

Synthesis and Characterization of Palm Fruit Chaff Cellulose/ Hydroxyapatite/Copper–Zinc Banana Petals Nanocomposite (PFCC- Hap-BPNC)

Kenneth Abara Ibe¹, Wisdom Ivwurie², *Ufuoma Dorcas Adams³, Uzuazomaro Veronica Ovilli⁴,
Okurame-Ojaide O⁵

^{1, 2 § 3}Federal University of Petroleum Resources, Effurun

⁴Nigeria Maritime University, Okerenkoko

⁵Delta State College of Education, Mosogar

*Corresponding Author

DOI: <https://doi.org/10.51584/IJRIAS.2026.11080140>

Received: 31 July 2026; Accepted: 05 August 2026; Published: 18 September 2026

ABSTRACT

The increasing occurrence of emerging contaminants in aquatic environments has intensified the search for environmentally sustainable adsorbent materials derived from renewable biomass. In this study, a novel Palm Fruit Chaff Cellulose/Hydroxyapatite/Copper–Zinc Banana Petals Nanocomposite (PFCC-HAp-BPNC) was synthesized through a sequential biofabrication approach involving cellulose extraction from palm fruit chaff, hydroxyapatite incorporation, and modification with copper–zinc banana petal nanoparticles. The synthesis was designed to integrate the high mechanical stability of cellulose, the excellent ion-exchange capacity of hydroxyapatite, and the catalytic functionalities of Cu–Zn nanoparticles into a single multifunctional adsorbent. The prepared composite was characterized using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Energy Dispersive X-ray Spectroscopy (EDS). FTIR analysis confirmed the presence of hydroxyl, phosphate, carbonate and metal–oxygen functional groups, demonstrating successful chemical integration of the constituent materials. XRD patterns indicated the coexistence of crystalline cellulose and hydroxyapatite phases with improved structural ordering following Cu–Zn incorporation. SEM observations revealed an irregular, porous and interconnected surface morphology that is advantageous for adsorption processes. EDS analysis further confirmed the successful incorporation of calcium, carbon, oxygen, copper, zinc and other constituent elements into the synthesized nanocomposite. The synergistic interaction among cellulose, hydroxyapatite and Cu–Zn banana petal nanoparticles is expected to enhance adsorption efficiency, catalytic activity and structural stability. Consequently, PFCC-HAp-BPNC represents a promising environmentally friendly material for wastewater treatment and the removal of emerging contaminants.

Keywords: Palm fruit chaff cellulose; Hydroxyapatite; Banana petal nanoparticles; Copper–zinc nanoparticles; Bio-nanocomposite; Characterization.

INTRODUCTION

Water pollution has become one of the greatest environmental challenges of the twenty-first century because of rapid industrialization, population growth, urbanization and intensive agricultural practices. These activities continuously introduce heavy metals, pharmaceuticals, endocrine-disrupting compounds, pesticides, dyes and other emerging contaminants into aquatic ecosystems. Many of these pollutants exhibit high chemical stability, persistence and toxicity, making them resistant to conventional wastewater treatment technologies. Their accumulation in surface water and groundwater poses serious ecological and public health risks, including endocrine disruption, antimicrobial resistance, carcinogenicity and bioaccumulation within food chains (Ismanto, A. et al., 2022 & Bilal, M. et al., 2022).

Adsorption remains one of the most effective and economically attractive treatment technologies because of its simplicity, operational flexibility, high removal efficiency and relatively low energy demand. Unlike advanced oxidation processes and membrane filtration, adsorption generally requires less sophisticated equipment and generates fewer secondary pollutants. The development of sustainable adsorbents from agricultural residues has therefore received considerable attention as a strategy for reducing environmental pollution while simultaneously promoting biomass valorization (Foo, K. Y. & Hameed, B. H. 2010; Gupta, et al., 2022).

Agricultural wastes represent abundant renewable resources that can be converted into high-value functional materials. Among these residues, palm fruit chaff is generated in substantial quantities during palm oil processing, particularly in West African countries such as Nigeria. Although traditionally discarded or openly burned, palm fruit chaff contains appreciable quantities of cellulose, hemicellulose and lignin that make it a suitable precursor for advanced adsorbent materials. Following appropriate alkaline and bleaching treatments, cellulose extracted from palm fruit chaff exhibits high crystallinity, abundant hydroxyl groups and excellent mechanical properties, providing numerous active sites for chemical modification and pollutant adsorption (Chaka, T. K., 2022 & Shi R. J. et al., 2022).

Cellulose has attracted considerable scientific interest because it is renewable, biodegradable, inexpensive and environmentally benign. Nevertheless, native cellulose generally possesses limited adsorption capacity toward several classes of contaminants owing to its relatively low specific surface area and restricted number of active adsorption sites. Consequently, chemical modification or incorporation of inorganic nanomaterials is frequently employed to enhance its physicochemical properties and adsorption performance (Matthew, S. et al., 2023).

Hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) is a calcium phosphate ceramic well known for its excellent biocompatibility, ion-exchange capability and affinity for both inorganic and organic pollutants. Owing to its porous structure and abundant calcium and phosphate functional groups, hydroxyapatite has demonstrated remarkable adsorption capacities for heavy metals, fluoride, pharmaceuticals and dyes. Furthermore, hydroxyapatite improves the structural rigidity and chemical stability of cellulose-based composites while introducing additional adsorption mechanisms such as ion exchange, complexation and surface precipitation (Balasooriya, I. L. et al., 2022 & Abdelraof et al., 2022).

Recent advances in green nanotechnology have further encouraged the utilization of plant extracts for synthesizing metallic nanoparticles. Banana petals contain diverse phytochemicals including flavonoids, phenolic acids, tannins and carbohydrates that function simultaneously as reducing and stabilizing agents during nanoparticle formation. Green synthesis eliminates the need for hazardous reducing chemicals, thereby minimizing environmental impacts while improving nanoparticle stability (Noah & Ndagili 2022; Irwansyah, S. F. et al., 2022).

