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CHARACTERISATION AND PERFORMANCE EVALUATION OF SUSTAINABLE EMPTY FRUIT BUNCH HYDRO-DEGRADABLE FILM

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ABSTRACT

Plastic has been reported as one of the main contributors to marine pollution. Attempts have been made to produce starch-based hydro-degradable materials as an alternative to plastic. However, the poor mechanical strength of starch films limits their real-life applications. The objective of this study is to explore the potential of using empty fruit bunch (EFB) in the formulation of hydro-degradable materials. The properties of EFB films produced from varying concentrations of cellulose were evaluated based on tensile strength, water uptake and morphology. Nanocrystalline cellulose with an average size of 15.29 ± 3.906 nm was successfully extracted from EFB. The highest tensile strength of ~6.55 ± 1.15 MPa was observed in the EFB film, which consisted of 30% of nanocrystalline cellulose. Additionally, approximately 90% water uptake was recorded for EFB films, despite the dense structure of the EFB film at high cellulose content. EFB films support the Sustainable Development Goals (SDG) because the EFB film utilises biomass as a source of cellulose, their hydro-degradability minimises marine debris such as plastic and they provide an environmentally friendly solution. Future studies could investigate the optimal humidity levels to ensure the desired durability of sustainable EFB films for packaging and edible film applications.

Keywords: empty fruit bunch, hydro-degradable film, marine plastic pollution, tensile strength, water uptake.

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INTRODUCTION

Marine pollution has become a global issue, particularly since the rapid rise of plastic production in the 1950s. According to Almroth and Eggert (2019), plastic contributes to ~80% of the marine litter, with more than 10 million tonnes of plastic released to the oceans every year. Plastic in the oceans causes entanglement, ingestion of plastics by marine organisms, and biodiversity loss (Thushari & Senevirathna, 2020). An alternative to plastic materials needs to be explored to address this problem. Attempts have been made to fabricate biodegradable plastics. However, biodegradable plastics cannot degrade effectively under subtropical natural conditions (Cheung & Not, 2024) and coastal settings (Omura et al., 2024). They also require the presence of microorganisms, such as those found on the deep-sea floor, for effective degradation. Recent efforts have focused on exploring hydro-degradable material as a potential alternative to biodegradable plastics (Chan & Tang, 2022).

Starch films have been explored for their potential as edible films in the food industry due to their cost-effectiveness and excellent film-forming abilities (Thakur et al., 2019). They are also easily hydrolysed in water across a wide range of pH values (Chan et al., 2024). Nevertheless, their

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inherently poor mechanical strength properties restrict their use in real-life applications. Prado et al. (2018) found that the presence of cellulose nanocrystals in the starch films enhanced tensile strength by ~14%. Similarly, Jiang et al. (2022) reported an increase of 40% in tensile strength when microcrystalline cellulose was added to the film. Thus, it can be concluded that the addition of cellulose enhanced the mechanical strength of starch films. Furthermore, using cellulose derived from biomass could contribute to developing sustainable and environmentally friendly materials for practical applications.

Oil palm remains a key contributor to Malaysia's economy and trade performance. In September 2025, exports of palm oil and palm oil-based products accounted for approximately 8.0% of total exports, amounting to RM11.0 billion, representing a 14.0% increase compared to the previous year (Department of Statistics Malaysia, 2025). The continued growth of the palm oil industry indicates a substantial generation of biomass residues, particularly empty fruit bunch (EFB), as a major by-product of palm oil processing. The high availability of EFB highlights its potential as a sustainable raw material for value-added applications, including the development of biodegradable and sustainable materials. EFB consists of 42.7% to 65.0% of cellulose and 17.1% to 33.5% of hemicellulose (Hossain et al., 2016). This makes EFB an ideal source of cellulose, which can be used to produce value-added products such as microcrystalline cellulose for reduced-fat processed meat products (Bohrer et al., 2023), pulp and papermaking (Mohamad & Jai, 2022), as well as packaging film (Zhang et al., 2024). Lately, Ben Hamou et al. (2025) reported that nanocrystalline cellulose (NCC) extracted from date palm trees improved the ionic conductivity of pure polyurethane from ~10^{-11} to ~10^{-5} S cm^{-1}. Similarly, Sjahro et al. (2025) produced a membrane using cellulose extracted from EFB. The membrane achieved ~99% of dye removal efficiency. These findings highlight the strong potential of NCC as a sustainable nanofiller for applications in green energy storage systems and wastewater treatment technologies. Overall, these studies demonstrate the significant potential of palm-derived cellulose as a renewable resource for developing sustainable functional materials.

Biodegradable material is defined as a material that is decomposed by microorganisms into CO_2, water, and biomass, whereas hydro-degradable materials degrade primarily through chemical hydrolysis with water without requiring microbial activity (Guo & Guo, 2022). Biodegradable materials often degrade slowly or inefficiently in marine and subtropical environments due to low microbial activity, and may persist like conventional plastics. On the other hand, hydro-degradable materials degrade more effectively in aquatic conditions within a shorter timeframe and offer a promising alternative for addressing marine pollution. Extensive works have been done to improve the mechanical properties of films with cellulose addition (Abenghal et al., 2025; Deng et al., 2025), but few studies systematically correlate cellulose loading with water uptake, mechanical strength, and morphology, particularly for hydro-degradable systems. Therefore, the objective of this study is to explore the potential of using EFB in formulating hydro-degradable material. It is hypothesised that incorporating cellulose extracted from EFB into starch-based films will enhance mechanical strength while reducing excessive water uptake, thereby producing a balanced hydro-degradable material suitable for sustainable packaging applications.

In this study, EFB films prepared using varying cellulose concentrations were evaluated in terms of mechanical strength, water uptake, and morphology. Finally, the sustainability aspects of the EFB films were discussed in the context of the Sustainable Development Goals (SDGs). This approach not only introduces a novel application pathway for EFB biomass but also establishes a systematic understanding of the composition-structure-property relationships governing film performance. Furthermore, the findings identify an optimised formulation that balances mechanical strength and hydro-degradability, addressing a key limitation of conventional starch-based materials. By bridging biomass valorisation, hydro-degradable material design, and functional performance, this research provides a new direction for developing sustainable packaging materials with improved applicability in aquatic and marine environments, thereby extending the practical relevance of EFB beyond traditional uses.

