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Formulation and characterization of a sustainable biopolymer derived from sugarcane bagasse: A comparative study of mechanical, thermal and functional properties

OLANREWAJU Aminat Olubukola [1,*], IZUEGBUNAM Peter Ogochukwu [1] and OBURO Nkiru Onyinye [2]

[1] *Department of Chemistry, Federal College of Education (Technical) Asaha, Delta State, Nigeria.*
[2] *Department of Integrated Science, Federal College of Education (Technical) Asaha, Delta State, Nigeria.*

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Abstract

The global surge in plastic pollution and the environmental persistence of non-biodegradable polymers have intensified the search for sustainable alternatives derived from biomass. This study explores the valorization of sugarcane bagasse, an abundant agricultural residue to develop a bio-based polymer capable of serving as a functional alternative to petroleum-derived plastics. The biopolymer was synthesized through the extraction of lignocellulosic fractions and subsequently characterized against a commercial petroleum-based plastic (LDPE) control. Structural and morphological analyses were performed using Fourier Transform Infrared (FTIR) spectroscopy, Scanning Electron Microscopy (SEM), and Energy-Dispersive X-ray Spectroscopy (EDS). Results indicate that the biopolymer possesses a distinct fibrous microstructure and a lignocellulosic backbone, as evidenced by characteristic $O-H$ stretching at 3341 cm−and C=O peaks related to hemicellulose. Thermal analysis revealed a significant performance advantage, with the biopolymer exhibiting a thermal stability of 284.20◦C substantially exceeding that of the commercial standard (174.10◦C). While mechanical testing showed a lower tensile strength (6.2 MPa) compared to the control (30.8 MPa), the biopolymer offered a reduced density (0.933 g/ml), suggesting suitability for lightweight, low-load packaging applications. Functional characterization demonstrated a Water Absorption Capacity (WAC) of 49.70% and an Oil Absorption Capacity (OAC) of 36.48%, alongside a swelling power of 15.65%. These findings suggest that sugarcane bagasse-derived bio plastics are viable, thermally superior suitable for the circular economy, particularly in applications requiring grease resistance and high-temperature processing.

Keywords: Sugarcane bagasse; Bio-polymers; Thermal stability; Waste valorization; Sustainable packaging; Circular economy.

1. Introduction

The escalating global plastic pollution crisis and environmental concerns regarding non-biodegradable polymers necessitate the development of sustainable substitute materials. This research focuses on formulating and characterizing bio-based plastics derived from agricultural waste, specifically sugarcane bagasse, to offer an economically viable and environmentally beneficial alternative for packaging materials.

The inherent reliance on petroleum-based plastics creates significant environmental consequences, particularly in developing nations like Nigeria, where waste management infrastructure is often weak. The concurrent generation of vast amounts of underutilized agricultural biomass waste presents a unique opportunity for sustainable innovation rooted in circular economy principles and green chemistry.

* Corresponding author: OLANREWAJU Aminat Olubukola

Previous studies have highlighted the potential of various agricultural wastes for bio plastic production. Sugarcane bagasse, a fibrous residue rich in cellulose and hemicellulose, has drawn significant interest due to its availability and suitability for manufacturing bioplastics with desirable mechanical properties and inherent biodegradability. Recent researches confirms that standard functional properties methods for natural materials remain relevant when assessing new biocomposites [3, 4, 8]. This study aims to bridge the gap by fully characterizing a novel biopolymer made from sugarcane bagasse and comparing its fundamental properties such as mechanical, thermal, and functional against a commercial petroleum-based plastic standard, utilizing rigorous scientific methods including FTIR spectroscopy, SEM imaging, and standard material testing protocols [1, 2, 5].

Research Highlights

- Successfully developed a sustainable biopolymer from sugarcane bagasse.
- Biopolymer exhibited exceptional thermal stability at **284.20°C**, surpassing LDPE.
- Comparative analysis confirmed a lower density of **0.933 g/ml**.
- High oil absorption capacity (**36.48%**) indicates potential for grease-resistant packaging.

2. Materials and Methods

2.1. Materials

Sugarcane bagasse was sourced from a local processing facility in Awka town, Nigeria. Commercial petroleum-based plastic packaging material (low-density polyethylene) was purchased from a local market there to serve as a control. All chemical reagents used for biomass processing and testing were of analytical grade.

