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HARNESSING LOCALLY DERIVED BIOCOMPOSITES FOR SUSTAINABLE WATER PURIFICATION AND ENVIRONMENTAL PROTECTION

Thompson Izuagie

Department of Chemistry, National Open University of Nigeria, Jabbi, Abuja

Corresponding author's email: Tizuagie@noun.edu.ng

ABSTRACT

Water pollution remains a serious challenge in Nigeria and other low-resource regions, where industrial effluents, agricultural runoff, hydrocarbons, and emerging contaminants continue to endanger ecosystems and public health. Conventional treatment technologies, though effective, are often costly, energy-intensive, and unsuitable for decentralised or rural deployment. This review explores the rising potential of locally sourced biocomposites as sustainable, low-cost, and multifunctional materials for water purification. Synthesising advances from 2020–2025, it evaluates biomass feedstocks, green-chemistry synthesis routes, hybrid composite design, contaminant-removal mechanisms, and emerging applications relevant to Nigeria. Evidence shows that biocomposites produced from agricultural residues, forestry waste, and marine biomass, such as rice husk, cassava peels, sawdust, and chitosan, exhibit strong performance in removing metals, dyes, pharmaceuticals, hydrocarbons, and pathogens *via* adsorption, ion exchange, redox reactions, photocatalysis, and antimicrobial activity. Innovations in nano-engineering, MOF–biopolymer hybrids, and clay-reinforced systems have enhanced sorption capacity, selectivity, reusability, and catalytic efficiency, in many cases rivalling commercial activated carbon. The review also identifies socio-economic benefits, including waste valorisation, local fabrication, and support for circular-economy initiatives. Despite encouraging laboratory results, challenges remain in material stability, scale-up, standardisation, lifecycle assessment, and infrastructural limitations. Nonetheless, Nigeria's biomass abundance and decentralised water-treatment needs position biocomposites as a promising route to expand clean-water access.

Keywords: Biocomposites, Sustainable Water treatment, Locally-derived, Biomass valorisation, Adsorption.

1.0 INTRODUCTION

Water pollution and ecosystem degradation have intensified worldwide due to rapid industrialisation, urban growth, intensive agriculture and the rising presence of persistent contaminants. Chemicals, microbes, pharmaceuticals and microplastics frequently co-occur, posing major risks to aquatic ecosystems and human health and slowing progress toward Sustainable Development Goal 6 on clean water and sanitation (Wang *et al.*, 2024). Conventional treatment systems such as coagulation–flocculation, activated sludge, membrane filtration and advanced oxidation, remain valuable but are capital-intensive, energy-demanding and often unsuitable for rural or decentralised settings, particularly where pollutant loads fluctuate widely and technical capacity is limited (Alkhaldi *et al.*, 2024).

A One Health perspective increasingly highlights water pollution as a multisectoral challenge connecting human, animal and environmental health (Wang *et al.*, 2024). Global access to safely managed water and sanitation remains insufficient, with many regions far from meeting the 2030 targets (Küfeoğlu, 2022). Sub-Saharan Africa faces the greatest disparities as population growth, climate variability and weak infrastructure heighten pressure on water systems. These gaps have accelerated research into

sustainable, decentralised treatment options using renewable materials such as biochars, polymeric adsorbents, metal-oxide hybrids and biopolymeric nanocomposites, which offer high sorption capacity, selectivity, regenerability and low production cost (Annu *et al.*, 2024; Alkhaldi *et al.*, 2024).

Nigeria reflects these global challenges acutely. Although basic water access has improved, safely managed drinking water remains very low, especially in rural and peri-urban communities (Sanitation & Water for All, 2022; UNICEF Nigeria, n.d.). Fewer than half of Nigerians have combined improved water and sanitation, and under 10 % benefit from safely managed services (Edefo, 2025). Industrial discharges from tanneries, textiles, refineries and agro-processing pollute rivers with heavy metals and organic contaminants (Ejiohuo *et al.*, 2025), while agricultural activities introduce nutrient and pesticide runoff. In the Niger Delta, decades of oil spills and artisanal refining have caused chronic hydrocarbon and metal contamination (Eili et al., 2025). Climate-related droughts and floods further compromise water quality and infrastructure (Sanitation & Water for All, 2022), deepening urban–rural inequalities (Nigeria Health Watch, 2023).

Locally derived biocomposites offer a promising pathway for Nigeria's decentralised water treatment needs. Agricultural residues such as rice husk and sugarcane bagasse can be transformed into activated carbons and biochars effective for multi-metal removal (Waziri & Mustapha, 2024). Advances in lignin–chitosan hybrids, biopolymeric nanocomposites and other bio-derived adsorbents also demonstrate strong performance in removing metals, dyes, pathogens and emerging contaminants (Annu *et al.*, 2024; Ben Khemis *et al.*, 2025). These align with circular-economy principles by converting abundant waste biomass into value-added treatment media (Zhou *et al.*, 2024). With Nigeria's rich clay, silica and laterite deposits, composite materials can be locally fabricated, reducing dependence on imported chemicals and creating economic opportunities.

