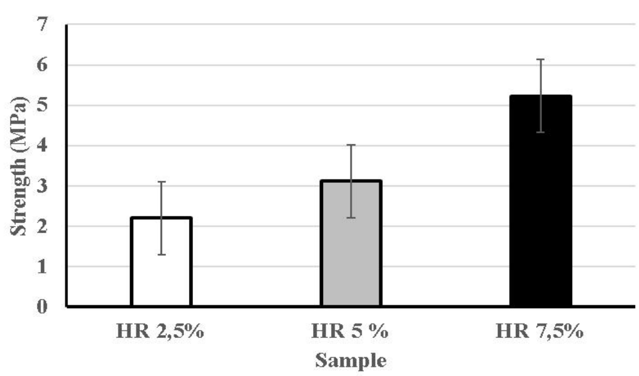


Figure 1. Tensile Strength of HDPE-Ramie Fiber Composite

The mechanical properties of composite materials are determined by the strength of the matrix and filler. HDPE–ramie fiber biocomposite, both constituents contribute significantly to the enhancement of the material strength. The material strength of the HDPE–ramie fiber composite depends not only on HDPE as the matrix but also on ramie fiber as the reinforcing phase. The tensile load applied at the grips is initially transferred to the HDPE matrix and subsequently transmitted to the ramie fiber reinforcement. The interfacial bonding between the fiber and matrix phases is crucial role in governing the efficiency of load transfer [20,21]. The formation of strong interfacial bonding between the matrix and the filler leads to an improvement in the overall material strength of the composite. This observation is consistent with SEM at **Figure** 6 which shows that a portion of the interfacial bonding between the matrix and filler is well formed.

The studies on biocomposites reinforced with various types of fibers have been widely reported. Biocomposites based on a PLA matrix reinforced with sugarcane bagasse fiber exhibited tensile strength values ranging from 16.06 MPa to 34.59 MPa [22]. Research on biocomposites has also been conducted using a PLA matrix reinforced with Tamarindus Indica Seed Powder fabricated through a 3D printing method. The tensile strength In horizontal fiber orientation obtained 16.7 MPa [23]. In addition, biocomposite studies have been carried out using an epoxy resin matrix reinforced with sisal and jute fibers. These studies reported material degradation behavior of the biocomposites after being subjected to aging periods of up to 500 and 1008 hours. The results indicated that, prior to degradation, the tensile strength of epoxy composites reinforced with jute fibers ranged from 15 to 27 MPa, while composites reinforced with sisal fibers exhibited tensile strength values between 15 and 34 MPa. After the aging process, a reduction in tensile strength was observed [24]. This study indicates that the HDPE–ramie fiber biocomposite still exhibits relatively low mechanical strength. This behavior is attributed to the insufficient interfacial bonding between the fibers and the matrix. As shown in **Figure** 6, A part of void showed in interfacial bonds between the fiber and the matrix.

The ductility and stiffness of the HDPE–ramie fiber biocomposite were evaluated to determine the material's elongation behavior and resistance of HDPE–ramie fiber biocomposite to elastic deformation under applied mechanical loading. The ductility and stiffness characteristics of the HDPE–ramie fiber biocomposite are presented in **Figures** 2 and 3. The ductility of the biocomposite HDPE–ramie fiber biocomposite decreased with from 1.32% in the HR 2.5% sample to 0.37% in the HR 5%. However, ductility increased to 0.74% in the HR 7.5%. Similarly, the stiffness of the HDPE–ramie fiber biocomposite exhibited a non-linear trend. The stiffness increased significantly from 166.75 MPa in the HR 2.5% sample to 845.40 MPa in the HR 5% sample then decreased in the HR 7.5% sample, reaching 711.49 MPa.