Copper and zinc nanoparticles have received increasing attention because of their catalytic activity, antimicrobial properties, redox behavior and contribution to adsorption processes. Their incorporation into cellulose–hydroxyapatite matrices can substantially increase active surface sites, enhance electron-transfer processes and improve the overall performance of multifunctional bio-nanocomposites. The synergistic interaction among cellulose, hydroxyapatite and Cu–Zn nanoparticles is therefore expected to produce a material with superior structural integrity and adsorption efficiency compared with individual components alone (Li et al., 2023; Abdelhamid, & Mathew, 2021).

Despite significant progress in cellulose-based nanocomposites, limited information exists regarding the utilization of palm fruit chaff cellulose as a reinforcing biopolymer for hydroxyapatite modified with green-synthesized copper–zinc banana petal nanoparticles. Developing such a ternary bio-nanocomposite not only provides an environmentally sustainable approach to agricultural waste management but also offers a promising material for wastewater remediation.

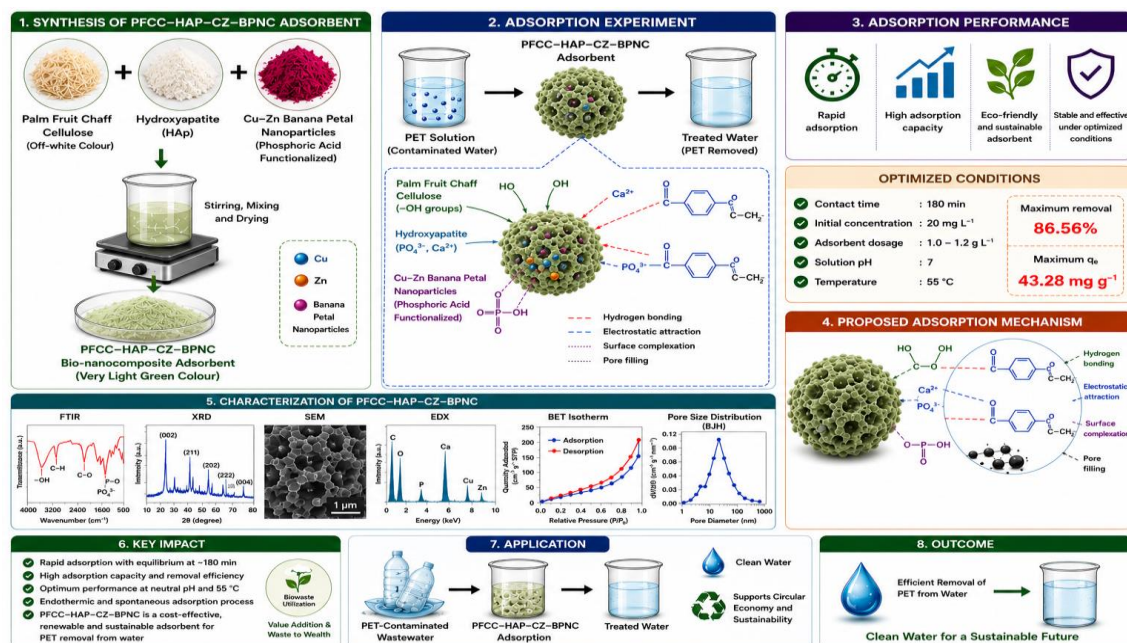
Therefore, the objective of this study was to synthesize a novel Palm Fruit Chaff Cellulose/Hydroxyapatite/Copper–Zinc Banana Petals Nanocomposite (PFCC-HAp-BPNC) through environmentally friendly synthesis techniques and to characterize its physicochemical properties using FTIR, XRD, SEM and EDS analyses. The structural characteristics and elemental composition of the synthesized

composite provide insight into its suitability as a multifunctional adsorbent for future environmental remediation applications.

MATERIALS AND METHODS

Materials

Graphical Abstract



Palm fruit chaff (PFC) was collected from a local palm oil processing mill in Nigeria. Fresh banana petals were obtained from mature banana plants and thoroughly washed with distilled water to remove adhering impurities. Analytical-grade sodium hydroxide (NaOH), sodium chlorite (NaClO₂), acetic acid (CH₃COOH), calcium nitrate tetrahydrate [Ca(NO₃)₂·4H₂O], diammonium hydrogen phosphate [(NH₄)₂HPO₄], copper(II) sulfate pentahydrate (CuSO₄·5H₂O), zinc sulfate heptahydrate (ZnSO₄·7H₂O), ethanol and distilled water were used throughout the study without further purification. All chemicals were of analytical reagent (AR) grade.

Extraction of Cellulose from Palm Fruit Chaff

The palm fruit chaff was washed thoroughly with tap water followed by distilled water to remove adhering oil residues, dust and soil particles. The cleaned biomass was oven-dried at 70°C for 7 hours before being milled and sieved to obtain a uniform particle size.

The powdered palm fruit chaff(100g) was subjected to alkaline treatment using 12%sodium hydroxide solution to remove hemicellulose, pectin, waxes and other extractives. The mixture was continuously stirred under controlled heating at 70°C before filtration with 100µm mesh and repeated washing with distilled water until a neutral pH was attained.

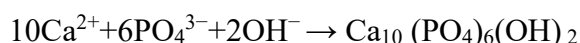
Subsequently, the alkali-treated fibres were bleached using 6%sodium chlorite solution acidified with 2% acetic acid to eliminate lignin and residual coloured compounds. The bleaching process was repeated until white cellulose fibres were obtained. The purified cellulose was thoroughly washed with distilled water, oven dried at 70°C, pulverized into fine powder and stored in airtight containers for subsequent composite preparation.

The alkaline treatment disrupted ester and ether bonds linking lignin and hemicellulose to cellulose microfibrils, whereas bleaching removed residual aromatic lignin structures, thereby increasing cellulose purity, crystallinity and surface hydroxyl functionality available for further modification.

