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ORIGINAL ARTICLE

Density and Tensile Properties Analysis of Biocomposite from Lid Film Waste and Oil Palm Empty Fruit Bunch Fiber

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ABSTRACT – Multilayer plastic waste, particularly from the bottled water industry, represents a persistent challenge in current plastic waste management strategies. Simultaneously, oil palm empty fruit bunch (OPEFB) waste, though often discarded, possesses significant potential for sustainable material development. This study explores the utilization of both waste streams as raw materials for biocomposite fabrication, thereby addressing environmental concerns while reducing dependence on virgin polymer resources. The multilayer lid film waste (comprising PET, LDPE, and LLDPE) and OPEFB fibers were processed through crushing, sieving, and extrusion to form pellets with varying OPEFB fiber loadings (30%, 50%, and 70% by weight). The resulting biocomposite was characterized using FTIR, XRD, SEM, density measurements, and tensile testing. The biocomposite containing 70% OPEFB exhibited the slowest degradation but also the lowest crystallinity (10.84%). In contrast, the 30% OPEFB composite showed the highest tensile strength (16.86 MPa) and elongation at break (3.23 MPa). SEM analysis revealed that a higher fiber content increased the porosity within the composite matrix. These findings demonstrate the potential of combining multilayer plastic and OPEFB waste for biocomposite applications, contributing to both material innovation and environmental sustainability.

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INTRODUCTION

Plastics are among the most widely used materials in modern society, particularly in the packaging sector, which represents the largest share of global plastic applications [1-2]. The growing demand for bottled drinking water in Indonesia has significantly contributed to plastic consumption, with more than 500 companies engaged in this sector, predominantly small- and medium-scale industries [3]. The volume of plastic waste, particularly post-industrial waste such as lid films from bottled water cups, has also increased [4-6]. Unlike the cup portion, which has been the focus of several recycling and reuse studies [7-8], lid films remain underutilized despite their multilayer structure—typically composed of PET, LDPE, and LLDPE—that provides desirable barrier and adhesion properties [9]. However, because of their degradation resistance, these films pose a serious environmental concern [10].

Indonesia produces abundant agricultural residues from its extensive oil palm plantations (BPS-DJP, 2020). One of the most significant by-products is oil palm empty fruit bunch (OPEFB) fiber, which has attracted attention as a reinforcing material in composite development due to its renewable nature, low cost, and favorable mechanical properties [11-12]. Although the potential of OPEFB fibers in various natural fiber-reinforced composites has been demonstrated in previous studies, their combination with plastic waste, such as lid films, has not been extensively explored.

OPEFB fiber is a lignocellulosic natural fiber with a relatively higher density than most polyolefins, owing to its high cellulose and hemicellulose content. This intrinsic characteristic contributes to an increase in the overall density of biocomposites when OPEFB fibers are incorporated into polymer matrices [13].

The integration of lid film waste with OPEFB fibers in biocomposite production offers a dual benefit: reducing plastic waste while enhancing the added value of agricultural residues. This study investigated the feasibility of developing a sustainable biocomposite from lid film waste and OPEFB fibers through extrusion-based processing and subsequent evaluation of thermal and mechanical behavior [14-15]. The findings of this study are expected to provide insights into environmentally friendly waste management alternatives and contribute to the advancement of natural fiber-based composite materials for potential applications in various fields.

EXPERIMENTAL METHOD

Materials and Instruments

The main materials used in this study were post-industrial lid film waste and oil palm empty fruit bunch (OPEFB) fiber. The lid film waste was collected from a mineral water packaging manufacturer in Depok, Indonesia, in the form of multilayer sheets consisting of approximately 20% polyethylene terephthalate (PET), 40% low-density polyethylene (LDPE), and 40% linear low-density polyethylene (LLDPE). The OPEFB fibers were obtained from local palm oil processing plants in Indonesia.

The instruments used in this study included a Mini Crusher Machine for shredding and size reduction of the lid film waste and OPEFB fibers; a Hot Melt Extruder Collin ZK 16 twin-screw compounder equipped with eight heating zones for biocomposite preparation; and an oven (Memmert, Germany) for drying the samples. The characterization instruments consisted of a Fourier transform infrared (FTIR) spectrometer (Bruker Alpha II) for functional group analysis, a pycnometer for density measurement following ASTM D792 using ethanol as the immersion liquid, an X-ray diffractometer (PANalytical, Netherlands) for crystallinity analysis, a Universal Testing Machine (UTM) Shimadzu AG-X Plus (50 kN) for tensile testing, and a Scanning Electron Microscope (SEM) Hitachi SU-3500 for surface morphology observation. A Haake Minijet Pro mini injection molding machine was employed to prepare the tensile test specimens.