MATERIALS AND METHODS

Material

The EFB was collected from Malaysian Palm Oil Board (MPOB). Glacial acetic acid 99% (QREC (Asia) Sdn. Bhd., Malaysia), sodium chloride pellets (Merck KGaA, Germany), sodium hydroxide pellet (Chemsoln, Malaysia) and glycerol were used for cellulose extraction and fabrication the hydro-degradable film. Cassava starch obtained from a local supermarket was used as the matrix-forming material.

Fabrication of Hydro-degradable EFB Film

The EFB was washed with a detergent solution and rinsed with tap water to remove grease and sand particles, followed by overnight drying at

60ºC. Next, 30 g of dried samples was added to 0.17 g/mL of sodium chloride solution. A total of 15 mL of glacial acetic acid was added to the mixture before it was refluxed for 4 hr. Subsequently, the mixture was filtered through cheesecloth and washed with distilled water to neutralise the remaining acid until a neutral pH of 7 was achieved. The filtered sample was added to a 1 M NaOH solution and refluxed for 1 hr. The neutralisation process was repeated until a neutral pH of 7 was achieved (Ramli et al., 2015). At this stage, the cellulose extraction from EFB was completed.

A total of 12 g of cassava starch was mixed with distilled water and heated at 65ºC for 15 min under continuous stirring for gelatinisation. Subsequently, 1.19 mL of glycerol was added to the mixture and the heating temperature was increased to 75ºC for an additional 15 min. Following this, 10 wt% to 50 wt% of the cellulose extracted from EFB, calculated relative to the mass of cassava starch, was slowly added to the gelatinised starch solution under stirring conditions to minimise agglomeration. The cellulose loading in the starch film was controlled within the 10 wt% to 50 wt% range. This specific range was chosen for the current study because preliminary observations showed that cellulose contents below 10 wt% yielded films with inadequate mechanical strength, while loadings exceeding 50 wt% compromised the hydro-degradability of the films. Lastly, the mixture was poured on glass trays and dried at 40ºC for overnight (Isroi et al., 2017). The formation of hydro-degradable films was completed at this stage. The percentage of cellulose from EFB is reflected in the sample identification (ID), where EFB10 denotes a hydro-degradable film containing 10 wt% cellulose.

Characterisation of Extracted Cellulose and EFB Hydro-Degradable Film

The quality of extracted cellulose was analysed using Fourier transform infrared spectroscopy (FTIR) (PerkinElmer Spectrum 100, PerkinElmer Inc., USA) and X-ray powder diffraction (XRD) (Panalytical Empyrean XRD, Malvern Panalytical Ltd., United Kingdom). The crystallinity index (CI) and diameter (D) of the cellulose were calculated using Equations (1) and (2). In Equation (1), indicates the maximum intensity of the cellulose crystalline and indicates the maximum intensity of the amorphous region of the sample.

$$CI\,(\%) = \frac{I_{002} - I_{am}}{I_{002}}\,\chi\,100 \qquad (1)$$

$$D = \frac{K\lambda}{\beta\,cos(\theta)} \qquad (2)$$

Equation (2) is also known as the Scherrer equation, where K was Scherrer constant (0.9 for spherical crystallites), λ is the ultraviolet wavelength (λ = 0.1546 nm), β is the full width at half maximum (rad), and θ is half of the diffraction angle (rad).

The morphologies of the extracted cellulose and EFB hydro-degradable film were imaged using the field emission scanning electron microscopy (FESEM) (Nova NanoSEM 230, FEI Company, USA), while the mechanical strength of the EFB films was evaluated using an Instron universal testing machine (Instron, USA) 100 kN at a crosshead speed of 0.5 mm/min. This complies with ASTM D882-18 (ASTM International, 2018). A digital micrometre (Mitutoyo 293-340-30, Mitutoyo, Japan) was used to measure the thickness of the EFB films at 20 different positions to ensure consistency. Lastly, the water uptake test was conducted according to ASTM D570-22 (ASTM International, 2022). Film specimens with 2 x 2 cm were immersed in 200 mL of reverse osmosis (RO) water for 24 hr. The percentage of water uptake was calculated using Equation (3).

$$\text{Water uptake} = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Wet weight}} \times 100\% \qquad (3)$$

RESULTS AND DISCUSSION

Characterisation of Cellulose Extracted from EFB

The FTIR spectra of raw EFB and extracted cellulose are depicted in *Figure 1*. The absorption band in the range of 3,600 to 3,200 cm^{-1} represents the stretching vibration of O–H groups (Roslan et al., 2021). This peak is more obvious in the extracted cellulose compared to the raw EFB, as more O–H groups are exposed after the removal of lignin and hemicellulose. Asymmetric stretching vibration of CH_2 can be seen in both samples at ~2,900 cm^{-1}, confirming the presence of a polysaccharide structure (Sjahro et al., 2025). In the fingerprint region, the extracted cellulose shows a stronger absorption band between 1,000–1,100 cm^{-1}, corresponding to C–O and C–O–C stretching vibrations of cellulose. In contrast, raw EFB exhibits a less distinct peak in this region due to the presence of amorphous components such as lignin and hemicellulose. A weak band around ~1,370 cm^{-1} is observed in both spectra and is associated with the bending vibration of C–H and C–O bonds in polysaccharide aromatic rings (Fatah et al., 2014). These are commonly found in cellulose-based materials.