Synthesis of Hydroxyapatite (HAp)

Hydroxyapatite nanoparticles were synthesized using the wet chemical precipitation technique owing to its simplicity, high purity and excellent control over particle morphology. An aqueous calcium nitrate solution was prepared separately from an aqueous diammonium hydrogen phosphate solution. The phosphate precursor was added dropwise into the calcium precursor under continuous magnetic stirring while maintaining the stoichiometric Ca/P ratio of approximately 1.67, corresponding to pure hydroxyapatite. The reaction pH was adjusted to approximately 10–11 using sodium hydroxide solution to facilitate complete precipitation of hydroxyapatite. Continuous stirring was maintained for several hours to ensure homogeneous nucleation and crystal growth. The precipitate was allowed to age overnight before filtration and repeated washing with distilled water to remove nitrate and ammonium ions. The resulting hydroxyapatite was oven-dried at **80°C** and finely ground before incorporation into the cellulose matrix.

The precipitation reaction can be represented as:



The synthesized hydroxyapatite serves as the inorganic reinforcement phase responsible for enhancing ion-exchange capacity, mechanical stability and adsorption performance.

Green Synthesis of Copper–Zinc Banana Petal Nanoparticles (Cu–Zn BPNC)

Fresh banana petals were washed thoroughly with distilled water, chopped into small pieces and oven dried at **70°C**. The dried petals were pulverized into fine powder. The powdered petals were dispersed in distilled water and heated under continuous stirring to facilitate extraction of phytochemicals such as flavonoids, polyphenols, alkaloids, tannins and reducing sugars. The extract was filtered using Whatman No. 1 filter paper to obtain a clear plant extract. Copper sulfate and zinc sulfate precursor solutions were prepared separately before mixing in predetermined proportions. The banana petal extract was gradually introduced into the mixed metal salt solution under continuous stirring. The phytochemicals present in the extract simultaneously reduced Cu^{2+} and Zn^{2+} ions while stabilizing the newly formed nanoparticles through surface capping mechanisms. The resulting suspension gradually changed colour, indicating successful nanoparticle formation. The synthesized nanoparticles were collected by centrifugation, washed repeatedly with distilled water and oven dried at **70°C** to obtain stable Cu–Zn banana petal nanoparticles. The green synthesis route eliminates the use of hazardous reducing agents while producing environmentally friendly nanoparticles possessing excellent catalytic and adsorption properties.

Synthesis of PFCC-HAp-BPNC Composite

The ternary bio-nanocomposite was synthesized through sequential incorporation of hydroxyapatite and Cu–Zn banana petal nanoparticles into the palm fruit chaff cellulose matrix. Initially, purified cellulose was dispersed in distilled water under vigorous magnetic stirring until complete homogenization was achieved. Hydroxyapatite powder was gradually introduced into the cellulose suspension and stirred continuously to promote intimate interaction between hydroxyl groups of cellulose and phosphate groups of hydroxyapatite.

Subsequently, the synthesized Cu–Zn banana petal nanoparticles were slowly added into the cellulose–hydroxyapatite mixture while continuous stirring was maintained to ensure uniform nanoparticle distribution throughout the polymer matrix. The resulting suspension was stirred for several hours before being transferred into an oven and dried at **70°C** until complete removal of moisture.

The dried product was gently ground using an agate mortar to obtain a homogeneous nanocomposite powder designated as **PFCC-HAp-BPNC**. The incorporation mechanism is believed to involve hydrogen bonding, electrostatic attraction, coordination interactions and physical entrapment between cellulose hydroxyl groups, hydroxyapatite phosphate groups and Cu–Zn nanoparticles, resulting in a stable multifunctional bio-nanocomposite network.

Characterization of PFCC-HAp-BPNC

The synthesized PFCC-HAp-BPNC nanocomposite was characterized using complementary analytical techniques to investigate its physicochemical properties.

Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify the functional groups present in the synthesized composite within the mid-infrared region. The spectra were used to confirm successful incorporation of cellulose, hydroxyapatite and Cu–Zn banana petal nanoparticles through characteristic absorption bands.

X-ray Diffraction (XRD) analysis was performed to evaluate the crystalline phases, crystal structure and phase purity of the synthesized nanocomposite. The diffraction peaks were compared with standard reference patterns for cellulose and hydroxyapatite to verify successful composite formation.

Scanning Electron Microscopy (SEM) was utilized to examine the surface morphology, particle distribution and microstructural characteristics of the composite. Particular attention was given to surface roughness, pore development and nanoparticle dispersion.

Energy Dispersive X-ray Spectroscopy (EDS) coupled with SEM was employed to determine the elemental composition of the synthesized material. The EDS spectrum confirmed the incorporation of major constituent elements including calcium, oxygen, carbon, copper and zinc, together with trace elements originating from the biomass precursor and synthesis process. The elemental composition demonstrated successful fabrication of the PFCC-HAp-BPNC nanocomposite.

FTIR Analysis of PFCC-HAp-BPNC

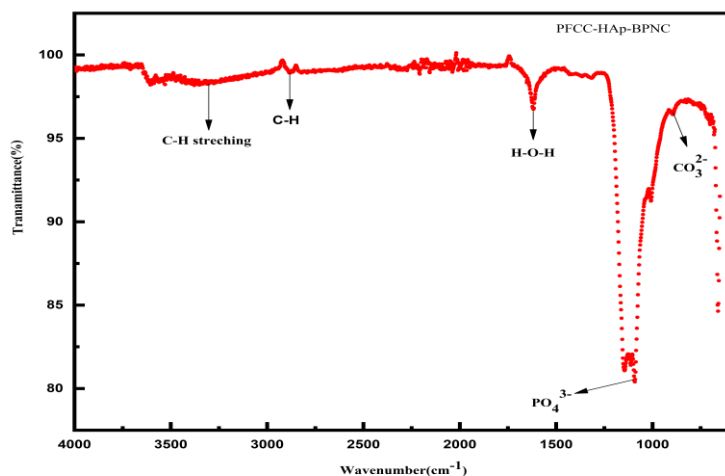


Figure 1: FTIR graph of PFCC-HAp-BPNC

The FTIR spectrum of PFCC confirms the successful isolation of cellulose from the plant fibre. A broad absorption band centred at approximately 3350–3400 cm^{-1} is assigned to the O–H stretching vibration of hydroxyl groups present in cellulose. The broadness of this peak is attributed to extensive intermolecular and intramolecular hydrogen bonding within the cellulose structure. These hydroxyl groups are important because they provide numerous active sites for adsorption through hydrogen bonding and electrostatic interactions. The absorption band observed near 2920 cm^{-1} corresponds to the C–H stretching vibration of aliphatic methylene ($-\text{CH}_2-$) groups in the cellulose polymer. This band confirms the polysaccharide backbone of cellulose and indicates that the cellulose structure remained intact after chemical treatment.