Method and Procedure

The lid film waste, initially supplied in large rolled sheets, was cut into smaller sections and shredded using a Mini Crusher Machine until fine particles were obtained. The OPEFB fibers were similarly chopped and sieved to a 50 mesh size. Both materials were then manually mixed according to predetermined weight percentages (wt%) to evaluate the effect of OPEFB fiber content on the resulting biocomposites. Experiments 1, 2, and 3 corresponded to OPEFB fiber contents of 30 wt%, 50 wt%, and 70 wt%, respectively, with the lid film waste content adjusted accordingly to 70 wt%, 50 wt%, and 30 wt% to maintain a total composition of 100 wt%. The mass of each component was calculated based on the total batch weight prior to processing.

The mixed materials were processed using a Hot Melt Extruder Collin ZK 16 at a screw speed of 70-80 rpm. The extrusion process was conducted at a set temperature of 150 °C with heating zone configurations of 45, 120, 135, 155, 150, 150, 150, and 150 °C. The extrudates were collected in pellet form, subsequently dried in an oven at 100 °C for 2 h, and stored in sealed plastic bags to minimize environmental exposure.

For characterization, FTIR analysis was performed directly on the oven-dried pellets at a wavenumber range of 4000-400 cm^{-1} to identify the functional groups. Density measurements were carried out using a pycnometer with ethanol as the immersion liquid to determine the specific gravity. XRD analysis required the pellets to be hot-pressed at 150 °C for 15 min under 10 MPa to obtain sheets (4 × 4 cm, ~1 mm thickness). The resulting diffractograms were analyzed to determine the crystalline and amorphous regions.

Tensile test specimens (dog-bone shape, ASTM D638) were prepared from the pellets using the Haake Minijet Pro injection molding machine with cylinder temperatures of 160–170 °C, mold temperature of 35–40 °C, and injection pressure of 750 bar. The mechanical properties, including the ultimate tensile strength (UTS) and elongation at break, were measured using a Shimadzu AG-X Plus UTM (50 kN).

For SEM analysis, the extruded samples (~5 cm length) were immersed in liquid nitrogen for ~3 s, fractured, and gold-coated using a DSCTR Smart Coater prior to imaging with the SEM Hitachi SU-3500.

