Synthesis and Characterization of Starch-Based Bioplastics Derived from Cassava (*Manihot esculenta*) Peels and Oil Palm Empty Fruit Bunch (*Elaeis guineensis*)

Maduabuchi Valentine Ibe[1], Verla Evelyn Ngozi[2], Ogonnaya Chinemerem Cynthia[1], Verla Andrew Wirnkor[1,*]

[1]Green Researchers in Analytical Chemistry and Environment (GRACE), Department of Chemistry, Imo State University, Owerri, PMB 2000, Imo State, Nigeria

[2]Department of Environmental Technology, Federal University of Technology, Owerri, Imo State, Nigeria

[*]Corresponding author

Email: verlaanadreww@gmail.com, Contact number: +23407069288937, Orcid ID: https://orcid.org/0000-0001-6837-2570

Abstract

The pervasive environmental pollution from conventional plastics necessitates the development of sustainable alternatives. This study presents the synthesis and characterization of starch-based bioplastics using agro-waste feedstocks: starch extracted from cassava peels and cellulose derived from Oil Palm Empty Fruit Bunch (OPEFB). Ten bioplastic variants were fabricated by varying the concentrations of cellulose (0-50% w/w) and glycerol (0-50% v/w as plasticizer), while maintaining a constant starch-to-water ratio (25g:100ml). The materials were characterized for their physico-mechanical and biodegradation properties. Results demonstrated that cellulose acts as a reinforcing agent, increasing tensile strength (from 3.7 MPa to 12.1 MPa) and Young's modulus (from 40 MPa to 240 MPa) while reducing water absorption (from 37.3% to 23.3%) and biodegradation (from 84.7% to 55.3% over 30 days). Conversely, glycerol enhanced flexibility and elongation at break but increased hydrophilicity and degradation rate. A strong positive correlation ($R^2 = 0.89$) was observed between water absorption and biodegradation, indicating that moisture content governs the degradation process. The findings confirm the viability of valorizing cassava peels and OPEFB into tunable bioplastics, offering a promising pathway for waste-to-wealth conversion and reducing plastic pollution.

Keywords

Agro-waste, Biodegradability, Cassava Peels, OPEFB, Valorization, Tensile Strength

1. Introduction

Plastics are integral to modern society but have led to a global environmental crisis, particularly due to the persistence of microplastics in ecosystems and their documented presence in human tissues [1,2]. The limitations of recycling and the finite nature of petroleum resources underscore the urgent need for sustainable, biodegradable alternatives.

Bioplastics, derived from renewable biological sources, present a viable solution. Starch, a natural polymer, is a promising base material due to its abundance, biodegradability, and film-forming ability [3]. However, neat starch-based plastics often suffer from high hydrophilicity and poor mechanical properties. To overcome these limitations, reinforcement with cellulose fibers and the use of plasticizers like glycerol are common strategies [4]. Bio-plastics, therefore play a vital role in replacing conventional plastics. In recent years they have been synthesized from various bio-based raw materials and have been used for production of some of our everyday products like disposable cups, toys, textiles etc. As bio based plastics they offer numerous advantages like, their faster decomposition which means less pollution, and also the fact that they are obtained from less expensive processes and more renewable sources like agro products and especially agro wastes which is the primary focus of this research.

1.1 Overview of the Agro-Waste Feedstocks

This research focuses on utilizing two abundant agro-wastes: cassava peels and Oil Palm Empty Fruit Bunch (OPEFB).

Oil Palm Empty Fruit Bunch (OPEFB):

This is an abundant waste product from the palm oil industry and tremendous amount of potential applications in both traditional and conventional uses. It is mainly made up of lignocellulosic contents like cellulose (42.7-65% of weight), hemicelluloses (17.1-33.5% of weight) and lignin (13.2-25.31% of weight)[5]. The oil palm industries are estimated to Dispose about 1.1 ton of OPEFB per ton of palm oil produces, most of these which are likely to be disposed to the environment or burnt thereby causing pollution [6].