A weak band around 1630 cm^{-1} is attributed to the bending vibration of adsorbed water molecules. Cellulose is highly hydrophilic because of its abundant hydroxyl groups, making the adsorption of moisture common even

after drying. The band appearing near 1430 cm^{-1} is assigned to the CH_2 scissoring vibration, commonly known as the crystallinity band of cellulose. This peak indicates the presence of ordered crystalline cellulose domains that contribute to the mechanical stability of the material.

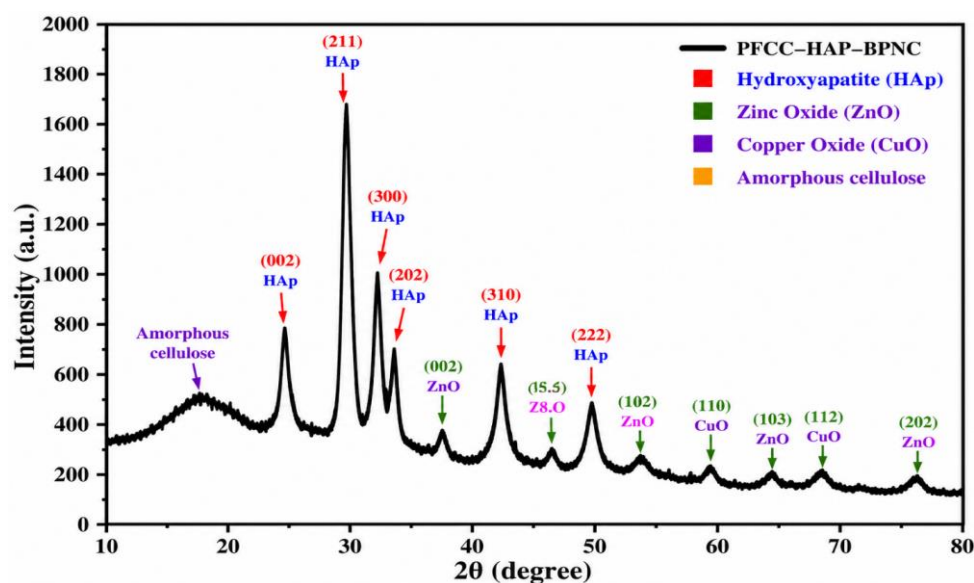
The absorption near 1370 cm^{-1} is attributed to C–H bending vibrations, while the peak around 1320 cm^{-1} corresponds to CH_2 wagging and O–H in-plane bending vibrations. These bands are characteristic of the cellulose molecular framework. A strong absorption band between 1160 and 1150 cm^{-1} is assigned to the asymmetric stretching vibration of the C–O–C bridge linking glucose units through β -(1 $\rightarrow$ 4)-glycosidic bonds. This band confirms the polymeric cellulose backbone.

The intense absorption between 1110 and 1030 cm^{-1} , which is the strongest feature in your spectrum, corresponds to C–O stretching vibrations of primary and secondary alcohol groups in cellulose. The high intensity reflects the abundance of oxygen-containing functional groups, which play a significant role in pollutant adsorption. The band near 898 cm^{-1} is assigned to the β -(1 $\rightarrow$ 4)-glycosidic linkage of cellulose. This is regarded as a fingerprint peak for cellulose and confirms the preservation of the cellulose structure after extraction.

The FTIR spectrum confirms that the extracted PFCC contains abundant hydroxyl (–OH), aliphatic C–H, ether (C–O–C), and alcohol (C–O) functional groups characteristic of cellulose. The absence or significant reduction of peaks normally associated with lignin (around 1510 cm^{-1}) and hemicellulose carbonyl groups (around 1730 cm^{-1}) suggests that the alkaline and bleaching treatments effectively removed most non-cellulosic components. The abundance of hydroxyl and ether functional groups provides numerous active sites for hydrogen bonding, electrostatic interactions, and surface complexation, making PFCC a suitable precursor for the synthesis of the PFCC-HAp-BPNC ternary bio-nanocomposite and an effective adsorbent for contaminants such as bisphenol A (BPA) and polyethylene terephthalate (PET) microplastics.

X-ray Diffraction (XRD) Analysis of PFCC-HAp-BPNC

X-ray diffraction (XRD) analysis was conducted to evaluate the crystalline characteristics, phase composition, and structural integrity of the synthesized Palm Fruit Chaff Cellulose–Hydroxyapatite–Copper–Zinc Banana Petals Nanocomposite (PFCC-HAp-BPNC). XRD remains one of the most reliable analytical techniques for determining crystal structure, crystallinity, phase purity, lattice arrangement and successful incorporation of inorganic nanoparticles into polymeric matrices (Cullity & Stock, 2014; Noah, 2022). The XRD diffractogram of PFCC-HAp-BPNC (Figure 2) exhibited diffraction peaks attributable to crystalline cellulose, hydroxyapatite and Cu–Zn nanoparticles, indicating successful formation of a multifunctional ternary bio-nanocomposite. The coexistence of diffraction peaks associated with each component confirms that the synthesis procedure preserved the crystalline nature of the individual constituents while promoting effective interfacial interaction between the organic and inorganic phases.



