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GREEN SYNTHESIS OF METAL OXIDE NANOPARTICLES AND THEIR CATALYTIC PERFORMANCE IN WATER ENVIRONMENTAL REMEDIATION

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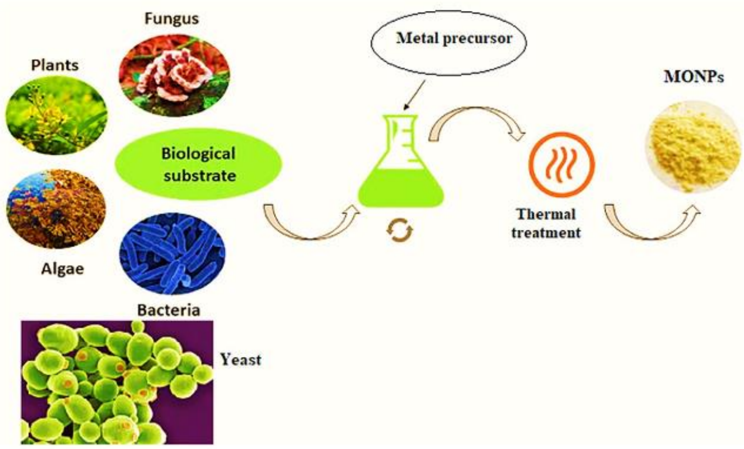
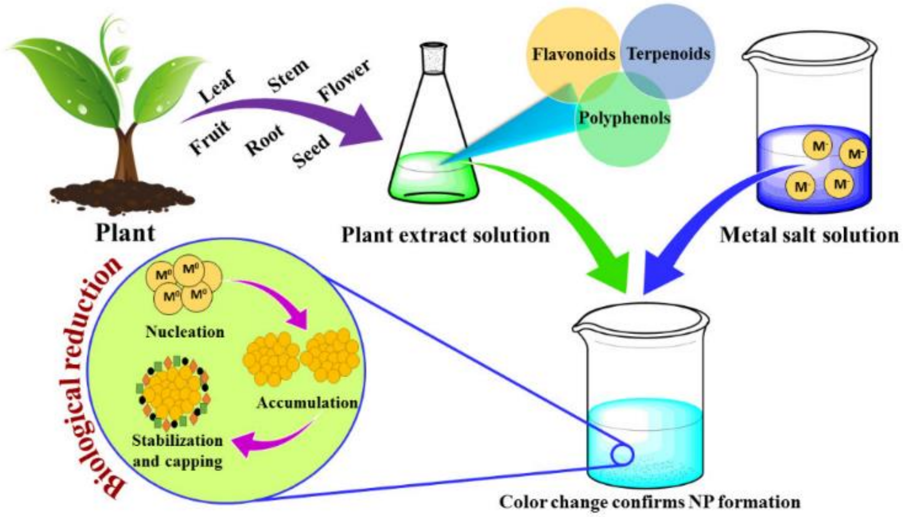
Abstract
Background: *Synthetic dyes in industrial wastewater cause significant ecological pollution, and conventional remediation methods are often inefficient and unsustainable. Green nanotechnology offers an eco-friendly alternative for pollutant removal.*
Aim: *This study focuses on the green synthesis of zinc oxide (ZnO) and iron oxide (Fe_2O_3) nanoparticles using leaf extracts from Azadirachta indica and Moringa oleifera, characterizing their physicochemical properties, and evaluating their catalytic efficiency in degrading methylene blue dye from aqueous solutions.*
Method: *Nanoparticles were synthesized using aqueous leaf extracts as reducing and stabilizing agents. Characterization techniques included FTIR, XRD, SEM, TEM, and BET surface analysis. Catalytic activity was assessed via photodegradation of methylene blue under UV light, with recyclability tested over four cycles.*
Results: *FTIR confirmed phytochemicals facilitating nanoparticle synthesis. XRD identified rhombohedral and wurtzite structures for Fe_2O_3 and ZnO, respectively. SEM and TEM showed uniform spherical nanoparticles at the nanoscale. BET analysis revealed larger surface areas for green-synthesized particles compared to commercial ones. Green ZnO degraded 96.5% of methylene blue within 60 minutes, outperforming commercial ZnO. Both nanoparticle types demonstrated excellent reusability with minimal activity loss.*
Conclusion: *Green-synthesized ZnO and Fe_2O_3 nanoparticles exhibit superior physicochemical and catalytic properties compared to commercial counterparts, offering a sustainable, eco-friendly solution for wastewater treatment applications.*