This paper therefore reviews Nigeria-relevant biocomposite-based treatment technologies, synthesising design principles, recent advances (2020–2025), removal mechanisms and implementation pathways suited for rural and peri-urban deployment. It aims to inform researchers, policymakers and practitioners seeking affordable, sustainable and locally sourced water-purification solutions.

2.0 CONCEPTUAL BASIS OF BIOCOMPOSITES

Biocomposites are engineered materials in which at least one component, either the matrix or reinforcement, is sourced from renewable biological resources such as polysaccharides, proteins, lignocellulosic fibres or biochar. In water treatment, these materials are formed by integrating biopolymers or biochar with inorganic phases (e.g., metal oxides, clays, or metal–organic frameworks) to create high-surface-area, functional structures capable of adsorption, ion exchange, redox transformations and photocatalysis (Aaliya *et al.*, 2021; Ilyas *et al.*, 2022). Their composition enables multifunctional pollutant removal while supporting sustainability goals through renewable feedstocks. Figure 1 illustrates the relationship between common biomass feedstocks and their corresponding water-treatment applications.

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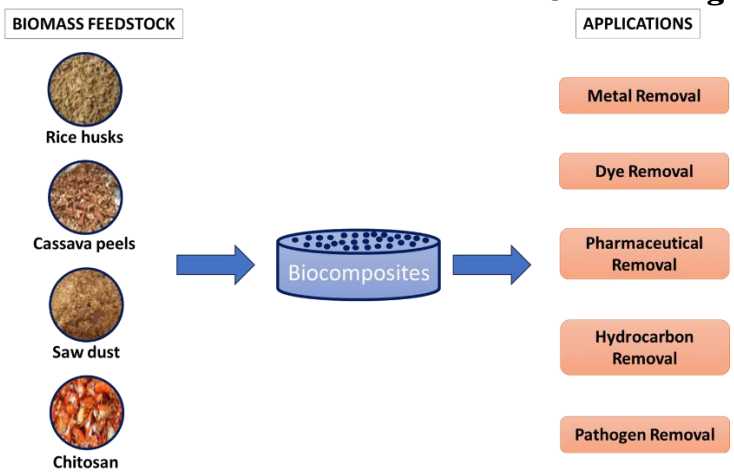

Figure 1. Biocomposite production pathway and water-treatment applications.

2.1 Types of Biocomposites

a) **Biopolymer–inorganic hybrids**: These combine natural polymers such as chitosan, alginate, cellulose and lignin with fillers like Fe_3O_4, TiO_2 or clays. Functional groups (–OH, $–NH_2$, –COOH) on the biopolymer enable metal binding and ion exchange, while the inorganic fraction enhances porosity, mechanical strength and catalytic capability (Alkhaldi *et al.*, 2024).

b) **Nano-engineered biocomposites, or bionanocomposites:** These incorporate nanoparticles (metal oxides, nanoclays, nanocarbons) into a biopolymer matrix. Their high interfacial area and tunable chemistry provide superior adsorption and selectivity, with increasing application in wastewater remediation (Ilyas *et al.*, 2022).

c) **Biochar-based composites:** These use pyrolysed biomass as a sorbent or support for metals, oxides or polymers. Engineered biochars exhibit strong affinity for metals, nutrients, dyes and pharmaceuticals, often achieving >90–98% removal efficiencies (Wang *et al.*, 2024; Yang *et al.*, 2025).

d) **MOF–biopolymer systems:** incorporate metal–organic frameworks within hydrogels or biopolymer membranes. The MOF phase provides ultrahigh surface area and catalytic activity, while the biopolymer enhances flexibility, processability and biocompatibility (Lal *et al.*, 2024).

Table 1. Representative types of biocomposites for water treatment

Type	Typical components	Dominant functions	Refs.
Biopolymer–inorganic hybrid	Chitosan/alginate + Fe_3O_4, TiO_2, clays	Adsorption, ion exchange, catalysis	Alkhaldi et al. (2024)
Nano-engineered biocomposite	Cellulose, starch + metal oxide NPs	High-capacity adsorption, antimicrobial	Ilyas et al. (2022)
Biochar-based composite	Biochar + metal oxides/polymers	Sorption, redox, persulfate activation	Wang et al. (2024); Yang et al. (2025)
MOF–biopolymer system	MOF + hydrogel/film	Size-selective adsorption, photocatalysis	Lal *et al.*, 2024

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2.2 Advantages over Conventional Materials

Biocomposites offer multiple advantages over synthetic polymers and purely inorganic sorbents:

i. **Biodegradability and renewability:** Derived from biomass, biopolymers such as cellulose, lignin and chitosan can degrade naturally, reducing environmental persistence (Aaliya et al., 2021; Ilyas et al., 2022).

ii. **Rich surface functionality:** Their hydroxyl, amino, carboxyl and phenolic groups enable metal chelation and interactions with organic pollutants; functionalisation or mineral loading enhances affinity and selectivity (Alkhaldi et al., 2024).

iii. **Lower toxicity and environmental footprint:** Life-cycle assessments show biochar and biopolymer composites often emit fewer greenhouse gases and pose lower ecotoxicity than synthetic resins, especially when derived from waste biomass (Wang *et al.*, 2024; Yang *et al.*, 2025).

iv. **Cost reduction via waste valorisation:** Using local residues such as agro-waste, crustacean shells. Thus, lowers feedstock costs and supports small-scale, community-level water treatment (Alkhaldi *et al.*, 2024).