It is currently used traditionally as fuel for boilers in the oil mills, or burnt and the ashes used as fertilizer. Some of its other emerging applications include, for biofuel production, as bio-composite and biosorbent.

Cassava Peels:

This is also a significantly abundant waste product of the agricultural sector, as it is estimated that about 50 million tonnes per year of peels, stumps, undersized, or damaged cassava are generated as wastes from cassava production and processing and are either burned or left to rot in piles, both of which pollute the air, soil, and groundwater.[5] It is mainly composed of Hemicellulose 23.4 - 32.36%, Cellulose 9.7 - 14.17%, Proteins 3.7 - 5.29%, Lignin 10.88 - 16.89% and starch 23.2 - 25.37% [7,8].

The numerous issues from environmental to human health problems associated with plastics are currently a keen area of research interest especially for the developing world where plastics are used in everyday life. Researchers are currently interested in an alternative material that could solve the above-mentioned problems and additionally be biodegradable and sustainable with viable economic potentials. Also, the issue of wastes treatment, recycle, treatment and disposal can be relatively expensive to handle, hence the efficient recycling of wastes into feedstock for production would be very economically viable and beneficial. In search of such a material, the current research topic was developed to inculcate two agro-wastes of enormous amounts released into the environment constantly without a proven economic use.

By synthesizing bioplastics from cassava peels and empty oil palm bunch as sustainable and eco-friendly alternatives to traditional petroleum-based plastics thereby contributing to the development of innovative and environmentally friendly approaches for reducing plastic waste, promoting sustainable agricultural practices and improved waste management.

This study aims to: (i) extract starch and cellulose from cassava peels and OPEFB, respectively; (ii) synthesize bioplastic films with varying compositions of cellulose and glycerol; and (iii) comprehensively characterize their mechanical properties, water absorption, and biodegradability to understand the structure-property relationships.

2. Materials and Methods

2.1 Raw Materials and Reagents

Cassava peels and OPEFB were sourced from local farms where they were found in Heaps as shown in Figure 1. All chemicals, including sodium hydroxide (NaOH), hydrogen peroxide (H_2O_2), sodium hypochlorite (NaClO), and glycerol, were of analytical grade.

Figure 1. Heaps of (a) Cassava peels and (b) OPEFB at sourcing sites

2.2 Starch Extraction from Cassava Peels

500g of fresh cassava peels were comminuted with distilled water (1:3 w/v ratio). The slurry was filtered through muslin cloth, and the filtrate was allowed to settle for 30 min. The supernatant was decanted, and the recovered wet starch was re-washed and dried in an oven at 65°C for 45 min. The resulting powder was characterized for yield, moisture, and ash content.

2.3 Cellulose Extraction from OPEFB

OPEFB fibers were sequentially treated: (i) dewaxing with ethanol (1:10 w/v, 1.5 h); (ii) alkaline treatment with 10% NaOH (1 h, frequent stirring) to remove hemicellulose and lignin; (iii) oxidation with H_2O_2 (1:100 w/v, 12 h); and (iv) bleaching with an acidified NaClO solution until a white cellulose pulp was obtained with the visual differences depicted in Figure 2. The product was rinsed, dried, and ground into a powder. Yield, moisture, and ash content were determined.

