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ARTICLE

Oil Palm Empty Fruit Bunch–Derived Cellulose as a Sustainable Reinforcement for Enhanced Starch-Based Bioplastic Films

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ABSTRACT: The limited mechanical performance of starch-based bioplastic films, particularly their low strength and stiffness, remains a major challenge for their broader application as sustainable packaging materials. This study aims to address this issue by utilizing cellulose fibers extracted from oil palm empty fruit bunch (OPEFB) waste as a reinforcing agent in corn starch–based bioplastic films. The bioplastic films were fabricated using a solution casting method with varying cellulose contents and subsequently characterized to evaluate their mechanical properties, crystalline structure, and thermal stability. The results demonstrate that the incorporation of cellulose fibers significantly enhances the tensile strength and Young's modulus of the bioplastic films. An optimum cellulose content of 12% (F12) resulted in the highest tensile strength of 7.40 MPa and Young's modulus of 395.97 MPa, indicating a substantial improvement in structural rigidity compared to the unreinforced film (F0). Although a reduction in elongation at break from 38.13% to 1.88% was observed, along with minor changes in crystallinity and thermal stability, the overall improvement in mechanical performance confirms the effectiveness of OPEFB-derived cellulose as a reinforcing agent. This study highlights the potential of oil palm agricultural waste as a sustainable cellulose source for the development of starch-based bioplastic films with enhanced mechanical properties and added environmental value.

KEYWORDS: Bioplastics; corn starch; OPEFB cellulose; mechanical properties; thermal properties; agricultural waste

1 Introduction

Plastic waste has increased significantly every year due to high consumption and long degradation time (hundreds of years), causing serious environmental problems. Currently, plastic is used in the packaging industry because it has the ability to form complex geometries. However, the single-use nature of plastics poses serious ecological problems. High production volumes, short service life, and challenges in treating waste after use make this issue an urgent environmental issue. Single-use packaging such as glass, plastic,

paper, aluminum and other metal alloys have a low recycling rate. For example, paper-based packaging that is successfully recycled is only about 20%, while the recycling rate of plastic is much lower [1]. Due to inadequate plastic waste management, around 1%–5% of all plastic produced ends up as waste in the land and sea environment. About 80% of plastic waste in the ocean comes from land, generally from landfills and roadside garbage piles that are not properly managed and then into the ocean by tidal currents and wind. It is estimated that around 2 million tons of plastic waste enter rivers every year, this phenomenon occurs in developing countries with limited management infrastructure and in developed industrial countries [2].

Effective solutions are needed to mitigate the adverse environmental impacts [3]. One of the solutions that can be developed is the use of eco-friendly packaging based on natural fiber biocomposites [1]. Biocomposites consist of two main components: a matrix acting as a binding agent and natural fibers serving as reinforcement. As a matrix, starch from various natural sources can be used such as cassava starch [1], Corn starch [4] as well as starch extracted from cassava peel waste [5] abundant ingredients in Indonesia as a cassava-producing country. Starch is a fully biodegradable polysaccharide and is the most promising ingredient due to its lower cost, wide availability, biodegradability, non-toxicity, and renewable [6]. However, starch has poor mechanical and thermal properties compared to synthetic polymers [7]. One approach that can overcome this problem is to add natural biopolymers as a strengthener, such as cellulose fibers derived from natural fibers.

Natural fibers that can be used such as corn husks [8], banana bunch [9] and oil palm empty fruit bunch (OPEFB) [5] as a reinforcer in biocomposite packaging. On the other hand, Indonesia is a leading palm oil-producing country with an estimated OPEFB waste produced reaching around 7 million tons annually [10]. The use of OPEFB as a reinforcement in environmentally friendly packaging is an innovation that can be developed to take advantage of abundant agricultural waste. A series of chemical treatments are usually required to remove lignin and hemicellulose from lignocellulose materials [11]. For example, alkalization is one of the chemical treatments using sodium hydroxide (NaOH), lime, ammonia, or alkaline hydrogen peroxide (AHP) [12–14]. The alkalization treatment also aims to remove impurities present in the fibers [15], improve fiber-matrix adhesion, and improve cellulose concentration and mechanical properties. The addition of cellulose fiber to the biocomposite aims to improve mechanical and thermal properties, in previous research the addition of 2%–8% cellulose fiber to cassava peel starch was able to increase the tensile value to 3.56 MPa [5]. Research that combines a natural matrix of starch with a natural fiber cellulose enhancer is interesting to develop so that it can be a packaging that does not adversely affect the environment. Research on OPEFB cellulose fiber-reinforced corn starch biocomposite as environmentally friendly packaging has never been carried out.

This study added 9% and 12% OPEFB cellulose fibers to the corn starch biocomposite. The selection of cellulose fiber content of 9% and 12% (w/w) is based on previous research conducted by Harmiansyah et al. the addition of cellulose fiber OPEFB 2%, 4%, 6% and 8% is able to increase the tensile strength value along with the addition of cellulose fiber [5] this result is strengthened by other studies such as corn husk fiber with the addition of corn husk fiber cellulose 2%, 4%, and 6% increase tensile strength values along with the addition of fibers [8]. However, different results were obtained in the study of Saputri et al. The increase in tensile strength value was only up to the addition of 7.5% fiber, while for the addition of cellulose fiber 10%, the tensile strength value decreased [16]. So, this study uses a concentration of 9% and 12% cellulose fiber in the biocomposite. The effect of the addition of OPEFB cellulose fibers on biocomposite films was analyzed based on mechanical properties, heat resistance, FTIR and XRD. This research develops the potential of OPEFB cellulose fiber as a reinforcer that is integrated into a maize starch-based biocomposite matrix. This innovation not only utilizes agricultural waste into environmentally friendly packaging that can replace conventional packaging but also provides added value to palm oil agroindustry waste in the future.