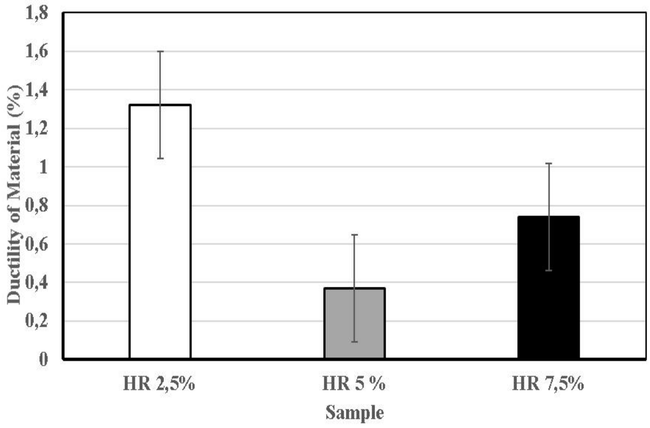


Figure 2. Material Ductility of HDPE-Ramie Fiber Composite Fiber

The nonlinear behavior of the material's ductility and stiffness differs from its tensile strength. The addition of ramie fiber to the HDPE matrix does not linearly increase the material's ductility and stiffness. This is because the ramie fiber distribution during the extrusion process is not homogeneous across the composite surface [25]. The difficulty of engineering the fiber direction within the extruder screw presents a challenge in the composite material manufacturing process. The fiber distribution results in differences in strength in one area compared to another [26] . This results in uneven stress distribution during tensile testing. As a result, the material exhibits nonlinear stiffness and ductility behavior.

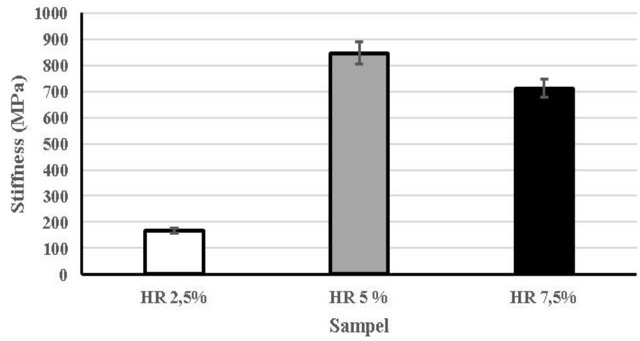


Figure 3. Material Stiffness of HDPE-Ramie Fiber Composite Fiber

The material strength of the HDPE–ramie fiber biocomposite showed the highest value in the HR 7.5% sample 5.23 MPa. However, this strength remains lower than the tensile strength requirement specified for HDPE geomembranes in ASTM D6693/D6693M-20, which is 9 MPa. Material ductility of the HDPE–ramie fiber biocomposite showed a maximum on HR 2,5% value of 1.32%, which is also significantly lower than the standard requirement for HDPE geomembranes, namely 8.6%. These results indicate that the presence of voids between the fiber and the matrix plays a crucial role in the geomembrane synthesis process. Voids at the fiber–matrix interface can lead to localized stress concentrations within the HDPE geomembrane structure, thereby reducing both the tensile strength and ductility of the material.

Impact Strength Analysis

The impact toughness of the HDPE–ramie fiber biocomposite was evaluated using an impact testing to determine the mechanical energy absorbed. As clearly illustrated in Figure 4, the impact toughness of the HDPE biocomposite reinforced with ramie fiber exhibits a improvement of impact toughness. The impact toughness of the HDPE–ramie fiber biocomposite increases proportionally with the increasing content of ramie fiber incorporated into the composite matrix. The HDPE–ramie fiber biocomposite containing 2.5% natural fiber exhibited the lowest impact toughness at 66.82 J/m². An increase was observed in the HDPE–ramie fiber biocomposite with 5% ramie fiber addition at 80.89 J/m². The highest impact toughness value of the HDPE–ramie fiber HDPE–ramie fiber biocomposite was obtained at a ramie fiber content of 7.5% at 96.17 J/m².