2.3 Nigerian Context for Feedstocks

Nigeria's large agricultural, forestry and marine biomass streams provide abundant feedstocks for biocomposite fabrication. Millions of tonnes of rice husk, cassava peels, sugarcane bagasse and banana pseudo-stems are produced annually, representing significant material and energy potential (Giwa *et al.*, 2025). Some of these feedstocks as illustrated in Table 2 are:

i. **Agricultural residues** such as rice husk and sugarcane bagasse are rich in lignocellulose and silica, making them ideal precursors for activated carbon and biochar. These materials have demonstrated strong efficiency for heavy-metal removal in refinery effluents (Waziri & Mustapha, 2024).

ii. **Forestry wastes** including sawdust and wood offcuts serve as reinforcement fibres or biochar precursors, enhancing mechanical stability and porosity in water-treatment composites (Aaliya *et al.*, 2021; Yang *et al.*, 2025).

iii. **Marine-derived chitosan** from crustacean shells (shrimp, crab, prawn) is an excellent bioadsorbent. Nigerian-sourced chitosan exhibits high deacetylation and has been successfully applied for phenol removal and other contaminants (Ibrahim *et al.*, 2022).

iv. **Mineral resources**: clays, silica sands, laterites support clay–biochar and clay–polymer composites with improved adsorption of metals and dyes due to their ion-exchange capacity (Wang et al., 2024).

Table 2. Illustrative Nigerian-relevant feedstocks for biocomposites

Feedstock category	Nigerian sources	Application	Refs.
Agricultural residues	Rice husk, bagasse, cassava peels	Activated carbon/biochar for metal removal	Waziri & Mustapha (2024)
Forestry wastes	Sawmill dust	Biochar/reinforcement	Giwa *et al.* (2025)
Marine shells	Shrimp/crab/prawn shells	Chitosan adsorbents	Ibrahim *et al.* (2022)

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Minerals	Clays, silica sands	Clay–biochar or polymer hybrids	Wang *et al.* (2024)

Leveraging these feedstocks within well-designed biocomposites offers Nigeria a sustainable, low-cost pathway for producing water-treatment materials tailored to its diverse pollution challenges.

3.0 SYNTHESIS STRATEGIES FOR LOCALLY DERIVED BIOCOMPOSITES

The synthesis of biocomposites from locally available biomass integrates biomass pre-treatment, composite fabrication and green-chemistry principles. Each stage – drying, milling, chemical pre-treatment, activation and hybridisation with minerals, metal oxides or MOFs, critically influences the resulting surface area, porosity, functional groups and overall water-treatment efficiency (Yaashikaa et al., 2020; Chew *et al.*, 2023).

3.1 Pre-treatment and Processing of Biomass

Biomass pre-treatment determines the suitability of precursors for biochar, activated carbon or biopolymer-based composites (See Table 3). Typical steps include drying (sun, oven or solar), followed by mechanical size reduction such as chopping, milling or grinding, and occasionally pelletisation or briquetting to improve heat transfer and handling (Munzeiwa *et al.*, 2025; Venegas-Vásconez *et al.*, 2025). Mechanical processing improves surface area and reduces crystallinity, thereby enhancing devolatilisation and reactivity during pyrolysis (Yaashikaa *et al.*, 2020).

Slow pyrolysis (350–700 °C) remains the dominant route for transforming biomass into biochar. Operating conditions of temperature, heating rate, residence time, govern aromaticity, pore structure and oxygen-containing surface groups. Higher temperatures typically produce more aromatic, microporous biochars suitable for adsorption (Suresh Babu *et al.*, 2024; Munzeiwa *et al.*, 2025). Acid or alkali pre-treatments (H_3PO_4, H_2SO_4, KOH, NaOH) can be applied before or during pyrolysis to enhance pore formation, introduce mineral templates or increase oxygenated functional groups (Ouyang *et al.*, 2023; Gao *et al.*, 2025).