RESULT AND DISCUSSION

Chemical Structure Analysis of Biocomposite

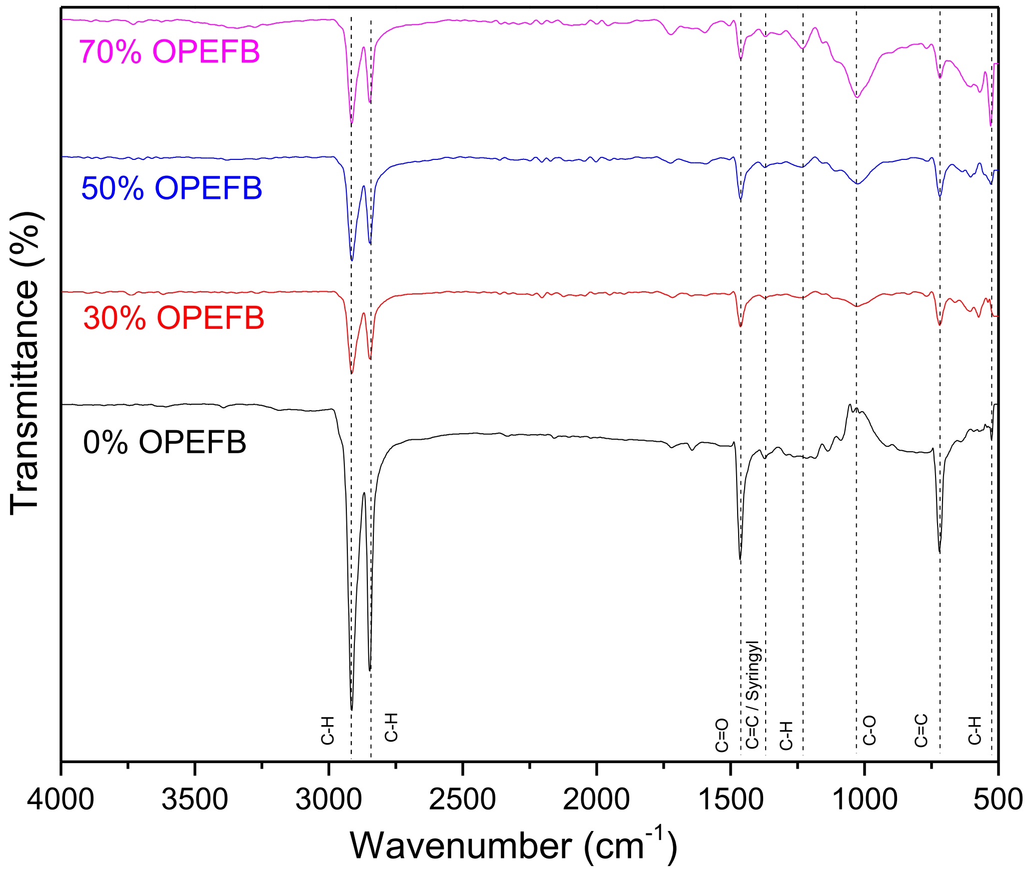

Figure 1. Biocomposite FTIR spectra on various OPEFB content.

Based on the FTIR spectra in Figure 1, variations in OPEFB fiber content do not result in significant changes in the overall spectral profile of the biocomposites. This observation indicates that the incorporation of OPEFB fibers into the lid film matrix does not lead to the formation of new chemical bonds, and the interaction between the polymer matrix and the fibers is predominantly physical in nature. FTIR analysis primarily identifies the presence of functional groups rather than their quantitative distribution [16].

The spectra of all compositions exhibit characteristic absorption bands corresponding to both the lid film polymers and the lignocellulosic components of OPEFB fibers. The absorption bands in the range of 2840–3000 cm^{-1} are attributed to C–H stretching vibrations from aliphatic chains commonly found in polyethylene-based materials. The presence of carbonyl (C=O) stretching vibrations around 1735–1750 cm^{-1} is associated with ester or carbonyl groups originating from PET layers and hemicellulose components in OPEFB fibers [17].

With increasing OPEFB content, additional absorption bands appear in the range of 1566–1650 cm^{-1}, corresponding to aromatic C=C stretching vibrations, which are characteristic of lignin structures. In particular, the absorption peaks observed around 1590–1610 cm^{-1} indicate the presence of syringyl units in lignin [18]. Furthermore, lignin-related syringyl vibrations are typically detected within the range of 1000–1600 cm^{-1}, which is consistent with the spectra obtained for higher OPEFB loadings [19].

The persistence of similar functional groups across all compositions, accompanied by minor peak shifts and intensity variations, suggests good chemical compatibility between the lid film matrix and OPEFB fibers without chemical degradation during extrusion [13]. These results indicate that the biocomposites are formed predominantly through physical blending while retaining the intrinsic functional groups of both constituents [20].

Table 1 shows the various functional groups that identified in the mixture of lid film and OEPFB materials in various compositions.

Table 1. Biocomposite functional groups with variety of OPEFB composition

Wavelength (cm^{-1})				Absorbance (cm^{-1})	Chemical Structure
0% OPEFB	30% OPEFB	50% OPEFB	70% OPEFB		
2917,51	2925,31	2917,14	2925,31	2840-3000	C-H
2851,52	2855,84	2850,4	2855,84	2840-3000	C-H
1711,92	1737,57	1733,48	1738,93	1735-1750	C=O
-	1593,4	1592,07	1593,4	1566-1650	C=C
1463,2	1459,7	1561,07	1459,7	1465-1450	C-H
1164,97	1170,94	1168,22	1168,22	1163-1210	C-O
722,08	724,18	720,09	716	665-730	C=C
555,84	545,74	545,74	544,38	20 ± 700	C-H

Density Analysis of Biocomposite

The density of the biocomposites increased as the OPEFB fiber content rose from 30 wt% to 50 wt%, with values increasing from 0.936 g/cm^3 to 1.191 g/cm^3. This increase can be attributed to the higher intrinsic density of OPEFB fibers compared to the polymer matrix, as well as improved packing efficiency at moderate fiber loadings. In these compositions, OPEFB fibers were more uniformly dispersed within the plastic matrix, allowing the fibers to occupy interstitial spaces between plastic particles and thereby reducing internal voids [21].

The increase in density at intermediate fiber contents is consistent with the rule of mixtures, where the overall density of the composite is influenced by the relative densities and volume fractions of its constituents. Additionally, sufficient melt flow during extrusion at 30–50 wt% OPEFB facilitated better matrix infiltration around the fibers, contributing to a more compact composite structure.

However, when the OPEFB content was increased to 70 wt%, the density decreased to 0.947 g/cm^3. This reduction is likely associated with excessive fiber loading, which promoted fiber agglomeration and hindered adequate matrix wetting. The formation of fiber clusters can trap air and generate voids within the composite, resulting in a less efficient packing structure despite the higher fiber fraction. Similar behavior has been reported in natural fiber-reinforced composites at high filler contents [11].

