

Review on Green Chemistry of Manganese Oxide Nanoparticles Using Plant Extracts: Characterization and Recent Applications

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Abstract

The rapid expansion of nanotechnology has led to significant advancements across biomedical, environmental, and energy sectors. Manganese oxide nanoparticles (MnO NPs) have garnered considerable attention due to their magnetic properties, redox activity, biocompatibility, and low toxicity. However, conventional synthesis methods often involve hazardous chemicals and energy-intensive processes. In response, green synthesis approaches – particularly plant-mediated methods – have emerged as sustainable, cost-effective, and environmentally benign alternatives. Utilizing phytochemicals such as flavonoids, terpenoids, and phenolics, plant extracts function as natural reducing and stabilizing agents during nanoparticle formation. This review highlights various plant species employed in MnO NP synthesis, including *Azadirachta indica*, *Camellia sinensis*, and *Ocimum sanctum*, and discusses key characterization techniques such as UV-Vis, XRD, FTIR, SEM, TEM, and DLS. Additionally, it explores recent real-world applications of green-synthesized MnO NPs in biomedicine (e.g., drug delivery, MRI imaging, antibacterial activity), environmental remediation (e.g., water purification, pollutant degradation), and energy storage and conversion (e.g., supercapacitors, lithium-ion batteries, fuel cells). The review underscores the promise of plant-based green synthesis as a scalable and eco-friendly route to advanced nanomaterials for diverse technological applications.

Keywords: *nanotechnology, manganese oxide nanoparticles, phytochemicals, plant-based green synthesis.*

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Introduction

In recent years, nanotechnology has revolutionized various scientific fields, including medicine, agriculture, catalysis, and environmental remediation. Among the various nanomaterials, manganese oxide nanoparticles (MnO NPs) have gained significant attention due to their low toxicity, redox activity, magnetic properties, and wide range of industrial and biomedical applications (Sharma et al., 2019). Traditional methods for synthesizing MnO NPs often involve toxic chemicals, high energy input, and complex procedures, posing environmental and health hazards.

To overcome these limitations, green synthesis methods, particularly those using plant extracts, have emerged as an eco-friendly and sustainable alternative. This approach utilizes phytochemicals – such as flavonoids, terpenoids, alkaloids, and phenolics – naturally present in plants, acting as both reducing and stabilizing agents during nanoparticle formation (Dauthal & Mukhopadhyay, 2016). Plant-mediated synthesis is advantageous due to its simplicity, cost-effectiveness, environmental compatibility, and the ability to control particle size and shape.

Several plant species have been successfully employed for the green synthesis of MnO NPs, including *Azadirachta indica* (Neem), *Camellia sinensis* (Green Tea), and *Ocimum sanctum* (Tulsi), demonstrating promising results in terms of nanoparticle yield and stability (Suriyaprabha et al., 2020). These green-synthesized nanoparticles exhibit diverse applications in biomedicine (antimicrobial, antioxidant, drug delivery), environmental protection (heavy metal removal, wastewater treatment), and energy storage (supercapacitors, lithium-ion batteries).

This review discusses the latest advances in the green synthesis of MnO NPs using plant extracts, emphasizing their characterization techniques, mechanistic aspects, and recent real-world applications.

Green Chemistry Approach for MnO NP Synthesis

The green chemistry approach for the synthesis of manganese oxide nanoparticles (MnO NPs) utilizes eco-friendly, non-toxic, and renewable resources to minimize the environmental footprint of nanomaterial production. In this method, plant extracts act as natural reducing, stabilizing, and capping agents, enabling nanoparticle formation without the need for hazardous chemicals or extreme reaction conditions (Iravani, 2011).

Plants are rich in secondary metabolites such as flavonoids, alkaloids, terpenoids, saponins, and phenolic compounds, which donate electrons to reduce manganese salts (e.g., KMnO_4 or MnCl_2) to MnO NPs. These phytochemicals also play a role in controlling nanoparticle morphology and preventing agglomeration, leading to more stable and uniform nanostructures (Dauthal & Mukhopadhyay, 2016).

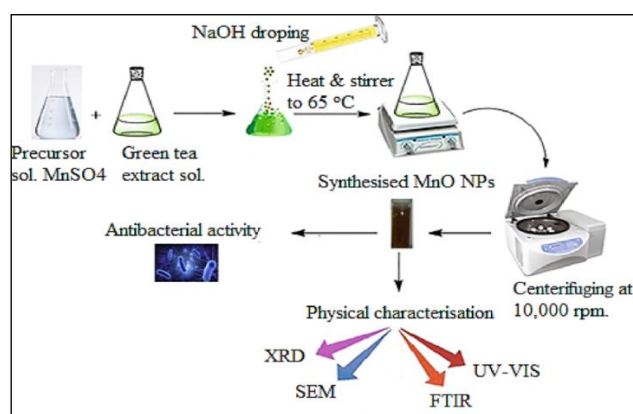


Figure 1. Preparation and Characterization of Manganese Oxide Nanoparticles

Source: Wahran saod et al. (2022)

The general steps in the green synthesis of MnO NPs include:

1. Preparation of plant extract (boiling or soaking leaves, bark, seeds, etc. in water or ethanol),



2. Mixing with manganese precursor solution, and
3. Incubation under ambient or mildly heated conditions, leading to nanoparticle formation.

