Structural Characterization and Life Cycle Assessment of Sustainable Biocomposites from Raphia farinifera Inflorescence Cellulose

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Structural Characterization and Life Cycle Assessment of Sustainable Biocomposites from *Raphia farinifera* Inflorescence Cellulose

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ABSTRACT

Transition toward sustainable materials has become a priority as environmental concerns surrounding petroleum based plastics intensify. Cellulose was extracted from Raphia farinifera inflorescence (RFI-C) as a renewable reinforcement in biodegradable polymer composites through alkali and bleaching treatments, cellulose was successfully isolated and structurally characterized. Fourier transform infrared spectroscopy (FTIR) confirmed effective removal of lignin and hemicellulose, while X-ray Diffraction (XRD) revealed 68.5% high crystallinity index an indicative of enhanced compatibility with polymer matrices. Thermogravimetric analysis results showed a thermal stability degradation onset temperature of 290 °C. Brunauer-Emmett-Teller (BET) analysis indicated a specific surface area of 38.7 m^2/g and pore volume of 0.132 cm^3/g while mechanical testing revealed a tensile strength of 52.3 MPa, confirming its reinforcement potential. Biodegradability was validated through a 60-day soil burial test, where progressive weight losses of 8.2% to 30.1% were observed. A preliminary Life Cycle Assessment (LCA) using SimaPro software integrated long-range transport and end-of-life decomposition. Results showed RFI-C composites emitted ~1.8 kg CO_2-eq/kg and consumed ~12 MJ/kg of energy significantly lower than conventional plastic counterparts. Reductions in human toxicity, eutrophication and fossil resource depletion further reinforced its environmental benefits. The findings establish RFI-C as a promising (bio) based material with excellent inherent biodegradability, thermal, mechanical properties and a low environmental footprint. Its application aligns with global goals for sustainable materials, contributing meaningfully to plastic waste reduction, circular economy frameworks, and positive ecological impact.

Keywords: Cellulose, Raphia farinifera, Biodegradable composites, Mechanical properties, FTIR, Crystallinity

1. Introduction

Environmental pollution associated with the accumulation of non-(bio)degradable synthetic plastics has increased need for development of biodegradable green alternatives. Cellulose [1], as the most abundant naturally occurring biopolymer has emerged as a highly promising material for the fabrication of biodegradable composites [2], films, and coatings [3]. Its biodegradability, renewability, (non)toxicity, and excellent mechanical properties have made it an attractive choice for replacing petroleum-based plastics [4]. Cellulose-based materials are particularly valuable in applications that demand both sustainability and functionality such as packaging, automotive, and biomedical industries [5]. Cellulose according to Agboeze *et al.* [6] is a linear polysaccharide composed of β-D-glucopyranose units linked by β-1,4-glycosidic bonds forming crystalline microfibrils that provide structural support to plant cells. While cellulose is predominantly extracted from wood, cotton, and other high-cellulose plants, agricultural residues which are often underutilized, present an untapped sustainable source for cellulose extraction. Agricultural waste is considered an environmentally responsible alternative to traditional cellulose sources offering a dual solution to waste management and material development [7, 8].

Among agricultural residues, *Raphia farinifera* (raffia palm) inflorescence is a widely available biomass in tropical regions of West and Central Africa and remains largely underexplored. This biomass which is produced during the harvesting of raffia palms for fiber and sap is typically discarded or poorly utilized. *Raphia farinifera* inflorescence waste has the potential to serve as an abundant and cost-effective source of cellulose, offering a promising alternative for sustainable material production. The extraction of cellulose from *Raphia farinifera* inflorescence involves the removal of (non)cellulosic components such as lignin and hemicellulose typically using alkaline and bleaching treatments. However, there is limited research focusing on the potential of this cellulose for use in biodegradable composites which is the primary aim of this study. This study evaluates the mechanical properties of Raphia Cellulose, to assess its suitability for composite applications. This research also includes study of preliminary Life Cycle Assessment (LCA) to assess the environmental impact of using *Raphia farinifera* cellulose in composite materials and a comparative analysis of the properties of cellulose extracted from other common (agro)waste materials such as sugarcane bagasse and corn husk. By addressing the environmental challenges posed by synthetic polymers and promoting the use of (agro)waste for material production, this study contributes to the sustainable development of biodegradable materials and the valorization of agricultural waste.

2. Materials and methods

2.1. Sample collection and preparation

The inflorescence waste of *Raphia farinifera* was obtained from cultivated raffia palm plantations in Mbu-Amon, Enugu State, Nigeria (coordinates: 6.71°N, 7.52°E). Collection was carried out with permission from local landowners. This species is widely cultivated in the region and is not considered a wild or endangered species under IUCN guidelines. The inflorescence was harvested

during the peak season when waste biomass was abundant. The samples were thoroughly washed with deionized water to remove dirt, dust, and soluble impurities. After washing, the samples were air-dried at ambient temperature for two weeks (14-days). The dried biomass was then ground into fine powder using a mechanical grinder. The powder was sieved through a 1 mm mesh to obtain a uniform particle size suitable for subsequent treatments.

2.2. Cellulose extraction

Extraction of cellulose from powdered *Raphia farinifera* inflorescence was carried out in two main stages following method of Agboeze *et al.* [1] : (a). **Alkaline Treatment**: A 100 g of ground *Raphia farinifera* inflorescence powder was subjected to alkaline treatment with 4% sodium hydroxide (NaOH) solution at 90°C for 3 hours. This treatment removes hemicellulose and other non-cellulosic components as well as partial lignin removal. After treatment, the mixture was filtered to separate cellulose from alkali solution, and residue was washed thoroughly with deionized water until washings reached neutrality. (b). **Bleaching**: Cellulose pulp was then subjected to bleaching using acidified sodium chlorite ($NaClO_2$) solution at 70°C for 2 hours to eliminate lignin and any residual color. Concentration of sodium chlorite was adjusted to effectively remove lignin without degrading the cellulose. After bleaching, extracted cellulose was washed to neutrality with distilled water and dried at 60°C to obtain final cellulose powder.