These results indicate that an optimal OPEFB fiber loading exists at intermediate compositions, where improved fiber distribution and reduced void content contribute to higher composite density.

Crystallinity Analysis of Biocomposite

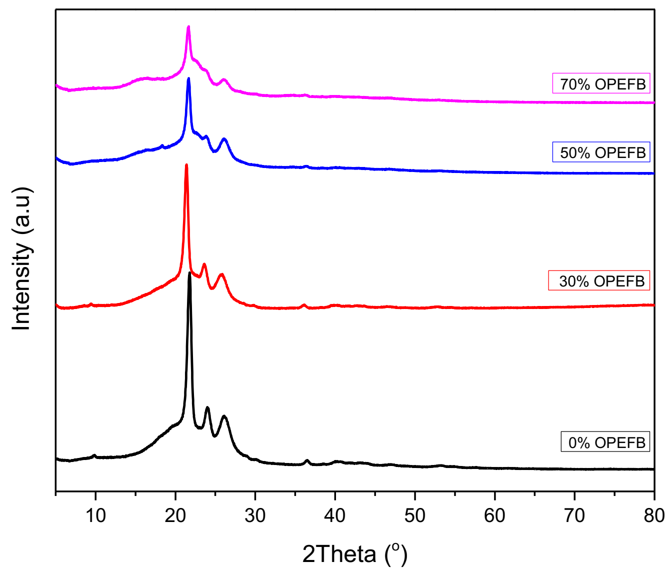

Figure 2. XRD overlay of biocomposite on various OPEFB composition.

Based on Figure 2, the XRD patterns of the biocomposites exhibit characteristic diffraction peaks associated with the semi-crystalline structure of the polymer matrix. The prominent diffraction peaks observed at 2θ ≈ 21–22° and 23–24° correspond to the (110) and (200) crystallographic planes of polyethylene, respectively.

With increasing OPEFB fiber content from 30 wt% to 70 wt%, a noticeable reduction in peak intensity and a broadening of the peak are observed. This indicates a decrease in crystallinity, consistent with the calculated values decreasing from 26.30% to 16.69% and 10.84%, respectively. The incorporation of OPEFB fibers introduces a higher proportion of amorphous lignocellulosic components, such as cellulose, hemicellulose, and lignin, which disrupts the regular packing of polymer chains.

Furthermore, the presence of rigid OPEFB fibers restricts polymer chain mobility during melt processing, leading to increased melt viscosity and reduced chain rearrangement during cooling. As a result, crystal growth is hindered, and fewer ordered crystalline regions are formed during solidification [22]. A slower crystallization process can also reduce nucleation efficiency and crystal perfection, thereby further decreasing crystallinity [23].

These results confirm that increasing OPEFB fiber content progressively suppresses the crystalline structure of the polymer matrix, resulting in a more amorphous biocomposite.

Tensile Properties of Biocomposite

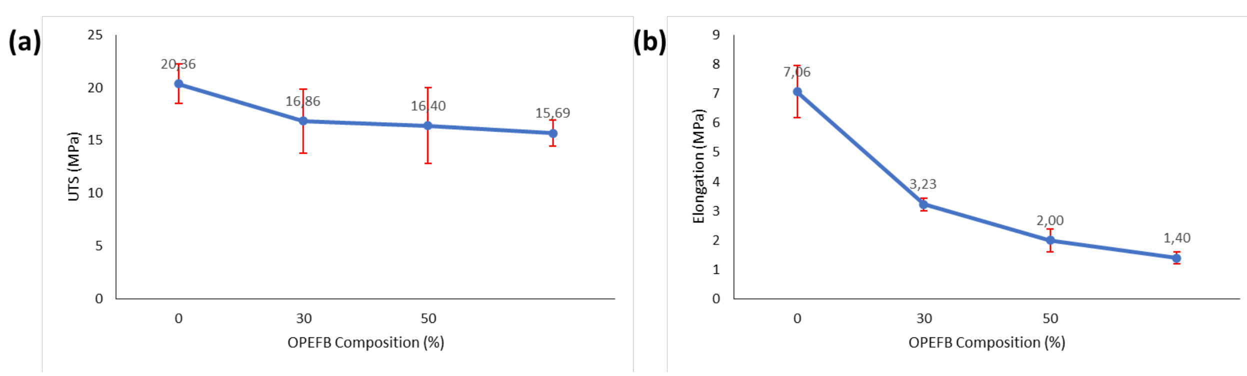

Figure 3. Ultimate Tensile Strengh (a) and Elongation (b) biocomposites on various OPEFB composition.

