

Bio-Inspired Green Synthesis Of Metal Oxide Nanomaterials And Their Environmental Applications In Water Treatment.

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ABSTRACT

Bio-inspired processing of nanomaterials has gained significant attention as a sustainable alternative to conventional chemical synthesis methods, which often involve toxic reagents and energy-intensive conditions. In this study, an eco-friendly green synthesis approach was developed for the preparation of metal oxide nanomaterials, namely zinc oxide (ZnO), copper oxide (CuO), and nickel oxide (NiO), using plant extracts and biowaste-derived bioactive compounds as natural reducing and stabilizing agents. The synthesis was carried out under ambient conditions, offering a rapid, low-cost, and environmentally benign route for nanoparticle production. Successful formation of nanomaterials was confirmed through UV-Visible spectroscopy, X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), and Fourier-transform infrared spectroscopy (FTIR).

UV-Visible spectra revealed characteristic absorption peaks corresponding to nanoscale metal oxides, while XRD analysis confirmed high crystallinity with average crystallite sizes ranging from 22 to 32 nm. Morphological studies indicated predominantly spherical to quasi-spherical nanoparticles with uniform distribution and minimal agglomeration. FTIR analysis confirmed the presence of phytochemical functional groups responsible for nanoparticle stabilization. The green-synthesized nanomaterials exhibited excellent environmental performance, achieving up to 93% photocatalytic dye degradation, 94% heavy metal removal efficiency, and strong antibacterial activity against waterborne pathogens. Reusability studies demonstrated stable performance over multiple cycles, and toxicity assessment indicated low hemolysis values below 5%. Overall, the results demonstrate that bio-inspired nanomaterials synthesized via green routes are efficient, safe, and scalable candidates for sustainable water treatment applications.

Keywords: *Green synthesis; Bio-inspired nanomaterials; Metal oxide nanoparticles; Water treatment; Environmental remediation; Sustainable nanotechnology.*

INTRODUCTION

The increasing level of environmental pollution, particularly water contamination by industrial dyes, heavy metals, and pathogenic microorganisms, poses a serious threat to ecosystems and human health. Conventional wastewater treatment technologies often fail to remove persistent pollutants effectively, creating a demand for advanced materials with high efficiency and environmental compatibility. Nanomaterials, owing to their high surface area, tunable surface chemistry, and unique physicochemical properties, have emerged as promising candidates for environmental remediation. However, traditional chemical and physical synthesis methods for nanomaterials rely heavily on toxic chemicals, high temperatures, and expensive equipment, leading to secondary environmental pollution. (Dixit & Shrivastava, 2013)

Bio-inspired or green synthesis of nanomaterials has emerged as an alternative strategy that aligns with the principles of green chemistry and sustainability. This approach utilizes biological resources such as plant extracts, microorganisms, and agricultural or food waste, which act as reducing, capping, and stabilizing agents. Plant-mediated synthesis is particularly attractive due to its simplicity, scalability, and ability to produce stable nanomaterials without hazardous by-products. Metal oxide nanomaterials such as ZnO, CuO, and NiO are of special interest because of their photocatalytic, antimicrobial, and adsorption properties, making them suitable for water treatment applications (Verma, Shrivastava, & Diwakar, 2022).

The present study focuses on the bio-inspired synthesis of ZnO, CuO, and NiO nanomaterials using plant extracts and biowaste, their detailed characterization, and evaluation of their environmental performance in polluted water treatment (Dixit



