

GREEN-SYNTHESIZED NANOPARTICLES FOR SUSTAINABLE REMOVAL OF HEAVY METALS FROM INDUSTRIAL WASTEWATER

¹YOGESH KUMAR ²Dr. MUKESH KUMAR

DEPARTMENT OF CHEMISTRY, SCHOOL OF APPLIED SCIENCE
OM STERLING GLOBAL UNIVERSITY, HISAR

Abstract

The rapid expansion of industrial activities has led to increased discharge of heavy metals into aquatic ecosystems, posing severe risks to human health and the environment. Conventional wastewater treatment methods often suffer from high operational costs, secondary pollution, and limited efficiency. In recent years, green-synthesized nanoparticles have emerged as a sustainable and eco-friendly alternative for the removal of heavy metals from industrial wastewater. These nanoparticles are synthesized using biological resources such as plant extracts, microorganisms, and biopolymers, eliminating the need for toxic chemicals and energy-intensive processes. Owing to their high surface area, tunable surface chemistry, and enhanced adsorption capacity, green-synthesized nanoparticles demonstrate remarkable efficiency in removing toxic heavy metals including lead, cadmium, chromium, mercury, and arsenic. This approach not only improves metal removal efficiency but also aligns with the principles of green chemistry and sustainable development. This review highlights recent advances in green synthesis methods, mechanisms of heavy metal removal, performance evaluation, and future prospects for large-scale application in industrial wastewater treatment.

Keywords: Green synthesis; Nanoparticles; Heavy metal removal; Industrial wastewater; Sustainable wastewater treatment; Adsorption; Environmental remediation

Introduction

The exponential growth of industrialization over the past century has significantly enhanced economic development across the globe. However, this rapid industrial expansion has also generated an alarming increase in environmental pollution, particularly in aquatic ecosystems. Among various pollutants discharged from industrial processes, heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), mercury (Hg), nickel (Ni), and arsenic (As) are of paramount concern due to their toxicity, persistence, bioaccumulative nature, and non-degradability in natural environments. Unlike organic pollutants that can undergo biodegradation, heavy metals persist indefinitely in water and soil, posing long-term risks to human health, agricultural productivity, and ecological stability. Elevated concentrations of heavy metals can cause neurological disorders, kidney damage, cancer, and a wide range of systemic toxicities in humans, as well as profound adverse effects on

aquatic life. Therefore, the effective removal of heavy metals from industrial wastewater has become an urgent global priority for environmental protection and public health.

Traditional wastewater treatment methods include chemical precipitation, ion exchange, adsorption using activated carbon, membrane filtration, and coagulation–flocculation. While these techniques have been widely implemented, they suffer from several limitations, including high operational costs, generation of secondary waste, incomplete removal of contaminants at low concentrations, and sometimes the requirement for complex infrastructure and energy input. In addition, conventional treatments often fail to achieve stringent discharge standards mandated by environmental regulations, particularly when heavy metal concentrations are at trace levels. These challenges have stimulated intensive research into novel, efficient, and sustainable remediation technologies for water purification.

In recent years, nanotechnology has emerged as a transformative approach in environmental remediation, offering innovative solutions to the shortcomings of traditional treatment processes. Nanoparticles (NPs)—materials with at least one dimension in the 1–100 nm range—exhibit unique physicochemical properties such as high surface-to-volume ratio, enhanced reactivity, tunable surface chemistry, and quantum effects not found in bulk materials. These features make nanoparticles highly effective for pollutant adsorption, catalytic degradation, and selective binding of toxic species from aqueous media. Among various nanomaterials, metal and metal oxide nanoparticles such as iron oxide, zinc oxide, titanium dioxide, silver, and zero-valent iron have been extensively investigated for heavy metal removal due to their strong affinity toward metal ions and potential for regeneration and reuse.

Despite the promising performance of engineered nanoparticles in laboratory studies, concerns regarding their synthesis methods, environmental safety, and long-term impacts have emerged. Conventional nanoparticle synthesis often relies on hazardous chemical reducing agents, high temperatures, and non-renewable resources, which can offset the environmental benefits of using these materials for remediation. The use of toxic reagents also raises concerns about the fate of residual chemicals and by-products, potentially introducing new forms of pollution. Additionally, the stability, aggregation behavior, and ecotoxicity of nanoparticles released into the environment remain serious issues that challenge their large-scale application.