Table 3. Effects of common biomass pre-treatments on biochar/composite properties

Pre-treatment step	Typical conditions	Main effects	Refs.
Drying & size reduction	60–105 °C; grinding/milling	Improved heat transfer, uniform pyrolysis	Yaashikaa *et al.* (2020)
Slow pyrolysis	350–700 °C, 0.5–2 h	Controls aromaticity, pore structure	Suresh Babu *et al.* (2024)
Alkali pre-treatment (KOH)	Impregnation → carbonisation	Higher porosity, increased basic sites	Jedynak *et al.* (2024); Nandi *et al.* (2023)
Acid pre-treatment (H_3PO_4)	Impregnation before pyrolysis	Mesoporosity, P–O/C–O groups	Ouyang *et al.* (2023); Chew *et al.* (2023)

3.2 Fabrication of Hybrid Composites

(a). Biopolymer–metal oxide hybrids

These hybrids (e.g., chitosan/Fe_3O_4, cellulose/CuO, starch/ZnO) are commonly synthesised through co-precipitation, sol–gel or *in-situ* growth methods. In chitosan/Fe_3O_4 systems, Fe^{2+}/Fe^{3+} salts precipitate in alkaline media, forming magnetite

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nanocrystals within the polymer network, enabling magnetic separability and high affinity for metals and dyes (Harimu *et al.*, 2022; Vo *et al.*, 2024). Variants such as chitosan–Fe_3O_4–SiO_2 carbonised composites efficiently remove mixed metal contaminants (Ali *et al.*, 2024). Sol–gel and hydrothermal methods similarly produce well-dispersed metal oxide nanoparticles anchored on polymer functional groups, enhancing adsorption and photocatalytic performance (Suresh *et al.*, 2022; Taha *et al.*, 2025).

(b). Biochar and activated carbon composites

Biochar can be used directly or activated physically (steam/CO_2, 700–900 °C) or chemically (H_3PO_4, KOH, $ZnCl_2$, NaOH), often achieving >1000 $m^2\ g^{-1}$ surface area and tunable micro/mesoporosity (Chew *et al.*, 2023; Hai *et al.*, 2025). H_3PO_4-activated biochars from agricultural residues show high recyclability, while KOH activation yields highly microporous carbons ideal for metal and dye removal (Ouyang *et al.*, 2023; Nandi *et al.*, 2023). Biochar can also be hybridised with Fe_3O_4, MnO_2 or clays to improve redox activity or cation-exchange capacity, supporting multi-contaminant removal systems.

(c). Clay and mineral hybrid systems

Clay–biopolymer composites are produced through intercalation, pillaring or polymer coating. Bentonite–biopolymer beads (chitosan, alginate, cellulose) formed via droplet gelation exhibit high metal uptake and mechanical stability (Essa *et al.*, 2024). Cellulose–bentonite films fabricated by solution casting also show strong adsorption of multiple pollutants (Shahzadi *et al.*, 2025). Functionalised bentonite hybrids (Fe-pillared bentonite, MgO/bentonite, GO–chitosan–bentonite) provide enhanced removal through combined cation exchange, complexation and surface precipitation (Vo *et al.*, 2024).

(d). MOF–biopolymer hybrids

These materials are synthesised either by in-situ MOF growth within hydrogels or by mixing pre-formed MOFs with polymer matrices. In-situ-grown MOF/hydrogel composites demonstrate high adsorption of antibiotics and dyes with excellent recyclability (Kaur *et al.*, 2023; Singh *et al.*, 2024). Recent studies report multifunctional pectin/chitosan Mo-MOF hydrogels capable of dye adsorption and antibacterial activity (Ghnim *et al.*, 2025). Reviews highlight one-pot gelation, stepwise loading and 3D printing as versatile fabrication approaches that enhance mechanical strength and porosity (Lim *et al.*, 2023; Dong *et al.*, 2024).

3.3 Green Chemistry Considerations

Modern synthesis strategies increasingly adopt:

i. **Low-energy methods** such as microwave pyrolysis and hydrothermal synthesis (Suresh Babu *et al.*, 2024; Venegas-Vásconez *et al.*, 2025).
ii. **Benign solvents** and moderate reaction conditions for green nanoparticle synthesis (Aigbe et al., 2024).
iii. **Plant-mediated nanoparticle routes**, using phytochemicals to reduce/cap metal oxides with minimal waste (Dheyab *et al.*, 2024; El-Seedi *et al.*, 2024; Balasubramani *et al.*, 2025).
iv. **Waste valorisation**, using food and agricultural residues as carbon/polymer sources to reduce lifecycle impacts (Chew *et al.*, 2023).

Together, these approaches integrate circular-economy principles while producing high-performance biocomposites tailored for water purification.

4.0 MECHANISMS OF WATER CONTAMINANT REMOVAL

Biocomposites remove pollutants through a combination of surface adsorption, ion exchange, redox and advanced oxidation processes, photocatalysis and microbial interactions. In most systems, these mechanisms act concurrently, with their

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relative importance governed by surface chemistry, porosity, solution pH/ionic strength and contaminant speciation (Wang *et al.*, 2024).