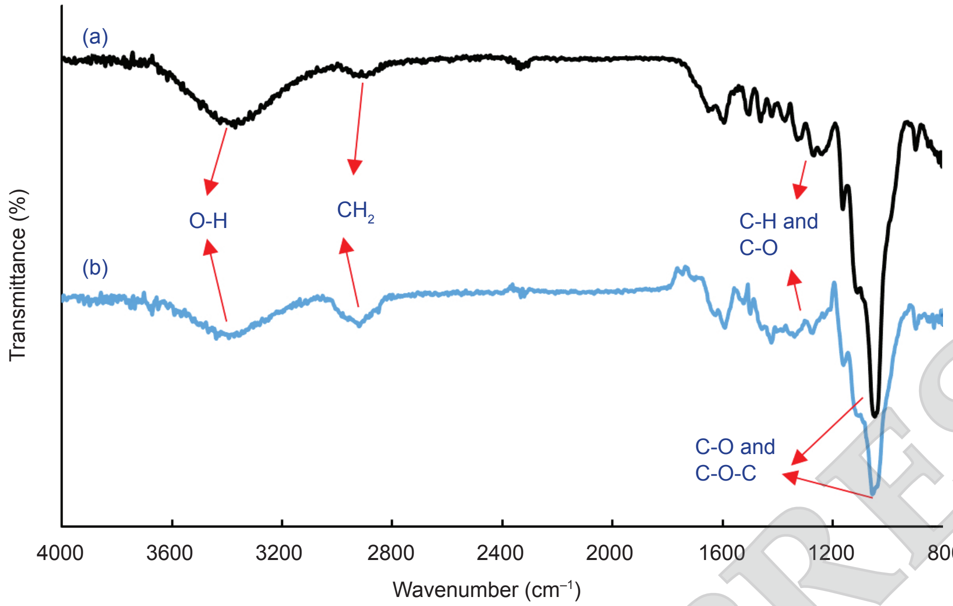

Figure 1. The Fourier transform infrared spectroscopy (FTIR) spectra of (a) extracted cellulose from empty fruit bunch (EFB), and (b) raw EFB, showing the changes in functional groups after removal of lignin and hemicellulose.

Figure 2 shows the XRD spectrum of the extracted cellulose. Peaks are observed at 2θ = 16.6°, 22.5° and 34.8°, which are assigned to the (110), (200) and (004) crystallographic planes, respectively (Salem et al., 2023). These are the common peaks found in cellulose I. During the acid hydrolysis process, hydrogen ions from acetic acid invade the loose amorphous region of cellulose, breaking the 1,4-β-glycosidic bonds (Xie et al., 2018). This indicates that the lignin and hemicellulose layers of the EFB were removed, exposing the cellulose compounds, which are compact in nature. The peaks in *Figure 2* show that the cellulose was successfully extracted from EFB. The average crystallite size of extracted cellulose is 15.29 ± 3.906 nm with a CI of 78.58%. Comparatively, the raw EFB had a CI value of 43.24% (Kuthi et al., 2015), due to the presence of amorphous structures such as lignin and hemicellulose. The CI of the extracted nanocrystalline cellulose is similar to the cellulose extracted from EFB via acid hydrolysis under sonication and hydro-thermal process adopted by Zulnazri et al. (2024) where 78.59% crystallinity was reported for their cellulose nanocrystals.

FESEM images presented in *Figure 3* show the morphologies of the extracted cellulose from EFB at different magnifications. The cellulose appears in fibrous form with a relatively smooth surface compared to raw EFB, as reported by Fatah et al. (2014), where the raw EFB surface was uneven and tangled with a lignin binder. The rough surface of raw EFB was due to the cemented components of lignin and hemicellulose, as well as the waxy materials. The removal of lignin and hemicellulose via the acid hydrolysis process resulted in the clean and smooth fibrous structure illustrated in *Figure 3c*. Notably, the observed microscale fibrous structures consist of bundles of cellulose fibrils containing nanometre-scale crystalline domains, which cannot be individually resolved by FESEM (García Betancourt & Osorio-Aguilar, 2022). This morphology is similar to the microcrystalline cellulose produced by Ismail et al. (2021) via steam-assisted acid hydrolysed EFB.

Performance of Hydro-Degradable EFB Film

Water uptake is a key parameter in hydro-degradable films, as it governs water penetration and hydrolysis-driven degradation. These parameters determine the balance between mechanical stability during use and controlled disintegration in aquatic environments. The water uptake performance of the EFB film is illustrated in *Figure 4*. All the films demonstrated high water uptake of ±90%, due to the inherent hydrophilic behaviour of starch, which is used as the film-forming material. It is notable that the water uptake by the EFB films reduced as the concentration of the nanocrystalline cellulose increased from EFB10 to EFB50. This is because the water sorption ability of the film was restricted by cellulose. According to Popescu et al. (2017), the compact structure of starch-cellulose in EFB film restricts chain mobility, which reduces the amount of free hydroxyl groups in the film. This limits water penetration into the film and consequently reduces water uptake.

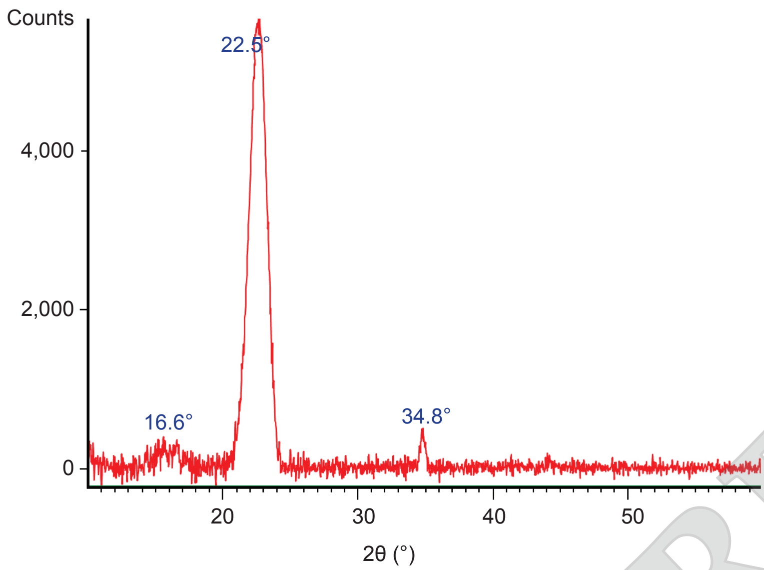

Figure 2. The X-ray powder diffraction (XRD) pattern of cellulose extracted from empty fruit bunch (EFB), showing characteristic diffraction peaks at 2θ ≈ 16.6°, 22.5°, and 34.8°, corresponding to the crystalline structure of cellulose.