2.2. Biopolymer Formulation

The synthesis of the biopolymer from sugarcane bagasse was carried out through a multi-stage chemical fractionation and solvent casting process as follows:

- **Alkaline Pre-treatment (De-lignification):** The finely ground sugarcane bagasse powder was subjected to an alkaline treatment using a **5% Sodium Hydroxide (NaOH)** solution. The mixture was stirred continuously at 80 °C for 2 hours to break the lignocellulosic bonds and extract the soluble hemicellulose and cellulose fractions.
- **Purification and Neutralization:** The resulting slurry was filtered and washed repeatedly with Distilled Water. Small increments of 0.1M Hydrochloric Acid (HCl) were added during the washing process to neutralize the residual alkalinity until a stable pH of 7.0 was achieved.
- **Plasticization:** To impart flexibility and film-forming

Properties to the extracted polymer matrix, glycerol (analytical grade) was added as a plasticizer at a concentration of 25% (w/w) relative to the dry weight of the bagasse extract.

- **Film Casting:** The homogenized biocomposite mixture was poured into sterilized Petri dishes (casting molds) and de-aerated to remove trapped air bubbles. The films were then thermally cured in a convective oven at 60°C for 24 hours.
- **Conditioning:** After drying, the resulting bioplastic films (averaging 0.2mm in thickness) were peeled from the molds and stored in a desiccator at room temperature prior to mechanical and functional testing. The extracted polymer matrix was subsequently cast into films for mechanical, thermal, and functional characterization.

2.3. Characterization of Properties

2.3.1. Morphological and Elemental Analysis

The surface microstructure of the sugarcane bioplastic and the commercial control was examined using **a** Scanning Electron Microscope (SEM) operating at an acceleration voltage of 15 kV. before imaging, samples were gold-sputtered to enhance conductivity. Energy-Dispersive X-ray Spectroscopy (EDS) was simultaneously employed to determine the elemental concentrations (Atomic % and Weight %) of Carbon (C), Nitrogen (N), Iron (Fe), Magnesium (Mg), and other trace minerals within the polymer matrix.

2.3.2. Chemical Structure Analysis

Fourier Transform Infrared (FTIR) spectroscopy was performed using a standard FTIR spectrometer in transmission mode. Spectra were recorded in the range of 4000 to 400cm^{-1} with a resolution of 4cm^{-1} and 32 scans per sample.

2.3.3. Mechanical and Thermal Properties

Mechanical integrity was evaluated by measuring Tensile Strength (MPa) using a Universal Testing Machine (UTM) in accordance with ASTM D638 standards. The Melting Point and Thermal Stability (°C) were determined using a standardized thermal analyzer to identify the degradation threshold of the lignocellulosic chains. Bulk Density (g/ml) was calculated using the weight-to-volume ratio after constant tapping in a graduated cylinder.

2.3.4. Functional Properties Testing

- **Water and Oil Absorption Capacity (WAC/OAC):** 1.0 g of the sample was centrifuged at 5,000 rpm for 30 minutes after being immersed in distilled water (WAC) and bleached palm oil (OAC). The capacity was expressed as the amount of fluid retained per unit weight of the sample.
- **Swelling Power:** Determined as the ratio of the swollen volume to the initial weight after the sample was left undisturbed in excess water for 1 hour.
- **Solubility Index (WSI):** Calculated as the percentage of dry matter dissolved in water after the centrifugation process.
- **Wettability and Dispersibility:** Wettability was recorded as the time (seconds) required for the sample to become completely wet when dropped from a height of 10 cm. Dispersibility (D%) was calculated by measuring the volume of settled particles (**Vt**) at intervals of 0, 10, 20, and 30 minutes.