2 Research Methodology

2.1 Materials

The main ingredient used in this study is oil palm empty fruit bunch (OPEFB) obtained in oil palm plantations in Lampung Province, Indonesia, and starch is obtained from corn seed extraction. Other materials used in this study are NaOH, Aquades, and Plasticizer. NaOH solution is used as a lignin remover in OPEFB fibers. The plasticizer in this study is used as a reinforcement or to overcome the fragility of biocomposites. The tools used in this study are in the form of ovens, filters, stirring tools, digital balances, spatulas, measuring cups, beaks, magnetic stirrer hotplates, TGA test tools, knives, and glass plates measuring 25 cm × 25 cm.

2.2 Extraction of Corn Starch

Corn starch extraction was performed by first separating the corn kernels from the cob and husk using a knife, followed by thorough washing. The kernels were then crushed and mixed with water at a ratio of 500 g corn to 250 mL water, and subsequently blended until homogeneous. The resulting mixture was filtered through a filter cloth to obtain the pulp and filtrate. The pulp recovered from the first filtration was subjected to a second extraction using a water-to-pulp ratio of 2:1. The filtrates obtained from both the first and second filtrations were combined and transferred into a plastic container. The combined filtrate was allowed to settle for 24 h to enable starch precipitation. After sedimentation, two distinct layers were formed: the starch sediment at the bottom and the supernatant water above. The supernatant was carefully discarded, and the resulting wet starch sediment was subsequently dried under sunlight for 24 h.

2.3 Extraction of Cellulose Fibers

The extraction process of OPEFB cellulose fiber is carried out in several stages. OPEFB fibers are cut into approximately 3–5 cm in size and cleaned using aquades. Then it is dried for 3 days until the weight is constant before going through the alkaliization process. The process of alkalizing OPEFB fiber is carried out by dissolving OPEFB fiber in water and given a NaOH solution with a concentration of 5% and heating at a temperature of 800°C for 1 h. Then the fibers are washed using aqueducts until they reach a neutral pH of 7. After reaching a neutral pH of 7, the OPEFB fibers are then dried. Next, the fibers are mashed with a blender to turn the fibers into smooth.

2.4 Fabrication of Biocomposite

The biocomposite film in this study includes, first, as much as 150 mL of water is put into a beaker and starch is added with a composition of 10 g. Next, the corn starch solution is heated using a magnetic stirrer hotplate at a temperature of 70°C, for a period of 22 min, until it gelatinization occurs. In this study, the plasticizer used was glycerol as much as 2 mL, with cellulose and corn added with variations of adding 0%, 9%, and 12% by weight. The gelatinized solution is poured in a glass mold and then dried in the oven at 40°C for 20 h. In the manufacture of biocomposites, three times are repeated on each variation with the same treatment. The method used in filmmaking is the solution casting method with solvent evaporation.

2.5 Characterization of Biocomposite

2.5.1 Mechanical Strength

The tensile test uses the ASTM D882 testing standard. The biocomposite sample is carefully cut into a size of 6.3 cm × 1 cm to undergo a tensile test and the thickness of the sample is <1 mm, which is performed to ensure its tensile strength. This test was carried out using the Shimadzu AGS-X (Kyoto, Japan) engine,

which is equipped with a 10 kN load cell. The experimental setup involves three repetitions for each variation to ensure the reliability of the results.

2.5.2 FTIR Analysis (Spectroscopy Transformasi Fourier-Inframerah)

FTIR analysis is used to identify functional groups in biocomposite samples. The tool used was FTIR Perkin Elmer Spectrum Two with a sample size of 2 cm × 2 cm. The functional group analyzed is at a wavelength of 4000–400 μm cm^{-1}, which is presented in transmittance (%) to that wavelength.

2.5.3 TGA Analysis (Thermal Gravimetry Analysis)

Thermogravimetric analysis (TGA) is performed to analyze the thermal properties of biocomposites. A 10 mg biocomposite sample was placed on a microscale inside the furnace with a nitrogen flow rate of 20 mL/min using the Perkin Elmer TGA 4000 machine. The sample is heated from 25 to 500°C with a heating rate of 10°/min.