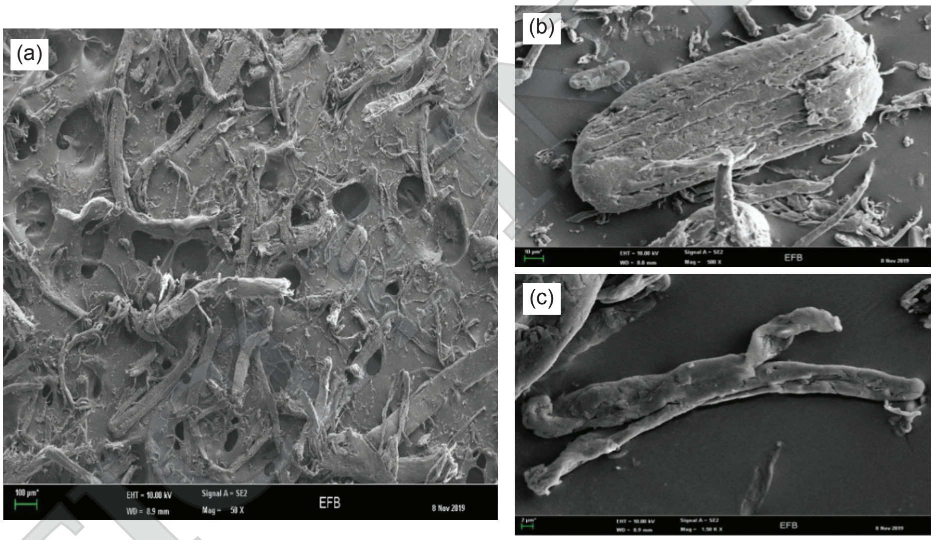

Figure 3. The field emission scanning electron microscopy (FESEM) images of extracted cellulose at (a) 50x, (b) 500x and (c) 1,500x magnification, showing the fibrous structure and surface morphology of the extracted cellulose.

A similar finding was reported by Yaacob et al. (2019), where the incorporation of cellulose fibres into sago starch film increased the contact angle of the film due to the hydrogen bonding between cellulose and sago starch. As a result, the water sorption was reduced from approximately 200% in the pure sago starch film to approximately 120% in the starch-cellulose composite film. More recent studies further support this behaviour. Islam et al. (2025) reported water uptake values ranging from 74.00%–92.00% for starch films reinforced with cellulose nanocrystals derived from coconut coir. Similarly, Chan and Tang (2022) observed water uptake in the range of 88.07%–89.54% for hydro-degradable starch films incorporating cellulose extracted from rice husk. In comparison, the EFB films developed in this study exhibit comparable water uptake (~90%), indicating that the performance of the proposed material is on par with recent high-performance starch-cellulose composite films. While higher water uptake promotes faster hydrolysis and environmental breakdown, excessive absorption reduces the mechanical strength and stability of EFB films. Therefore, controlling water uptake is essential to balance durability during use and efficient degradation after disposal, making the films more suitable for sustainable packaging applications.

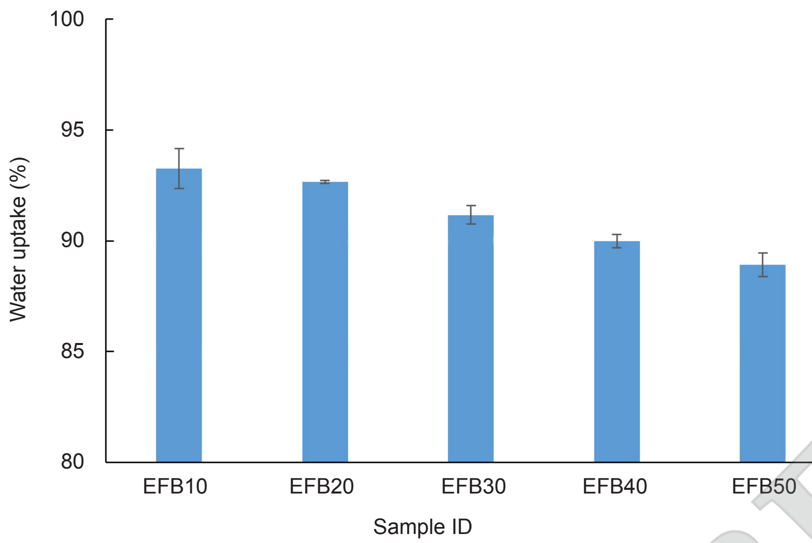

Figure 4. Water uptake performance of empty fruit bunch (EFB) hydro-degradable films.

Compared to the work published by Islam et al. (2025), the water uptake between 74.00% to 92.00% was recorded for the starch film incorporated with cellulose nanocrystals extracted from coconut coir. Similarly, Chan and Tang (2022) produced the hydro-degradable starch films using cellulose extracted from rice husk. The water uptake of the film was within the range of 88.07% and 89.54%.

Table 1 presents the effect of cellulose on the thickness, tensile strength and Young's modulus of the EFB films. No tensile data is available for EFB10 and EFB20 because the films were too weak to conduct the tensile test. This is in agreement with the FESEM images presented in *Figure 5a*. The surface of EFB10 has a relatively smooth surface with limited fibre distribution. The cellulose particles are sparsely embedded within the starch matrix, resulting in a weak interfacial interaction between the cellulose and starch chains. This loose microstructure suggests that the cellulose reinforcement is insufficient to form a strong network within the film. When the cellulose concentration increased to 30% in EFB30, the tensile strength was reported as 6.5480 ± 1.1553 MPa. In *Figure 5b*, EFB30 exhibits a more integrated and interconnected morphology. The cellulose fibres appear more uniformly distributed within the gelatinised starch matrix, forming a continuous reinforcement network. As a result, the EFB30 film demonstrates higher tensile strength compared to EFB10.

Nevertheless, further increases in the cellulose content in EFB50 do not contribute a significant impact to the tensile strength and Young's modulus. The surface morphology becomes denser and more aggregated due to the higher cellulose loading, as illustrated in *Figure 5c*. The excessive cellulose content leads to partial fibre agglomeration and the formation of thicker structural domains within the film. This is proven by the increase in film thickness from 0.4336 ± 0.0310 mm for EFB30 to 0.4936 ± 0.0329 mm for EFB50, as shown in *Table 1*. Notably, a dense morphology is observed in *Figure 5b* and *5c* for EFB30 and EFB50, compared to *Figure 5a* for EFB10. This finding is consistent with the data reported by Singh et al. (2022), where a high cellulose content in a film altered the original structure of the matrix, resulting in a dense and thick inner structure. This suggests that the EFB30 film is the optimised formulation for a hydro-degradable film as it exhibits a good balance of high tensile properties and water uptake percentage.