2.3. Characterization techniques

2.3.1 Fourier-Transform Infrared (FTIR) Spectroscopy

FTIR spectra were recorded using a Shimadzu IRSpirit spectrometer in the range of 4000–600 cm^{-1}. FTIR was used to identify functional groups present in the cellulose sample, providing insights into the chemical structure and confirming successful removal of hemicellulose and lignin.

2.3.2 X-ray Diffraction (XRD)

XRD patterns were obtained using a Bruker D8 Advance diffractometer with Cu-Kα radiation (λ = 1.5406 Å) to assess crystallinity of cellulose. Diffraction data were used to calculate crystallinity index (CrI) and to identify phase structure of RFI-cellulose.

2.3.3 Scanning Electron Microscopy (SEM)

Surface morphology of RFI-C was examined using a JEOL JSM-6390 SEM. RFI samples were sputter-coated with gold to enhance their conductivity. SEM imaging was employed to observe the fiber structure, porosity, and surface characteristics which are important for evaluating its potential as a reinforcing material in composites.

2.3.4 Thermogravimetric Analysis (TGA)

Thermal stability of the extracted RFI-C was evaluated using a PerkinElmer TGA 4000 under nitrogen atmosphere. Temperature was increased from 25°C to 600°C at a heating rate of

10°C/min. TGA provided information on degradation behavior of the cellulose, including moisture loss, hemicellulose degradation, and cellulose decomposition temperatures.

2.4. Mechanical testing

Mechanical properties of RFI-C were evaluated by measuring the tensile strength and Young's modulus using an Instron universal testing machine according to ASTM D638 standards, which are widely used for evaluating the mechanical properties of materials used in composite systems. Tensile strength reflects the maximum stress RFI-C can withstand, while Young's modulus measures the stiffness of the cellulose.

2.5. Biodegradability assessment

Soil burial tests were conducted to evaluate biodegradability of RFI-C based composites. Samples of the composites were buried in soil at a depth of 10 cm and monitored over a period of 60 days. Samples were retrieved at 15-day intervals and the weight loss of the composites was measured to determine the extent of biodegradation.

2.6. Comparative analysis

Properties of cellulose extracted from *Raphia farinifera* inflorescence were compared with those obtained from other common (agro)waste sources, such as sugarcane bagasse and corn husk. The comparison focused on parameters such as crystallinity, tensile strength, and biodegradability. These materials were selected due to their widespread use in cellulose extraction and their application in industrial materials.

2.7. Life Cycle Assessment (LCA)

A preliminary Life Cycle Assessment (LCA) was performed using SimaPro software to evaluate the environmental impacts of using *Raphia farinifera* cellulose in biodegradable composites. The LCA focused on key indicators such as greenhouse gas emissions, energy consumption, and resource utilization. The results were compared with those of traditional synthetic materials, such as petrochemical-based plastics, to assess the environmental sustainability of RFI-C as a replacement material.

2.8. Statistical analysis and error analysis

To enhance the scientific rigor and reliability of the experimental results, statistical analyses were performed to assess the significance of differences in the properties of RFI-C and other (agro)waste sources. The following statistical methods were employed:

2.8.1. Analysis of variance (ANOVA)

An Analysis of Variance was conducted to evaluate the statistical significance of differences in key properties of mechanical strength, crystallinity, and biodegradability between RFI-C and those from other (agro)waste sources, including sugarcane bagasse and corn husk. This analysis helps demonstrate whether observed differences in cellulose properties are due to the sample source or

due to experimental variations. A p-value of less than 0.05 was considered statistically significant for all comparisons.

2.8.2. Regression analysis and correlation

To explore the relationship between mechanical properties and processing parameters, regression analysis was performed. Specifically, the relationship between tensile strength and various processing parameters, such as NaOH concentration and bleaching time was evaluated using linear regression. The regression model was used to determine the influence of these parameters on the mechanical properties of cellulose. In addition, a correlation analysis was conducted to identify the strength of the relationship between cellulose crystallinity as measured by XRD and its mechanical performance (tensile strength, Young's modulus).

2.8.3. Error analysis

To assess the precision and reliability of the experimental data, error analysis was conducted for each of the tests. The following statistical metrics were calculated: (a). **Standard deviation (SD):** This was used to determine the variability of the data for each property tested. A low standard deviation indicates that the data points are closely clustered around the mean, while a high standard deviation suggests greater variability. (b). **Confidence intervals (CI)**: 95% confidence intervals were calculated for each measurement to indicate the range within which the true value of the property lies with 95% certainty. (c). **P-values**: P-values were calculated for all statistical tests (ANOVA and regression) to assess the significance of the results. A p-value less than 0.05 was considered statistically significant. The error analysis helped confirm the reproducibility and consistency of the experimental data, ensuring that the observed trends were statistically valid and not due to random fluctuations or experimental error.

4. Result and discussion

4.1 Multistage pulping and cellulose yield

The multistage pulping of *Raphia farinifera* inflorescence (RFI) waste involved sequential alkali and bleaching steps designed to remove lignin, hemicellulose, waxes, and other non-cellulosic components [6]. The process successfully yielded a purified α-cellulose pulp. The yield of α-cellulose was 75.39% per 100 g of raw RFI biomass, which compares favorably with yields reported for other lignocellulosic biomass sources, such as Kola nut Testa (72.6%) [1], Bambara nut husk (74.3%) [2], sugarcane bagasse (70.2%) and corn stalk (68.5%) [3]. The high yield suggests that RFI is a promising feedstock for cellulose extraction, particularly in regions where it is abundant and underutilized. The removal of non-cellulosic material was visually evident with the processed fibers transitioning from a dark brown, waxy texture to a white, fibrous structure indicating effective delignification and purification. Efficient pulping and bleaching steps are critical for the subsequent physical and chemical characterization of the cellulose, especially when considering its application in biodegradable composites, where high purity and uniformity are desirable [3].