4.1 Adsorption Mechanisms

(a). Physisorption, chemisorption and ion exchange. Adsorption on biochar and biocomposites as illustrated in Table 4 involves physisorption (van der Waals forces and pore filling), chemisorption (surface complexation and inner-sphere bonding) and ion exchange between surface functional groups and dissolved ions (Akhtar, 2025). Physisorption is often described by Freundlich-type multilayer behaviour, whereas chemisorption commonly fits Langmuir isotherms and pseudo-second-order kinetics (Dong *et al.*, 2024). Ion exchange dominates for metal cations and ammonium interacting with deprotonated carboxylates, sulfonates and clay layers (Kumkum and Kumar, 2024).

(b). Role of functional groups. Hydroxyl, carboxyl and amino groups on biochar, cellulose, chitosan and lignin provide electron-donating and hydrogen-bonding sites, enabling complexation with metals and π–π/hydrophobic interactions with organics (Dong *et al.*, 2024). P- and N-functionalities introduced during activation enhance electrostatic attraction and favour surface precipitation of metal (hydr)oxides (Sireesha *et al*., 2025). Nature For example, P-modified cocopeat biochar removed Cr(VI) via concurrent surface complexation, ion exchange, electrostatic attraction and precipitation (Sireesha *et al.*, 2025).

Table 4. Dominant mechanisms in adsorption-based removal

Mechanism	Key interactions	Typical materials	Main targets	Refs.
Physisorption	van der Waals, pore filling	High-surface-area biochar, AC	Dyes, pharmaceuticals	Akhtar, 2025
Chemisorption	Surface complexation, covalent/coordination bonding	Functionalised biochar, chitosan hybrids	Heavy metals, oxyanions	Dong *et al.*, 2024
Ion exchange	Exchange with –COO^-, –SO_3^-, clay interlayers	Biochar–clay, bentonite–biopolymer beads	Metal cations, NH_4^+	Kumkum & Kumar, 2024

4.2 Catalytic and Advanced Oxidation Processes

Biocomposites containing Fe, Mn, Cu or catalytically active carbons can activate oxidants (H_2O_2, persulfate, peroxymonosulfate) to generate •OH and SO_4•$^-$. Fenton and Fenton-like systems use Fe(II)/Fe(III) cycling, while heterogeneous catalysts such as Fe–biochar or Fe_3O_4–clay immobilise iron, easing separation and reuse (Hübner & Von Gunten, 2024). Biochar-based catalysts activate persulfate via graphitic sites, defects and N/S/P doping, which tune redox behaviour (Jazić *et al.*, 2024). Fe/Fe_2O_3-loaded biochar, for example, degrades dyes through combined adsorption, radical oxidation and iron redox cycling (Chen *et al.*, 2022). Such multifunctionality is attractive for decentralised systems, as it both concentrates and destroys contaminants with less sludge than pure adsorption.

4.3 Photocatalysis

(a). Light-driven degradation of organics. Photocatalytic biocomposites integrate semiconductors (TiO_2, ZnO, g-C_3N_4, ferrites, CeO_2) that generate electron–hole pairs

under UV/visible light. Electrons reduce O_2 to ROS ($\bullet O_2^-$, •OH), while holes oxidise water and organics, leading to mineralisation of dyes, pharmaceuticals and endocrine disruptors (Majeed *et al.*, 2025). TiO_2-based nanocomposites routinely achieve >80–90% degradation of methylene blue, rhodamine B and phenol over repeated cycles (Abukhanafer *et al*., 2025).

(b). Semiconductor–biopolymer interactions: Biopolymers (chitosan, cellulose, polyaniline, polypyrrole) act as supports, binders or co-catalysts, improving nanoparticle dispersion and adding adsorption sites. They can also facilitate charge transfer and suppress electron–hole recombination (Enesca & Andronic, 2022). Hybrid systems with rGO, carbon dots or biochar broaden light absorption and enhance photocatalytic efficiency relative to bare semiconductors (Majeed *et al.*, 2025).

4.4 Microbial and Biological Interactions

Metal and metal-oxide nanocomposites (Ag, CuO, ZnO, TiO_2) embedded in biopolymers or biochar provide antimicrobial properties in addition to adsorption and photocatalysis. Their action involves ROS generation, membrane disruption, and damage to proteins and DNA (Yusuf *et al.*, 2021). Layered and supported nanomaterials can inactivate bacteria, viruses and fungi while minimising nanoparticle release (Yusuf *et al.*, 2021). Green-synthesised CuO, Ag and bimetallic nanoparticles from plant extracts (including neem) show strong antimicrobial activity in hospital and municipal wastewater (Kumar *et al.*, 2022). However, concerns about ecotoxicity and resistance, especially from free nanoparticles, support immobilisation within stable biocomposites (Ngoepe *et al.*, 2025).