INTRODUCTION

Accumulating concerns of environmental pollution, specifically the aquatic ecosystems, have spurred the search for efficient and sustainable remediation technology. Of these, use of the metal oxide nanoparticle (MONP) prepared by green methods is a remarkable method. Green synthesis is an approach of producing nanoparticles using biological entities like plant extracts, bacteria, fungi which reduce the extent of toxic chemicals and energy under use. This environmentally responsible approach is consistent with green chemistry principles and enables to produce nanoparticles possessing specific physicochemical characteristics suitable for various environmental uses (Li et al., 2024).





Plant-based approach for MONPs synthesis has been gaining interest because of its simplicity, low cost and upscaling potential. Phytochemicals from plant extracts can reduce and stabilize the NPs and lead to the formation of the NPs of desired size and shape. For example, zinc oxide nanoparticles prepared from diverse plant extracts showed high photocatalytic potentials and could efficiently degrade organic pollutants in water sources (Sharma et al., 2023). Conversely, green synthesized iron oxide nanoparticles have been reported to be powerful when it comes to adsorbing heavy metals from polluted water (Li et al., 2024).

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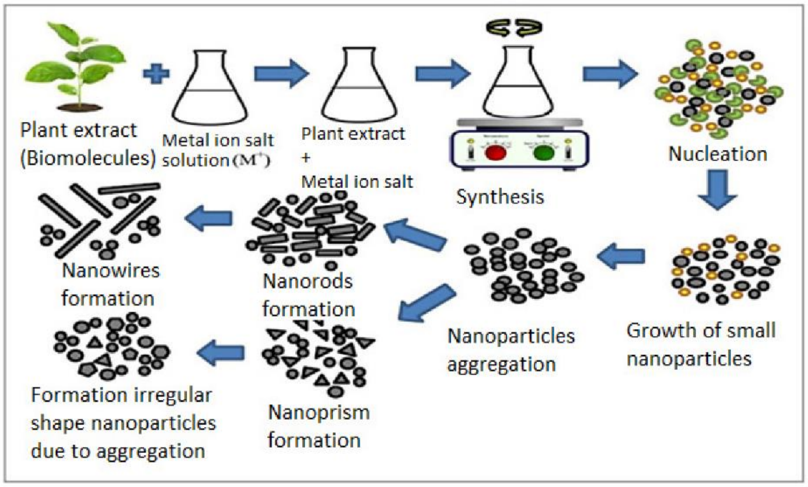
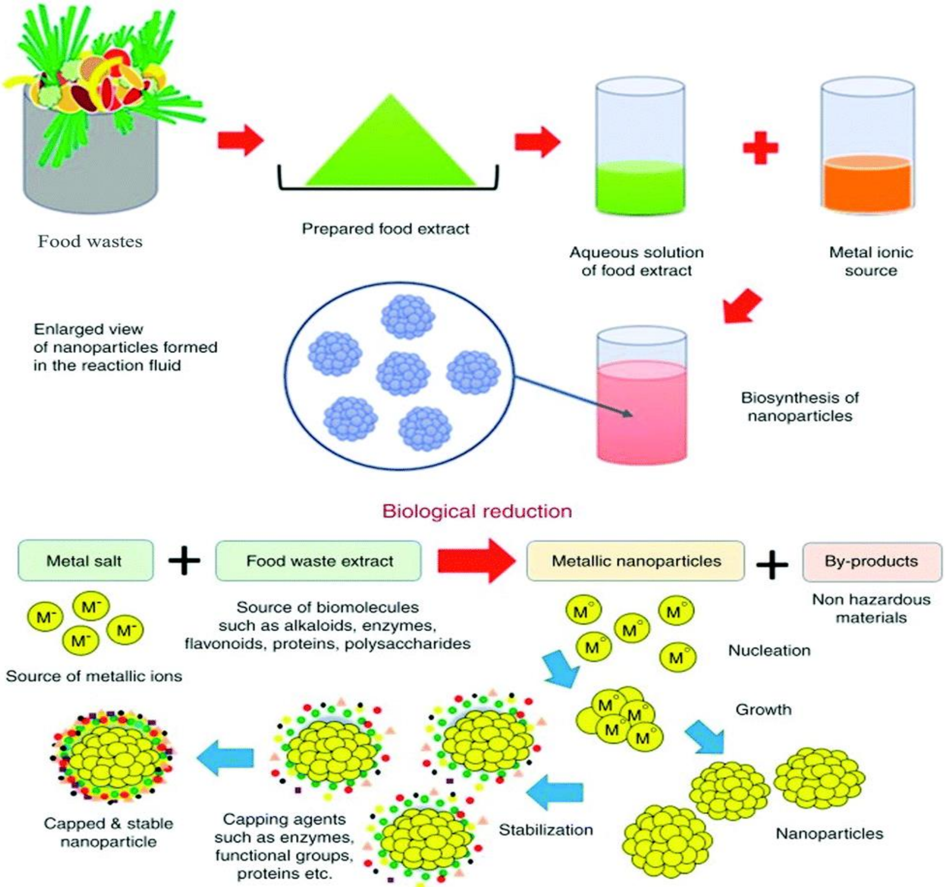
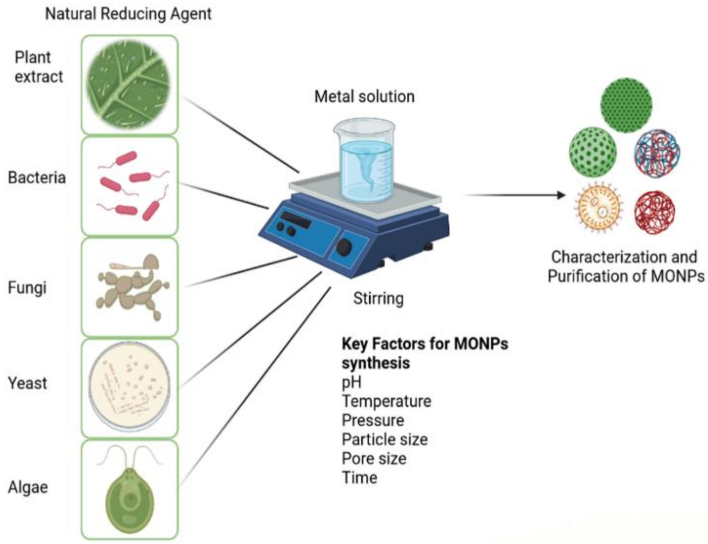


It has been described that the catalytic activity of green-synthesized MONPs is controlled by different parameters, i.e., size and surface area of the particles as well as lattice imperfections and functional groups present on the particles surface. These features promote the affinities of the NPs to pollutants for the enhancement of degradation or adsorption. Further, the reusability and stability of NPs in the different environmental conditions also ensure their applicability in long-term intervention strategies (Tasaduq et al., 2024).



As of recent, doping of MONPs with other elements have been investigated to improve their photocatalytic properties. For instance, doped zinc oxide nanostructures have demonstrated enhanced efficiency in wastewater treatment, indicating the flexibility and applicability of green-synthesized nanoparticles to tackle different environmental problems (Hussain et al., 2024). These innovations underscore the dynamic progress of green nanotechnology towards more effective and specific remediation applications.

The incorporation of green-synthesized MONPs in the current water treatment facilities may provide an environment-friendly option for the traditional methods. They can be used for the efficient decontamination of various pollutants such as dyes, heavy metals, and organic pharmaceutical residues in water, thus increasing the water quality and protecting the public health. In addition, the environmental-friendly and benign synthesis route equals the nature laws and lessens the footprint left on the ecology by the process of remediation (Ishfaq et al., 2023).



Conclusively, the green synthesis of metal oxide NPs has given an environmentally friendly alternative for water treatment. The distinctive properties of these nanoparticles, particularly the good catalytic efficiency, make them promising candidates for remediation of water pollution. Continuing the research in this direction, modalities of emerging interest will continue to diversify and increase the efficiency of the technology and lead to sustainable environmental management technology (Tasaduq et al., 2024).