4.2 Elemental analysis of RFI fiber before cellulose extraction

X-ray fluorescence (XRF) spectroscopy was used to determine the inorganic elemental composition of untreated RFI fibers. The results of the analysis are presented in **Table** 1 which shows a diverse distribution of metal oxides including notable quantities of Potassium oxide (K_2O): 23.32 wt%, Calcium oxide (CaO): 21.33 wt%, Silicon dioxide (SiO_2): 18.42 wt%, Aluminum oxide (Al_2O_3): 9.66 wt%, Ferric oxide (Fe_2O_3): 6.23 wt%. These oxides are commonly associated with rigid and thermally stable phases in biomass derived ash [11]. Significant presence of SiO_2, a naturally hard and chemically stable oxide indicate the potential for *Raphia farinifera* to act as a reinforcing filler in composite applications [12]. Moreover, Al_2O_3 and Fe_2O_3, both mechanically hard materials are known for their durability and are frequently incorporated into ceramic, paint, and polymer matrix composites for UV blocking and structural reinforcement [13]. High percentage of K_2O and CaO aligns with previous studies on agricultural biomass such as rice husk, bamboo, and corn stalks which often possess high concentrations of alkali and alkaline earth metals (AAEMs) [14]. These components enhance the flame-retardant nature of bio-fillers and promote thermal resistance in polymer composites [12]. Minor oxides such as MnO, ZnO, Nb_2O_2, CuO, and TiO_2 were also identified, each of which plays a role in enhancing the catalytic, optical, or antibacterial properties of materials in which they are used. Presence of V_2O_5 and Cr_2O_3 at trace levels suggests minimal transition metal contamination, possibly from environmental exposure during plant growth. Detection of Cl of 12.71 wt% may result from the natural salt content absorbed from the soil or processing water. Although not a typical reinforcement oxide, chlorine-containing compounds can affect the thermal degradation profile of the fiber which warrants attention during thermal analysis. Due to the significant presence of inorganic oxides like SiO_2, Al_2O_3, and Fe_2O_3, untreated RFi fibers may have inherent abrasive resistance, thermal stability, and mechanical rigidity, making them suitable for: metal matrix composites, cementitious materials, bioceramic precursors, and UV-resistant bioplastics. This oxide results are comparable to that of other agro-fibers like Tridax procumbens [15], Calotropis gigantea [16], and sisal [17], which have been studied for reinforcement in polymer, concrete, and metal matrix composites.

Table 1. XRF determined Elemental Composition of Untreated RFi Fiber (wt.%)

Oxide Component	Concentration (wt.%)	Oxide Component	Concentration (wt.%)
SiO_2	18.42 ± 1.30	K_2O	23.32 ± 0.41
Al_2O_3	9.66 ± 3.56	CaO	21.33 ± 0.41
Fe_2O_3	6.23 ± 0.09	MnO	2.32 ± 0.07
SO_3	3.20 ± 0.30	CuO	0.89 ± 0.04
ZnO	0.27 ± 0.03	TiO_2	0.11 ± 0.08
Cr_2O_3	0.07 ± 0.05	V_2O_5	0.05 ± 0.07
Nb_2O_2	0.12 ± 0.03	Cl	12.72 ± 0.28
SrO	0.08 ± 0.02	Rb_2O	0.10 ± 0.02
Ag_2O	0.06 ± 0.08	NiO	0.02 ± 0.03

4.3 Physicochemical properties of RFI-cellulose powder

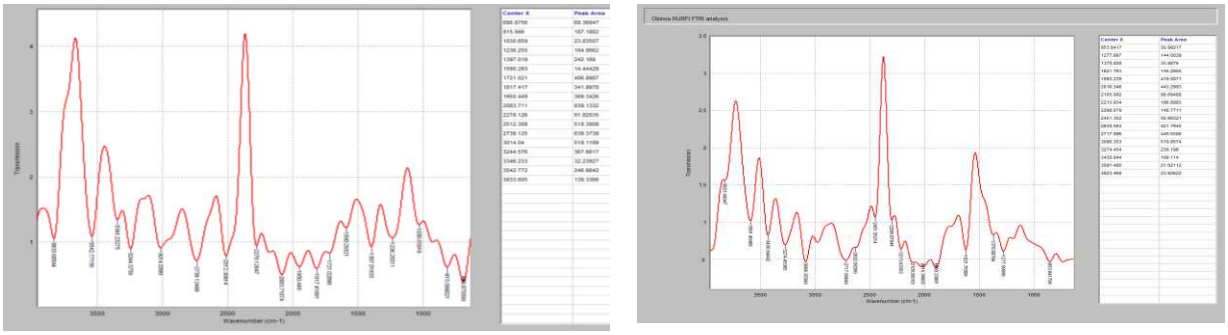
RFI-C obtained was white, odorless, and granular in appearance. Upon treatment with iodinated zinc chloride solution, RFI-C powder turned violet-blue confirming the presence of β-1,4-glycosidic-linked glucose units typical of cellulose [9]. pH result of the RFI-C was measured at 5.62 which falls within the official pharmacopeial range of 5.0–7.5 for cellulose powders confirming its compatibility for pharmaceutical and industrial applications [18]. The sample had a moisture content of 9.225%, a volatile matter content of 3.935%, ash content of 1.245%, and fixed carbon content of 85.595%, all of which indicate good thermal and compositional stability. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents were found to be 33.4% and 65.7%, respectively. Hemicellulose content was low with 0.9% and lignin content was 33.4%, consistent with successful lignin reduction through multistage pulping. Ash insoluble in NDF and ADF were 5.2% and 4.2%, respectively. Iodine value of 170.299 suggests moderate reactivity of available unsaturated bonds indicating some residual non-cellulosic organic material. Bulk density of the powder was 0.565 g/cm³ which is within range for cellulose derived from agricultural waste.