4.5 Case Studies from Nigeria and the Global South

i. **Cassava-based adsorbents.** Cassava peels and residues have been used as modified adsorbents for metals and dyes, achieving high removal when activated or functionalised (Gajendiran *et al.,* 2023). In Nigeria, cassava peel sorbents removed Ni, Pb, Cr and Zn from leachate with efficiencies up to ~83% (Okovido et al., 2024), and column systems with immobilised peels effectively treated Cu, Cd, Zn and Ni (Simate, & Ndlovu, 2014).

ii. **Neem-based biocomposites.** Neem biomass–derived biochars and biosorbents remove Cr(VI) and dyes via complexation, ion exchange and redox processes (Thangagiri *et al.*, 2022). Activated neem fruit/leaf adsorbents show favourable kinetics for Cr(VI) and dyes, while neem-mediated metal-oxide nanoparticles combine adsorption with antimicrobial activity (Hamadneh *et al.*, 2025).

iii. **Bagasse-derived silica and biochar composites.** Sugarcane bagasse and ash have been used to produce silica nanoparticles, activated carbons and cellulose–chitosan composites for heavy-metal and dye removal in Latin America, Asia and Africa (Nimah *et al.*, 2023). Bagasse-derived carbons and biopolymer composites show promising capacities and regenerability for Pb(II) and multi-metal systems (Muhammad *et al.*, 2020).

Collectively, these examples highlight how locally sourced biocomposites in Nigeria and the wider Global South can integrate adsorption, redox, photocatalytic and antimicrobial mechanisms within a single material platform, enabling multi-contaminant control under circular-economy and low-cost constraints.

5.0 PERFORMANCE EVALUATION OF LOCALLY DERIVED BIOCOMPOSITES

Performance evaluation centres on the range of contaminants removed, efficiency relative to conventional materials and stability across multiple regeneration cycles. Recent assessments show that well-engineered biochar-based and polymeric biocomposites can equal or exceed the performance of commercial activated carbon (AC) and

synthetic resins – particularly when nanostructuring, mineral hybridisation and targeted functionalisation are applied (Alkhaldi *et al.*, 2024; Wang *et al.*, 2024).

5.1 Key Water Pollutants Addressed

Locally sourced biocomposites have been tested against a wide spectrum of contaminants:

i. **Heavy metals (Pb, Cu, Zn, Cd, Ni, Cr(VI))**: Biochars from cassava peel, rice husk and sugarcane bagasse (and their chitosan or clay hybrids) show strong capacities via complexation, ion exchange and surface precipitation (Wang *et al.*, 2024). Phosphorus-modified cocopeat biochar exhibited markedly enhanced Cu(II) and Ni(II) adsorption compared with unmodified versions (Sireesha *et al.*, 2025).
ii. **Synthetic dyes and industrial organics:** Chitosan/Fe_3O_4, cellulose/TiO_2 and similar hybrids achieve >90% colour removal through combined adsorption and photocatalytic degradation (Alkhaldi *et al.*, 2024; Majeed *et al.*, 2025).
iii. **Pharmaceuticals and pesticides:** Activated biochars and polymeric adsorbents enriched in aromatic or N/O groups interact strongly with antibiotics, NSAIDs and pesticides through π–π stacking and hydrogen bonding, often removing >80–90% of target compounds (Dong *et al.*, 2024).
iv. **Hydrocarbons:** Bagasse- and peel-derived carbons have reduced COD and petroleum hydrocarbons in cassava-processing wastewater and refinery effluents to regulatory limits (Waziri & Mustapha, 2024).
v. **Pathogens:** Biocomposites bearing ZnO, CuO or Ag nanoparticles provide simultaneous adsorption and disinfection through ROS production and membrane disruption (Alkhaldi *et al.*, 2024).

5.2 Analytical Techniques

Performance evaluation integrates a suite of analytical tools:

i. FTIR for identifying surface functional groups and confirming bonding changes (Dong *et al.*, 2024).
ii. XRD to determine crystalline phases such as Fe_3O_4, ZnO, TiO_2, silica and clay minerals.
iii. SEM/EDX for assessing morphology and pore texture (Chew *et al.*, 2023).
iv. BET surface area analysis to link pore characteristics with adsorption capacity (Wang *et al.*, 2024).
v. TGA to evaluate thermal stability and organic/mineral composition.
vi. XPS for analysing oxidation states (e.g., Cr(VI) → Cr(III)) (Sireesha *et al.*, 2025).
vii. UV–Vis and ICP-OES/MS for quantifying dye, pharmaceutical and metal removal (Waziri & Mustapha, 2024).

These techniques provide essential correlation between structure, chemistry and observed performance.

5.3 Comparative Assessment

When compared with commercial AC and synthetic resins, locally derived biocomposites perform competitively:

i. **Adsorption capacity and kinetics**: Waste-derived ACs and engineered biochars routinely reach 150–400 mg g^{-1} for metals and dyes – matching commercial AC, while cassava-residue and modified cocopeat/chitosan composites achieve similar performance for Cr(VI), Cu(II) and Ni(II) (Chew *et al.*, 2023; Wang *et al.*, 2024).
ii. **Nanostructuring and hybridisation benefits:** Creating hierarchical micro–mesoporosity and integrating nano-Fe_3O_4 or nano-ZnO improves electron transfer, increases active-site density and enhances adsorption–catalytic synergy. Hybrid materials such as biochar–chitosan, biochar–clay, MOF–biopolymer, often outperform their single-component counterparts (Alkhaldi *et al.*, 2024).

iii. **Cost and sustainability:** Biomass-derived carbons have lower production costs and embodied energy than coal-based AC, especially when using milder activation or waste feedstocks (Chew et al., 2023).