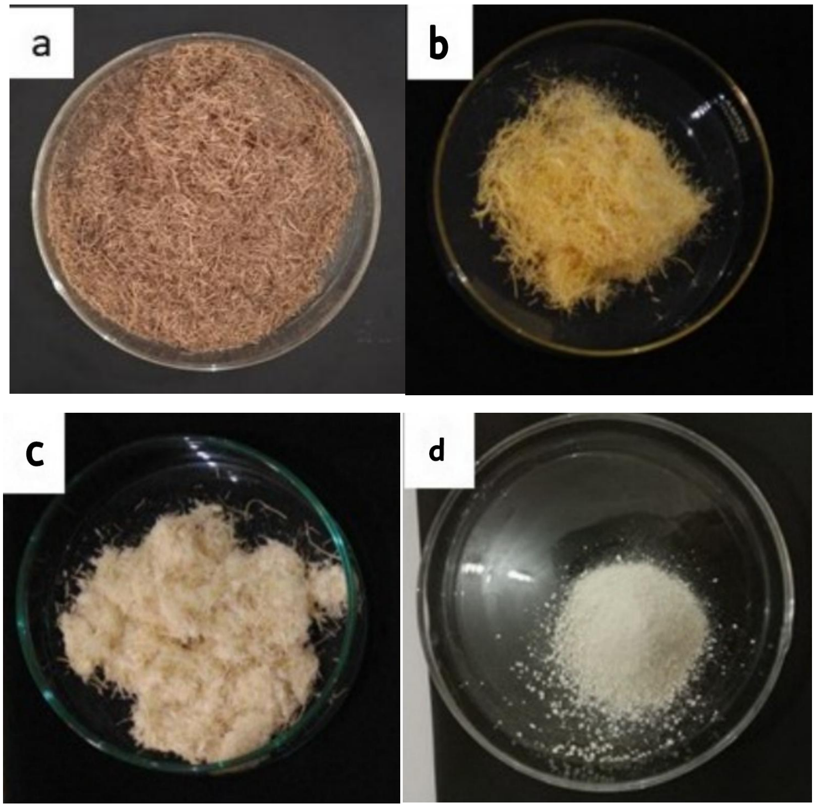

Figure 2. OPEFB during processing: (a) ground fiber, (b) after $NaOH/H_2O_2$, (c) after NaOH/NaClO, (d) final cellulose powder

2.4 Bioplastic Synthesis

A base solution was prepared by gelatinizing 25g of cassava starch in 100ml of distilled water at 70°C for 10 min with constant stirring. Pre-determined amounts of cellulose (0-15g) and glycerol (0-40ml) were added to the gelatinized starch according to the formulations in Table 1. The homogeneous mixture was cast onto tile plates, air-dried for 24 h, oven-dried at 70°C for 5 min, and finally air-dried for another 48 h. The resulting films were peeled and stored in airtight bags for analysis. A schematic step by step process of the synthesis is illustrated below in Figure 3.