The performance of the EFB-based films was further critically compared with high-performance starch-cellulose composites and commercially available biodegradable films. Recent studies have reported that advanced starch-cellulose films reinforced with nanocellulose exhibit tensile strengths typically in the range of 10.0–33.0 MPa and reduced water uptake from 92% to 74% in the presence of citric acid (Islam et al., 2025). Similarly, starch-based bio-composites reinforced with cellulose nanofibres from potato peel by-products exhibited tensile strength of 21 to 55 MPa, with water uptake values of 5% to 15% (Medina-Jaramillo et al., 2025). On the other hand, commercially available biodegradable plastics such as polystyrene and aliphatic-aromatic copolyester generally exhibit a wider range of tensile strengths from 9.8 to >30.0 MPa (BASF SE, 2025; Islam et al., 2025). But their degradation in marine environments remains limited and slow (Barron & Sparks, 2020; Feijoo et al., 2025). The EFB30 film in this study demonstrates a tensile strength of ~6.55 MPa with water uptake of ~90%, placing it within the lower-to-moderate range of high-performance bio-

TABLE 1. THE THICKNESS DATA AND STRENGTH OF HYDRO-DEGRADABLE EMPTY FRUIT BUNCH (EFB) FILM

Sample ID	Thickness (mm)	Tensile strength (MPa)	Young's modulus (MPa)
EFB30	0.4336 ± 0.0310	6.5480 ± 1.1553	102.4575 ± 6.6794
EFB40	0.4720 ± 0.0280	5.2560 ± 1.2988	95.5040 ± 5.7624
EFB50	0.4936 ± 0.0329	5.6840 ± 1.0568	102.7680 ± 4.9506

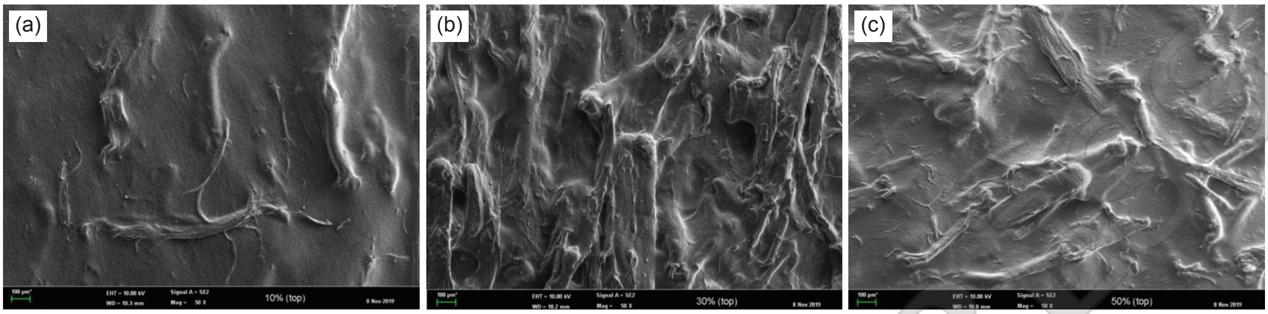

Figure 5. The field emission scanning electron microscopy (FESEM) images of hydro-degradable EFB film with sample ID, (a) EFB10, (b) EFB30 and (c) EFB50 at 50x magnification.

based films while maintaining desirable hydro-degradability. This highlights a key trade-off between mechanical durability and environmental degradability. Compared to these materials, the EFB-based hydro-degradable film offers a more balanced performance by enabling sufficient mechanical integrity during use while facilitating faster breakdown in aqueous environments. Therefore, although the mechanical performance is lower than that of commercial biodegradable plastics, the proposed material provides a competitive and environmentally responsive alternative for short-term packaging applications.

These findings highlight the potential of EFB-derived cellulose as a reinforcing agent in starch-based hydro-degradable films for sustainable packaging applications. While starch films are environmentally friendly, their practical use is often limited by poor mechanical strength and high-water sensitivity. The incorporation of cellulose extracted from oil palm EFB enhances the structural integrity of the film while maintaining its hydro-degradability. Furthermore, the utilisation of EFB, an abundant agro-industrial waste from the palm oil industry, supports biomass valorisation and promotes the development of environmentally sustainable packaging materials.

Sustainability of Hydro-degradable EFB Film

The advancement of hydro-degradable EFB films is crucial for driving sustainable solutions by bridging scientific progress with global environmental and economic objectives. Aligning technological innovations with the SDGs ensures that scientific breakthroughs contribute meaningfully to global sustainability efforts (Obaideen et al., 2022a). In this study, the EFB hydro-degradable films demonstrated approximately 90% water uptake while maintaining moderate mechanical strength, indicating their potential for controlled environmental degradation and practical short-life applications. EFB films, with their hydro-degradable nature, directly address multiple SDGs by reducing pollution, enhancing resource efficiency, and promoting sustainable industry practices. The utilisation of EFB-derived cellulose further demonstrates the valorisation of agricultural biomass waste into functional materials with added environmental value.

A key benefit of hydro-degradable EFB films lies in their potential to significantly decrease plastic waste, reinforcing SDG 12: Responsible Consumption and Production. This aligns with Target 12.5, which advocates for reducing waste through prevention, recycling, and reuse (Obaideen et al., 2022b). By transforming EFB, an abundant agricultural byproduct, into hydro-degradable films, the project minimises landfill waste and fosters a circular economy. The successful incorporation of 30 wt% to 50 wt% cellulose into starch films demonstrates the feasibility of converting biomass residues into value-added materials with enhanced structural properties. The sustainable conversion of agricultural residues into functional packaging materials reduces dependency on virgin petroleum-based resources, promoting responsible consumption patterns.

The positive environmental impact extends to protecting marine ecosystems, supporting SDG 14: Life Below Water. Specifically, Target 14.1 seeks to reduce marine pollution caused by plastics and other land-based contaminants (Gulseven, 2020). Since plastic waste accounts for a significant share of ocean pollution, the adoption of hydro-degradable materials can mitigate the accumulation of harmful debris in aquatic environments. The high-water uptake (~90%) observed in the EFB films indicates strong hydrolysis potential, supporting faster breakdown in water-based environments compared to conventional plastics. Furthermore, these films may reduce the long-term formation of microplastics, which are known to disrupt marine biodiversity and endanger aquatic food chains.