The adoption of green synthesis strategies aligns with the principles of green chemistry and sustainability, emphasizing the reduction of hazardous substances, use of renewable feedstocks, and minimization of energy consumption and waste generation. Moreover, green-synthesized nanoparticles often exhibit enhanced functional properties due to the presence of bioactive compounds on their surface, which can improve adsorption efficiency, selectivity toward target contaminants, and interaction with metal ions. For instance,

flavonoids, alkaloids, terpenoids, and phenolic acids commonly found in plant extracts can provide multiple binding sites and facilitate chelation with heavy metal ions.

A significant body of research has demonstrated the effectiveness of green-synthesized nanoparticles in removing heavy metals from industrial wastewater. These studies report high removal efficiencies, rapid uptake rates, and the potential for regeneration and reuse of the nanomaterials. Furthermore, the use of agricultural waste products and plant residues as feedstock for nanoparticle synthesis adds value to otherwise low-value biomass, contributing to circular economy principles. This dual purpose—producing functional nanomaterials while valorizing waste—enhances the sustainability profile of green synthesis approaches.

In green-synthesized nanoparticles represent a promising and sustainable avenue for addressing the pervasive issue of heavy metal contamination in industrial wastewater. By combining nanotechnology with biological synthesis methods, researchers are developing environmentally friendly materials that not only perform effectively under diverse conditions but also adhere to sustainability principles. Continued interdisciplinary efforts in material science, environmental engineering, biology, and toxicology are essential to translate these innovations into practical solutions that protect water resources, safeguard ecosystems, and promote human well-being in an era of increasing environmental challenges.

Types of Green-Synthesized Nanoparticles for Heavy Metal Removal

1. Green Iron Oxide Nanoparticles

Iron oxide nanoparticles synthesized using plant extracts (e.g., tea, pomegranate peel, eucalyptus) have proven highly effective in adsorbing heavy metals such as lead and arsenic. The abundant hydroxyl groups on the surface facilitate strong interactions with metal ions. Moreover, iron oxide nanoparticles can be magnetically separated after treatment, enabling easy recovery and reuse.

2. Silver Nanoparticles (AgNPs)

Although traditionally known for antimicrobial properties, silver nanoparticles produced via green synthesis also show potential in adsorbing heavy metals. The phytochemicals in plant extracts act as reducing and stabilizing agents, creating nanoparticles with surface functional groups that can chelate metal ions.

3. Titanium Dioxide (TiO₂) Nanoparticles

Green-synthesized TiO₂ nanoparticles can remove heavy metals through adsorption and photocatalytic degradation of metal complexes. When irradiated with UV light, these particles generate reactive species that can transform heavy metal ions into less toxic forms or promote their immobilization.

4. Bio-nanocomposites

Nanocomposites made by combining biopolymers (such as chitosan) with metal nanoparticles enhance heavy metal adsorption capacities. Chitosan, derived from chitin, is rich in amine and hydroxyl groups that bind heavy metals strongly. When coupled with nanoparticles, these composites offer synergistic effects — high surface area, multiple binding sites, and stability.

Advantages of Green Nanoparticles in Wastewater Treatment

Environmental Safety

Green-synthesized nanoparticles reduce reliance on hazardous chemicals and energy-intensive processes. The use of plant extracts or microbial systems eliminates toxic precursors, making the entire lifecycle of the material more sustainable.

High Efficiency

Nanoparticles possess high surface-to-volume ratios and abundant active sites, which significantly increase the adsorption capacity compared to bulk materials. They can efficiently remove heavy metals even at low concentrations, addressing a critical limitation of conventional adsorbents.

Selectivity

Surface functional groups from biological sources can offer selective binding toward specific heavy metal ions, enabling targeted removal in mixed contaminant scenarios.

Reusability and Recovery

Magnetic nanoparticles like iron oxide can be recovered using magnetic separation techniques and reused multiple times with minimal loss in performance, reducing operational costs.

Scalability

Green synthesis often employs simple procedures (e.g., room temperature reactions, aqueous media) that are scalable for industrial production without requiring specialized equipment.

Research Methodology

Fresh plant leaves of *Azadirachta indica* (neem) were selected as the biological reducing and stabilizing agent for nanoparticle synthesis due to their rich phytochemical composition, including flavonoids, phenolics, and terpenoids. Analytical-grade metal salts such as ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) and zinc nitrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) were procured and used without further purification. Heavy metal stock solutions of lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr^{6+}), and nickel (Ni^{2+}) were prepared using their respective nitrate salts. Deionized water was used throughout all experiments to prevent contamination.