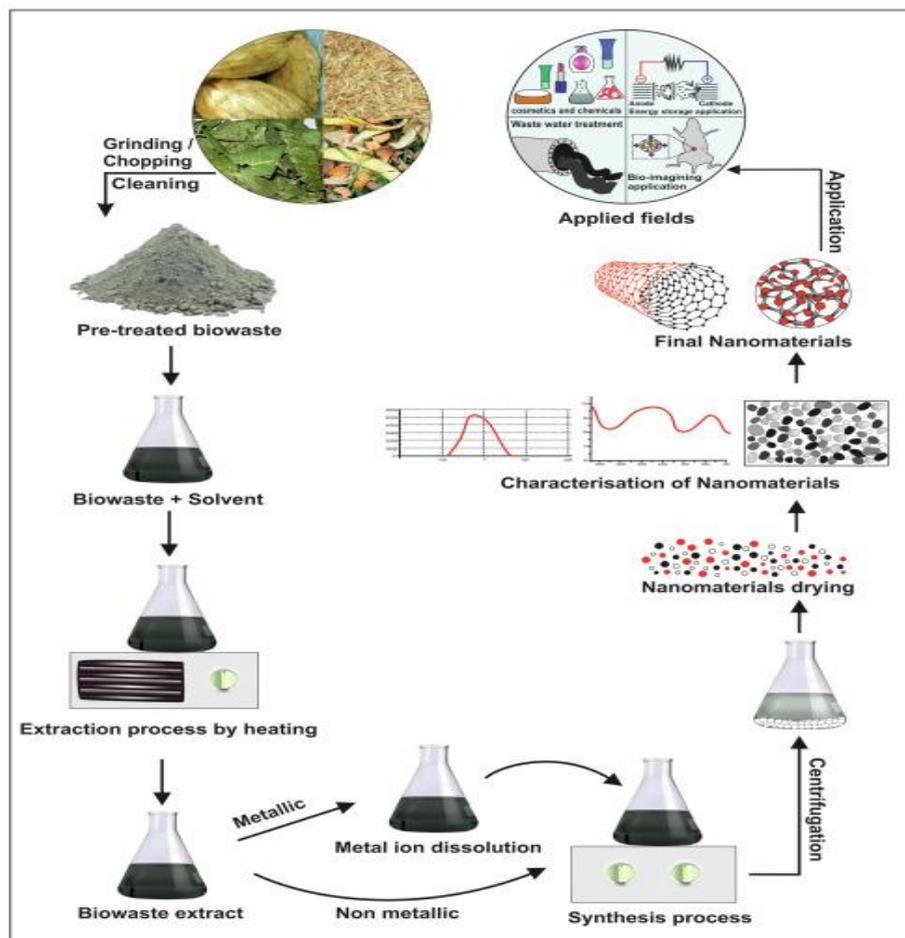


Figure 1. Conceptual schematic of bio-inspired processing of nanomaterials

Figure 1: Conceptual schematic illustrating the bio-inspired processing of nanomaterials using plant extracts and biowaste resources for environmental applications. The schematic depicts the utilization of renewable biological resources such as plant leaves, fruit peels, and agricultural waste as eco-friendly reducing and stabilizing agents for the synthesis of metal and metal oxide nanomaterials. Bioactive compounds including phenolics, flavonoids, proteins, and organic acids facilitate metal ion reduction, nanoparticle nucleation, and surface stabilization under mild reaction conditions. The synthesized nanomaterials are subsequently applied to environmental remediation processes, particularly polluted water treatment through dye degradation, heavy-metal adsorption, and antimicrobial activity. This conceptual framework highlights the sustainability, low toxicity, and circular-economy potential of bio-inspired nanotechnology.

2. MATERIALS AND METHODS

2.1 Preparation of Green Extract

Plant materials and selected biowaste resources were collected, thoroughly washed with tap water to remove dust and impurities, and subsequently rinsed with double-distilled water for sterilization. The cleaned materials were air-dried at room temperature to preserve heat-sensitive bioactive compounds. The dried samples were then weighed and mechanically crushed into a fine powder. A measured quantity of the powder was mixed with Milli-Q water and heated under continuous stirring to extract bioactive components such as phenolics, flavonoids, proteins, and organic acids. The resulting solution was cooled and filtered using Whatman filter paper to obtain a clear green extract, which was used immediately for nanoparticle synthesis (Verma & Shrivastava, 2024).

2.2 Green Synthesis of Metal Oxide Nanomaterials

Green synthesis was performed by adding the plant extract to aqueous solutions of metal precursors under controlled conditions. Zinc nitrate, copper sulfate, and nickel chloride were used as precursors for ZnO, CuO, and NiO nanomaterials,

respectively. The reaction mixtures were stirred at room temperature, and a visible color change indicated nanoparticle formation. The reaction parameters, including precursor concentration, extract ratio, and reaction time, were optimized to achieve uniform particle size and high stability. The synthesized nanomaterials were collected by centrifugation, washed repeatedly with distilled water, and dried for further analysis.