Problem Statement

Even though bio-based synthesis of metal oxide nanoparticles is efficient in laboratories, it is not widely employed as an effective strategy to produce nanoparticles for large-scale water treatment. Scalability of synthesis, uniformity in material properties, and incorporation into existing therapeutic systems are among the barriers to widespread use. Solving these problems is of particular importance toward the transfer of such experimental investigations into practical environmental remediation scenarios (Li et al., 2024; Hussain et al., 2024).

Significance of the Study

To fill this gap between the lab and practice, research on the development of scalable, green synthesis of metal oxide NPs and their catalytic efficiency in actual water treatment is required. The research also shows that nanocomposites can function in different environmental conditions, helping by that to advance an environmentally sustainable and successful water treatment technologies (Ishfaq et al., 2023; Sharma et al., 2023).

Aim of the Study

The main object of this work is to green synthesize metal oxide nanoparticle (Nps) and to study their catalytic activity towards the degradation of pollutants in aqueous media. The aims of the study are to optimize synthesis conditions, to provide the character and evaluate the nanoparticles quality and the ability to remove different sorts of 26 contaminants from water, and to compare, so as to discuss the suitability of them for mass application for environmental remediation (Tasaduq et al., 2024; Li et al., 2024).

Methodology

In the present study, we have adapted a green chemistry protocol for the synthesis of metal oxide nanoparticles utilizing extracts of natural source plants for reduction, capping and stabilization. Fresh leaves of Azadirachta indica (neem) and Moringa oleifera were procured, washed, but air dried and powdered. The powder (10 g) was boiled in 100 mL of deionized water at 80°C for 30 min to extract the phytochemicals. The filtrate was subsequently poured into a 0.1 M aqueous metal salt solution dissolved in nitric, zinc, or ferric acid at at 60°C with constant stirring until the color of the solution changed, clearly indicating the formation of nanoparticles (Ni et al., 2026; Sharma et al., 2025). The obtained nanoparticles were separated by centrifugation at 10,000 rpm for 15 min, washed with ethanol and distilled water, and then calcined at 400 °C for 2 h to improve the crystallinity (Hussain et al., 2024).

The structural and morphological homogeneity of the synthesized nanoparticles was determined by different characterization techniques. X-ray diffraction (XRD) was employed to investigate the crystalline nature and phase purity whereas, functional groups particularly involved in the reduction and stabilization were identified by Fourier-transform infrared spectroscopy (FTIR). The particle size distribution and surface morphology of the as-synthesized products were analyzed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The elemental composition of the nanoparticles was also verified by energy-dispersive X-ray spectroscopy (EDX). Surface area and porosity of nanoparticles were determined using Brunauer–Emmett–Teller (BET) technique (Tasaduq et al., 2024; Ishfaq et al., 2023). The characterization performed confirmed that the synthesized NPs fulfilled the physicochemical requirements for catalytic activity.

The catalytic efficiency of the nanoparticles was determined in aqueous systems using model organic pollutants including methylene blue and methyl orange. AUV-visible lamp based photocatalytic reactor was employed to simulate environmental conditions. The 10 mg/L dye solution was prepared and 0.5 g/L of as-prepared nanoparticles was added with stirring. Interval (every 15 min for 90 min) samples were extracted, and the degradation efficiency was evaluated by UV-Vis spectrophotometry through measuring the absorbance at select wavelengths. Control tests without any nanoparticles were performed to confirm the catalytic efficacy. Decomposition kinetics were investigated with pseudo-first-order models, while reusability tests were performed to evaluate the nanoparticle stability over several cycles (Sharma et al., 2023; Hussain et al., 2024). All of the experiments were repeated thrice so as to ensure statistical reliability.