On land, the shift from traditional plastics to hydro-degradable alternatives supports SDG 15: Life on Land (Wang et al., 2020). Plastic residues contribute to soil contamination and ecosystem disruption. Target 15.3 emphasises the restoration of degraded land, and EFB films contribute by reducing the persistence of non-biodegradable waste in terrestrial environments. Additionally, the use of renewable EFB cellulose extracted from oil palm biomass promotes sustainable waste management while reducing open biomass disposal practices. These findings support sustainable ecosystem management and reduced environmental pollution from plastics.

From an industrial perspective, the application of EFB films enhances SDG 9: Industry, Innovation, and Infrastructure. The replacement of petroleum-based plastics with renewable EFB-derived cellulose supports Target 9.4, which focuses on increasing resource efficiency and sustainable industrialisation (Yousef et al., 2024). The tensile strength obtained for EFB30 (6.55 MPa) demonstrates that the films possess sufficient structural integrity for potential applications in disposable packaging, edible films, and short-life materials. Moreover, the reported relationship between cellulose loading, morphology, and mechanical behaviour provides valuable insight for future optimisation of sustainable film production. The commercial utilisation of EFB biomass may also create new economic opportunities and encourage investment in sustainable material technologies.

Additionally, EFB films contribute to SDG 13: Climate Action by reducing dependence on fossil fuel-derived plastic and promoting biomass-based material utilisation (Campbell et al., 2018). Target 13.2 advocates for incorporating climate change mitigation strategies into national policies, which can be supported through the wider adoption of hydro-degradable films. The conversion of abundant agricultural waste into functional films demonstrates a low-value-to-high-value biomass utilisation pathway that may contribute to a reduced environmental burden associated with plastic waste accumulation. Raising awareness and improving institutional capacity in sustainable materials further aligns with Target 13.3, which promotes education and innovation in climate action.

The integration of EFB-based hydro-degradable films into mainstream applications has the potential to improve waste management and industrial sustainability. The present findings demonstrate that the balance between water uptake, morphology, and mechanical strength can be tailored through cellulose loading, allowing the films to achieve both functionality and hydro-degradability. Policymakers and industry leaders may leverage these findings to encourage the transition toward biodegradable and hydro-degradable alternatives. Moreover, the economic viability of utilising agricultural waste ensures broader accessibility in both developed and developing nations, fostering long-term environmental and economic benefits. By directly linking experimental findings with SDG-related outcomes, this study highlights a practical and scalable approach for reducing plastic pollution while promoting sustainability-driven material innovation.

Limitation and Recommendation

Incorporating EFB into the fabrication of starch-based hydro-degradable materials has been successful, as it exhibited a good balance between strength and water uptake. Nevertheless, its application could be restricted to dry environments, as humid conditions could accelerate water absorption and lead to premature degradation, thereby reducing the functional lifespan of the material. In addition, rapid degradation under high humidity may limit its structural stability during storage and use. Future work could focus on identifying an acceptable humidity level to achieve the desired lifespan of EFB films for packing and edible film applications.

This study discusses sustainability based on the use of agricultural waste, namely EFB and the hydro-degradable nature of starch-cellulose materials, which suggests potential environmental benefits such as waste reduction and improved degradability. However, these claims are qualitative in nature, as no life cycle assessment (LCA) or degradation studies were conducted. Future work should include quantitative evaluation through LCA and hydro-degradation analysis to validate the environmental impact and strengthen the sustainability assessment of the developed materials.

In addition, the study was conducted with limited replicates (n = 3), which may restrict the statistical robustness of the results; therefore, future work should incorporate a larger sample size and appropriate statistical analysis to strengthen data reliability.

CONCLUSION

Nanocrystalline cellulose with an average size of 15.29 ± 3.906 nm was successfully extracted from EFB. This was confirmed by the FTIR spectrum, where a higher intensity of OH groups was observed after the removal of lignin and hemicellulose from raw EFB. Water uptake of EFB films reduced as the concentration of the nanocrystalline cellulose increased due to restricted chain mobility. Nevertheless, the water uptake was maintained at ±90% with tensile strength ranging from 5.2 to 6.5 MPa. EFB-based hydro-degradable films align with the SDGs and present a viable alternative to conventional plastic and hydro-degradable packaging materials. EFB film could be developed into temporary structural materials, such as seed tapes or disposable liners, contributing to sustainable agricultural and environmental management practices. These hydro-degradable films align with SDGs by addressing pollution, soil quality, responsible production, and sustainable industry. They mitigate marine and land pollution, foster a circular economy, and reduce fossil fuel reliance. Their adoption promotes regulatory support, economic growth, and environmental sustainability.

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REFERENCES

Abenghal, L., Bley, J., Tolnai, B., Njamen, G., & Chabot, B. (2025). Cellulose filaments as sustainable packaging materials: Enhancing barrier properties with cationic starch and alkylketene dimer. *International Journal of Biological Macromolecules, 321*(Part 3), 146493. https://doi.org/10.1016/j.ijbiomac.2025.146493

Almroth, B. C., & Eggert, H. (2019). Marine plastic pollution: Sources, impacts, and policy issues. *Review of Environmental Economics and Policy*, *13*(2), 317–326. https://doi.org/10.1093/reep/rez012

ASTM International. (2018). *Standard test method for tensile properties of thin plastic sheeting* (Standard No. D882-18). https://doi.org/10.1520/D0882-18

ASTM International. (2022). *Standard test method for water absorption of plastics* (Standard No. D570-22). https://doi.org/10.1520/D0570-22

Barron, A., & Sparks, T. D. (2020). Commercial marine-degradable polymers for flexible packaging. *iScience*, *23*(8), 101353. https://doi.org/10.1016/j.isci.2020.101353

BASF SE. (2025). *ecoflex® F Blend C1200: Certified compostable polyester for compostable film* (Product information, Version 3.0).