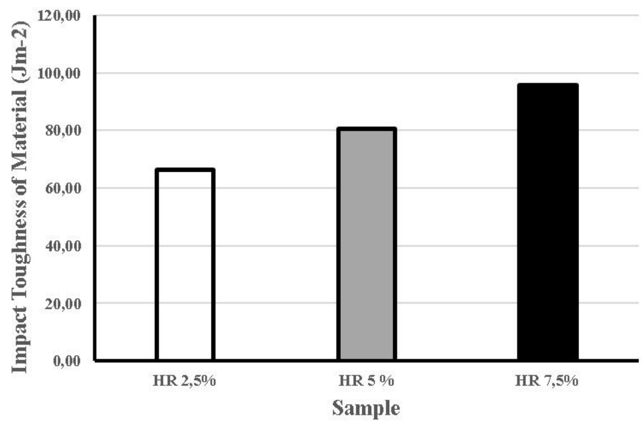


Figure 4. Impact Toughness of HDPE-Ramie Fiber Composite Fiber

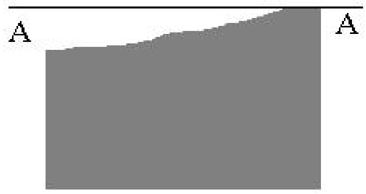
The increase of impact toughness in HDPE–ramie fiber biocomposite is attributed to the increased addition of ramie fiber as a reinforcing filler within the biocomposite system [27] . The enhancement in impact toughness is consistent with tensile strength of the HDPE–ramie fiber biocomposite [28]. The higher ramie fiber content within HDPE–ramie fiber biocomposite contribute to stronger interfacial bonding between the rami fiber and the HDPE matrix [29] . The increased of impact toughness in HDPE–ramie fiber biocomposite is appropriated with SEM results, which refer to the presence of interfacial bonding between the ramie fibers and the HDPE matrix. Interfacial bonding between between the rami fiber and the HDPE matrix enhancing distribution of mechanical energy from the impact testing pendulum to inner material and enhancement of impact toughness in HDPE–ramie fiber biocomposite.

Impact toughness in biocomposite materials has been investigated in biocomposites reinforced with kenaf fibers. The incorporation of kenaf fibers into biocomposites has been reported to result in impact toughness from 12 kJ/m² to 15.2 kJ/m² [30]. Biocomposites reinforced with oil palm empty fruit bunch fibers have demonstrated relatively favorable impact toughness from 343.3 J/m² to 715 J/m² [31] . Biocomposites reinforced with cotton filter waste fibers have also exhibited impact toughness values between 61 J/m² and 88.5 J/m² [32]. Impact toughness indicate that the incorporation of fibers into biocomposites significantly influences the impact toughness of the biocomposite. Furthermore, the interfacial bonding between the filler and the matrix plays a critical role in the synthesis and overall mechanical performance of the composite system.

Failure Analysis

Material failure analysis determined by the material's behavior under external loads. **Table** 1 shows failure profile of HDPE and Rami fiber composite materials. Failure analysis was performed by comparing the fracture results with the fracture profiles.

Table 1. Failure Profile on HDPE and Ramie Fiber Composite Material

Sample Code	Failure Picture	Failure Profile
HR 2,5%		
HR 5%		
HR 7%		

The 2.5% HR and 5% HR samples exhibited regular fracture. This fracture is indicated by the formation of a fracture profile resembling a straight line. Crack initiation begins at a V-notch and then spreads throughout the sample. Samples with this fracture profile indicate brittle fracture. Brittle fracture occurs in brittle materials. The 7% HR sample exhibited a vibrational fracture pattern and formed grooves, indicating that the 7% HR sample is a more ductile material [21].

Surface Morphology Analysis

Surface morphology analysis characterized by a scanning electron microscope at Syiah Kuala University, Banda Aceh. Data obtained included fiber diameter, composite surface area, and the bond between the matrix and filler. The smallest diameter was shown at 4 µm, and the largest at 12 µm (fig. 5). The average fiber diameter was approximately 8 µm.