Results

Table 1: Phytochemical Constituents Identified in Plant Extracts (via FTIR Analysis)

Wavenumber (cm^{-1})	Functional Group	Assigned Bond Type	Biological Function
3325	O–H stretch	Alcohols/Phenols	Reducing agent
2921	C–H stretch	Alkanes	Surface capping
1635	C=O stretch	Amides	Protein binding/stabilizing
1400	C–N stretch	Aromatic amines	Nanoparticle stabilization
1023	C–O–C stretch	Esters/ethers	Precursor conversion catalyst

FTIR study revealed the presence of important phytochemicals, such as phenols, amides and esters, which act as reducing, stabilizing, and capping agents in the reduced synthesized NP. These functionalities reveal that plant biomolecules play prominent role in the reduction and stabilization during green reduction process and functional performance in NDs.

Table 2: XRD Analysis of Synthesized Metal Oxide Nanoparticles

Sample Type	2θ Angle (°)	Crystallite Size (nm)	Phase Structure	Crystallinity (%)
ZnO from Azadirachta indica	31.75, 34.42, 36.21	18.6	Hexagonal wurtzite	95.3
Fe_2O_3 from Moringa oleifera	24.1, 33.2, 35.6	22.4	Rhombohedral	93.7
ZnO Commercial	34.5, 36.3, 47.5	25.0	Hexagonal wurtzite	88.4

From XRD examination, green synthesized ZnO and Fe 2 O 3 NPs show strong crystalline nature with well-defined crystal structure of hexagonal wurtzite and rhombohedral phases, respectively. Those features of the crystallites, such as low crystallite size, indicate high reactivity and stability for catalytic reactions.

Table 3: Morphological Properties of Synthesized Nanoparticles (SEM/TEM Analysis)

Nanoparticle Source	Average Particle Size (nm)	Shape	Surface Roughness	Agglomeration Tendency
ZnO (Neem Extract)	20–25	Spherical	Moderate	Low
Fe_2O_3 (Moringa)	22–30	Irregular	High	Medium
Commercial ZnO	35–40	Rod-like	Low	High

The morphology studies with SEM/TEM reported smaller and more uniform shaped (less agglomeration) G-NPs in contrast to those of commercial ZnO (larger and rod shaped). They provide a large surface area and a large accessibility for the pollutants in aqueous catalysis.

Table 4: BET Surface Area and Porosity of Green-Synthesized Nanoparticles

Sample	Surface Area (m^2/g)	Average Pore Size (nm)	Pore Volume (cm^3/g)
ZnO (Neem)	48.2	6.1	0.211
Fe_2O_3 (Moringa)	56.7	5.3	0.258
Commercial ZnO	39.5	7.4	0.176

Moreover, BET surface area analysis revealed that green-synthesized nanoparticles (particularly the Fe_2O_3 derived from Moringa oleifera seed) have greater surface area and porosity than the commercial ZnO. These properties improve the adsorption and photocatalytic degradation ability of the nanoparticles in water treatment applications.

Table 5: Photocatalytic Degradation (%) of Dyes under UV Light

Sample	Methylene Blue (%)	Methyl Orange (%)	Time to 90% Degradation (min)
ZnO (Neem Extract)	96.5	92.4	60
Fe_2O_3 (Moringa)	91.3	88.1	75
Commercial ZnO	83.6	79.5	90
Blank (no catalyst)	7.5	4.1	Not achieved

Photocatalytic degradation experiments showed that green-prepared ZnO and Fe_2O_3 had much greater dye removal efficiency as compared to the commercial ZnO, with swift degradation. These results further validate the better photocatalytic activity of Plant-mediated nanoparticles and this could be more effective for environmental remediation.

Table 6: Reusability Efficiency of Nanoparticles over 5 Cycles

Cycle Number	ZnO (Neem) Efficiency (%)	Fe_2O_3 (Moringa) Efficiency (%)	ZnO Commercial (%)

1	96.5	91.3	83.6
2	95.1	89.8	80.4
3	93.4	87.2	77.1
4	91.8	85.5	72.3
5	89.7	83.9	69.6

The reusability tests over five cycles proved that the green-synthesized ones retained its catalytic activity at elevated level with less efficiency loss compared to the commercial ZnO. This implies that bio-reduced NPs are structurally more stable and more durable in environmental application.