2.5.4 XRD Analysis (X-Ray Diffraction)

XRD is used to analyze the crystallinity of biocomposites. Measurements were obtained by scanning samples at 2θ from 5° to 80° with a current of 40 mA at 40 kV and 280 nm of CuKα radiation using D8 Advance (Bruker), Bragg-Brentano Diffraction. Before testing, the sample is dried in the oven at 60°C for two hours. The crystallinity index is measured using Segal's method:

$$Crl(\%) = \frac{I_{200} - I_{\text{am}}}{I_{200}} \tag{1}$$

where I_{200} is the maximum diffraction peak intensity at 2θ = 22.6° (crystalline area). I_{am} is the peak of diffraction at 2θ = 18° (amorphous area). The size of a crystal is measured by the Scherrer equation. The Scherrer equation is then used to calculate the size of the crystallinity of the sample:

$$\text{D} = \frac{k\lambda}{\beta cos\theta} \tag{2}$$

where D is the size of the crystalline (nm), k is the Scherrer constant (0.94), λ is the wavelength of X-ray radiation (λ = 1.5406 Å), β is the FWHM of the maximum intensity (I_{200}) and θ is the Bragg Angle

In the context of X-ray diffraction analysis, the following variables are of particular importance: crystallite size (D), Scherrer constant (k), X-ray radiation wavelength (λ), full width at half maximum (FWHM) of the reflection field (β), and Bragg angle (θ). The Scherrer constant is defined as k = 1 for needle-shaped crystalline equatorial reflection. The wavelength of X-ray radiation, or λ, is expressed in Å and is equivalent to 1.5406 Å. The full width at the maximum half of the field of reflection, or β, is measured in radians. Finally, the Bragg angle, or θ, is defined as the angle between the X-ray beam and the crystallite plane.

2.5.5 Data Analysis

Experimental data were analyzed in the SPSS application using one-way variance analysis (ANOVA) at $p < 0.05$ to test for differences between treatments. If significant differences are found between treatments, the Duncan multiple range test (DMRT) is used to test whether the results differ significantly between samples in the treatment group.

3 Result and Discussion

3.1 OPEFB Cellulose

OPEFB fibers consist of cellulose, hemicellulose and lignin in general. Some studies report the chemical composition content of OPEFB can be seen in Table 1. Chemical treatments such as alkalization can increase the hydrogen bonds between fibers and starch-like matrices which has the impact of increasing the mechanical properties and thermal resistance of biocomposites.

Table 1: Report of chemical composition content of OPEFB untreated.

Cellulose (%)	Hemicellulose (%)	Lignin (%)	Others (%)	Ref.
37.07	24.81	27.78	10.80	[17]
49.33	13.31	23.4	–	[18]
37.50	28.43	20.62	13.45	[19]
43.80	35.00	16.40	4.80	[20]

Based on Table 2 5% NaOH treatment can degrade lignin, hemicellulose and impurities on the surface of OPEFB fibers, and cellulose increased to 94.26%. The results of this study are in line with the research conducted by Mansur et al. that alkaline treatment is more effective in increasing the concentration of cellulose than other chemical treatments [21]. NaOH is able to stretch the carbonyls of the acetyl hemicellulose and lignin groups and reduce some of the non-cellulose components [22].

Table 2: The chemical composition content of OPEFB alkali treatment.

Composition	Content%
Lignin	0.92
Water Content	3.38
Hemicellulose	1.44
Cellulose	94.26

Fig. 1 shows the SEM micrograph on the surface of the OPEFB fiber, the surface of the fiber treated with alkali treatment shows a cleaner and rougher fiber condition than the untreated fiber, the white spots in Fig. 1a show impurities on the surface of the fiber. NaOH treatment with a concentration of 5% showed a rough and clean surface which indicated that the alkaline treatment was able to degrade non-cellulose substances such as wax, dirt, fatty substances, and round protrusions called tillose. On the other hand, the alkalization treatment affects the physical properties of the OPEFB fibers such as the diameter of the fiber, the size of the fiber diameter is reduced to 0.27 from 0.47 mm. This also reinforces that alkalization treatment can degrade non-cellulose content and impurities on the fiber surface [23]. Some previous studies related to alkaline treatment of OPEFB can be seen in Table 3.

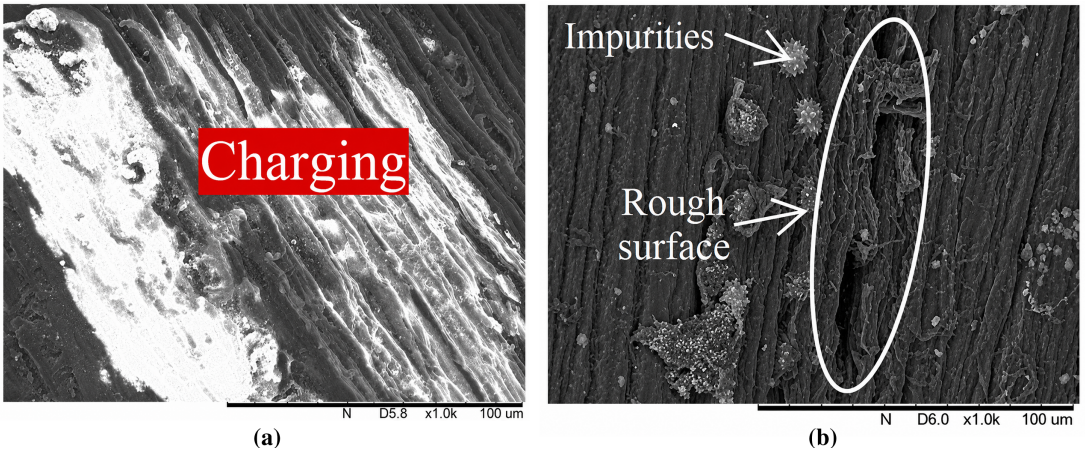

Figure 1: Surface morphologies of OPEFB fiber: (**a**) untreated; (**b**) alkali treatment [23].