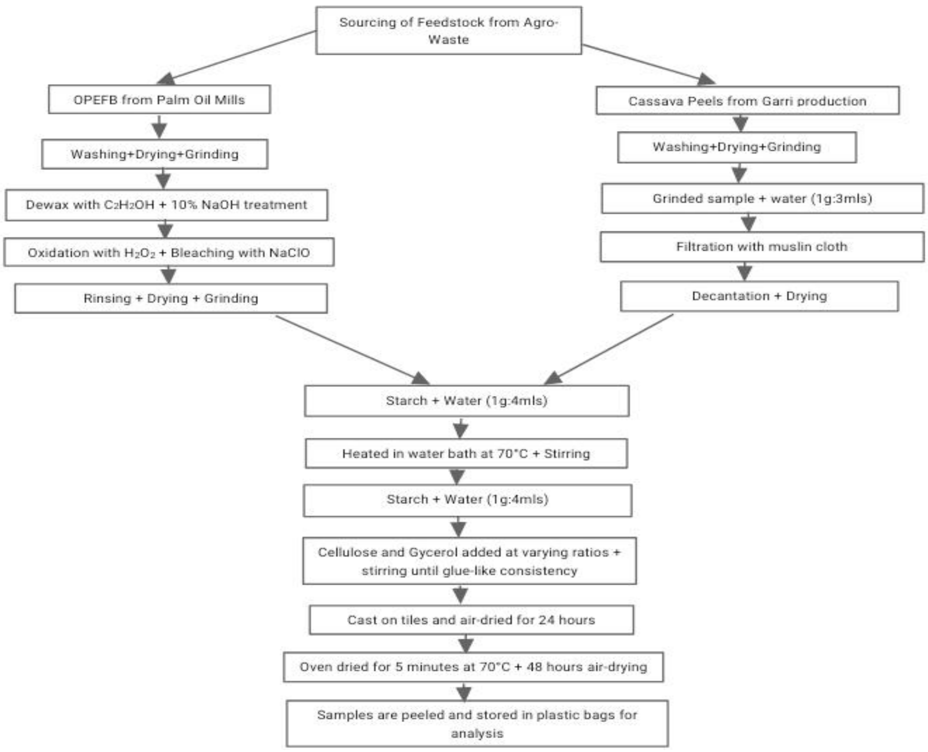

Figure 3. Flowchart of the bioplastic synthesis process

Table 1. Formulation of Bioplastic (BP) Samples

Sample	Starch (g)	Water (ml)	Glycerol (ml)	Cellulose (g)
BP-A	25	100	20	0.0
BP-B	25	100	20	3.75
BP-C	25	100	20	7.50
BP-D	25	100	20	11.25
BP-E	25	100	20	15.00
BP-F	25	100	0	7.50
BP-G	25	100	10	7.50
BP-H	25	100	30	7.50
BP-I	25	100	40	7.50
BP-J	25	100	0	0.0

Figure 4. Freshly cast bioplastic solutions

Figure 5. Bioplastic films after 24 hours of air-drying

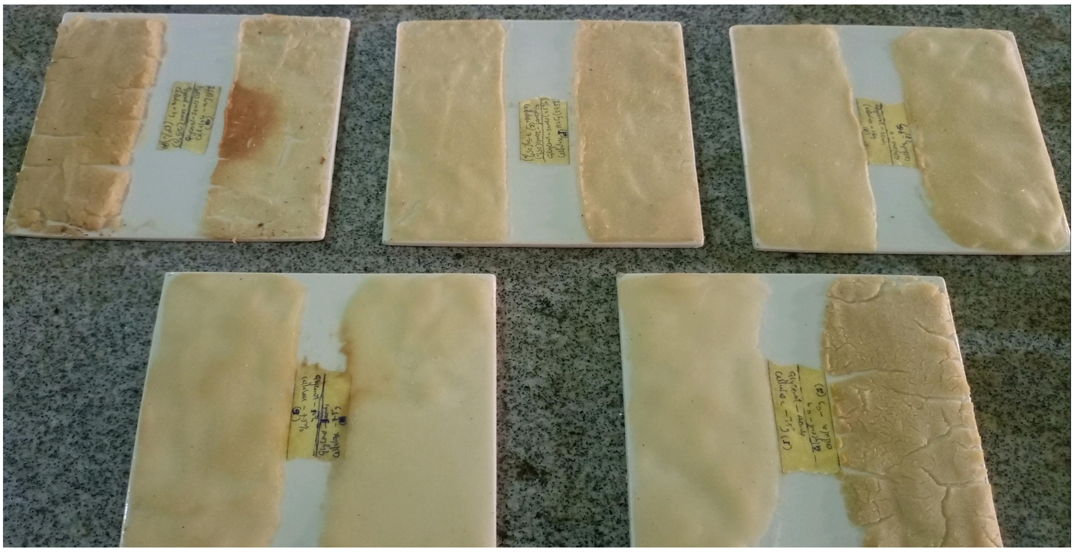

Figure 6. Bioplastic films after oven-drying

Figure 7. Final bioplastic films sealed for storage

The Table 1 above illustrates the additives variations in the synthesized bioplastic samples. While Figure 4-7 gives visuals on the synthesized bioplastic samples from casting stage to storage.

2.5 Characterization

Water Absorption: Pre-weighed dry samples were immersed in distilled water for 1 h, blotted dry, and re-weighed.