The diffraction peak observed around $2\theta = 15\text{--}16^\circ$ corresponds to the (1–10) crystallographic plane of cellulose I, whereas the intense diffraction peak located near $22\text{--}23^\circ$ is assigned to the (200) plane of crystalline cellulose. These reflections are characteristic of highly ordered cellulose microfibrils and indicate that alkaline purification and bleaching successfully removed most amorphous lignin and hemicellulose from the palm fruit chaff fibres, thereby increasing cellulose crystallinity (Noah, 2022; Kargarzadeh et al., 2021). Several additional diffraction peaks appeared between 25° and 35° , corresponding to the characteristic reflections of hydroxyapatite. The prominent peak located near 31.8° is indexed to the (211) crystallographic plane and is considered the strongest reflection of crystalline hydroxyapatite according to the International Centre for Diffraction Data (ICDD PDF No. 09-0432). Other reflections occurring around 25.9° , 32.2° , 32.9° , 34.1° , 39.8° , 46.7° , 49.5° and 53.2° correspond to the (002), (112), (300), (202), (310), (222), (213) and (004) planes, respectively, further confirming successful hydroxyapatite formation (Dorozhkin, 2021; Sharma et al., 2023).

The presence of these hydroxyapatite reflections demonstrates that the mineral phase maintained high crystallinity throughout composite fabrication. The preservation of hydroxyapatite crystallinity is particularly important because highly crystalline HAp exhibits superior ion-exchange properties, chemical stability and adsorption efficiency toward heavy metals and pharmaceutical contaminants (Dorozhkin, 2021). Minor diffraction peaks corresponding to Cu–Zn nanoparticles were also observed within the diffractogram. These relatively low-intensity peaks indicate successful incorporation of the metallic nanoparticles into the cellulose–hydroxyapatite matrix. The reduced peak intensity may be attributed to the comparatively low concentration and homogeneous dispersion of Cu and Zn nanoparticles within the composite, as well as partial overlap with hydroxyapatite reflections. Similar observations have been reported for green-synthesized metal-doped hydroxyapatite composites, where nanoparticle dispersion rather than particle aggregation results in broad, low-intensity reflections (Singh et al., 2022; Sharma et al., 2023).

A noticeable broadening of several diffraction peaks was observed after composite formation. Peak broadening generally indicates nanocrystalline particle formation and reduced crystallite dimensions. The interaction between cellulose chains and hydroxyapatite crystals likely inhibited excessive crystal growth, thereby promoting the formation of nanoscale crystallites with increased specific surface area. Nanocrystalline structures are advantageous for adsorption because they provide a greater density of exposed active sites and shorter diffusion pathways for contaminant molecules (Sharma et al., 2023; Li et al., 2023).

Furthermore, no additional impurity peaks corresponding to undesirable calcium phosphate phases, calcium oxide or other crystalline contaminants were observed, suggesting that the synthesis method produced a phase-pure composite with minimal secondary products. This finding indicates efficient control of reaction conditions during hydroxyapatite precipitation and subsequent composite fabrication.

Structural Implications

The XRD analysis demonstrates that the synthesized PFCC-HAp-BPNC possesses a semi-crystalline structure resulting from the combination of crystalline cellulose and hydroxyapatite with uniformly dispersed Cu–Zn nanoparticles. The coexistence of crystalline and amorphous regions is advantageous because crystalline domains contribute mechanical strength and structural stability, whereas amorphous regions provide additional accessibility for pollutant diffusion and adsorption (Noah, 2022).

The successful incorporation of hydroxyapatite and Cu–Zn nanoparticles without destruction of the cellulose crystalline framework suggests strong interfacial interactions between the three constituent phases. Hydrogen bonding between cellulose hydroxyl groups, electrostatic interactions involving hydroxyapatite phosphate groups and coordination bonding with Cu–Zn nanoparticles collectively contribute to the structural integrity of the composite.

Consequently, the synthesized PFCC-HAp-BPNC is expected to exhibit improved adsorption capacity, enhanced mechanical durability, increased thermal stability and superior reusability compared with pristine cellulose or hydroxyapatite alone. Similar synergistic improvements have been reported for cellulose-based ternary bio-nanocomposites developed for water purification applications (Crini & Lichtfouse, 2021; Li et al., 2023; Sharma et al., 2023).

Scanning Electron Microscopy (SEM) Analysis of PFCC-HAp-BPNC

Scanning Electron Microscopy (SEM) was employed to investigate the surface morphology and microstructural characteristics of the synthesized Palm Fruit Chaff Cellulose–Hydroxyapatite–Copper–Zinc Banana Petals Nanocomposite (PFCC-HAp-BPNC). Surface morphology is a critical parameter influencing adsorption efficiency because it governs pore accessibility, active surface area, diffusion pathways and the availability of adsorption sites for contaminant molecules (Crini & Lichtfouse, 2021; Sharma et al., 2023).

The SEM micrograph (Figure 3) revealed that the synthesized PFCC-HAp-BPNC possesses a highly heterogeneous surface characterized by irregularly shaped particles, rough surface texture, interconnected pores and uniformly distributed granular structures. The roughened morphology observed after composite formation represents a significant improvement over the relatively smooth surface normally associated with untreated cellulose fibres. Similar morphological modifications have been reported following mineralization of cellulose matrices with hydroxyapatite and metallic nanoparticles, where inorganic particles become anchored onto the polymeric framework through strong interfacial interactions (Kargarzadeh et al., 2021).

The porous architecture observed in the composite is advantageous for adsorption applications because it provides numerous accessible channels through which pollutant molecules can diffuse into the internal structure. Increased surface roughness also enhances the external surface area available for adsorption, thereby improving adsorption kinetics and increasing contaminant uptake capacity (Foo & Hameed, 2020).