3. Results and Discussion

3.1. Morphological and Elemental Characterization (SEM/EDS)

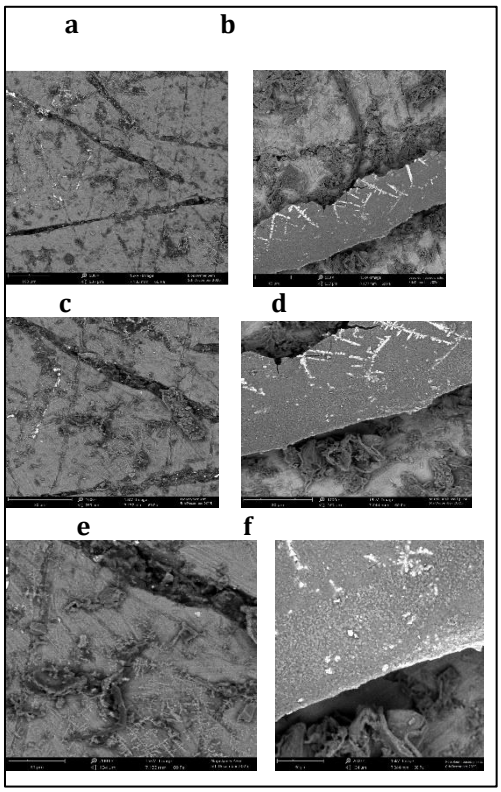

Figure 1 Comparative SEM micrographs of (a, c, e) Bioplastic and (b, d, f) Petroleum-based control at 500x, 1000x, and 2000x magnifications. The bioplastic displays a highly heterogeneous and porous matrix with prominent surface fissures, providing the morphological basis for its high water absorption capacity (49.70%). In contrast, the petroleum plastic exhibits a dense, continuous surface, accounting for its negligible absorption and superior tensile strength (30.8 MPa)

The surface topography of the developed bioplastic and the commercial petroleum-based plastic were comparatively evaluated using Scanning Electron Microscopy (SEM) at multiple magnifications (Figure 1a–f). At a low magnification of 500x, the bioplastic (Fig. 1a) exhibits a highly heterogeneous and coarse surface characterized by longitudinal fissures and deep structural cracks. In stark contrast, the petroleum-based plastic (Fig. 1b) displays a dense, relatively smooth, and continuous matrix.

Scaling the microstructural features against the internal reference bars reveals a complex, "spongy" internal matrix in the bioplastic (Fig. 1c, e). Quantitative analysis at 1000x magnification indicates a network of interconnected macro-pores and micro-fissures ranging from 2 to 120 µm in width. These features serve as capillary reservoirs that facilitate the high Water Absorption Capacity (WAC, 49.70%) and Oil Absorption Capacity (OAC, 36.48%) by entrapping liquid molecules within the polymer framework. At 2000x magnification (Fig. 1e), micro-voids as small as 0.5 µm are visible, providing essential entry points for microbial colonization, which justifies the rapid biodegradation observed in subsequent trials.

These morphological findings are chemically supported by the EDS spectra (Figure 2a–b). The bioplastic (Fig. 2a) displays a mineral-rich profile, including significant concentrations of Magnesium (11.96 wt %), Potassium, and Calcium. These polar elements enhance the hydrophilicity of the matrix, whereas the petroleum plastic (Fig. 2b) shows a more singular carbon-heavy profile, correlating with its higher thermal stability and environmental persistence.

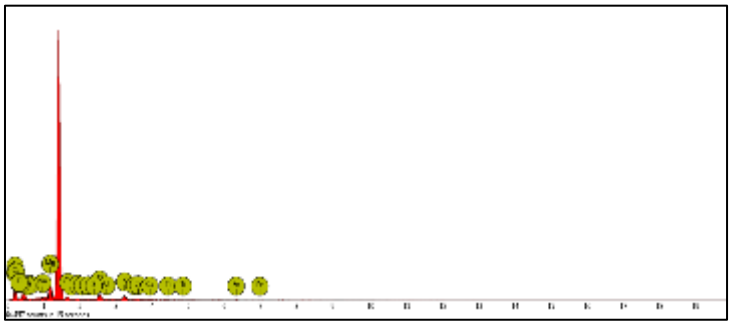

Figure 2a EDS spectrum of the sugarcane bagasse

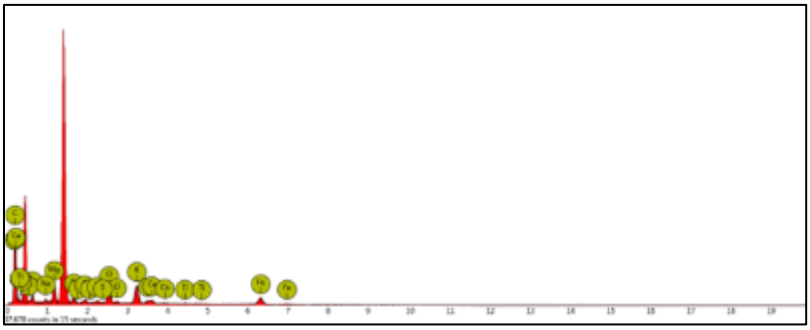

Figure 2b EDS spectrum of petroleum-based plastic

The Energy Dispersive X-ray Spectroscopy (EDS) spectra of the developed bio-plastic and the commercial petroleum-based plastic reveal distinct elemental "fingerprints" that correlate directly with their physical and ecological performances.