Table 3: Previous research report related to OPEFB alkaline treatment.

No.	Fiber	Alkali Treatment	Conditions	Result					Ref.
				Chemical Composition (%)			Crl (%)	Thermal	
				Cellulose	Hemicellulose	Lignin			
1	Oil Palm Empty Fruit Bunch	4% NaOH	80°C for 2 h	87.70	–	–	73.0	382.64	[24]
2	Oil Palm Empty Fruit Bunch	1. Peracetic Acid AS(PA) Treatment 2. Alkaline Peroxide (AP) Treatment	1. 35°C, 9 h, stirring 90 rpm 2. 45°C, 12 h, 90 rpm stirring	51.3	23.0	4.7	–	–	[25]
3	Oil Palm Empty Fruit Bunch	15% NaOH	130°C for 40 min	–	–	–	60.5	–	[26]
4	Oil Palm Empty Fruit Bunch	4% NaOH	Room temperature, for 24 h,	–	–	–	51.8	330	[27]
5	Oil Palm Empty Fruit Bunch	10% NaOH	150°C for 30 min	73	14.9	12.1	–	–	[28]

3.2 Mechanical Strength

3.2.1 Tensile Strength

The tensile strength test results in Fig. 2 show that the variation in the addition of cellulose in oil palm empty fruit bunch (OPEFB) affects the mechanical properties of corn starch-based biocomposite films. Samples without the addition of cellulose (F0) had the lowest tensile strength, which was 5.62 MPa. The low tensile strength value at F0 can be attributed to the nature of the starch matrix which has a relatively weak amorphous structure and intermolecular bonds. Pure starch generally produces a film that is brittle and less resistant to tensile loads due to the lack of reinforcing elements [29].

The addition of 9% cellulose OPEFB to the F9 sample increased the tensile strength to 6.88 MPa, indicating a strengthening effect. Cellulose fibers are known to have a high modulus of elasticity, a strong crystalline structure, as well as many hydroxyl groups that can form hydrogen bonds with starch. This interaction strengthens the matrix–filler adhesion so that the tensile load distribution is better, so that the film has a higher resistance to deformation [30]. In the F12 sample, with the addition of 12% cellulose, the

tensile strength value increased further to 7.40 MPa. This increase indicates that cellulose still makes a positive contribution to this concentration. A higher amount of cellulose increases the number of bonding points as well as improves the internal structure of the film so that it is stiffer and tensile resistant. Aliotta et al. [31] report that an increase in the fraction of the cellulose filler is able to increase the mechanical strength of the composite due to the occurrence of a more effective stress transfer from the matrix to the filler. Overall, the increase in tensile strength in all three samples showed that cellulose OPEFB functions effectively as a reinforcing filler. Cellulose is able to improve the rigidity, dimensional stability, and intermolecular strength of the starch matrix so that the film has better mechanical resistance than pure starch film.

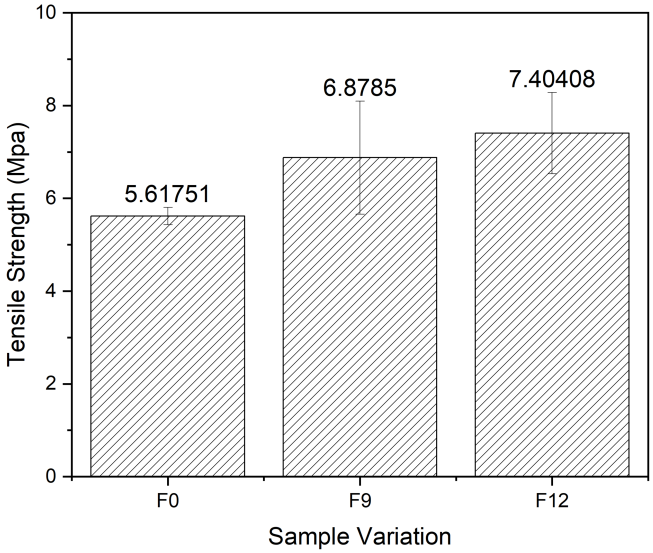

Figure 2: Tensile strength of biocomposite.

The results of ANOVA analysis showed a significance value of 0.107 ($p > 0.05$), which indicates that at the 95% confidence level, there was no significant difference in tensile strength between the F0, F9, and F12 samples. The Duncan test also showed that all samples were in the same homogeneous group. Nevertheless, the tendency to increase tensile strength in Fig. 2 still shows an improvement in mechanical properties in practice, although the data variability between repetitions is still high so the difference is not statistically significant. These results are in line with research conducted by Khouaja et al. [32] stated that the effect of strengthening cellulose would be more pronounced if the filler dispersion was more evenly distributed and the filmmaking process was more stable. Based on the tensile strength standard of Low-Density Polyethylene (LDPE) ranging from 7.85–34.5 MPa, the tensile strength value in this study does not meet the minimum LDPE standard but has the potential to meet the standard, further development is needed regarding the addition of cellulose fiber above 12% because of the trend of increasing tensile strength value with the addition of cellulose fiber to obtain tensile strength values that meet the standard.