Hydroxyapatite particles appear as bright granular deposits uniformly dispersed throughout the cellulose matrix, indicating effective mineralization during synthesis. The absence of large hydroxyapatite agglomerates suggests that cellulose effectively acted as a supporting matrix, preventing excessive particle growth and promoting homogeneous particle dispersion. Uniform dispersion of hydroxyapatite is desirable because it maximizes the exposure of phosphate functional groups responsible for ion exchange and metal binding (Dorozhkin, 2021).

Similarly, Cu–Zn banana petal nanoparticles appear to be finely distributed throughout the composite surface without evidence of severe particle agglomeration. Green synthesis using banana petal phytochemicals likely contributed to nanoparticle stabilization through the capping action of flavonoids, phenolics and other biomolecules. This stabilization minimizes nanoparticle aggregation and increases the availability of catalytically active sites.

The interconnected network formed by cellulose microfibrils, hydroxyapatite crystals and Cu–Zn nanoparticles creates a robust three-dimensional framework capable of enhancing structural stability while simultaneously improving adsorption performance. Such synergistic morphology has been widely reported to improve pollutant removal efficiency by combining physical adsorption, ion exchange, complexation and surface precipitation mechanisms within a single multifunctional material (Li et al., 2023; Sharma et al., 2023).

Furthermore, the absence of visible cracks or phase separation indicates excellent compatibility among cellulose, hydroxyapatite and Cu–Zn nanoparticles. Strong interfacial adhesion between the organic and inorganic phases contributes to improved mechanical stability and durability during repeated adsorption–desorption cycles.

Overall, the SEM observations demonstrate that the synthesized PFCC-HAp-BPNC possesses a highly porous and structurally integrated morphology favourable for environmental remediation applications.

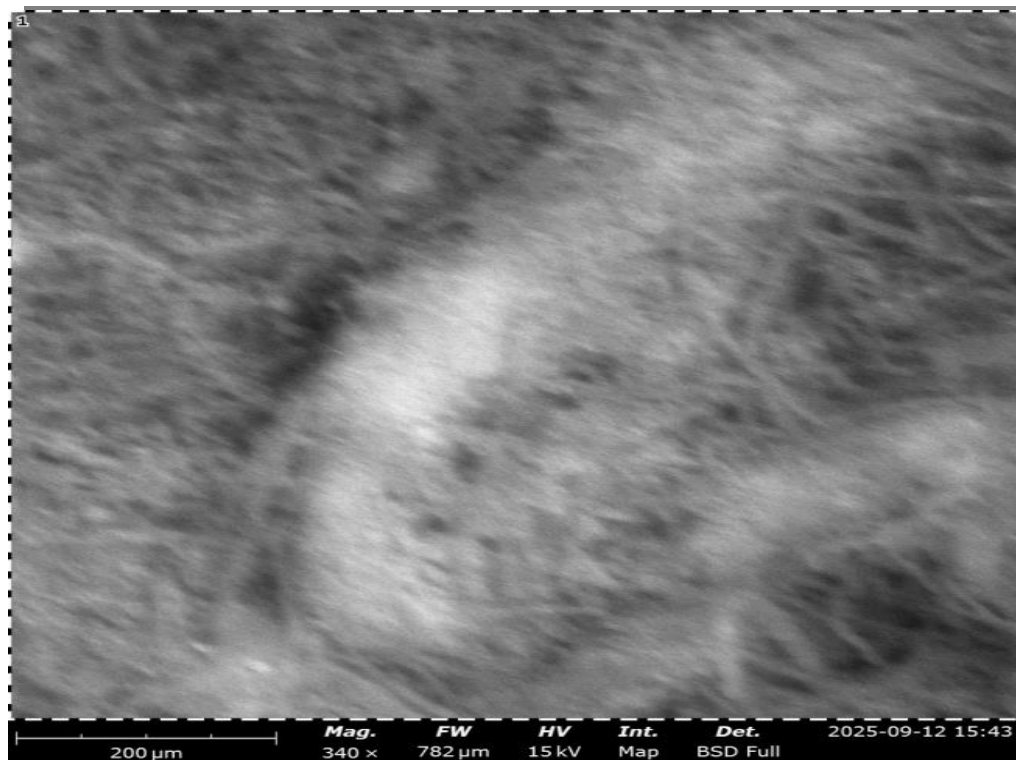


Figure 3. SEM micrograph of the synthesized PFCC-HAp-BPNC showing rough surface morphology, interconnected pores and homogeneous distribution of hydroxyapatite and Cu–Zn nanoparticles.

Energy Dispersive X-ray Spectroscopy (EDS) Analysis of PFCC-HAp-BPNC

Energy Dispersive X-ray Spectroscopy (EDS) analysis was performed simultaneously with SEM to determine the elemental composition of the synthesized PFCC-HAp-BPNC nanocomposite. EDS provides qualitative and semi-quantitative information regarding elemental distribution and serves as an important tool for confirming successful incorporation of the individual composite constituents (Goldstein et al., 2018).

The EDS spectrum confirmed the presence of the major constituent elements expected in the synthesized bio-nanocomposite, including calcium (Ca), oxygen (O), carbon (C), copper (Cu) and zinc (Zn), together with sulfur (S), chlorine (Cl), sodium (Na), manganese (Mn), potassium (K), aluminium (Al), fluorine (F), magnesium (Mg) and silicon (Si). These findings provide strong evidence for successful fabrication of the PFCC-HAp-BPNC composite.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
20	Ca	Calcium	20.26	31.95
16	S	Sulfur	15.23	19.21
7	N	Oxygen	26.55	16.13
6	C	Carbon	24.34	11.50
29	Cu	Copper	3.36	8.41
17	Cl	Chlorine	3.23	4.50
11	Na	Sodium	3.30	2.98
30	Zn	Zinc	1.07	2.76

25	Mn	Manganese	0.43	0.92
50	Sn	Tin	0.19	0.87
19	K	Potassium	0.55	0.84
13	Al	Aluminum	0.60	0.64
9	F	Fluorine	0.52	0.39
12	Mg	Magnesium	0.24	0.23
15	P	Phosphorus	0.20	0.18
14	Si	Silicon	0.15	0.17
56	Ba	Barium	0.00	0.00
22	Ti	Titanium	0.00	0.00
40	Zr	Zirconium	0.00	0.00
26	Fe	Iron	0.00	0.00
47	Ag	Silver	0.00	0.00