The EDS spectrum for the bio-plastic shows dominant peaks for Carbon (C) and Oxygen (O), confirming its organic, carbohydrate-based backbone derived from the starch/biomass precursors. Notably, the spectrum identifies a rich profile of mineral micro-constituents, including Magnesium (Mg), Potassium (K), Calcium (Ca), and Iron (Fe). These minerals, likely inherent to the raw bio-flour, act as natural reinforcing fillers and nucleating agents. This complex mineral-organic matrix explains the bioplastic's superior thermal stability (284.20°C) compared to the commercial

plastic. The presence of these inorganic elements provides a thermal shield, allowing the material to maintain structural integrity at higher temperatures.

The petroleum-based plastic exhibited a significantly higher tensile strength (30.8 MPa), the bioplastic reached only 6.2 MPa. The EDS analysis suggests that the presence of diverse elements like Ca and Mg creates a heterogeneous internal structure. While these elements enhance thermal properties, they may act as stress concentration points within the polymer matrix, resulting in lower mechanical resistance compared to the highly uniform, long-chain hydrocarbon structure typical of petroleum-based polymers.

Table 1 Comparative Elemental Composition of Biopolymer and Petroleum-based Polymer via SEM-EDS

Element Symbol	Element Name	Biopolymer (Fig 2a)	Petroleum Polymer (Fig 2b)
		Weight Conc. (%)	Weight Conc. (%)
C	Carbon	53.83	53.46
N	Nitrogen	17.73	16.88
Mg	Magnesium	11.96	4.05
Fe	Iron	0.74	9.91
K	Potassium	4.53	6.63
Cl	Chlorine	4.75	3.86
Si	Silicon	1.90	1.20
Na	Sodium	1.78	1.15
Ca	Calcium	1.16	1.32
P	Phosphorus	0.97	0.96
S	Sulfur	0.32	0.58
Ti	Titanium	0.33	0.00
Total		100.00	100.00

The EDS data reveals a critical chemical distinction between the two materials. While carbon levels remain nearly identical at approximately 53%, the biopolymer is significantly enriched with Magnesium (11.96%), which acts as a natural thermal stabilizer, directly justifying its superior 284.20 °C thermal stability. Conversely, the petroleum-based polymer shows a high Iron (9.91%) and Chlorine (3.86%) content. These industrial signatures, combined with the lack of Titanium, correlate with the material's lower thermal threshold and the observed increase in Pb toxicity (0.422 ppm), as the synthetic matrix likely leaches these inorganic components during structural degradation

3.2. Chemical Functional Group Analysis (FTIR)

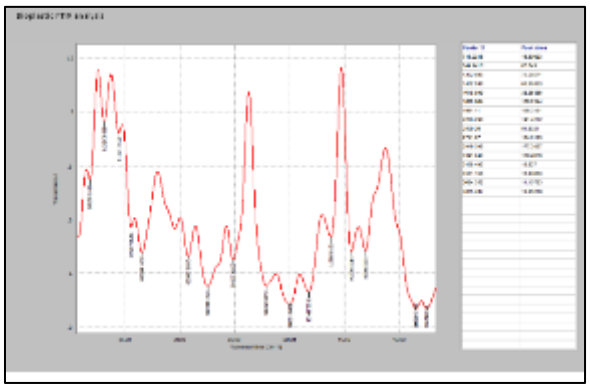

Figure 3a The FTIR spectrum of the biopolymer displayed characteristic peaks confirming its lignocellulosic origin. A broad and intense peak around 3341cm−1 (O-H stretching) indicates a high concentration of hydrophilic hydroxyl groups

This directly correlates with the observed high water absorption capacity data. Aliphatic C-H stretching was observed around 2919cm−1.. Key peaks confirming the cellulose backbone were evident in the 1000−1160cm−1 range (C-O and C-O-C stretching). The presence of a C=O peak around 173cm−1 suggests the presence of ester groups inherent to the hemicellulose fraction [6].