3.2.2 Elongation

Fig. 3 shows that the elongation value of the biocomposite film has decreased drastically as the concentration of OPEFB cellulose increases. Samples without the addition of cellulose (F0) had the highest elongation value, which was 38.13%, while the sample with the addition of 9% cellulose (F9) only reached 2.74%, and the F12 sample (12% cellulose) was even lower, which was 1.89%. The high elongation value at F0 illustrates that pure starch-based films have better flexibility properties. This happens because the structure

of starch polymers that are not reinforced by fillers is more plastic and is capable of undergoing major deformation before breaking. The starch matrix contains hydroxyl groups that can form internal hydrogen bonds, but overall its mechanical character is still relatively soft and less rigid [33]. The addition of OPEFB cellulose starting at 9% led to a significant decrease in elongation. Cellulose has a rigid crystalline structure and a high modulus of elasticity. When cellulose is added to the starch matrix, there is an increase in stiffness and the formation of more intermolecular hydrogen bonds between cellulose and starch. This makes the movement of the polymer chain more limited, making it more difficult for the film to deform before cracking occurs [34].

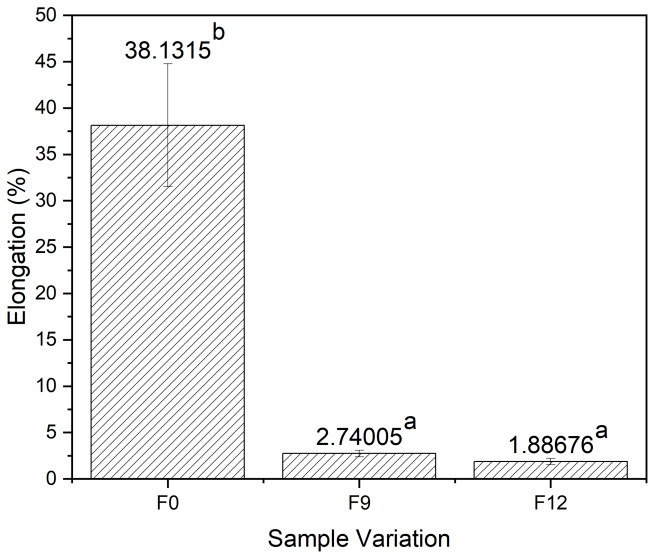

Figure 3: Strain with variation in cellulose.

A further decrease in F12 (1.89%) indicates that the increase in cellulose filler significantly increases the rigidity of the composite. At this concentration, a high amount of cellulose not only increases intermolecular bonding, but can also cause agglomeration at some point. According to research that has been conducted by Hafid et al. [35] explained that the agglomeration creates a stress concentration point, so that the film becomes more brittle and the elongation decreases drastically. Thus, the higher the addition of cellulose, the lower the film's ability to undergo strain, which is in line with the general nature of biopolymer-based composites where increased tensile strength is usually accompanied by decreased elongation [4].

The results of statistical analysis show that variations in cellulose concentration have a significant effect on the elongation value of the film. This is shown by the difference in the superscript letters on the graph, where F0 is in group b, while F9 and F12 are in group a. The pattern indicates that F0 differs markedly from the two samples with the addition of cellulose, while F9 and F12 do not show significant differences from each other. This result is in line with the visual pattern on the chart, where F0 has a much higher elongation value than the other two formulations. The decrease in value from 2.74% (F9) to 1.89% (F12) is relatively small, so it does not produce a statistically significant difference.

3.2.3 Young's Modulus

Young's modulus is an important parameter that indicates the rigidity and resistance of the material to elastic deformation. Fig. 4 shows the modulus value of Young's corn-based film biocomposite which increases with the increase in the concentration of cellulose of oil palm empty fruit bunch (OPEFB). In the F0 sample

(without the addition of cellulose), the Young's modulus value obtained was only 15.02 MPa, indicating that the pure starch film has a more amorphous structure and is less able to withstand tensile loads. This is because starch polymer chains do not have the structural reinforcement of fillers, so the material tends to be flexible and easily deformed. Some previous studies have also reported that starch films without reinforcers have a low modulus of elasticity due to the weak internal structure of the polymer—as reported by Dong et al. (2024) [36] that pure starch film tends to be soft and easily deformed.

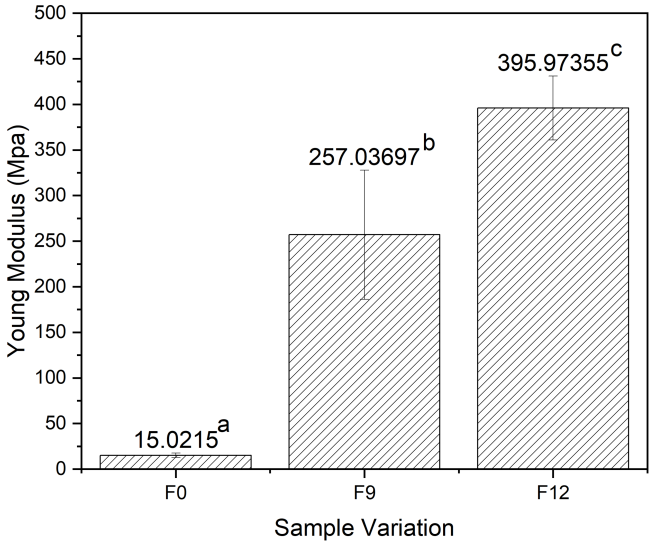

Figure 4: Modulus of elasticity with variations of cellulose.