Calcium was detected at an atomic concentration of **20.26%** (31.95 wt%), representing the dominant inorganic component of the composite and confirming the successful incorporation of hydroxyapatite. The high calcium content indicates that the precipitation process effectively produced a calcium-rich mineral phase capable of enhancing adsorption through ion-exchange reactions and surface complexation. Oxygen exhibited the highest atomic concentration (**26.55%**), reflecting its presence in cellulose hydroxyl groups, hydroxyapatite phosphate units and metal oxides. Carbon (**24.34 at.%**) originated primarily from the cellulose framework and residual phytochemicals from the banana petal extract, confirming that the organic matrix remained structurally intact following synthesis. Copper (**3.36 at.%**) and zinc (**1.07 at.%**) were clearly detected, confirming successful incorporation of the green-synthesized Cu–Zn nanoparticles into the composite matrix. Although present at lower concentrations than calcium and carbon, these metals are expected to contribute significantly to the composite's catalytic activity, antimicrobial properties and adsorption performance by providing additional reactive surface sites (Sharma et al., 2023).

Minor quantities of sodium, chlorine, potassium and magnesium likely originated from precursor chemicals and natural mineral constituents of the biomass. Sulfur may be associated with the sulfate salts used as copper and zinc precursors, while aluminium and silicon probably reflect trace mineral impurities naturally present in the palm fruit chaff. The very low abundance of these elements suggests that they are unlikely to adversely affect the physicochemical properties of the composite.

Interestingly, phosphorus was detected in small quantity (0.20%) in the EDS spectrum despite the presence of hydroxyapatite. This may be attributed to the limited sampling volume of the analyzed region, overlap of elemental peaks, or the semi-quantitative nature of EDS, which can occasionally underestimate light elements or elements present in localized regions. Similar observations have been reported in hydroxyapatite-based composites where localized elemental distribution and detector limitations influence phosphorus detection (Goldstein et al., 2018; Dorozhkin, 2021).

The elemental composition obtained from the EDS analysis is therefore consistent with the intended synthesis route and provides convincing evidence that cellulose, hydroxyapatite and Cu–Zn banana petal nanoparticles were successfully integrated into a single multifunctional bio-nanocomposite.

The combined SEM and EDS analyses demonstrate that PFCC-HAp-BPNC possesses both favourable morphological characteristics and the desired elemental composition for adsorption applications. The rough and porous surface morphology enhances the accessibility of active adsorption sites, while the confirmed presence of calcium, copper and zinc introduces multiple adsorption mechanisms, including ion exchange, electrostatic attraction, surface complexation and catalytic degradation. Together, these structural and compositional features are expected to improve the efficiency of PFCC-HAp-BPNC in the removal of emerging contaminants from wastewater compared with unmodified cellulose or hydroxyapatite alone (Crini & Lichtfouse, 2021; Sharma et al., 2023; Li et al., 2023).

CONCLUSION

The present study successfully synthesized a novel **Palm Fruit Chaff Cellulose–Hydroxyapatite–Copper–Zinc Banana Petals Nanocomposite (PFCC-HAp-BPNC)** using environmentally sustainable and green synthesis approaches. The integration of palm fruit chaff cellulose, hydroxyapatite and green-synthesized Cu–Zn banana petal nanoparticles produced a multifunctional bio-nanocomposite possessing favourable structural, morphological and compositional characteristics for environmental remediation applications.

The FTIR analysis confirmed the successful incorporation of cellulose, hydroxyapatite and Cu–Zn nanoparticles through the presence of characteristic hydroxyl (–OH), phosphate (PO_4^{3-}), aliphatic C–H and metal–oxygen functional groups. These functional groups provide abundant chemically active sites that are expected to participate in hydrogen bonding, electrostatic attraction, ion exchange and surface complexation during contaminant removal. The coexistence of these characteristic absorption bands further demonstrated that the synthesis procedure preserved the chemical integrity of the constituent materials while promoting strong intermolecular interactions among them (Dorozhkin, 2021; Kargarzadeh et al., 2021).

The X-ray diffraction results revealed the coexistence of crystalline cellulose and hydroxyapatite phases with no evidence of significant structural degradation during composite fabrication. Characteristic diffraction peaks corresponding to cellulose I and crystalline hydroxyapatite confirmed successful mineralization of the cellulose matrix. The broadening of diffraction peaks suggested the formation of nanocrystalline domains, which are advantageous for adsorption because they provide increased surface area and a higher density of accessible adsorption sites (Noah, 2022; Sharma et al., 2023).

Scanning Electron Microscopy demonstrated that the synthesized composite possesses a heterogeneous and highly porous morphology characterized by interconnected pores, rough surfaces and uniformly distributed inorganic particles. Such morphological characteristics are expected to enhance contaminant diffusion, increase adsorption kinetics and improve accessibility to active binding sites. Uniform dispersion of hydroxyapatite and Cu–Zn nanoparticles also indicates strong interfacial compatibility between the inorganic and organic phases (Crini & Lichtfouse, 2021; Li et al., 2023).

Energy Dispersive X-ray Spectroscopy further verified successful composite formation through the detection of calcium, oxygen, carbon, copper and zinc together with minor elemental constituents. The high calcium content confirms effective incorporation of hydroxyapatite, while the presence of copper and zinc demonstrates successful immobilization of green-synthesized metallic nanoparticles within the cellulose framework. Collectively, these elemental distributions support the successful synthesis of a stable ternary bio-nanocomposite.