Together, these findings indicate that local biocomposites provide high performance at lower environmental and financial cost.

5.4 Regeneration and Reusability

Operational sustainability depends on maintaining activity across repeated cycles:

i. Thermal regeneration (200–400 °C) restores pore structure but may slowly reduce functional groups (Yang *et al.*, 2025).
ii. Chemical regeneration with dilute acids or bases recovers 70–90% of capacity in chitosan and lignocellulosic composites after 4–6 cycles (Sireesha *et al.*, 2025).
iii. Solvent regeneration (ethanol, acetone) effectively restores hydrophobic-organic adsorption without degrading polymer matrices (Alkhaldi *et al.*, 2024).
iv. Self-regeneration through photocatalysis in TiO_2- and ZnO-based systems mineralises adsorbed organics under light, freeing active sites with minimal external chemicals (Majeed *et al.*, 2025).

Well-designed biocomposites generally retain 60–95% of initial performance over successive cycles, especially when reinforced with clays, silica or metal oxides to prevent collapse of the biopolymer network (Wang *et al.*, 2024).

6.0 CHALLENGES AND LIMITATIONS

Despite promising laboratory results, locally derived biocomposites face several technical, environmental and infrastructural barriers that must be addressed before they can be deployed at scale, especially in low-resource settings.

(a) Material Stability and Shelf-Life: Many biocomposites rely on hydrophilic biopolymers such as chitosan, starch and cellulose, which tend to swell, soften or lose mechanical integrity during prolonged water exposure, altering pore structure and adsorption performance (Amiri *et al.*, 2023). Their biodegradability (an environmental advantage) also makes them vulnerable to microbial and enzymatic attack, particularly in warm, nutrient-rich tropical waters (Yao *et al.,* 2024). Hybrid composites containing metal oxides, clays or MOFs pose additional risks: under acidic or high-ionic-strength conditions, partial dissolution of Fe, Zn, Cu or Al phases has been observed, raising concerns about secondary contamination (Damiri *et al.*, 2022). Improving crosslinking, encapsulation and employing accelerated ageing tests that reflect real water chemistries will be essential for ensuring long-term stability and low leaching.

(b). Scale-up and Standardization: Biomass variability remains one of the most significant obstacles to reproducible large-scale production. Agricultural residues vary by crop type, season and soil conditions, leading to biochars with inconsistent ash content, porosity and surface chemistry even under similar processing conditions (Wang *et al.*, 2024).

Recent reviews show that while lab-scale studies report strong removal efficiencies, field translation is hampered by inconsistent feedstock characterisation and poorly documented pyrolysis/activation parameters (Fang *et al.*, 2025). Establishing quality-control frameworks, minimum reporting standards and harmonised metrics (capacity, kinetics, leaching, regeneration) is therefore critical for enabling regulators, water utilities and designers to compare products and certify materials.

(c). Environmental and Toxicological Concerns: For nanostructured and metal-loaded biocomposites, environmental safety remains a major uncertainty. Concerns include nanoparticle release, chronic exposure to dissolved metals and unknown long-term ecotoxicological effects, especially in soils and sediments where spent sorbents may accumulate (Damiri *et al.*, 2022). Life-

cycle assessments (LCAs) of biocomposites remain limited and often emphasise removal performance rather than upstream and downstream impacts. Recent work shows that nanomaterial-based adsorbents can have high energy and material footprints, with insufficient evaluation of disposal, regeneration emissions or hazardous by-product formation (Ramadan et al., 2024). Similar gaps exist for biochar-based nanocomposites, calling for more comprehensive ecotoxicity testing before widespread adoption (Fang *et al.*, 2025).

(d). Infrastructural and Economic Barriers: Even when materials are technically sound, systemic constraints can limit deployment. Many utilities in low- and middle-income countries face chronic underinvestment, outdated infrastructure and institutional resistance to adopting new technologies (Ahmed *et al.*, 2023). Wastewater systems often suffer high rates of non-functionality due to limited O&M capacity, lack of spare parts and insufficient technical support (WaterAid, 2019). For biocomposites, the scarcity of pilot-scale facilities and advanced characterisation tools (e.g., XPS, BET, high-resolution microscopy) restricts optimisation and generation of regulatory-quality datasets. Although decentralised point-of-use systems can bypass some infrastructure limits, they still require reliable supply chains, user training and sustainable financing models (Sombei *et al.*, 2025). Addressing these systemic challenges is as crucial as improving material performance if locally derived biocomposites are to transition from promising prototypes to widely implemented water-treatment solutions.