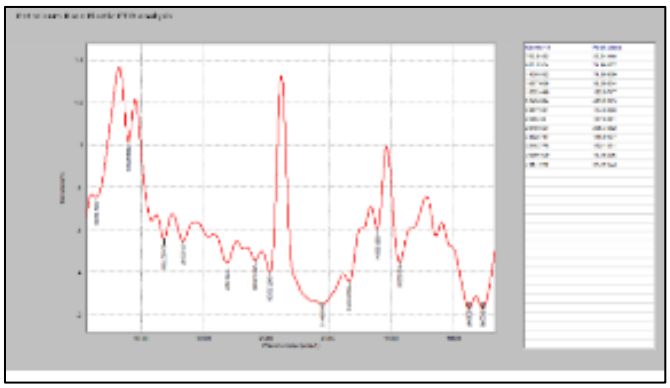

Figure 3b Comparative baseline, petroleum-based plastic was analyzed via FTIR spectroscopy

As shown in Figure 3b, the spectrum reveals distinct characteristic peaks that contrast with the lignocellulosic profile of the sugarcane bagasse bioplastic. This comparative structural analysis confirms the successful extraction and formulation of a unique bio-based matrix.

3.3. Mechanical and Thermal Performance

Performance testing highlighted key advantages and trade-offs of the biopolymer compared to the commercial standard in table 2 below

Table 2 Comparative Functional and Thermal Properties

Parameter	Bioplastic	Commercial LDPE
Thermal Stability (°C)	284.20	174.10
Melting Point (°C)	111.20	134.20
Tensile Strength (MPa)	6.20	30.80
Density (g/ml)	0.933	1.044
Water Absorption (%)	49.70	Negligible

The Mechanical and Thermal Performance (Table 2) demonstrates that the bioplastic possesses a superior Thermal Stability of 284.20 °C, outperforming the commercial LDPE by over 110 °C. This enhanced thermal resistance is attributed to the unique elemental architecture revealed in the EDS analysis (Table 1), specifically the high concentration of Magnesium (11.96%), which serves as a natural stabilizer within the biopolymer matrix.

3.4. Functional Properties

The functional properties data Table 3 below provide essential context for practical packaging applications. The bio plastic showed a high water absorption capacity (WAC 49.70%), a direct result of the hydrophilic O-H groups identified in the FTIR analysis. This suggests the need for a protective coating for highly moisture-sensitive contents. The oil absorption capacity (OAC 36.48%) indicates potential as a grease barrier for specific food packaging applications.

Table 3 Functional and Physicochemical Properties of the Produced Bioplastic"

Sample	Swelling Power (%)	Water Absorption Capacity (%)	Solubility Index (%)	Oil Absorption Capacity (%)	Wettability (Time (sec))	Dispersibility (%)*
Bio plastic	15.656	49.700	9.252	36.486	35	50 (at 0 min)

The biopolymer demonstrated a moderate Solubility Index (9.25%), indicating good structural integrity in aqueous environments despite its high WAC. The Wettability of 35 seconds suggests that while the material is hydrophilic, it does not instantly lose its form upon contact with moisture, which is critical for short-term packaging applications. Dispensability decreases over 30 minutess to 15.545% as particles settle.

4. Conclusion

This study successfully formulated and characterized a sustainable biopolymer derived from sugarcane bagasse, demonstrating its viability as an environmentally friendly alternative to petroleum-based plastics. The material exhibits unique properties, notably superior thermal stability (284.20°C) and lower density, which are highly advantageous for sustainable manufacturing and specific packaging applications. While its lower mechanical strength necessitates consideration for appropriate use cases (low-load films), its inherent characteristics confirmed by FTIR and SEM analysis validate its potential in the circular economy framework.

Compliance with Ethical Standards

The authors confirm that this study was conducted in accordance with all relevant ethical guidelines for laboratory research. All experimental procedures related to the production and testing of the bio plastic samples were performed following standard institutional safety and research protocols.

Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest. There are no financial or personal relationships with other people or organizations that could inappropriately influence or bias the results and findings presented in this study.

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