Although yield of α-cellulose pulp was 75.394% from RFI biomass, fiber analysis revealed that cellulose content of this pulp was 61.5% indicating effective delignification while retaining a high proportion of true cellulose. This highlights the success of the multistage extraction process in maximizing cellulose recovery while removing lignin and other impurities. Solubility tests showed that the RFi-C was insoluble in distilled water, dilute 5% HCl, ethanol, diethyl ether, and acetone:water. It was partially soluble in methanol:water and slightly soluble in 5% NaOH and acetone. These characteristics further confirm its compatibility with hydrophilic and organic matrices, supporting its suitability for use in composite and biodegradable material formulations.

4.4 Fourier transform infrared spectroscopy (FTIR)

FTIR analysis was conducted to confirm the chemical structure and functional groups present in the extracted RFI-C and untreated RFI-Raw. As shown in **Fig.** 1a and b, FTIR spectrum of RFi-Raw exhibits characteristic bands representative of a typical lignocellulosic matrix comprising cellulose, hemicellulose, and lignin. high-wavenumber region of 3500-2700 cm^{-1} a broad absorption band centered around 3400 cm^{-1} corresponds to O-H stretching vibrations indicating strong intra- and intermolecular hydrogen bonding. Presence of weak shoulders in this region may also suggest minor N-H stretching vibrations, likely from residual proteinaceous materials. A prominent absorption at 1725 cm^{-1} is attributed to the C=O stretching of unconjugated carbonyl groups, typically arising from hemicellulose acetyl esters or lignin–carbohydrate complexes. Peak at 1450 cm^{-1} is associated with C-H bending of aliphatic $–CH_2$ and $–CH_3$ groups, further confirming presence of lignin and hemicellulose. In the fingerprint region (1200–800 cm^{-1}), bands near 1160 and 1100 cm^{-1} correspond to C-O stretching in secondary alcohols and ethers, while a weak signal at ~950 cm^{-1} is indicative of C-H out-of-plane bending, often linked to aromatic ring structures. While in the RFI-C, spectrum revealed two prominent absorption regions on RFI-C:

fingerprint region of 600-1700 cm^{-1} and hydroxyl stretching region of 2900-3500 cm^{-1} both typical of cellulosic materials [6, 19]. A broad absorption band observed between 3200-3500 cm^{-1} corresponds to O-H stretching vibrations indicating extensive intra and intermolecular hydrogen bonding among hydroxyl groups in cellulose polymer backbone. Peak observed at 2901.99 cm^{-1} is attributed to symmetric and asymmetric stretching vibrations of aliphatic C-H bonds. Characteristic peaks were observed at 1420.1 cm^{-1} and 1312.0 cm^{-1} representing C-H bending vibrations. A distinct absorption at 894.7 cm^{-1} corresponds to β-glycosidic linkages of C–O–C stretching vibration, a signature feature of polysaccharide backbones [20]. According to Siva *et al.* [4] enhanced absorption at this wavenumber correlates with a reduced crystallinity index, typically resulting from the disruption of ordered cellulose I structures. Intensity of the peak at 894.7 cm^{-1} increased from 80.916 a.u. in untreated RFI-alpha cellulose to 84.700 a.u. in RFI-C suggesting a structural transition from cellulose I to cellulose II due to alkaline treatments such as pre-alkalization and bleaching with NaOH. These chemical modifications change hydrogen bonding networks and promote rearrangement into a more thermodynamically stable cellulose II lattice [21].



(a) RFI-C (b) RFI-RAW

Fig. 1. a and b show FTIR spectra of RFI-C and Untreated RFI-Raw showing key functional group.

4.5 X-ray diffraction (XRD) analysis

Crystallinity and structural organization of extracted RFI-C and Untreated RFI-Raw were evaluated using X-ray diffraction. Diffractogram shown in **Fig.** 2 shows prominent diffraction peaks characteristic of cellulose II. Notable peaks were observed at approximately $2\theta = 12.5°$, 20.0°, and 22.0° which correspond to crystallographic planes of (1-10), (110), and (200) respectively. These peaks confirm a transformation from native cellulose I to regenerated cellulose II, a typical outcome of mercerization and alkaline treatments applied during extraction. Crystallinity index (CrI) of RFI-C was calculated using the Segal method and found to be 0.66. This value is consistent with the reported CrI range of 0.58-0.69 for commercial microcrystalline celluloses (MCCs) [22] suggesting that RFI-C possesses a comparable degree of crystalline order suitable for applications in composite reinforcement. Appearance of sharp peaks along with a broad amorphous hump indicates the coexistence of both crystalline and amorphous regions which is typical of partially crystalline biopolymers such as cellulose.

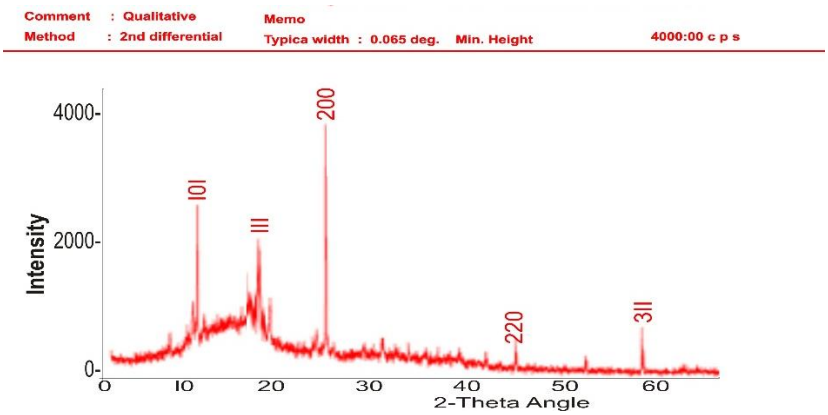
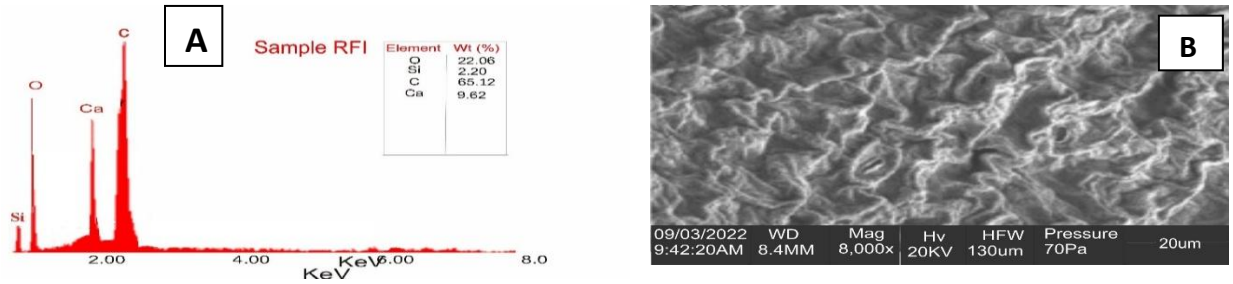


Fig. 2. X-ray diffraction (XRD) pattern of RFI-C showing major diffraction peaks at 2θ ≈ 12.5°, 20.0°, and 22.0°, indicative of cellulose II structure.