This method stands out for its simplicity, low cost, biocompatibility, and scalability, making it highly suitable for industrial and biomedical applications (Sharma et al., 2019). Furthermore, the approach aligns with the 12 principles of green chemistry by reducing chemical waste, avoiding hazardous substances, and promoting safer synthesis routes.

Table 1. Example of Plant-Mediated MnO NP Synthesis

Plant Name	Scientific Name	Plant Part Used	Role in Synthesis
Neem	<i>Azadirachta indica</i>	Leaves	Reducing & stabilizing agent Balachandran et al. (2022)
Green Tea	<i>Camellia sinensis</i>	Leaves	Antioxidants aid in reduction Singh, J., et al. (2021)
Tulsi (Holy Basil)	<i>Ocimum sanctum</i>	Leaves	Bioactive compounds for nanoparticle cap Kumar et al. (2021)
Aloe Vera	<i>Aloe barbadensis miller</i>	Leaf gel	Natural reducing agent Ramesh et al. (2020)
Banana Peel	<i>Musa paradisiaca</i>	Peel	Rich in polyphenols for NP stabilization Sharma, D., et al. (2019)

Characterization Techniques

Characterization is critical to confirm nanoparticle synthesis, determine morphology, crystallinity, size, and surface functionality. Common techniques include:

UV-Visible Spectroscopy (UV-Vis)

- Purpose: Confirms the formation of MnO nanoparticles via surface plasmon resonance.
- Details: MnO NPs typically show absorbance peaks in the range of 300–400 nm. (M. Khuswairi, et al 2021)

X-Ray Diffraction (XRD)

- Purpose: Determines crystal structure, phase, and average crystallite size.
- Details: Peaks match standard JCPDS files for MnO phases. (Dinesh, S., et al 2020)

Fourier Transform Infrared Spectroscopy (FTIR)

- Purpose: Identifies functional groups from plant extracts involved in reduction and capping.
- Details: Bands near 500–600 cm^{-1} correspond to MnO stretching. (Raghavendra, A., et al 2020)

Scanning Electron Microscopy (SEM)

- Purpose: Reveals surface morphology and particle size distribution.
- Details: Shows mostly spherical or irregular particles, often agglomerated. (Ghosh, S., et al 2022)

Transmission Electron Microscopy (TEM)

- Purpose: Provides detailed internal structure and exact nanoparticle size.



- Details: Size typically ranges from 10–50 nm depending on synthesis. (Nasrollahzadeh, M., et al 2019)

Dynamic Light Scattering (DLS) & Zeta Potential

- Purpose: Measures particle size distribution and stability in solution.
- Details: Helps evaluate colloidal stability (zeta potential ± 30 mV is considered stable). (Jain, D., et al 2021)

Recent Applications

Biomedical Applications

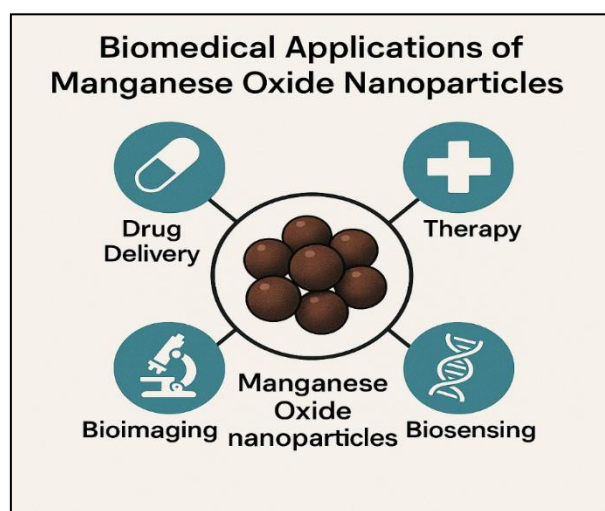


Figure 2. Biomedical Application

Source: Xin Zhang et al. (2023)

1. MRI Contrast Agents

MnO NPs are widely used as T₁-weighted MRI contrast agents due to the paramagnetic properties of Mn²⁺ ions, which enhance image contrast without the toxicity associated with gadolinium-based agents. (Na, H. B., Song, I. C., & Hyeon, T. 2009)