Ben Hamou, K., Chai, K., Mobarak, N. N., Dzulkarnain, N. A., Badri, K. H., Kaddami, H., Ahmad, A., & Su'ait, M. S. (2025). Enhancing electrochemical and thermo-mechanical performance of bio-based polyurethane nanocomposites polymer electrolyte reinforced with nanocrystalline cellulose for energy storage devices applications. *Electrochimica Acta*, *536*, 146692. https://doi.org/10.1016/j.electacta.2025.146692

Bohrer, B. M., Izadifar, M., & Barbut, S. (2023). Structural and functional properties of modified cellulose ingredients and their application in reduced-fat meat batters. *Meat Science*, *195*, 109011. https://doi.org/10.1016/j.meatsci.2022.109011

Campbell, B. M., Hansen, J., Rioux, J., Stirling, C. M., Twomlow, S., & Wollenberg, E. L. (2018). Urgent action to combat climate change and its impacts (SDG 13): Transforming agriculture and food systems. *Current Opinion in Environmental Sustainability*, *34*, 13–20. https://doi.org/10.1016/j.cosust.2018.06.005

Chan, M.-K., & Tang, T.-H. (2022). The properties of starch/cellulose/polyvinyl alcohol composite as hydrodegradable film. *Polymers and Polymer Composites*, *30*, 1–8. https://doi.org/10.1177/09673911221100353

Chan, M. K., Wang, C. C., Tee, Y. S., Tan, M. H., Janasekaran, S., Aziz, I. A., Musa, S. I., & Khir, M. R. M. (2024). Starch/wood powder/glycerol/lemongrass essential oil composite as hydro-degradable materials for 3D printing. *Starch -Stärke*, *76*(9-10), 2300108. https://doi.org/10.1002/star.202300108

Cheung, C. K. H., & Not, C. (2024). Degradation efficiency of biodegradable plastics in subtropical open-air and marine environments: Implications for plastic pollution. *The Science of the Total Environment*, *938*, 173397. https://doi.org/10.1016/j.scitotenv.2024.173397

Deng, N., Ma, Y., Li, P., Zeng, J., Gong, Z., Su, J., Li, J., Cao, D., Wang, B., Xu, J., & Chen, K. (2025). Mechanically robust lignin-cellulose films with triple barrier functions for antagonistic food preservation. *Chemical Engineering Journal*, *521*, 166561. https://doi.org/10.1016/j.cej.2025.166561

Department of Statistics Malaysia. (2025). *Malaysia External Trade Statistics Bulletin (September 2025)*.

Fatah, I. Y. A., Khalil, H. P. S. A., Hossain, M. S., Aziz, A. A., Davoudpour, Y., Dungani, R., & Bhat, A. (2014). Exploration of a chemo-mechanical technique for the isolation of nanofibrillated cellulosic fiber from oil palm empty fruit bunch as a reinforcing agent in composites materials. *Polymers*, *6*(10), 2611–2624. https://doi.org/10.3390/polym6102611

Feijoo, P., Marín, A., Sánchez-Safont, E., Tena-Medialdea, J., García-March, J. R., Gámez-Pérez, J., & Cabedo, L. (2025). Marine degradation of plastics in Western Mediterranean Sea: Comparison between biodegradable and conventional polymers. *Polymer Degradation and Stability*, *234*, 111222. https://doi.org/10.1016/j.polymdegradstab.2025.111222

García Betancourt, M. L., & Osorio-Aguilar, D. M. (2022). Physicochemical characterization of nanocellulose: Composite, crystallinity, morphology. In A. Barhoum (Ed.), *Handbook of nanocelluloses: Classification, properties, fabrication, and emerging applications* (pp. 83–117). Springer. https://doi.org/10.1007/978-3-030-89621-8_9

Gulseven, O. (2020). Measuring achievements towards SDG 14, life below water, in the United Arab Emirates. *Marine Policy*, *117*, 103972. https://doi.org/10.1016/j.marpol.2020.103972

Guo, C., & Guo, H. (2022). Progress in the degradability of biodegradable film materials for packaging. *Membranes*, *12*(5), 500. https://doi.org/10.3390/membranes12050500

Hossain, M. A., Laxmi, J., & Ganesan, P. (2016). Prospect of hydrogen production from oil palm biomass by thermochemical process – A review. *International Journal of Hydrogen Energy*, *41*(38), 16637–16655. https://doi.org/10.1016/j.ijhydene.2016.07.104

Islam, M. H., Ara, M. H., Khan, M. A., Naime, J., Khan, M. A. R., Rahman, M. L., & Ruhane, T. A. (2025). Preparation of cellulose nanocrystals biofilm from coconut coir as an alternative source of food packaging material. *ACS Omega*, *10*(9), 8960–8970. https://doi.org/10.1021/acsomega.4c06400

Ismail, F., Ali Othman, N., A.W., N., Abd.Hamid, F., & Astimar, A. A. (2021). Preparation of microcrystalline cellulose from oil palm empty fruit bunch fibre using steam-assisted acid hydrolysis. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *81*, 88–98. https://doi.org/10.37934/arfmts.81.1.8898

Isroi, I., Cifriadi, A., Panji, T., Wibowo, N. A., & Syamsu, K. (2017). Bioplastic production from cellulose of oil palm empty fruit bunch. *IOP Conference Series: Earth and Environmental Science*, *65*, 012011. https://doi.org/10.1088/1755-1315/65/1/012011

Jiang, J., Zhang, X., Gao, S., Li, M., & Hou, H. (2022). Effects of adding methods and modification types of cellulose on the physicochemical properties of starch/PBAT blown films. *International Journal of Biological Macromolecules*, *223*(Part A), 1335–1343. https://doi.org/10.1016/j.ijbiomac.2022.11.118

Kuthi, F., Haji Badri, K., & Azman, A. (2015). X-ray diffraction patterns of oil palm empty fruit bunch fibers with varying crystallinity. *Advanced Materials Research*, *1087*, 321–328. https://doi.org/10.4028/www.scientific.net/AMR.1087.321

Medina-Jaramillo, C., Coelho-Leandro, G., Ayala-Valencia, G., & López-Córdoba, A. (2025). Starch-based biocomposites reinforced with cellulose nanofibers from potato peel byproducts. *Scientific Reports*, *15*(1), 38412. https://doi.org/10.1038/s41598-025-22303-9

Mohamad, N. A. N., & Jai, J. (2022). Response surface methodology for optimization of cellulose extraction from banana stem using NaOH-EDTA for pulp and papermaking. *Heliyon*, *8*(3), e09114. https://doi.org/10.1016/j.heliyon.2022.e09114