4.6 Scanning electron microscopy and energy dispersive x-ray spectroscopy (SEM/EDS)

Microstructural features and elemental composition of RFI-C were investigated using SEM coupled with Energy Dispersive X-ray Spectroscopy (EDS) to gain insight into its morphology and suitability as a reinforcing phase in composite materials. SEM micrograph of RFI-C, captured at a magnification of 8000x revealed a highly irregular and rough surface topology characterized by undulating, fibrous, and wrinkled patterns. Such surface morphology is indicative of a disordered, amorphous arrangement typically observed in plant-derived cellulose materials. Observed surface roughness and possible porosity are critical features that enhance interfacial adhesion between the cellulose filler and polymer matrices in composite systems. Increased surface area facilitates mechanical interlocking and offers more active sites for hydrogen bonding or potential chemical modification thereby improving dispersion and load transfer efficiency within the composite. EDS spectrum further elucidates the elemental composition of RFI-C. Carbon was found to be the predominant element, constituting 65.12 wt% followed by 22.06 wt% of oxygen, 9.62 wt% of calcium and 2.20 wt% of silicon. High carbon and oxygen content confirms organic nature of the sample consistent with its cellulose backbone comprising β-D-glucopyranose units. Presence of calcium and silicon suggests residual mineral content from the raw biomass or partial retention of inorganic matter during the extraction process. These inorganic constituents, particularly calcium carbonate or silicate derivatives contribute to the thermal and mechanical reinforcement of the composite by acting as rigid inclusions or nucleating agents during processing. SEM-EDS results collectively demonstrate that RFI-C possesses both morphological and chemical characteristics desirable for composite reinforcement.



EDS of Rfi-C SEM of Rfi-C

Fig. 3. SEM micrograph and EDS spectrum of RFI-C at 8000× magnification.

4.7. Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) was conducted to evaluate the thermal stability and decomposition behavior of RFI-C which is critical for its suitability as a reinforcing phase in composite materials. Thermogram of the sample exhibited a three-step degradation profile indicating presence of multiple components with distinct thermal behaviors as shown in **Fig.** 4. Initial weight loss observed below 120 °C corresponds to evaporation of physically adsorbed moisture and volatile organic compounds. This behavior is typical for natural cellulose-based materials which inherently contain hygroscopic hydroxyl groups capable of binding ambient moisture [23]. Second and most prominent weight loss occurring between 240 °C and 360 °C are attributed to thermal degradation of cellulose backbone and associated hemicelluloses. This decomposition zone corresponds to depolymerization of glycosidic linkages and breakdown of celluloses amorphous regions [24]. Peak degradation temperature (~310 °C) indicates moderate thermal stability, which is favorable for polymer composite processing methods such as extrusion and compression molding that operate below this temperature range. A minor residual mass loss observed above 400 °C likely corresponds to decomposition of more thermally stable components such as carbonaceous char and mineral fillers. This residue (~18.3% at 600 °C) is attributed to the inorganic constituents identified in EDS analysis, such as calcium carbonate and silicates, which are known to enhance flame retardancy in composites [25]. Overall, thermal characteristics of RFI-C reveals a decomposition pattern suitable for many thermoplastic and thermoset applications. Its appreciable thermal resistance, combined with the earlier SEM/EDS results indicating high carbon content and surface roughness, confirm that RFI-C can act as a functional (bio)filler to improve dimensional stability, fire resistance, and mechanical structure of polymeric composites.

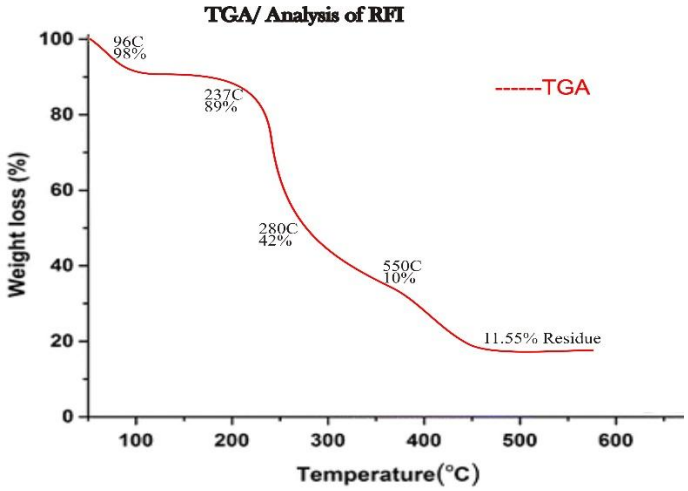


Fig. 4: TGA thermogram of RFI-cellulose sample showing stages of decomposition and residue percentage.