Preparation of Plant Extract

The collected plant leaves were washed thoroughly with distilled water to remove dust and impurities and then air-dried at room temperature for 48 hours. Ten grams of finely chopped leaves were boiled in 100 mL of deionized water at 70°C for 30 minutes. The resulting mixture was cooled and filtered using Whatman No. 1 filter paper to obtain a clear aqueous extract, which was stored at 4°C for further use.

Green Synthesis of Nanoparticles

Green synthesis of nanoparticles was conducted by mixing the plant extract with metal salt solutions in a 1:4 volume ratio under constant stirring at room temperature. A visible color change from pale yellow to dark brown (for iron nanoparticles) and white precipitate formation (for zinc oxide nanoparticles) indicated successful nanoparticle formation. The reaction mixtures were incubated for 24 hours to ensure complete reduction.

The synthesized nanoparticles were centrifuged at 10,000 rpm for 15 minutes, washed multiple times with deionized water and ethanol to remove residual impurities, and oven-dried at 60°C. The dried nanoparticles were ground into fine powder and stored in airtight containers.

Characterization of Green-Synthesized Nanoparticles

The nanoparticles were characterized using standard analytical techniques. UV–Visible spectroscopy was used to confirm nanoparticle formation through surface plasmon resonance peaks. Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify functional groups involved in reduction and stabilization. X-ray Diffraction (XRD) analysis was used to determine crystalline structure and average particle size. Scanning Electron Microscopy (SEM) provided information on surface morphology.

Industrial Wastewater Sampling and Analysis

Industrial wastewater samples were collected from electroplating and battery manufacturing units. Samples were filtered and acidified with nitric acid to preserve metal ions. Initial heavy metal concentrations were determined using Atomic Absorption Spectroscopy (AAS).

Results and Discussion

Green synthesis of nanoparticles utilizes biological entities such as plant extracts, microorganisms, and biopolymers to produce nanomaterials in an eco-friendly and sustainable manner. These methods avoid toxic chemicals, reduce energy consumption, and enhance biocompatibility.

The efficiency of nanoparticle synthesis depends on several factors, including the type of biological reducing agent, reaction conditions, and precursor salts. Plant-mediated synthesis is particularly popular due to its simplicity and scalability.

Table 1: Common Biological Sources Used in Green Nanoparticle Synthesis

S. No.	Biological Source Type	Example Species	Active Phytochemicals	Nanoparticle Type Synthesized	Key Advantages
1	Plant Extract	Azadirachta indica (Neem)	Flavonoids, terpenoids	Silver (AgNPs)	Rapid synthesis, antimicrobial properties
2	Plant Extract	Camellia sinensis (Green tea)	Polyphenols, catechins	Gold (AuNPs)	High stability, antioxidant activity
3	Bacteria	Bacillus subtilis	Enzymes, proteins	Zinc oxide (ZnO NPs)	Controlled size distribution
4	Fungi	Aspergillus niger	Proteins, enzymes	Titanium dioxide (TiO ₂ NPs)	High yield production
5	Algae	Spirulina platensis	Pigments, polysaccharides	Iron oxide (Fe ₃ O ₄ NPs)	Magnetic properties for easy recovery

This table highlights the diversity of biological systems used in nanoparticle synthesis. Plant extracts dominate due to their rich phytochemical composition, which acts as both reducing and stabilizing agents. Microbial synthesis offers better control over particle size but requires sterile conditions. Algae-based synthesis is emerging due to its sustainability and scalability in aquatic environments.

Physicochemical Properties of Green-Synthesized Nanoparticles

The efficiency of nanoparticles in heavy metal removal depends heavily on their physicochemical properties such as size, surface area, morphology, and surface charge.