Ash Content: 10g of sample was combusted in a muffle furnace at 550°C for 1 h.

Biodegradability: Pre-weighed samples were buried in dumping soil for 30 days, exhumed, cleaned, and dried to determine weight loss.

Mechanical Properties: Tensile strength, Young’s modulus, and elongation at break were determined using a Universal Testing Machine according to ASTM D638.

Flexibility: Manually assessed via bending and folding tests.

3. Results

3.1 Feedstock and Bioplastic Characterization

Starch and cellulose were successfully isolated with yields of 34% and 22.6%, respectively, and low ash content (0.18% and 2.7%), indicating effective extraction of pure polymers (Table 2).

Table 2. Characteristics of Extracted Starch and Cellulose

Parameter	Cassava Peel Starch	OPEFB Cellulose
% Yield	34.0	22.6
% Moisture Content	11.0	43.0
% Ash Content	0.18	2.7
pH	5.61	5.98

3.2 Effect of Composition on Bioplastic Properties

The properties of the bioplastics were highly dependent on the cellulose-to-glycerol ratio (Table 3).

Table 3. Properties of Synthesized Bioplastic Samples

Sample	Ash (%)	Water Absorption (%)	Degradation (%)	Tensile Strength (MPa)	Young's Modulus (MPa)	Elongation at Break (%)
BP-A	0.9	37.3	84.7	3.7	40	35
BP-B	1.1	32.7	78.0	7.6	80	30
BP-C	1.3	29.3	70.0	9.0	120	24
BP-D	1.6	25.3	63.3	11.4	200	18
BP-E	1.8	23.3	55.3	12.1	240	12
BP-F	1.4	19.3	60.0	17.7	350	5
BP-G	1.4	24.7	64.7	13.3	280	10
BP-H	1.3	31.3	74.7	7.5	80	37
BP-I	1.2	34.7	80.0	6.1	60	40
BP-J	0.8	26.0	70.0	2.2	20	2

3.2.1 Mechanical Properties

The incorporation of cellulose significantly enhanced the mechanical integrity of the films. As cellulose content increased from 0% (BP-A) to 50% (BP-E), tensile strength and Young's modulus increased by ~227% and 500%, respectively. This is attributed to the strong hydrogen bonding between the starch matrix and cellulose fibers, which restricts chain mobility and reinforces the structure [4]. Conversely, elongation decreased, indicating increased stiffness.

Glycerol, as a plasticizer, disrupted the inter-chain hydrogen bonds in starch, increasing free volume and chain mobility. This led to higher flexibility and elongation at break (e.g., BP-H and BP-I) but concurrently reduced tensile strength and modulus.

3.2.2 Water Absorption and Biodegradation

Water absorption decreased systematically with increasing cellulose content (from 37.3% in BP-A to 23.3% in BP-E), due to the hydrophobic nature of cellulose and the denser, less porous network it creates [9,10]. In contrast, higher glycerol content increased water absorption, as the hydrophilic hydroxyl groups of glycerol attract and retain water molecules [11,12].

A direct correlation was observed between water absorption and the extent of biodegradation ($R^2 = 0.89$). Samples with higher moisture uptake (e.g., BP-A, BP-I) exhibited faster degradation (>80% in 30 days), as water facilitates microbial activity and enzymatic hydrolysis of the polymer chains [13,14]. The sample with the highest cellulose and no glycerol (BP-F) showed the lowest water absorption (19.3%) and a moderate degradation rate (60%), demonstrating that degradation can be modulated by composition.

4. Discussion

This research successfully demonstrates the valorization of two abundant agro-wastes, cassava peels and oil palm empty fruit bunches (OPEFB), into functional bioplastic materials. The results clearly indicate that the properties of the synthesized bioplastics are highly tunable by adjusting the cellulose and glycerol content. To critically evaluate these findings, this discussion compares the observed trends with established literature, proposes underlying mechanisms, and identifies methodological limitations to provide a more nuanced interpretation of the results.