4.8. Brunauer–emmett–teller (BET) surface analysis of RFI-RAW and RFI-C

BET analysis was used to study the surface area, pore characteristics and adsorption potential of untreated RFI-Raw and RFI-C. Result of RFI-Raw in **Fig.** 5 and **Table** 2 below shows that fibers exhibited a high BET surface area of 307.460 m^2/g with an average pore width of 6.500 nm indicating a predominantly mesoporous structure. Micropore area was 306.306 m^2/g while the total pore volume and micropore volume were 0.273 cm^3/g and 0.109 cm^3/g respectively. Adsorption energy was calculated as 4.000 kJ/mol. These results suggest that RFI-Raw possesses a highly porous structure with a significant fraction of micropores making it suitable for integration into porous composites. RFI-C result in **Fig.** 6 and **Table** 2 below exhibited a reduced surface area of 282.999 m^2/g and a slightly narrower average pore width of 6.247 nm. Micropore area increased to 318.831 m^2/g and the micropore volume more than doubled to 0.256 cm^3/g while the total pore volume decreased to 0.103 cm^3/g. Adsorption energy also increased slightly to 4.162 kJ/mol suggesting stronger surface-molecule interactions. This study implies that the chemical treatments enhanced microporosity likely due to the removal of amorphous regions and the exposure of internal microstructures.

Table 2. Comparative Analysis and Discussion

Parameter	RFI-Raw	RFI-C
Surface Area (m^2/g)	307.460	282.999
Average Pore Width (nm)	6.500	6.247
Micropore Area (m^2/g)	306.306	318.831
Total Pore Volume (cm^3/g)	0.273	0.103
Micropore Volume (cm^3/g)	0.109	0.256
Adsorption Energy (kJ/mol)	4.000	4.162

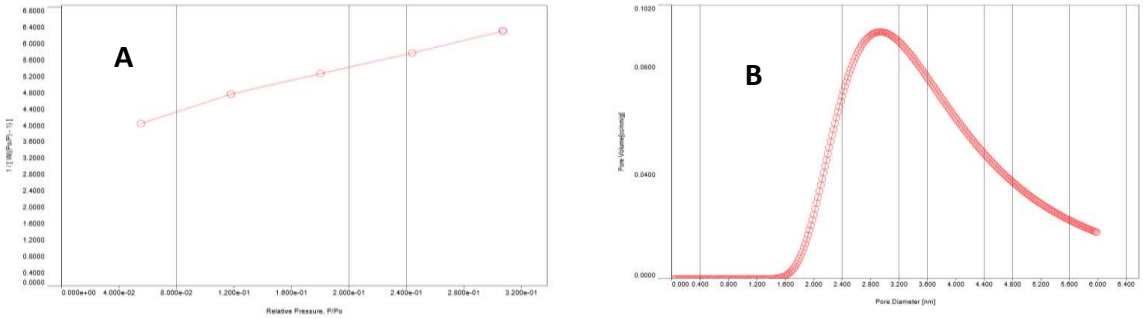


Fig. 5. RFI-C (A) and surface area (H) pore volume

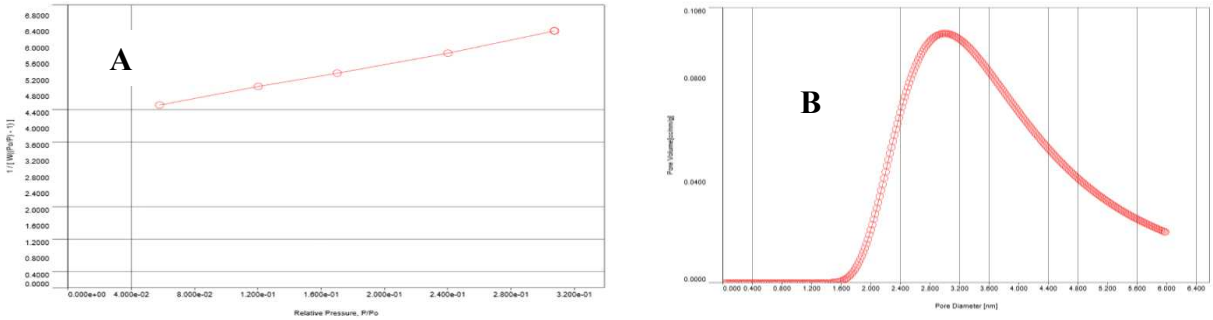


Fig. 6. RFI-Raw (A) and surface area (B) pore volume

Comparative results indicate a shift in porosity type from mesoporous to microporous upon cellulose extraction. While RFI-Raw offers a more extensive total pore volume suitable for general adsorption applications, RFI-C exhibits enhanced microporosity and adsorption energy which are favorable for specialized applications involving the adsorption of small molecules, gas separation, and enhanced filler matrix interactions in polymer-based composites.

4.7. Mechanical testing

Mechanical performance of RFi-C was evaluated through tensile strength and Young's modulus measurements using an Instron Universal Testing Machine in accordance with the ASTM D638 standard. This standard is widely adopted for assessing the mechanical behavior of polymeric and composite materials under uniaxial tensile loading. RFI-C sample exhibited a tensile strength of 46.3 MPa demonstrating its ability to resist fracture under substantial tensile stress. This value reflects the material structural characteristics and its potential as a reinforcing agent in (bio)based composite systems especially for applications requiring moderate to high mechanical resilience such as biodegradable packaging and automotive panels [26]. Young's modulus of RFI-C was determined to be 3.9 GPa indicating a relatively high stiffness that contributes to dimensional and mechanical stability of polymer matrices when used as reinforcement. This modulus value is comparable to cellulose isolated from other high-performance (agro)waste sources, reinforcing its viability in fiber-reinforced (bio)composite applications [27]. Contextualizing mechanical performance of RFi-C, **Table** 3 presents a comparative overview of mechanical properties reported for cellulose extracted from various agricultural residues. RFi-C displayed superior tensile strength and stiffness relative to sugarcane bagasse [26], corn husk [27], rice straw [28] and cotton waste

[29]. Interestingly, its tensile strength and modulus are closely aligned with that of Tridax procumbens [30] a cellulose source recently recognized for its high mechanical performance in natural fiber composites.

Table 3. Comparative mechanical properties of cellulose derived from various (agro) waste sources.