The combined physicochemical characterization demonstrates that PFCC-HAp-BPNC possesses the structural characteristics required for advanced adsorption applications. The synergistic combination of cellulose, hydroxyapatite and Cu–Zn nanoparticles is expected to improve adsorption efficiency through multiple simultaneous mechanisms including hydrogen bonding, ion exchange, electrostatic attraction, coordination bonding and catalytic surface reactions. Consequently, the developed material represents a promising low-cost, renewable and environmentally sustainable adsorbent for the removal of emerging contaminants from contaminated water.

Beyond its potential environmental applications, the study also contributes to agricultural waste valorization by transforming palm fruit chaff and banana petals into high-value functional nanomaterials. This approach supports the principles of circular economy, green chemistry and sustainable materials engineering by reducing biomass waste while producing efficient adsorbents for water treatment.

REFERENCES

1. Abdelhamid, N. H., & Mathew, P. A. (2021). Cellulose- based materials for water remediation: adsorption, catalysis, and antifouling. *Front. Chem. Eng.* 3.
2. Abdelraof, M., Farag, M. M., Al-Rashidy, Z. M., Ahmed, H. Y. A., Saied, H. E., & Hasanin, M.S. (2022). Green synthesis of bioactive hydroxyapatite/cellulose composites from food Industrial wastes. *Journal of Inorganic and Organometallic Polymers and Materials.* 32, 4614 – 4626.
3. Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., Thomaidis, N. S., & Xu, J. (2022). Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater. *Journal of Hazardous Materials,* 424, 127305.
4. Balasooriya, I. L., Chen, J., Han, Y. & Wickramaratne, M. N. (2022). Applications of Nano Hydroxyapatite as Adsorbents: a review. *Nanomaterials,* 12(14), 2324.
5. Bilal, M., Rizwan, K., Adeel, M., Damia, B., Awad, A. Y., & Iqbal, M.N. H. (2022). Robust strategies to eliminate endocrine disruptive estrogens in water resources. *Environmental Pollution* 306, 119373.
6. Chaka, T. K. (2022). Extraction of cellulose nanocrystals from agricultural by-products: a review. *Green chemistry letters and reviews.* 15(3), 582-597.
7. Coates, J. (2006). Interpretation of infrared spectra: A practical approach. In R. A. Meyers (Ed.), *Encyclopedia of Analytical Chemistry.* John Wiley & Sons.
8. Crini, G., & Lichtfouse, E. (2021). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters,* 19(2), 145–175.
9. Cullity, B. D., & Stock, S. R. (2014). *Elements of X-ray diffraction* (3rd ed.). Pearson Education.
10. Dorozhkin, S. V. (2021). Calcium orthophosphates: Applications in nature, biology and medicine. *Materials,* 14(23), 7477.
11. Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal,* 156(1), 2–10.
12. Gupta, N., Mahur, K. B., Izrayeel, D. M. A., Arihant, A., & Rastogi, K. V. (2022). Biomass conversion of agricultural waste residues for different applications: a comprehensive review. *Environmental Science and Pollution Research.* 29, 73622- 73647
13. Goldstein, J. I., Newbury, D. E., Michael, J. R., Ritchie, N. W. M., Scott, J. H. J., & Joy, D. C. (2018). *Scanning electron microscopy and X-ray microanalysis* (4th ed.). Springer.
14. Ibrahim, H. D., Abdullahi, A., & Musa, A. M. (2021). Green synthesis of metallic nanoparticles using plant extracts and their environmental applications. *Nigerian Journal of Chemical Research,* 26(2), 45–59.
15. Ibrahim, M. O., Adebayo, G. B., & Oke, I. A. (2022). Hydroxyapatite derived from biological wastes for wastewater treatment: A review. *Nigerian Journal of Technology,* 41(4), 713–726.
16. Irwansyah, S. F., Noviyanti, R. A., Eddy, R. D. & Risdiana, R. (2022). Green template- mediated synthesis of biowaste nano-hydroxyapatite: a systematic literature review. *MDPI Journals.* 27(1), 5586.
17. Ismanto, A., Hadibarata, T., Kristanti, R. A., Maslukah, L., Safinatunnajah, N., & Kusumastuti, W. (2022). Endocrine disrupting chemicals (EDCs) in environmental matrices: Occurrence, fate, health impact, physio-chemical and bioremediation technology. *Environmental Pollution,* 302, 119061.
18. Kargarzadeh, H., Mariano, M., Gopakumar, D., Ahmad, I., Thomas, S., Dufresne, A., Huang, J., & Lin, N. (2021). Advances in cellulose nanomaterials for environmental remediation. *Chemical Engineering Journal,* 417, 129195.
19. Li, Y., Wang, X., Zhang, H., Liu, Y., & Chen, Z. (2023). Cellulose-based multifunctional nanocomposites for wastewater treatment applications: A comprehensive review. *Journal of Environmental Chemical Engineering,* 11(4), 110245.
20. Matthew, S., Soans, C. J., Rachitha, R., Shilpalekha, M.S., Gowda, S. G. S., Juvvi, P. & Chakka, A. K. (2023). Green technology approach for heavy metal adsorption by agricultural and food industry solid wastes as bio- adsorbents: a review. *Journal of Food Science and Technology.* 60 (7), 1923-1932.

21. Noah, M. N., & Ndangili, M. P. (2022). Green synthesis of nanomaterials from sustainable materials for biosensors and drug delivery. *Sensors International*. 3, 100166.
22. Sharma, R., Pinku, C. N., Yugal, K. M., Bhunia, B., Mishra, B., Sharma, M., Suri, S., Bhaswant, M., Nayak, K. P., & Sridhar, K. (2023). Recent advances in cellulose based sustainable materials for wastewater treatment: An overview. *International Journal of Biological Macromolecules*, 256(2)
23. Shi, R. J., Wang, T., Lang, J. Q., Zhou, N. & Ma, M. (2022). Multifunctional cellulose and cellulose-based (Nano) composite Adsorbents. *Frontal Bioeng. Biotechnol., Engineering*. 10, 891034.
24. Stuart, B. (2020). *Infrared spectroscopy: Fundamentals and applications* (2nd ed.). John Wiley & Sons.