Based on Figure 6, the higher the OPEFB composition in the biocomposite results in a lower tensile strength (UTS). This is not in line with composite theory as reinforcement is added to increase the mechanical strength of materials [24].

In this case, OPEFB fibers act as - fillers for composite materials. If the composition of OPEFB fibers is too low, the tensile strength is not optimal. However, if the composition of OPEFB fiber is too high, it will cause several possible effects such as fiber weathering caused by OPEFB fiber as filler which is much higher than the lid film. The greater the composition of the OPEFB, it will reduce the maximum strain or strength of the material in bearing the load before failure or fracture. This is because the creep strength of OPEFB is smaller than the creep strength of the film lid material. So that when the composition of OPEFB is more dominant, the strength of the creeper will decrease [25].

Morphological Analysis of Biocomposite

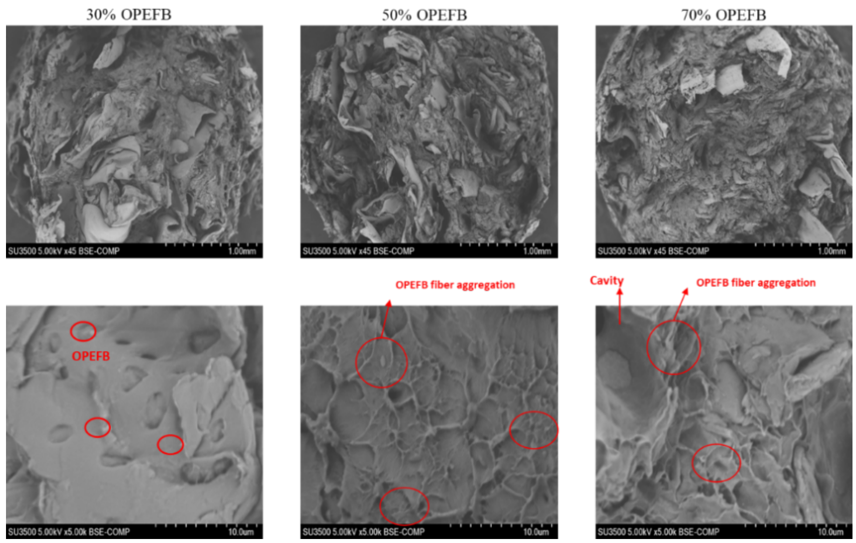

Figure 4. Cross-sectional morphology of biocomposites with various OPEFB composition at magnification of 45x (Top) and 5000x (Bottom) under cryogenic fracture conditions.

In Figure 4, with the condition of 30% OPEFB shows that the spherical area is a cross-sectional part of the OPEFB fiber, so that with the increase in the amount of OPEFB fiber content, a more random morphological structure will be seen and there are many fiber aggregations such as when the OPEFB content is 50% and 70%. Fiber aggregation is characterized by the presence of pores or gaps that are not filled with the matrix so that the material is less well mixed at a temperature of 150 ºC and it can be interpreted that the lid film in small quantities does not function as a binder for OPEFB fibers [26]. This is in accordance with research on the presence of pores in the results of SEM analysis of OPEFB fibers [27].

CONCLUSION

This study demonstrated the feasibility of utilizing post-industrial lid film waste from bottled water packaging in combination with oil palm empty fruit bunch (OPEFB) fibers to develop sustainable biocomposites. Feasibility is assessed based on the material's economic competitiveness rather than through complete mechanical optimization. Based on comparative production cost analysis reported in previous studies, rPE/OPEFB-based WPC exhibits a total production cost of approximately USD 2,753 per ton, which is comparable to rPE/teak-based WPC (USD 2,733 per ton) and lower than rPE/rice husk-based WPC (USD 2,810 per ton). This production cost range is considered feasible for further industrial development of WPC materials derived from wate resources. Therefore, despite the need for further improvement in interfacial bonding and mechanical performance, post-industrial lid film waste from bottled water and OPEFB fibers shows strong potential for scale-up and value-added industrial applications.

The combination of lid film waste and OPEFB fibers provides a promising pathway for value-added utilization of two abundant waste streams in Indonesia, contributing to both plastic waste reduction and agricultural residue management. Although improvements in mechanical properties remain a challenge, this research establishes a foundation for further development of eco-friendly composites. Future studies needed to explore more about compatibilizers and alternative processing methods to enhance interfacial adhesion and broaden potential applications of these biocomposites in sustainable materials engineering.

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