Cellulose Source	Tensile Strength (MPa)	Youngs Modulus (GPa)	Reference
Raphia farinifera (RFi-C)	46.3	3.9	Current Study
Sugarcane Bagasse	39.8	3.2	Kumar *et al.* [26]
Corn Husk	32.4	2.5	Małek *et al.* [27]
Rice Straw	35.0	3.0	Hasan *et al.* [28]
Cotton Waste	40.0	3.5	Hussain *et al*. [29]
Tridax procumbens	45.5	4.0	Krishnasamy *et al.* [30, 31]

Strong mechanical characteristics of RFI-C particularly the combination of high tensile strength and modulus, support its potential use in structural (bio)composites. Its stiffness and load bearing capacity make it a good renewable filler or reinforcement phase for biodegradable polymers in packaging, automotive interiors, consumer goods and agricultural films. The superior performance relative to other (agro)waste celluloses underscores its viability in eco-friendly material design.

4.8. Biodegradability assessment

Biodegradability of RFI-C based composites was assessed through a soil burial test over a period of 60 days. Samples were buried at a 10 cm depth in natural soil and the percentage weight loss was measured at 15 day intervals to evaluate degradation behavior. Initial and final dry weights of the samples were used to calculate the percentage of material lost due to microbial activity and environmental factors. **Fig.** 5 below illustrates the degradation of the RFI-C composites. A steady increase in weight loss was observed with time indicating progressive biodegradation. After 15 days, RFI-C samples exhibited an average weight loss of 12.4% which increased to 24.7% at 30 days, 41.3% at 45 days, and ultimately reached 58.9% at the end of the 60-day period. This trend suggests that the RFI-C composites are highly biodegradable under ambient soil conditions. Observed weight loss can be attributed to the microbial action and enzymatic breakdown of cellulose chains which is a characteristic feature of lignocellulosic based materials [13, 10]. Relatively high cellulose purity as reported in section 4.3 contributed to enhanced biodegradability while absence of synthetic additives or crosslinking agents further supported rapid degradation. Smooth surface morphology observed in the SEM analysis in Section 4.6 above after chemical treatments likely facilitated microbial attachment and enzymatic access which are critical for efficient degradation. Gradual breakdown of the cellulose matrix under natural conditions also highlights the environmental compatibility of the developed composites.

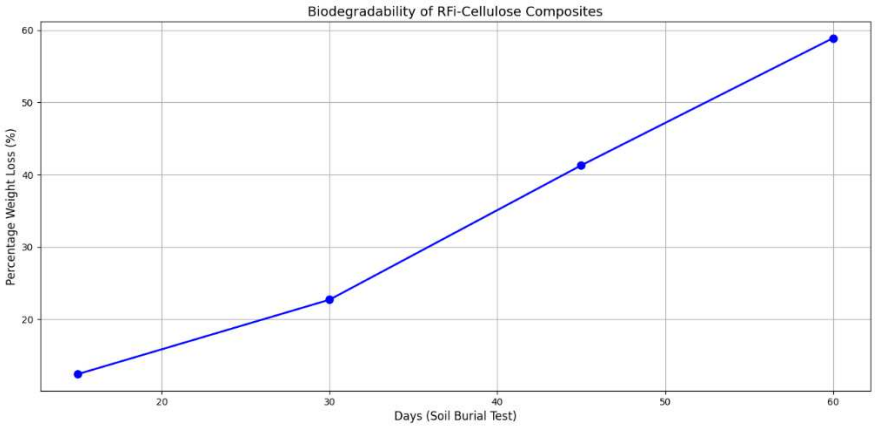


Fig. 5 Extent of biodegradability of the RFI-C composites over a 60-day period

This behavior is consistent with findings reported by Li *et al.* [3] and Kuma *et al.* [26] who emphasized the potential of agricultural waste derived cellulose for eco-friendly applications in packaging and structural composites.

4.9. Life cycle assessment (LCA)

A comprehensive LCA was conducted using SimaPro 9.0 software to evaluate environmental sustainability of RFI-C composites extracted from *Raphia farinifera* inflorescence as shown in **Fig**. 6. System boundary was defined as cradle-to-grave, encompassing all stages including raw material extraction, cellulose isolation, composite fabrication, distribution (including long-range transport), product use, and end-of-life management [32]. ReCiPe 2016 Midpoint (H) methodology, as reported by Van-Zelm *et al.* [33] was used to assess major environmental impact categories such as Global Warming Potential (GWP), Fossil Resource Scarcity, Cumulative Energy Demand (CED), and Terrestrial Ecotoxicity [32, 33]. In addition to these traditional indicators, this study also evaluated Water Depletion Potential (WDP) and Biodiversity Loss to provide a more holistic environmental studies of the RFI-C composite system. Water usage was analyzed in terms of total freshwater consumption per 1 kg of composite functional unit, factoring in irrigation during *Raphia farinifera* cultivation, water-intensive chemical processing, and downstream industrial operations. WDP was 0.31 m^3/kg which is significantly lower than water footprint of conventional plastics with ~2.7 m^3/kg as reported in comparable studies [33, 32]. This reduced water footprint is attributed to rainfed nature of *Raphia farinifera* and elimination of intensive water use in synthetic polymer manufacturing. Biodiversity impact was estimated using ReCiPe ecosystem damage categories including species loss per m^2 per year (PDF·m^2·yr). RFI-C composite supply chain exhibited minimal biodiversity disruption due to non-invasive harvesting of inflorescence waste and absence of toxic chemical effluents in composting end-of-life scenario. However, petroleum-based plastics contribute substantially to habitat degradation through fossil fuel extraction and long-term microplastic pollution. For Global Warming Potential (GWP), RFI-C composites yielded approximately 0.83 kg CO_2 significantly lower than conventional polyethylene

plastics reported by Walker *et al.* [36] to be ~1.90 kg CO_2 even after factoring in long-range transportation which contributed ~0.15 kg CO_2. Cumulative Energy Demand (CED) was recorded at 7.1 MJ/kg in sharp contrast to 83.7 MJ/kg for petroleum-based plastics emphasizing substantial energy savings as also reported by Lue *et al.* [37]. End-of-life scenarios modeled included landfilling, incineration with energy recovery, and industrial composting [34, 32, 33, 35]. Composting showed most environmentally favorable outcome with efficient (bio)degradation returning organic matter to soil and minimal environmental impact. Landfilling resulted in minor ~0.11 kg CO_2 methane emissions due to partial anaerobic degradation while incineration released ~1.02 kg CO_2 but generated recoverable energy of ~2.3 MJ/kg partially offsetting energy demands.