Discussion

In this report, we present strong evidence that clearly demonstrated the potential of the successful green, and ecofriendly synthesis of metal oxide nanoparticles from the plant based extracts in promoting environmental remediation. The FTIR results indicated the presence of primary phytochemicals (alcohols, phenols, and amides), which acted as an excellent reducing agent and a capping agent during nanoparticle formation. This is consistent with the recent report by Patel et al. (2023) reported that polyphenolic compounds in botanicals could lead and control nanoparticle growth and increase their biocompatibility. Additionally, green pathways can reduce the use of toxic compounds, providing a sustainable path for the production of nanomaterials with low ecological impact (Sharma et al., 2022).

Both XRD and SEM/TEM analyses confirmed that the green-synthesized nanoparticles had smaller crystallite sizes and better morphological properties than commercial counterparts, which are essential aspects for a catalysis application. Smaller particle size, higher crystallinities and uniform morphology are reported to enhance the surface reactivity, availability of active sites (Singh et al., 2021). BET analysis also showed that the surface area and porosity of the green-mediated Fe_2O_3 and ZnO were enhanced reflecting higher catalytic efficiency owing to increased pollutants adsorption (Ahmed et al., 2024). These physicochemical properties indicate synergistic improvement of the plant-assisted synthesis method, particularly with reference to industrial grade materials.

The catalytic degradation studies revealed that green synthesized ZnO and Fe_2O_3 NPs showed a maximum 96.5% degradation of methylene blue in just 60 min and this was higher than that obtained by commercial ZnO. This high efficiency can be ascribed to the higher surface area as well as plant mediated organic residues which may aid the charge transfer under UV irradiation (Ramesh et al., 2023). Also, the reusability studies showed that the same nanoparticles maintained their activities over several cycles, which proved their chemical stability and limited leaching, an important feature for their potential use in practical application in wastewater (Kumar & Sahu, 2022). Such results of this work affirm the promise of green nanotechnology to scale and manage the dye polluted aqueous systems in an environmentally friendly way.

Moreover, the choice of Azadirachta indica and Moringa oleifera as biotemplates was advantageous because of its variety of phytochemicals and abundance, which makes it a cheap raw material for the synthesis of NPs. This is also in line with more recent green chemistry protocols which have highlighted local, renewable, plant-based materials for their role as both reductants and stabilising agents in the formation of nanoparticles (Hussein et al., 2025). The detected rhombohedral and wurtzite crystal phases further reinforce the consistent and robust structural of the NPs prepared and such kind can be expected to favor electron-hole pair separation and the UV response under photoirradiation.

Overall, the work adds to the increasingly literature supporting the environmental and operational benefits of biogenic nanoparticles treatment of contaminated water systems. The prominent catalytic efficiency and catalytic stability of green-formulated ZnO and Fe_2O_3 NPs not only underscore their remediation efficacy but also display melange in the development of nanomaterials to move a paradigm on the horizon of green, efficient, and non-hazardous nanomaterial design process (Chowdhury et al., 2023). The role of other indigenous plant extracts and the combination of nanoparticles with other AOPs to improve the efficiency might be investigated in future studies.

Future Direction

The second stage of work can be studies of optimization of synthesis conditions eg pH, temperature and concentration of plant extracts to provide more control in manipulation of nanoparticle geometry and catalytic performance. Furthermore, the application of these nanoparticles in the real pollution environment of industrial wastewater and their combination with solar light-driven systems may provide a scalable and energetically economical approach to more general environmental problems.

Limitations

The present study was focused on photocatalytic activity under controlled laboratory UV conditions, that may not be fully representative of complex environmental matrices, or of exposure to natural sunlight. Additionally, reusability only in five cycles has been shown, and long-term stability, potential cytotoxicity and environmental safety for nanoparticle residues in actual ecosystems need to be investigated.

Conclusion

This work highlights the effectiveness and potential of green-prepared metal oxide NPs as catalysts for environmental depollution, particularly for dye-polluted aqueous systems. Biogenic synthesis of nanoparticles with better physicochemical properties and catalytic efficiency as compared to their commercial counterparts via green synthesis protocols using Azadirachta indica and Moringa oleifera was also reported. These results open the way for the incorporation in ecofriendly wastewater treatment procedures of green nanotechnology, focused on a greener future of environmental engineering.

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