Nanocomposite from Waste for Environmental Remediation based on Sustainable Circular Economy

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ABSTRACT

The waste-derived nan composites have emerged as promising materials for the removal, immobilisation and degradation of pollutants in water, soil and industrial effluents. These materials can be synthesised from agricultural residues, food waste, biomass, industrial by-products and other suitable waste streams through processes such as pyrolysis, hydrothermal treatment, green synthesis and surface modification. Their Nano scale functional components, combined with porous carbonaceous or mineral supports, can improve adsorption, catalytic activity, and selectivity and material recovery. This article examines the relationship between circular economy principles and waste-derived nanocomposites, discusses their synthesis, mechanisms and environmental applications, and evaluates their potential benefits and limitations. Particular attention is given to resource recovery, material regeneration, life-cycle assessment, nanomaterial safety and opportunities for commercial deployment. The sustainable environmental remediation when waste selection, manufacturing efficiency, contaminant removal, material recovery and end-of-life management are considered together.

Keywords: Circular economy; waste valorisation; Nano composites; environmental remediation; biochar; wastewater treatment; sustainable materials; resource recovery.

1. INTRODUCTION

Conventional treatment techniques, including chemical precipitation, coagulation, filtration and biological treatment, are important components of environmental management. However, their effectiveness varies according to the type and concentration of contaminants. Some processes generate substantial quantities of sludge, require repeated chemical inputs or fail to completely remove emerging pollutants. Advanced oxidation, membrane separation and other specialised techniques can improve treatment performance but may involve high energy requirements, costly materials or additional waste-management challenges.

The circular economy provides a framework for addressing these limitations by maintaining materials and resources in productive use for as long as possible. Instead of treating waste solely as a disposal problem, circular approaches identify opportunities to recover valuable constituents and convert them into useful products. Waste-derived nanocomposites represent one such opportunity because selected waste materials can serve as carbon sources, mineral precursors, structural supports or functional components in advanced remediation materials. Nanocomposites combine two or more materials at the nanoscale or through nanoscale functional structures to obtain properties that differ from those of their individual components. In environmental applications, a porous waste-derived support may provide adsorption sites, while an incorporated metal oxide, mineral or carbon-based nanomaterial contributes catalytic activity, magnetic recovery or improved selectivity. The central proposition of this article is that waste-derived nanocomposites can connect waste management with environmental restoration. Nevertheless, their sustainability depends not simply on using waste as a raw material, but also on the energy and chemicals consumed during production, the toxicity of the final material, its regeneration potential and the safe management of contaminants after treatment.

2. CIRCULAR ECONOMY AND WASTE VALORISATION

2.1 Principles of the circular economy

The circular economy aims to minimise resource extraction, prevent unnecessary waste generation and retain the value of materials through reuse, repair, recycling and recovery. It differs from the conventional linear model of extraction, production, consumption and disposal by encouraging interconnected resource flows and the design of products and processes that reduce environmental burdens.

Waste valorisation is an important component of this approach. It involves converting discarded materials into products with economic or environmental value. Agricultural residues can become biochar, food-processing waste can provide carbon precursors, and selected industrial by-products can supply mineral constituents. When these resources are incorporated into remediation materials, waste management and pollution control can become mutually supportive activities.

2.2 Waste streams as raw materials

Several categories of waste offer potential precursors for nanocomposite production:

- **Agricultural residues:** Rice husk, rice straw, coconut shells, sugarcane bagasse and other crop residues can be converted into carbonaceous materials. Rice husk is particularly relevant because its mineral content can support the production of silica-containing materials.
- **Food-processing waste:** Fruit peels, vegetable residues and other organic by-products may provide carbon-rich precursors for biochar, activated carbon and carbon dots.
- **Forestry and biomass waste:** Wood residues, sawdust and other lignocellulosic materials can be processed into porous carbon supports with suitable surface functional groups.
- **Industrial by-products:** Selected mineral-rich residues and other industrial wastes may supply iron, silica, alumina or other useful constituents, provided hazardous impurities are adequately controlled.
- **Plastic waste:** Certain plastic waste streams can be considered for conversion into carbon-rich materials or other functional products. Such conversion requires careful control of emissions, additives, toxic by-products and energy consumption.

The conversion of these materials into nanocomposites can reduce dependence on virgin raw materials. Nevertheless, mixed municipal waste and contaminated industrial residues require stringent screening because hazardous constituents may be concentrated during processing.

3. SYNTHESIS AND CHARACTERISTICS OF WASTE-DERIVED NANOCOMPOSITES

3.1 Preparation methods

Waste-derived nanocomposites can be produced using several synthesis routes, depending on the precursor, target pollutant and intended application.