4.1 Interfacial Adhesion and Mechanical Properties

The observed enhancement in tensile strength and Young's modulus with increasing cellulose content is a well-documented phenomenon, often attributed to the reinforcement of the starch matrix by the rigid cellulose fibers . However, the relatively modest gains, especially when compared to some commercial bioplastics, suggest a potential limitation: poor interfacial adhesion between the hydrophilic starch matrix and the cellulose fibers.

The findings align with a study by Yang et al., which highlighted that despite the potential of OPEFB fibers as reinforcement, "low interfacial adhesion and interactivity of fibres in the bio-composites still exist, which impedes the performance of fibres in the reinforced composites" [15]. The lack of a chemical compatibilizer in the synthesis method likely resulted in weak bonding at the fiber-matrix interface. Consequently, under mechanical stress, debonding may have occurred prematurely, limiting the full reinforcing potential of the cellulose. Future work could incorporate citric acid, which has been shown to act as a "bridge" between starch/fibers and other components, forming ester bonds and new hydrogen bonds that significantly improve interfacial adhesion and, thus, mechanical performance.

Conversely, the role of glycerol as a plasticizer is evident in the increased elongation at break. The reduction in tensile strength with high glycerol content is a classic trade-off, as plasticizer molecules disrupt the strong hydrogen bonding network within the starch chains, increasing free volume and chain mobility at the expense of stiffness and strength.

4.2 The Interplay of Components and Water Resistance

The inverse relationship between cellulose content and water absorption is a key finding. Cellulose fibers, though hydrophilic, can create a denser, more tortuous network within the starch matrix, hindering water diffusion and filling porous pathways . Glycerol, being highly hydrophilic, exerts the opposite effect; its hydroxyl groups actively attract and retain water molecules, explaining the increased water absorption in samples with high glycerol and low cellulose content (e.g., BP-A, BP-I).

The results further shows a competitive plasticization and anti-plasticization effect. Where at optimal levels, cellulose can act as an anti-plasticizer, restricting starch chain mobility and reducing the free volume available for water penetration. The superior performance of sample BP-F (25% cellulose, 0% glycerol) in terms of low water absorption supports this model, as the system lacks a hydrophilic plasticizer and is reinforced by a dense fiber network.

The strong positive correlation ($R^2 = 0.89$) between water absorption and biodegradation is logical, as absorbed water facilitates microbial activity and enzymatic hydrolysis of the polymer chains. However, this finding necessitates a critique of the "biodegradability" claim. The test was conducted in a soil environment where the specific conditions (e.g., microbial consortia, temperature, humidity) were not strictly controlled or reported. As highlighted in broader bioplastics reviews, many materials labeled as biodegradable are often "industrially compostable," requiring specific, controlled conditions to break down effectively . Their conclusion that these materials are biodegradable should therefore be tempered, noting that degradation rates can be "drastically slower" in less controlled environments like landfills, and the potential for microplastic fragmentation remains an emerging concern.

4.3 Benchmarking Performance and Contextualizing the Research Gap

Comparison between properties of obtained bioplastic variants against other starch-based materials from the literature, as shown in Table 4.

Table 4. Comparative Mechanical Properties of Starch-Based Bioplastics

Material Composition	Tensile Strength (MPa)	Elongation at Break (%)	Sou rce
This study (BP-F)	17.7	5	Your Data
This study (BP-E)	12.1	12	Your Data
Thermoplastic Corn Starch	4.48 - 8.14	Not Specified	
Potato Starch with PVA & Plasticizers	7.47 - 9.8	Not Specified	
Starch/OPEFB with CEPO*	>20 (Estimated from context)	Improved	

*CEPO: Citric Acid-Epoxidized Palm Oil oligomer, a compatibilizer

4.4 Methodological Limitations and Characterization Depth

A significant limitation of the present study lies in the scope of its characterization. The reliance on primarily physical and mechanical tests, while useful, does not provide molecular-level insight.