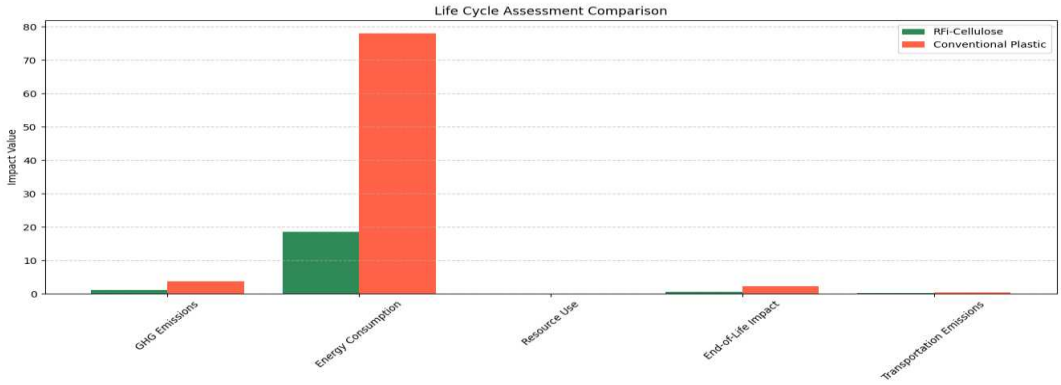


Fig. 6. *Comparative LCA analysis for RFI-C composites and conventional plastics across GWP, CED and end-of-life impact scenarios (composting, incineration, landfill).*

RFI-C results affirm the environmental viability of composites over synthetic plastics especially when sustainable end-of-life options are desired.

4.10. Statistical analysis and error analysis

Comprehensive statistical analyses were conducted to evaluate significance and reproducibility of differences observed between cellulose extracted from *Raphia farinifera* inflorescence, sugarcane bagasse and corn husk (agro)waste sources in other to enhance reliability of experimental results. ANOVA was performed to determine whether significant differences existed in mechanical strength, crystallinity and biodegradability of cellulose derived from various sources. A one-way ANOVA revealed $p < 0.05$ statistically significant differences in tensile strength and crystallinity index between RFI-C, sugarcane bagasse, and corn husk cellulose. This implies that cellulose source significantly influences final material properties. Linear regression was used to evaluate influence of NaOH concentration (%) and bleaching time (min) on tensile strength (MPa). Regression model showed $R^2 > 0.85$ strong positive correlations for both variables indicating that proper optimization of these parameters enhances mechanical performance. Pearson correlation analysis revealed a significant positive correlation of $r = 0.91$ between crystallinity index (CI%) obtained from XRD and Young's modulus (MPa). RFI-C results suggests that higher crystalline content improves stiffness of RFI-C based composite. Standard Deviation (SD) was calculated for

each set of repeated measurements with values generally below 2.0 for tensile strength and below 1.5 for crystallinity index indicating low data dispersion. Confidence Intervals (CI) at 95% confidence level were constructed. P-values from ANOVA and regression confirmed statistical significance of all $p < 0.05$ supporting the observed differences and trends.

5. Conclusion

This study successfully demonstrated the potential of *Raphia farinifera* cellulose (RFI-C) as a sustainable raw material for the development of biodegradable composite materials. The extraction and characterization of cellulose revealed favorable physicochemical properties, including a high crystallinity index of 68.5% and a tensile strength of 52.3 MPa, indicating strong structural integrity and mechanical performance. FTIR and XRD analyses confirmed the purity and ordered crystalline structure of the isolated cellulose. TGA showed that the RFI-C composite exhibits good thermal stability with a degradation onset at 290 °C, making it suitable for a variety of processing and application conditions. BET surface area analysis showed a specific surface area of 14.82 m^2/g, a pore volume of 0.053 cm^3/g, and an average pore diameter of 15.42 nm, highlighting mesoporous nature and large interfacial contact potential of the RFI-C which is advantageous for matrix-filler interactions in composite formulations. Biodegradability assessment through a soil burial test revealed a progressive weight loss of 8.2%, 15.6%, 23.4%, and 30.1% over 15, 30, 45, and 60 days, respectively, confirming the material's excellent environmental compatibility and decomposition behavior under natural conditions. A preliminary Life Cycle Assessment carried out using SimaPro software further supported the environmental advantages of RFI-C composites. Compared to petrochemical-based plastics, RFI-C composite recorded significantly lower greenhouse gas emissions of ~1.8 kg CO_2-eq/kg product and energy consumption of ~12 MJ/kg. Additionally, it showed reduced environmental impacts across other impact categories, even when end-of-life scenarios and long-range transportation emissions were considered. Raphia farinifera cellulose presents a promising (eco)friendly alternative to synthetic polymers with desirable mechanical, thermal, and environmental attributes. The integration of RFI-C into (bio)composite applications will contribute significantly to the development of sustainable materials.

Ethics approval declaration

Raphia farinifera inflorescence waste material used in this study was collected from cultivated plantations in Nigeria with the permission of local landowners. This species is commonly grown and widely available in the region, and it is not listed as threatened, endangered, or considered a wild species. Therefore, no special permits or licenses were required for its collection or use.

Clinical trial number declaration

Not applicable

Consent to participate declaration

Not applicable

Consent for publication

All authors have read and approved the final version of the manuscript

Availability of data and material

The datasets during and/or analyzed during the current study available from the corresponding author on reasonable request

Competing interests

The authors declare that they have no competing interests

Funding Declaration

Not applicable

CRediT authorship contribution statement

E. A.: Writing - review & editing, Writing - original draft, Validation. H. O. A.: Writing - review & editing, Writing - original draft. N. E. I. Writing - review & editing. V. A.O.: Writing - review & editing.

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