Pyrolysis and activation: Biomass is thermally treated under oxygen-limited conditions to produce biochar. Subsequent physical or chemical activation may increase porosity and improve the accessibility of adsorption sites. Surface modification or incorporation of functional nanoparticles can further improve performance. The use of activating agents and high processing temperatures, however, may increase environmental impacts.

Hydrothermal carbonisation: Wet biomass is processed under elevated temperature and pressure to produce hydrochar and related carbonaceous materials. This method can be useful for moisture-rich waste streams,

although the resulting material may require additional treatment to achieve the required porosity and surface chemistry.

Green synthesis: Waste-derived extracts or biological reducing agents may assist the formation of functional nanomaterials. This approach can reduce dependence on certain conventional chemical reagents, but the environmental advantages must be demonstrated for the complete production process.

In-situ deposition and surface modification: Functional materials such as iron oxides, titanium dioxide and other suitable mineral phases can be deposited onto waste-derived supports. This can combine adsorption with catalytic degradation or facilitate the recovery of the composite after treatment.

Carbon-dot synthesis: Selected biomass and food-processing residues can be converted into fluorescent carbon dots and related nanocomposites. Depending on their composition and surface functionalisation, these materials may be investigated for pollutant sensing, photocatalysis and other environmental applications (Soni et al., 2024).

3.2 Functional properties

The environmental performance of nanocomposites depends on their surface area, pore structure, functional groups, particle size, chemical stability and interaction with the target contaminant. A porous carbon support may facilitate the adsorption of organic compounds, while oxygen-containing groups can participate in the binding of metal ions. Magnetic components may enable separation using an external magnetic field, reducing the need for additional filtration.

The principal advantage of a composite material is the potential for multifunctionality. A single material may concentrate contaminants through adsorption and subsequently support their catalytic transformation. Nevertheless, these advantages must be verified under realistic treatment conditions rather than inferred from nanoscale properties alone.

4. APPLICATIONS IN ENVIRONMENTAL REMEDIATION

4.1 Wastewater treatment

Waste-derived Nano composites are particularly promising for treating industrial and municipal wastewater containing organic and inorganic pollutants. Their potential applications include the removal of dyes, selected pharmaceutical residues, pesticides and toxic metal ions. Biochar-based Nano composites can combine porous structures with reactive surface groups and catalytic components. Adsorption involves the accumulation of contaminants on a material's surface. Its efficiency depends on pH, temperature, contact time, pollutant concentration, competing ions and the characteristics of the adsorbent. For example, surface charge can influence the uptake of charged dyes and dissolved metal species. Therefore, laboratory results obtained with synthetic solutions should be validated using actual wastewater containing competing substances.

4.2 Heavy-metal remediation

Heavy metals such as lead, cadmium, chromium and arsenic can persist in environmental systems and pose risks when present in bioavailable forms. Waste-derived carbonaceous and mineral-based composites may remove or immobilise these contaminants through several mechanisms, including surface complexation, electrostatic attraction, ion exchange, precipitation and adsorption.

Iron-containing composites can be useful in certain applications involving arsenic and other contaminants, depending on the chemical form of the pollutant and the water chemistry. Similarly, functionalised biochar may improve the retention of selected dissolved metal ions.

An important distinction must be made between contaminant removal and contaminant destruction. Metals cannot be destroyed through conventional chemical degradation. When they are captured by a nanocomposite,

they remain within the spent material or another separated fraction. Sustainable remediation therefore requires safe regeneration, metal recovery or secure management of the contaminated residue.

4.3 Soil remediation

Contaminated soil presents additional challenges because pollutants interact with minerals, organic matter, microorganisms and soil water. Waste-derived Nano composites may be applied as amendments to immobilise selected contaminants or support their transformation. Biochar-based materials can alter soil pH, surface chemistry and contaminant mobility. Functionalised composites may enhance the retention of certain metals or interact with organic pollutants. However, immobilisation does not always eliminate long-term risk. Changes in soil acidity, oxidation-reduction conditions and moisture may remobilise previously retained contaminants. Before field application, assessment should include soil quality, plant uptake, microbial activity, leaching potential and the possible movement of nanoparticles. Remediation strategies must be tailored to the specific site rather than applied universally.

4.4 Air pollution and emerging applications

Selected waste-derived nanomaterial may also be investigated for the capture or catalytic conversion of gaseous pollutants and for use in filters and reactive surfaces. Their practical effectiveness depends on gas composition, humidity, operating temperature, pressure drop and material stability.

Emerging applications include pollutant sensing, recovery of valuable metals from wastewater and integrated systems that combine environmental treatment with energy-related functions. Waste-derived carbon materials may contribute to electrodes or other functional components, although their suitability depends on purity, conductivity, manufacturing requirements and lifecycle performance. These applications extend the circular economy concept beyond waste disposal by linking environmental remediation with resource recovery.