The addition of 9% OPEFB cellulose to the F9 sample significantly increased Young's modulus to 257.03 MPa. This increase occurs because cellulose has high crystalline characteristics and a rigid fibril structure, so when mixed with the starch matrix, strong interactions are formed in the form of hydrogen bonds between molecules. This interaction creates a tighter, more stable composite network so that the stress needed to produce deformation is greater. These results are consistent with research conducted by Othman et al. [37] which states that the addition of cellulose microfibrils to the starch matrix significantly increases its modulus and mechanical strength.

At a concentration of 12% cellulose (F12), Young's modulus increases further to 395.97 MPa, suggesting that at this level cellulose is still well dispersed in the corn matrix to provide maximum strength. An increase from F9 to F12 shows that OPEFB cellulose works very effectively as a strengthening filler. The high crystalline structure of cellulose and strong mechanical properties make it capable of forming stiffer composite tissues, so the biocomposite film becomes much stiffer. These findings are in line with Fazeli & Simão research [38] which suggests that increased cellulose concentrations tend to increase the modulus of elasticity to some extent, as long as the dispersion of the filler remains homogeneous in the polymer matrix.

Based on the results of statistical analysis, each treatment of F0, F9, and F12 showed significant differences, indicated by the different superscript letters (a, b, c) on the graph. This shows that the increase in Young's modulus in Fig. 4 is directly due to the addition of OPEFB cellulose as a reinforcing material. Thus, both mechanically and statistically, the addition of OPEFB cellulose has been shown to increase the stiffness and durability of corn-based films, resulting in stronger and more stable film biocomposites.

3.3 FTIR Analysis

The FTIR spectrum showed some peak polysaccharide characteristics in all samples, The results of FTIR in this study can be seen in Fig. 5. The wide peak at 3288–3312 cm^{-1} is related to the O–H strain, indicating the presence of hydroxyl groups of starch, cellulose, and glycerol [39]. The sample was 9%, which showed the most significant shift in the number of wavelengths, from 3286 cm^{-1} (control) to 3312 cm^{-1}. The shift to a higher wave number (called blue shift or hypsochromic shift) in O-H vibrations is strong evidence of the weakening of hydrogen bonds that were initially regular and strong. In the context of biocomposites, this phenomenon shows that additives (plasticizers) manage to effectively intercalate themselves between the starch polymer chains and OPEFB fibers. This weakening of the internal hydrogen bond is essential because it increases the mobility of the polymer chain, which is a prerequisite for successful thermoplastic plasticization. It can be concluded that the concentration of 9% reaches the optimal point where the weakening of the H bond results in the highest flexibility. In contrast, a 12% sample showed a peak that was back close to control, which was 3288 cm^{-1}. This poll indicates that the addition of additives above 9% reaches the saturation limit. Excess plasticizers may no longer interact effectively with the polymer matrix. This can lead to self-aggregation of the plasticizer or a partial recovery of stronger secondary hydrogen bonds (e.g., on the remaining -OH group), which reduces the effectiveness of plasticization compared to a 9% sample [40].

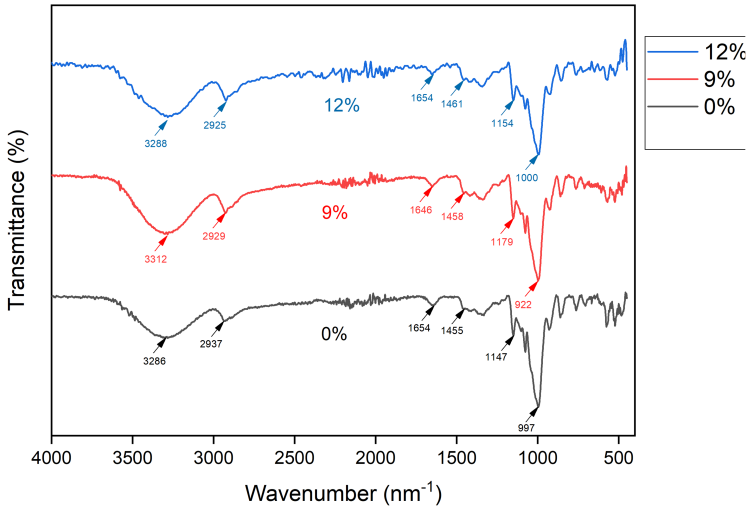

Figure 5: FTIR spectrum of the biocomposites.

The peak of aliphatic C-H stretching was observed at 2937 cm^{-1} (0%), 2929 cm^{-1} (9%), and 2925 cm^{-1} (12%). This peak is characteristic for the CH group in the starch backbone as well as in aliphatic plasticizers (glycerol). There is a consistent trend of shifting to a lower number of waves (red shift or bathochromic shift) as additive concentrations increase, accompanied by a potential increase in intensity (although absolute intensity is difficult to assess without normalization). This shift suggests that the vibrational environment of the C-H group is changing, usually becoming denser or less free. The increased C-H contribution of the plasticizer inserted into the matrix causes this red shift, which reinforces the conclusion that the concentration of the aliphatic component does indeed increase from 0% to 12% [41].