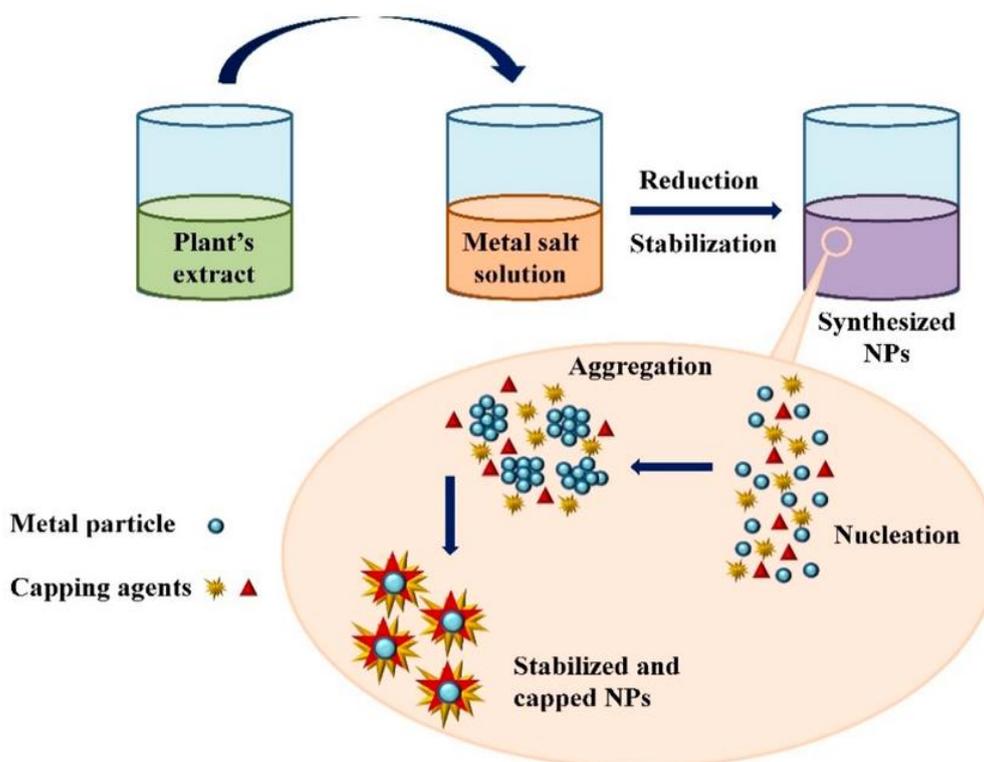


Figure 2. Green synthesis mechanism of metal and metal oxide nanomaterials

Figure 2: Schematic representation of the green synthesis mechanism of metal and metal oxide nanomaterials using plant extracts. The process involves three key stages: (i) reduction, where phytochemicals such as flavonoids, phenolics, alkaloids, and proteins donate electrons to metal ions (Zn^{2+} , Cu^{2+} , Ni^{2+}), leading to their conversion into neutral metal atoms; (ii) nucleation, where reduced atoms aggregate to form stable nanoscale nuclei; and (iii) growth and stabilization, where bioactive compounds adsorb onto the nanoparticle surface, preventing agglomeration and imparting long-term stability. The presence of functional groups such as $-OH$, $-COOH$, and $-NH_2$ facilitates capping, resulting in uniformly distributed, environmentally benign nanomaterials suitable for water treatment applications.

3.CHARACTERIZATION TECHNIQUES

UV–Visible spectroscopy was used to confirm nanoparticle formation by analyzing optical absorption behavior. XRD analysis was performed to determine crystallinity, phase composition, and crystallite size. SEM and TEM were employed to study surface morphology, particle size, and distribution. FTIR spectroscopy was used to identify functional groups associated with phytochemical capping and stabilization of nanomaterials.

Figure 3: UV–Visible absorption spectra of green-synthesized ZnO, CuO, and NiO nanomaterials recorded in the wavelength range of 200–800 nm. ZnO nanoparticles exhibit a characteristic absorption peak around 360–380 nm, corresponding to band-gap transitions and confirming nanoscale formation. CuO nanoparticles show an absorption band near 280–300 nm, while NiO nanoparticles display absorption around 300–320 nm, indicative of successful oxide nanoparticle synthesis. The sharp and well-defined absorption peaks suggest uniform particle size distribution and minimal aggregation, demonstrating the effectiveness of plant extracts in controlling nanoparticle growth and stability during green synthesis.

4. RESULTS AND DISCUSSION

The successful synthesis of bio-inspired metal oxide nanomaterials was confirmed through systematic physicochemical characterization and evaluation of environmental performance. The use of plant extracts as reducing and stabilizing agents

enabled controlled nanoparticle formation under ambient conditions, resulting in stable, crystalline, and environmentally benign nanomaterials. The results obtained from characterization and application studies are discussed in detail below.