Obaideen, K., Abdelkareem, M. A., Wilberforce, T., Elsaid, K., Sayed, E. T., Maghrabie, H. M., & Olabi, A. G. (2022a). Biogas role in achievement of the sustainable development goals: Evaluation, challenges, and guidelines. *Journal of the Taiwan Institute of Chemical Engineers*, *131*, 104207. https://doi.org/10.1016/j.jtice.2022.104207

Obaideen, K., Shehata, N., Sayed, E. T., Abdelkareem, M. A., Mahmoud, M. S., & Olabi, A. G. (2022b). The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. *Energy Nexus*, *7*, 100112. https://doi.org/10.1016/j.nexus.2022.100112

Omura, T., Isobe, N., Miura, T., Ishii, S., Mori, M., Ishitani, Y., Kimura, S., Hidaka, K., Komiyama, K., Suzuki, M., Kasuya, K.-I., Nomaki, H., Nakajima, R., Tsuchiya, M., Kawagucci, S., Mori, H., Nakayama, A., Kunioka, M., Kamino, K., & Iwata, T. (2024). Microbial decomposition of biodegradable plastics on the deep-sea floor. *Nature Communications*, *15*(1), 568. https://doi.org/10.1038/s41467-023-44368-8

Popescu, M.-C., Dogaru, B.-I., & Popescu, C.-M. (2017). The influence of cellulose nanocrystals content on the water sorption properties of bio-based composite films. *Materials & Design*, *132*, 170–177. https://doi.org/10.1016/j.matdes.2017.06.067

Prado, N., Raabe, J., Mirmehdi, M., Ramos, A., Junior, M., & Tonoli, G. H. D. (2018). Strength improvement of hydroxypropyl methylcellulose/starch films using cellulose nanocrystals. *Cerne*, *23*(4), 423–434. https://doi.org/10.1590/01047760201723042303

Ramli, R., Junadi, N., Beg, H., & Yunus, R. (2015). Microcrystalline cellulose (MCC) from oil palm empty fruit bunch (EFB) fiber via simultaneous ultrasonic and alkali treatment. *International Journal of Chemical, Nuclear, Materials and Metallurgical Engineering*, *9*(1), 8–11.

Roslan, R., Yaakob, M. N. A., & Jafri, N. F. (2021). Extraction of lignin from empty fruit bunch fiber via microwave-assisted acid hydrotrope solvent. *Current Science and Technology*, *1*(2), 26–33. https://doi.org/10.15282/cst.v1i2.6754

Salem, K., Kasera, N., Rahman, M., Habibi, Y., Eichhorn, S. J., French, A. D., Pal, L., & Lucia, L. A. (2023). Comparison and assessment of methods for cellulose crystallinity determination. *Chemical Society Reviews*, *52*(18), 6417–6446. https://doi.org/10.1039/D2CS00569G

Singh, G. P., Bangar, S. P., Yang, T., Trif, M., Kumar, V., & Kumar, D. (2022). Effect on the properties of edible starch-based films by the incorporation of additives: A review. *Polymers*, *14*(10), 1987. https://doi.org/10.3390/polym14101987

Sjahro, N., Yunus, R., Abdullah, L. C., Nainggolan, M., Abdul Rashid, S., Asis, A. J., Syafiie, S., Habib, S. H., & Harun, N. (2025). Valorization of oil palm empty fruit bunch (OPEFB) as membrane polymer via non-solvent induced phase separation method (NIPS) for removal of aqueous contaminants. *Discover Sustainability*, *6*(1), 319. https://doi.org/10.1007/s43621-025-01184-y

Thakur, R., Pristijono, P., Scarlett, C. J., Bowyer, M., Singh, S. P., & Vuong, Q. V. (2019). Starch-based films: Major factors affecting their properties. *International Journal of Biological Macromolecules*, *132*, 1079–1089. https://doi.org/10.1016/j.ijbiomac.2019.03.190

Thushari, G. G. N., & Senevirathna, J. D. M. (2020). Plastic pollution in the marine environment. *Heliyon*, *6*(8), e04709. https://doi.org/10.1016/j.heliyon.2020.e04709

Wang, T., Giuliani, G., Lehmann, A., Jiang, Y., Shao, X., Li, L., & Zhao, H. (2020). Supporting SDG 15, life on land: Identifying the main drivers of land degradation in Honghe Prefecture, China, between 2005 and 2015. *ISPRS International Journal of Geo-Information*, *9*, 710. https://doi.org/10.3390/ijgi9120710

Xie, H., Du, H., Yang, X., & Si, C. (2018). Recent strategies in preparation of cellulose nanocrystals and cellulose nanofibrils derived from raw cellulose materials. *International Journal of Polymer Science*, *2018*, 7923068. https://doi.org/10.1155/2018/7923068

Yaacob, N., Yusof, A., Mohamed, A. Z., & Haji Badri, K. (2019). Effect of cellulose fiber loading on the properties of starch-based films. *AIP Conference Proceedings*, *2111*, 050009. https://doi.org/10.1063/1.5111257

Yousef, B. A. A., Obaideen, K., AlMallahi, M. N., Alajmi, N., Radwan, A., Al-Shihabi, S., & Elgendi, M. (2024). On the contribution of concentrated solar power (CSP) to the sustainable development goals (SDGs): A bibliometric analysis. *Energy Strategy Reviews*, *52*, 101356. https://doi.org/10.1016/j.esr.2024.101356

Zhang, X., Fang, C., Cheng, Y., Li, M., & Liu, J. (2024). Fine extraction of cellulose from corn straw and the application for eco-friendly packaging films enhanced with polyvinyl alcohol. *International Journal of Biological Macromolecules*, *268*(Part 2), 131984. https://doi.org/10.1016/j.ijbiomac.2024.131984

Zulnazri, Z., Dewi, R., Muarif, A., Fikri, A., Fithra, H., Roesyadi, A., Sangian, H. F., & Alva, S. (2024). Effect of hydrochloric acid hydrolysis under sonication and hydrothermal process to produce cellulose nanocrystals from oil palm empty fruit bunch (OPEFB). *Polymers*, *16*(13), 1866. https://doi.org/10.3390/polym16131866