The H-O-H peak of adsorbed water is clearly visible in the region of 1640–1655 cm^{-1} specifically at 1655 cm^{-1} (0% and 12%) and 1646 cm^{-1} (9%). The slightly lower wave count in the 9% sample (1646 cm^{-1}) and its relatively prominent appearance can mean that this sample has the highest adsorption water content [42,43]. The 9% sample showed maximum (amorphous) weakening of hydrogen bonds, the

resulting polymer structure had more "open" OH groups and was available to bind to water molecules from the environment. This is a common trade-off: increased plasticization and flexibility often increase hygroscopicity and reduce the water resistance of the material [44].

The presented carbonyl group does not show a strong peak in the region of 1730–1750 cm^{-1} This C=O peak is very important because it serves as an indicator of chemical modifications, such as esterification that may occur between the starch/cellulose hydroxyl group and the crosslinking agent (if used) or the presence of triglyceride or fatty acid residues that may be present in OPEFB or added as additives [44]. The absence of a strong peak suggests that the interaction between OPEFB and starch in this study is most likely physical (hydrogen bonding) and not the result of a new covalent bond.

3.4 Thermal Stability

Analysis of the initial degradation temperature (T_{onset}) and peak DTG (T_{max}) of corn starch biocomposites with variations in fiber concentration is shown in Fig. 6. TGA-DTG in this case to measure the resistance of the biocomposite to mass loss during heating and the rate of mass loss to temperature [45,46]. Three stages of degradation are identified for maize starch biocomposites from Fig. 6a: range 25°C–150°C as water particulate evaporation, volatilization of fructose fragments, and plasticizers with smaller molecular weights [47–49], the second degradation stage at 250°C–350°C resulting in depolymerization and degradation of the carbon chain in the starch matrix [48,50]. Finally, at a temperature of 350°C–500°C leaving residual residue.

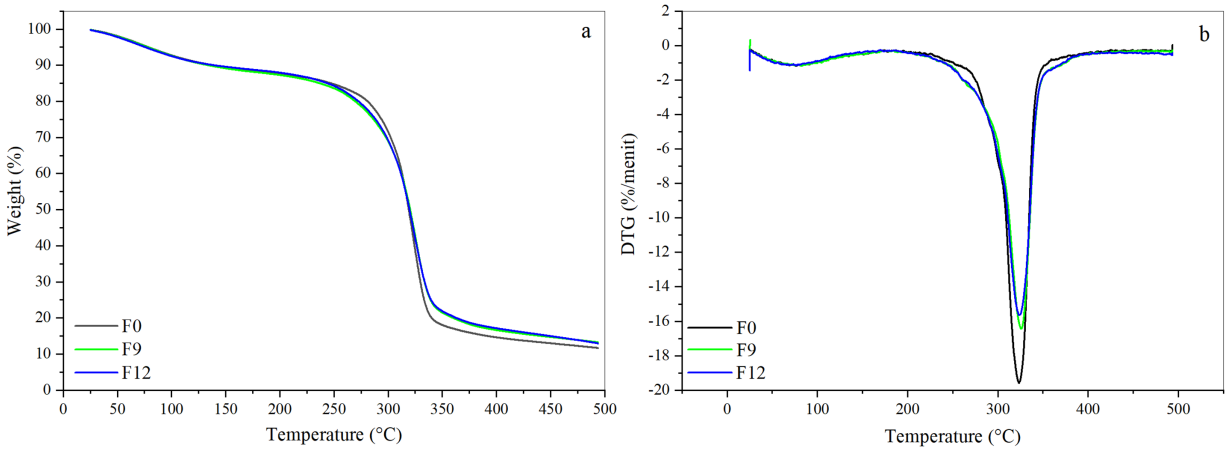

Figure 6: Thermal analysis of corn starch biocomposite film: (**a**) TGA (Thermogravimetric Analysis), and (**b**) DTG (Derivative Thermogravimetry).

Pure corn starch has a T_{max} value of 284°C, while OPEFB cellulose produced from the research of Zianor Azrina et al., produces a much higher T_{max} value of 382.64°C [24,51] This comparison was conducted to evaluate the contribution of cellulose to the improvement of the thermal properties of the biocomposite. It can be seen that in Table 4. an increase in T_{max} value of 326.06°C was observed upon the addition of 9% cellulose (F9), compared to 323.74°C recorded in the formulation without cellulose (F0). This increase indicates that the presence of cellulose fibrils plays a role in improving thermal stability through the formation of interface interactions and restriction of starch chain mobility, although the overall degradation mechanism is still dominated by the starch matrix as a continuous phase. This finding is supported by degradation data in the second stage (Table 4), where F9 experienced a decrease in mass loss to 62.12%

compared to F0 which reached 66.65%. The decrease in mass in the second stage indicates that the addition of cellulose is effective in inhibiting the main degradation process of the starch matrix.