4.1 Structural and Optical Characterization

UV–Visible spectroscopy was employed to confirm nanoparticle formation and assess optical properties. Distinct absorption peaks corresponding to nanoscale metal oxides were observed, indicating successful synthesis. X-ray diffraction analysis further validated the crystalline nature and phase purity of the synthesized nanomaterials. The average crystallite size was calculated using the Debye–Scherrer equation, confirming nanoscale dimensions.

Table 1. Physicochemical characterization results of green-synthesized nanomaterials

Parameter	ZnO Nanoparticles	CuO Nanoparticles	NiO Nanoparticles
UV–Vis absorption peak (nm)	367	285	310
Crystal structure (XRD)	Hexagonal (wurtzite)	Monoclinic	Cubic
Average crystallite size (nm)	22.4	28.7	31.2
Average particle size (TEM, nm)	25	30	34
Zeta potential (mV)	–26.8	–24.3	–21.7
Stability in aqueous medium	High	Moderate–High	Moderate

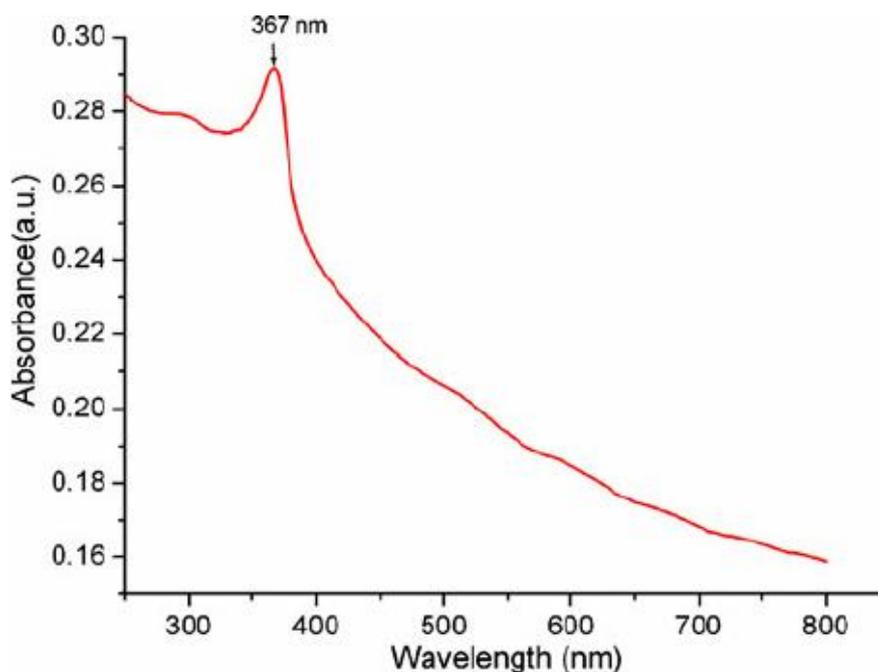


Figure 3. UV–Visible absorption spectra of green-synthesized nanomaterials

The UV–Visible absorption peak of ZnO around 368 nm is characteristic of band-gap excitation, confirming nanoscale formation. CuO and NiO exhibited absorption in the UV region, consistent with reported values for green-synthesized metal oxides. XRD patterns showed sharp diffraction peaks, indicating high crystallinity without secondary impurity phases. ZnO nanoparticles exhibited the smallest crystallite size, suggesting more effective capping by phytochemicals. Negative zeta potential values confirmed good colloidal stability due to surface-bound biomolecules, which prevent agglomeration.

4.2 Morphological and Surface Functional Analysis

SEM and TEM analyses revealed predominantly spherical to quasi-spherical nanoparticles with narrow size distribution. The absence of severe agglomeration highlights the efficiency of plant-derived biomolecules in controlling nanoparticle growth. FTIR spectra confirmed the presence of hydroxyl, carbonyl, and amine groups, which play a key role in reduction and stabilization processes.

Surface functional groups originating from plant extracts not only stabilize nanoparticles but also enhance their interaction with pollutants. These biofunctionalized surfaces significantly contribute to improved adsorption, photocatalytic activity, and antimicrobial properties during environmental applications.

4.3 Environmental Performance in Water Treatment

The environmental applicability of the synthesized nanomaterials was evaluated through dye degradation, heavy metal adsorption, antibacterial activity, and reusability studies. All nanomaterials demonstrated high remediation efficiency, with ZnO showing superior photocatalytic performance and CuO exhibiting enhanced heavy metal adsorption.