The surface morphology of the sample showed a closed surface exhibits a folded surface without significant demage or crack (**Figure** 6). The fiber distribution in the HDPE–ramie fiber biocomposite shows a random dispersion and appears to a limited presence of void on fiber-matrix interface. This indicates that several bonds were observed between the matrix and filler [33,34]

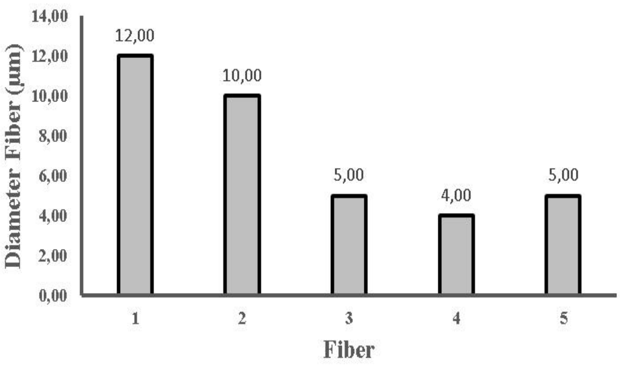


Figure 5. Diameter HDPE-Ramie Fiber Composite Fiber

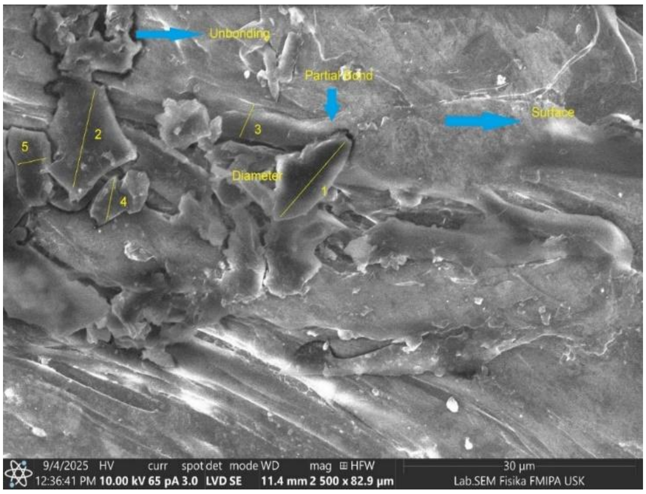


Figure 6. Surface Morphology of HDPE-Ramie Fiber

CONCLUSION

This study successfully fabricated an HDPE–ramie fiber biocomposite from waste materials, namely HDPE waste and ramie fibers using an extrusion method. The HDPE–ramie fiber biocomposite was successfully processed at a temperature of 170 °C of 20 rpm using a single-screw extrusion method. The successful fabrication of the HDPE–ramie fiber biocomposite was primarily determined by the interfacial bonding formed between the HDPE matrix and the ramie fiber reinforcement. The most optimal tensile strength and impact toughness were observed in the HDPE–ramie fiber biocomposite containing 7.5% ramie fiber. The sample with 7.5% ramie fiber exhibited the highest tensile strength and impact toughness. This fiber content enhanced the interfacial bonding between the matrix and the filler within the HDPE–ramie fiber biocomposite and improving its tensile strength and impact resistance. This finding was supported by SEM characterization which revealed partial interfacial bonding between the matrix and the filler and as well as by failure analysis indicating ductile fracture behavior. However, the fabrication of the HDPE–ramie fiber biocomposite using single-screw extrusion presents limitations in controlling fiber orientation as the material flows from the hopper to the die. This limitation results in non-uniform fiber dispersion and random fiber orientation leading to non-linear ductility and stiffness behavior. Therefore, further investigation is required regarding surface treatment of ramie fibers to enhance interfacial bonding between the matrix and the filler and to reduce void formation at the interface of HDPE–ramie fiber biocomposite. Improved interfacial adhesion and reduced void content are expected to produce more optimal mechanical properties of the geomembrane material and enabling its application in vannamei shrimp aquaculture.

ACKNOWLEDGMENT

The author would like to express sincere gratitude to the Institute for Research and Community Service (LPPM) for funding this research in PNBP Funded Research Program of Universitas Malikussaleh in 2025.

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