2. Drug Delivery

MnO NPs can serve as pH-responsive carriers for anticancer drugs. In acidic tumor environments, MnO dissolves, releasing Mn²⁺ and the encapsulated drug. (Li, Y., Liu, Z., Hou, Y., Chen, W., & Liu, C. 2017)

3. Photo thermal and Photodynamic Therapy

MnO NPs can be functionalized for photothermal therapy (PTT) and photodynamic therapy (PDT), providing a dual treatment modality for cancer. (Liu, J., Bu, W., Pan, L., & Shi, J. 2013)

4. Reactive Oxygen Species (ROS) Generation & Antibacterial

Activity MnO NPs can generate ROS, damaging bacterial cell walls and cancer cells, making them useful for antibacterial and anticancer applications. (Wang, Z., Deng, H., Zhang, Y., & Wu, Y. 2018)

5. Bio sensing



MnO NPs are used in biosensors due to their redox activity and high surface area, enabling detection of glucose, hydrogen peroxide, and other biomolecules. (Chinnadayya, S. R., Park, D. S., & Cho, S. (2018))

Environmental Applications

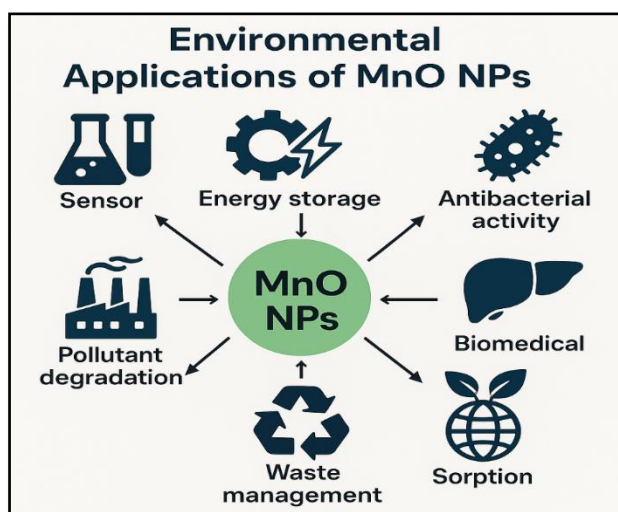


Figure 3. Environmental Applications

Source: Sonika Dawadi et al. (2020)

1. Water Purification and Wastewater Treatment

MnO NPs can effectively remove heavy metals (e.g., arsenic, lead, cadmium) and organic pollutants (e.g., dyes, phenols) from water through adsorption and redox reactions.

- Example: MnO NPs demonstrated high efficiency in removing arsenic (V) and arsenic (III) from contaminated water due to their high adsorption capacity. *Zhao, S., et al. (2017)*

2. Degradation of Organic Pollutants

MnO NPs act as catalysts in oxidative degradation of dyes and pesticides under sunlight or UV light.

- Example: Degradation of methylene blue and rhodamine B using MnO NPs in photocatalytic processes. *Giri, S., et al. (2013)*

3. Air Pollution Control

MnO NPs are used in catalytic converters to reduce NO_x and CO emissions and can be employed in air filters for capturing volatile organic compounds (VOCs). *Lin, S., et al. (2015)*

4. Soil Remediation

MnO NPs can oxidize and immobilize heavy metals and organic contaminants in soils, reducing their mobility and toxicity. *Xiong, Z., et al. (2018)*.

Energy Applications

1. Fuel Cells

MnO NPs have been used as catalysts or catalyst supports in alkaline fuel cells and metal-air batteries, especially Zn-air and Li-air.



- Role: Catalyze oxygen reduction reaction (ORR), a critical process in fuel cell cathodes.
- Advantage: MnO provides good ORR activity in alkaline media, and it is a non-precious metal alternative to Pt. Liang, Y., et al. (2011)

2. Solar Energy Conversion

MnO NPs have been used in photoelectrochemical cells (PECs) and solar water splitting systems.

- Function: MnO can act as a co-catalyst or redox mediator due to its bandgap and photochemical properties.
- Potential: Promising material for low-cost photocatalysts in renewable energy systems. Sharma, G., et al. (2019)

3. Hydrogen Storage

MnO nanostructures have been studied for hydrogen storage due to their porous structure and redox activity.

- Key Point: MnO-based hybrids show reversible hydrogen absorption, making them candidates for clean energy storage. Jain, R., et al. (2016).

Challenges and Future Perspectives

Despite promising results, challenges remain:

- Lack of mechanistic understanding of biosynthesis.
- Need for large-scale production techniques.
- Long-term toxicity and environmental impact studies.

Future research should focus on:

- Standardization of synthesis protocols.
- Exploring underutilized plant sources.
- In vivo biomedical application testing.

Conclusion

The green synthesis of MnO nanoparticles using plant extracts presents an environmentally benign route for nanoparticle production. The characterized nanoparticles show potential in diverse fields including medicine, environment, and energy. However, further interdisciplinary studies are needed to fully realize their potential.

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