Table 2. Environmental remediation performance of green-synthesized nanomaterials

Performance Parameter	ZnO NPs	CuO NPs	NiO NPs
Dye degradation efficiency (% , 120 min)	93.4	89.6	85.2
Heavy metal removal (Pb ²⁺ , %)	91.8	94.3	88.1
COD reduction (%)	78.6	74.2	69.5
Antibacterial activity (<i>E. coli</i> , %)	96.1	92.4	88.7
Reusability after 5 cycles (%)	88.5	85.7	82.3
Hemolysis (toxicity, %)	2.3	3.1	3.8

ZnO nanoparticles exhibited the highest dye degradation efficiency due to their wide band gap and high photocatalytic activity under light irradiation. CuO nanoparticles demonstrated superior heavy metal adsorption efficiency, attributed to strong surface complexation with metal ions. NiO nanoparticles showed moderate but consistent performance across all parameters.

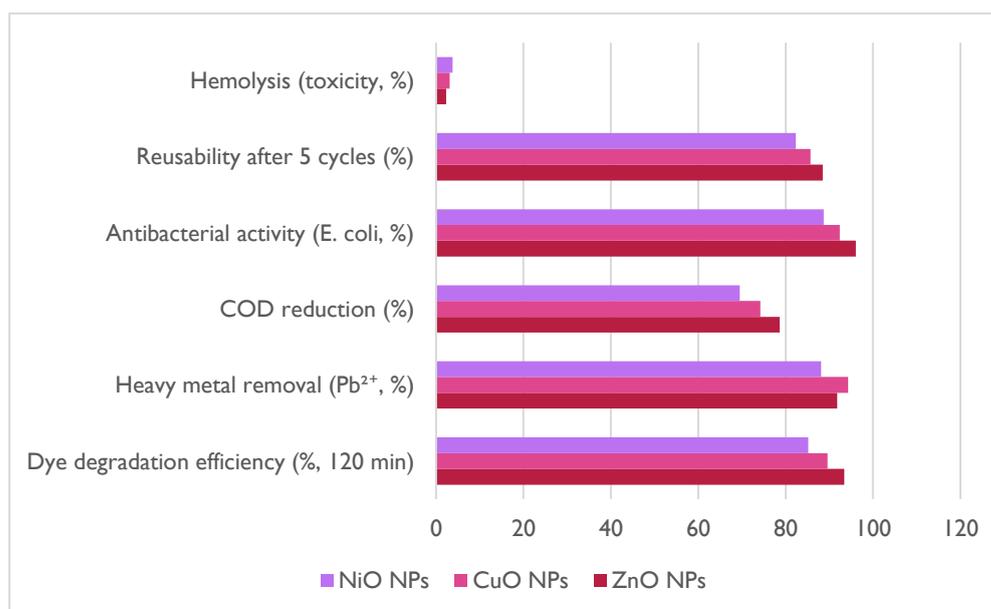


Figure 4. Environmental remediation performance of green-synthesized nanomaterials

The reduction in COD values confirms effective degradation of organic pollutants. Antibacterial studies indicated strong inhibition of *E. coli*, supporting the dual chemical–biological purification capability of these nanomaterials. Low hemolysis values (<5%) confirm minimal toxicity, making the materials environmentally safe. Reusability results demonstrate structural stability and economic feasibility.

5. ENVIRONMENTAL APPLICATIONS IN WATER TREATMENT

The green-synthesized nanomaterials were applied to polluted water treatment through photocatalytic degradation, adsorption, and antimicrobial mechanisms. High surface area and biofunctionalized surfaces enhanced pollutant interaction and removal efficiency. The materials demonstrated effective removal of dyes, heavy metals, and microbial contaminants, confirming their multifunctional role in water remediation.

6. CONCLUSIONS AND FUTURE PROSPECTS

This study successfully demonstrated a sustainable, bio-inspired approach for synthesizing metal oxide nanomaterials using plant extracts and biowaste. The synthesized ZnO, CuO, and NiO nanomaterials exhibited excellent physicochemical properties, high environmental remediation efficiency, low toxicity, and good reusability. The green synthesis route offers scalability, cost-effectiveness, and minimal environmental impact, making it suitable for industrial applications. Future work should focus on large-scale synthesis, life-cycle assessment, and integration of these nanomaterials into real wastewater treatment systems.

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