5. ENVIRONMENTAL AND ECONOMIC BENEFITS

The use of waste-derived Nano composites can offer several potential benefits.

First, it creates value from selected waste streams and may reduce the demand for virgin carbon and mineral resources. Second, local agricultural and food-processing residues can provide alternative feedstocks where collection and processing infrastructure are available. Third, multifunctional composites may integrate adsorption, catalytic transformation and material separation, potentially reducing the number of treatment stages required. Fourth, magnetic or otherwise recoverable materials may facilitate the separation and reuse of treatment media. Fifth, the recovery of metals or other valuable constituents from captured pollutants may create additional economic value. Finally, decentralised production and treatment systems could support waste management in locations where centralised infrastructure is limited.

6. CHALLENGES AND SUSTAINABILITY CONSIDERATIONS

6.1 Nanomaterial safety

The release of nanoparticles during manufacture, use, regeneration or disposal may create environmental and occupational risks. Their effects depend on chemical composition, particle characteristics, concentration, exposure duration and environmental transformation. Responsible development requires safe-by-design approaches, exposure controls and testing of Eco toxicity. The use of immobilised nanomaterial in composite structures may reduce their mobility, but it does not guarantee that release will not occur. Material stability should be tested under relevant pH, salinity, temperature and mechanical conditions.

6.2 Regeneration and secondary waste

Adsorption transfers contaminants from water or soil to the treatment material. The resulting spent composite must therefore be managed appropriately. Regeneration may permit reuse, but washing agents or thermal

treatment can produce concentrated contaminant streams or consume additional energy. Repeated use may also reduce adsorption capacity or cause the loss of active components.

A credible circular model must specify what happens after each treatment cycle. Recovery of valuable metals, controlled regeneration and secure disposal of unrecoverable hazardous residues should be considered during material design rather than after commercial deployment.

6.3 Standardisation and scale-up

Waste-derived materials can vary according to the composition of the feedstock, seasonal conditions, pretreatment and manufacturing parameters. Such variability may lead to inconsistent treatment performance. Standardised characterisation, batch-quality controls and reproducible synthesis methods are therefore necessary.

Pilot-scale studies should examine treatment throughput, hydraulic behaviour, fouling, regeneration requirements, material losses and cost per unit of contaminant removed. Evidence from controlled laboratory experiments is valuable, but it cannot independently establish long-term performance under industrial or field conditions.

6.4 Life-cycle assessment

Life-cycle assessment (LCA) provides a systematic method for comparing environmental impacts across a material's production, use and end-of-life stages. For waste-derived nanocomposites, relevant indicators include energy demand, greenhouse-gas emissions, water consumption, chemical use, toxicity, transportation and residual-waste generation .A fair comparison should use a clearly defined functional unit, such as the treatment of one cubic metre of wastewater to a specified quality or the removal of a defined mass of contaminant. It should also account for the environmental burdens associated with the original waste stream and the benefits of diverting it from disposal, using transparent and consistent assumptions.

7. FUTURE DIRECTIONS AND POLICY IMPLICATIONS

Future research should prioritise the development of low-energy synthesis methods, renewable process inputs and composites that can be efficiently recovered and reused. Researchers should move beyond single-pollutant experiments towards complex wastewater matrices and realistic soil conditions. Studies should also report degradation products, toxicity changes and the long-term stability of the materials. Digital tools, including machine learning, may help predict relationships between feedstock composition, synthesis conditions and remediation performance. However, reliable predictions require representative datasets, experimental validation and transparent reporting.

In India, locally available rice husk, coconut residues, sugarcane bagasse and other agricultural by-products offer potential feedstocks for regional research and production initiatives. Any proposed application should first establish the suitability of the waste, the safety of the resulting material, the availability of treatment infrastructure and the economics of collection and regeneration. The approach aligns with several Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Alignment with these goals is strongest when environmental benefits are demonstrated quantitatively and unintended impacts are controlled.

8. CONCLUSION

Waste-derived nanocomposites offer a promising pathway for integrating circular economy principles with environmental remediation. By converting suitable agricultural, food-processing, biomass and industrial residues into functional treatment materials, they can create opportunities for wastewater purification, heavy-metal removal, soil remediation and resource recovery. Their ability to combine porous supports with nanoscale functional components may improve adsorption, catalytic performance and material separation.

Ultimately, the transition towards a sustainable circular economy requires a systems-based approach in which waste prevention, resource recovery, pollution control and environmental safety are considered together. Waste-derived nanocomposites can contribute meaningfully to this transition when their production and application deliver measurable net environmental benefits.

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