The use of Fourier Transform Infrared (FTIR) spectroscopy could have confirmed the theoretical hydrogen bonding between starch and cellulose or revealed the absence of stronger covalent (ester) bonds. Such evidence is crucial for explaining mechanical properties.

Thermogravimetric Analysis (TGA) would have provided critical information on the thermal stability of the bioplastics, an essential property for potential processing and application.

Techniques like X-ray Diffraction (XRD) could have illuminated how the addition of cellulose and glycerol affects the crystallinity of the starch matrix, which directly influences strength and water resistance.

The transparency and flexibility tests were qualitative. Employing UV-Vis spectroscopy quantitatively (as seen in other studies) and using a dynamometer for folding endurance would have yielded more objective and publishable data.

Furthermore, while the research focuses on waste valorization, a broader critique involves the unknown full environmental impact. A Life Cycle Assessment (LCA), as demonstrated in studies on bioplastics from food waste , is necessary to confirm whether the benefits of using agro-waste truly outweigh the environmental costs of processing, such as energy and water consumption.

4.5 Broader Implications and Future Research Directions

Despite the limitations, this work successfully demonstrates a viable pathway for converting low-value agro-wastes into promising bioplastic materials. It contributes to the principles of the circular economy by utilizing waste streams, potentially reducing the environmental burden associated with both agro-waste disposal and conventional plastic production .

Based on the critique above, the following future research directions are strongly recommended:

Chemical Compatibilization: Incorporation of crosslinkers like citric acid or epoxidized plant oils to improve the starch-cellulose interface .

Advanced Characterization: Employment of FTIR, TGA, and XRD to understand the chemical, thermal, and structural properties of the bioplastics .

Standardized Degradation Studies: Conducting biodegradation tests under both controlled industrial composting and ambient environmental conditions to provide a more accurate assessment of end-of-life scenarios

Life Cycle Assessment (LCA): Performing a cradle-to-gate LCA to quantitatively evaluate the environmental benefits and trade-offs of the production process compared to conventional plastics and other bioplastics [15].

5. Conclusion

In this research we have successfully valorized cassava peels and Oil Palm Empty Fruit Bunch (OPEFB), demonstrating their conversion into functional starch-based bioplastics. The study established that the bioplastics' properties are highly tunable by varying the cellulose (as a reinforcing filler for enhanced strength, reduced hydrophilicity, and slower degradation) and glycerol (as a plasticizer for increased flexibility at the cost of strength and water resistance) content.

The critical finding of a strong correlation between water absorption and biodegradation highlights the role of hydrophilicity in the degradation mechanism. This tunability allows for specific application targeting, such as rigid packaging (e.g., BP-D, BP-E) or flexible films (e.g., BP-H). Ultimately, this work offers a sustainable and economically viable solution for agro-waste management, significantly contributing to the circular bioeconomy and the mitigation of plastic pollution, though further exploration of chemical interactions and environmental assessment is warranted to advance practical application.

6. Future Work

Further investigations should include:

Spectroscopic Analysis: FTIR to confirm chemical interactions between starch, cellulose, and glycerol.

Advanced Characterization: Thermogravimetric Analysis (TGA) for thermal stability and Scanning Electron Microscopy (SEM) for morphological analysis.

Performance Optimization: Exploration of other natural plasticizers and compatibilizers to improve mechanical properties and water resistance further.

Life Cycle Assessment (LCA): To evaluate the environmental impact and commercial viability of the developed bioplastics.