7.0 SOCIO-ECONOMIC AND ENVIRONMENTAL IMPACT IN NIGERIA

Locally derived biocomposites offer substantial socio-economic and environmental benefits for Nigeria, particularly through their alignment with national priorities on waste management, rural water access, and sustainable industrial development. By converting abundant agricultural and marine residues into high-value water-treatment materials, these technologies transform environmental liabilities into productive resources, reducing waste burdens while promoting green livelihoods (Giwa *et al.*, 2025). Waste valorization pathways such as converting rice husk, cassava peels, coconut shells, sawdust, shrimp shells and sugarcane bagasse into biochar, chitosan or silica-based composites enable low-cost production and enhance resource efficiency in agro-based communities.

These innovations support circular-economy integration, advancing Sustainable Development Goals SDG 6 (Clean Water), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). By replacing imported chemicals with renewable, waste-derived materials, biocomposites lower carbon footprints, minimize chemical dependency and encourage sustainable production–consumption patterns (Wang *et al.*, 2024).

At the community level, biocomposites enable decentralized water treatment, from rural and peri-urban household filters to portable emergency-response systems for flood-affected areas. Their low cost, simplicity and compatibility with gravity-fed or batch systems make them particularly valuable in regions lacking piped water or reliable electricity (Sombei *et al.*, 2025). Evidence from several Nigerian pilot studies shows that biochar-based filtration units can reduce turbidity, metals and pathogens at the household scale while requiring minimal maintenance.

Moreover, widespread adoption can stimulate local job creation, especially in youth-led micro-enterprises that fabricate biochar, process chitosan, assemble filtration cartridges, or operate community-level treatment hubs. Biomass-rich states including Benue, Kogi, Ogun, Ondo, Delta and Akwa Ibom, stand to benefit from small-scale fabrication clusters linked to

agricultural cooperatives and local industries (Giwa *et al*., 2025). Such green enterprises enhance rural incomes, diversify livelihoods and strengthen Nigeria's growing bio-economy.

8. FUTURE RESEARCH DIRECTIONS

The path forward for locally derived biocomposites lies in evolving toward multifunctional, digitally optimized, and field-deployable water-treatment materials – especially relevant for Nigeria and similar settings.

(a). Advanced Hybrid Design: Hybrid materials that combine biopolymers with inorganic/Nanomaterials. For example, metal-organic frameworks (MOFs) embedded in biopolymer matrices show high promise for multi-contaminant removal (Singh *et al*., 2024).

(b). Smart and Responsive Biocomposites: Stimuli-responsive biocomposites (e.g., magnetic retrieval, pH-sensitivity, light-activated regeneration) are an emerging priority. Reviews highlight polymer-nanomaterial composites showing enhanced separation and reusability (Balcerak-Woźniak *et al.*, 2024).

(c). Digital Design and AI-Driven Optimisation: Machine learning and digital modelling are becoming critical for predicting performance, optimising feedstock processing, activation conditions and composite design. For instance, a comprehensive review shows how sustainable polymeric adsorbents can benefit from data-driven design (Alkhaldi *et al.*, 2024).

(d). Integration into Decentralised Water Treatment Systems: For Nigeria and other low-resource regions, integrating biocomposites into point-of-use filters, mobile treatment units, or community systems is key for real-world impact. A recent review of bio-based adsorbents shows promise for low-cost, decentralized water treatment (Vara *et al.*, 2024).

9.0 CONCLUSION

Locally derived biocomposites represent a rapidly evolving class of materials with significant potential to address the persistent challenges of water pollution, environmental degradation, and limited treatment infrastructure in developing regions. This review highlights how diverse biomass resources including agricultural residues, forestry wastes, and marine-derived materials, can be transformed into high-performance adsorbents, catalysts, and multifunctional hybrids capable of removing heavy metals, dyes, pharmaceuticals, pesticides, hydrocarbons, and microbial contaminants. Advances in hybrid design, nanostructuring, surface functionalisation, and green synthesis have further enhanced efficiency, selectivity, and regeneration capacity, allowing biocomposites to rival or surpass conventional activated carbon and synthetic resins in many applications.

For developing contexts, biocomposites offer an inherently sustainable and accessible solution, grounded in low-cost feedstocks, reduced chemical dependency, and lower environmental footprints. Their compatibility with decentralised, point-of-use and community-scale systems positions them as practical options for rural and peri-urban areas where centralised water infrastructure is weak or absent. Importantly, biocomposites align with global sustainability goals by promoting waste valorisation, encouraging climate-friendly production systems, and fostering improved water security.

Nigeria holds a unique strategic advantage in this landscape due to its abundant biomass resources (cassava peels, rice husk, bagasse, sawdust, coconut shells, and crustacean shells) alongside rich mineral deposits suitable for composite fabrication. Coupling these resources with a growing emphasis on circular-economy approaches provides a strong foundation for local

material innovation, job creation, and sustainable water-treatment industries. With continued research, investment in pilot-scale facilities, and supportive policy frameworks, Nigeria can become a regional leader in developing and deploying biocomposite-based technologies that support clean water access, environmental protection, and socio-economic resilience.

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