In addition, the increase in thermal stability can be caused by the presence of a thermally stable cellulose crystalline structure, so that it is able to form a strong hydrogen bond interaction with the matrix and has intrinsically refractory properties, and is evenly distributed [52]. The results of F9 resulted in a weight loss of 86.65% lower than F0 and F12 and the lowest residual residue in F9 can be seen in Table 4. This difference in F9 indicates a higher amount of crystalline cellulose so that the F9 result can be resistant to fire. However, the addition of 12% cellulose (F12) decreases thermal stability which is likely to occur cellulose agglomeration, decreased effectiveness of interface interaction with the matrix, and the formation of voids that accelerate the thermal degradation process. As a result, the initial degradation temperature and the DTG peak temperature shifted to lower values [53].

Table 4: Thermal properties of corn starch biocomposites and the addition of cellulose fiber of empty bunches of oil palm.

Treatment	Initial Degradation Temperature (°C) T_{onset}	Peak DTG Temperature (°C) T_{max}	Degradation (%)			Weight Loss (%)	Residue 500°C (%)
			T1	T2	T3		
F0	305.05	323.74	10.9	66.65	6.39	88.221	11.669
F9	307.06	326.06	10.7	62.12	8.25	86.651	13.243
F12	302	324.41	10.2	62.38	8.96	86.921	12.946

Note: T1, T2, T3 are the degradation stages of Stage 1, Stage 2, Stage 3.

3.5 XRD Analysis

XRD analysis was performed to characterize the crystallinity of the biocomposite film, as shown in Fig. 7. Based on the results of *X-Ray Diffraction* (XRD) analysis, corn starch biocomposites with variations in OPEFB cellulose addition of 0% (F0), 9% (F9), and 12% (F12) showed a decreasing trend of crystallinity index along with the increase in the added cellulose fraction. Samples without cellulose (F0) had the highest crystallinity index of 23.15%, which then decreased to 19.10% at F9 and reached the lowest value of 16.91% at F12. In the control sample (F0), it showed the highest crystallinity index of 23.15% indicating that the matrix structure of corn starch was in a relatively more orderly condition. The absence of a filler phase allows starch chains to interact optimally through intermolecular hydrogen bonds, so that the process of chain rearrangement and the formation of crystalline regions can take place well during the film formation process [54,55].

At the addition of 9% of OPEFB cellulose (F9), the crystallinity index decreased to 19.10%. This decrease indicates that the presence of cellulose begins to affect the regularity of the starch matrix structure. The hydroxyl group (–OH) that cellulose has competes with the –OH group in starch in the formation of hydrogen bonds, thus inhibiting the process of resetting starch chains into a crystalline arrangement [56]. In addition, the presence of cellulose in the matrix leads to an increase in amorphous fractions due to a reduced ability of starch chains to form regular structures [40]. The most significant decrease in the crystallinity index occurred in the sample with the addition of OPEFB cellulose by 12% (F12), with a crystallinity value of 16.91%. At this concentration, cellulose disperses inhomogeneously and forms agglomerations within the starch matrix, which is indicated by a coarser and non-uniform film morphology. Such agglomeration limits the mobility of starch chains and inhibits the formation of regular crystal structures, thereby increasing the amorphous phase fraction [57]. This is in line with previous reports that the interaction of hydrogen

bonds between starch and cellulose can disrupt the regularity of polymer chains and lead to a decrease in the crystallinity index [58].

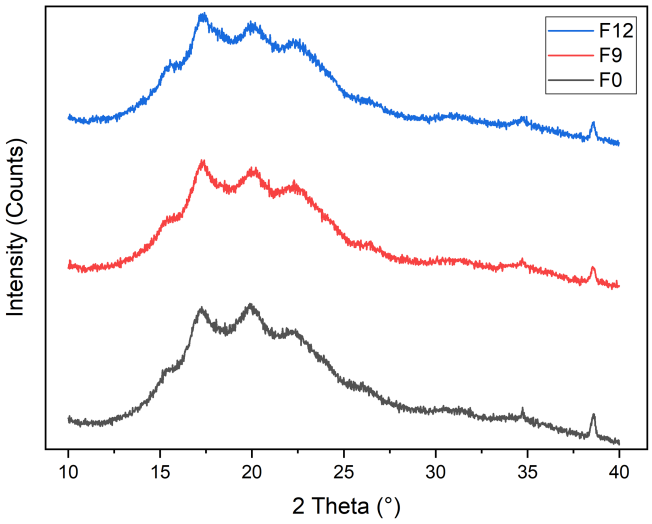

Figure 7: Graphic XRD.

4 Conclusions

OPEFB-reinforced corn starch biocomposite has been successfully developed, the results show that the addition of OPEFB cellulose fiber to the corn starch biocomposite significantly increases the tensile strength and Young's modulus of the bioplastic film. The optimal cellulose content of 12% results in the highest tensile strength of 7.40 MPa and Young's modulus of 395.97 MPa, showing a substantial increase in structural rigidity compared to unreinforced films. Although a reduction in elongation at break from 38.13% to 1.88% was observed, along with minor changes in crystallinity and thermal stability, the overall improvement in mechanical performance confirmed the effectiveness of OPEFB-derived cellulose as a reinforcer on biocomposites. Biocomposites in this study have the potential to be developed as environmentally friendly packaging.

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