References

[1] Saha, G., Saha, S. (2024). Tiny articles, big problems: The threat of microplastics to marine life and human health. Processes, 12(7), 1401. https://doi.org/10.3390/pr12071401

[2] Montano, L., Giogini, E., Nortastefano, V., Notari, T., Ricciadi, M., Piscopo, M., Motta, O. (2023). Raman microspectroscopy evidence of microplastics in human semen. Journal Science of The Total Environment. 901: 165922. https://doi.org/10.1016/j.scitotenv.2023.165922

[3] Verla, A. W., Ibe, M. V., Verla, E. N., Olorunfemi, E. B., Ejiako, J. E., Asuquo, M. S., & Mbuka-Nwosu, I. E. (2025). Agro-waste valorization into bio-plastics: A systematic review of types, synthesis and characteristics. Green Chemistry Innovations. 1(1). https://doi.org/10.64229/fxgtxt52

[4] Yang, J., Chen, Y. Li, C., Ching, Y. C., Wang, R., Wei, Y., Liang, G., Xu, S.(2024). Synthesis and characterization of bioplastics based on silyated starch and acrylated epoxidized soybean oil. Industrial Crops and Products. 222(2). 119670

[5] CGIAR. (2019). Transforming cassava wastes to wealth as a climate-change mitigation strategy in Nigeria.

[6] Hossain, M. S., Chowdhury, A. A., Uddin, M. N., & Rahman, M. M. (2021). A review on pyrolysis of oil palm empty fruit bunch for bio-fuel and chemicals. Journal of Cleaner Production, 324, 129252. https://doi.org/10.1016/j.jclepro.2021.129252

[7] Otache, M. A., Ubwa, S. T., Godwin, A. K. (2017). Proximate analysis and mineral composition of peels of three sweet cassava cultivars. Asian Journal of Physical and Chemical Sciences. 3(4): 1-10. https://doi.org/10.9734/AJOPACS/2017/36502

[8] Sisak, M. A. A., Daik, R., Ramli, S. (2015). Characterization of cellulose extracted from oil palm empty fruit bunch. AIP Conference Proceedings. https://doi.org/10.1063/1.4931295

[9] Perdoch, W., Treu, A., Mazela, B., Majka, J. (2024). Hydrophobic and hygroscopic properties of cellulose treated with silicone agents. European Journal of Wood and Wood Products. 82, 821-832. https://doi.org/10.1007/s00107-024-02049-3

[10] Lopez, V., Erlandsson, J., Wagberg, L., Larsson, P. A. (2018). Novel cellulose-based lightweight, wet-resilient materials with tunable porosity, density and strength. ACS Sustainable Chemistry & Engineering. 6(8). https://doi.org/10.1021/acssuschemeng.8b01165

[11] Hernando, H., Marpongahtun, Julianti, E., Nuryawanedible, A., Amaturrahim, S. A., Piliang, A. F. R., Yanhar, M. R., Goei, R., Soykeabkaew, N., Saputra, A. M. A., Gea, S. (2024). Impact of glycerol on oil palm trunk starch bioplastics enhanced with citric-acid epoxidized palm oil oligomers. Case Studies in Chemical and Environmental Engineering. 10, 100839. https://doi.org/10.1016/j.cscee.2024.100839

[12] Basiak, E., Lenart, A., Debeaufort, F. (2018). How glycerol and water contents affect the structural and functional properties of starch-based films. Polymers (Basel). 10(4): 412. https://doi.org/10.3390/polym10040412

[13] Rezae, K., Jenab, E., Temelli, F. (2007). Effects of water on enzyme performance with an emphasis on the reactions in supercritical fluids. Crit Rev Biotechnol. 27(4):183-95. https://doi.org/10.1080/07388550701775901

[14] Afonso, A. C., Saavedra, M. J., Gomes, I. B., Simoes, M., Simoes, L. C. (2025). Current microbiological challenges in drinking water. Journal of Water Process Engineering. 72, 107614. https://doi.org/10.1016/j.jwpe.2025.107614

[15] Anitha, R., Jayakumar, K., Vijay, S. G., Joice, M. E. (2024). Synthesis and characterization of starch-based bioplastics: A promising alternative for a sustainable future. The International Conference on Processing and Performance of Materials (ICPPM 2023). https://doi.org/10.3390/engproc2024061030202406103