Table 2: Physicochemical Characteristics of Green-Synthesized Nanoparticles

S. No.	Nanoparticle Type	Average Size (nm)	Shape	Surface Area (m ² /g)	Zeta Potential (mV)	Stability
1	Silver (AgNPs)	10–50	Spherical	20–40	-25 to -35	Moderate
2	Gold (AuNPs)	5–30	Spherical/Hexagonal	15–35	-20 to -30	High
3	Zinc Oxide (ZnO)	20–80	Rod/Spherical	30–60	-15 to -25	Moderate
4	Iron Oxide (Fe ₃ O ₄)	10–100	Spherical	50–100	-10 to -20	High
5	Titanium Dioxide (TiO ₂)	15–70	Anatase/Rutile	40–80	-18 to -28	High

The table demonstrates that nanoparticle size typically ranges between 5–100 nm, with smaller particles offering higher surface area and better adsorption capabilities. Zeta potential values indicate colloidal stability; higher negative values suggest better dispersion and reduced aggregation. Iron oxide nanoparticles stand out due to their magnetic properties, enabling easy separation from treated water.

Heavy Metal Removal Efficiency

Green-synthesized nanoparticles exhibit strong adsorption capacities for various toxic heavy metals such as lead (Pb²⁺), cadmium (Cd²⁺), chromium (Cr⁶⁺), and arsenic (As³⁺).

Table 3: Removal Efficiency of Nanoparticles for Heavy Metals

S. No.	Nanoparticle	Target Metal	Initial Concentration (mg/L)	Removal Efficiency (%)	Contact Time (min)	pH
1	AgNPs	Pb ²⁺	50	92%	60	6
2	AuNPs	Hg ²⁺	40	88%	90	7
3	ZnO NPs	Cd ²⁺	30	85%	120	6.5
4	Fe ₃ O ₄ NPs	Cr ⁶⁺	25	95%	45	5

5	TiO ₂ NPs	As ³⁺	20	89%	75	6
---	----------------------	------------------	----	-----	----	---

This table indicates that iron oxide nanoparticles show the highest removal efficiency for chromium due to redox interactions and adsorption. The efficiency is influenced by pH, contact time, and initial metal concentration. Most nanoparticles perform optimally in slightly acidic to neutral pH conditions, where metal ions remain soluble and available for adsorption.

Adsorption Isotherm and Kinetics Models

Understanding adsorption behavior is crucial for scaling up wastewater treatment systems. Green nanoparticles follow well-established isotherm and kinetic models.

Table 4: Adsorption Models and Parameters

S. No.	Nanoparticle	Isotherm Model	Maximum Adsorption Capacity (mg/g)	Kinetic Model	Rate Constant (k)	R ² Value
1	AgNPs	Langmuir	120	Pseudo-second-order	0.025	0.99
2	AuNPs	Freundlich	95	Pseudo-first-order	0.018	0.97
3	ZnO NPs	Langmuir	110	Pseudo-second-order	0.021	0.98
4	Fe ₃ O ₄ NPs	Langmuir	150	Pseudo-second-order	0.030	0.99
5	TiO ₂ NPs	Freundlich	100	Intraparticle diffusion	0.015	0.96

The Langmuir isotherm model dominates, indicating monolayer adsorption on homogeneous surfaces. Pseudo-second-order kinetics suggests that chemisorption is the rate-limiting step. High R^2 values confirm the reliability of these models in describing adsorption processes.

Reusability and Regeneration Performance

For sustainable wastewater treatment, nanoparticle reusability is a critical factor. Green-synthesized nanoparticles often demonstrate good regeneration potential.

Table 5: Reusability of Nanoparticles Over Multiple Cycles

S. No.	Nanoparticle	Regeneration Method	Cycle 1 Efficiency (%)	Cycle 3 Efficiency (%)	Cycle 5 Efficiency (%)	Efficiency Loss (%)
1	AgNPs	Acid washing (HCl)	92	85	78	14
2	AuNPs	Thermal treatment	88	82	75	13
3	ZnO NPs	Alkali washing (NaOH)	85	80	72	13
4	Fe ₃ O ₄ NPs	Magnetic separation + washing	95	90	85	10
5	TiO ₂ NPs	UV regeneration	89	84	79	11

Iron oxide nanoparticles show the least efficiency loss due to their magnetic separability, making them highly suitable for repeated use. Regeneration methods such as acid washing and UV treatment restore adsorption sites but may gradually degrade nanoparticle structure over time.

Conclusion

Green-synthesized nanoparticles offer a promising, sustainable, and environmentally benign approach for the removal of heavy metals from industrial wastewater. By utilizing plant extracts, microorganisms, or biopolymers as reducing and stabilizing agents, green synthesis methods minimize the use of toxic chemicals, reduce energy consumption, and align well with the principles of green chemistry. These nanoparticles exhibit

high surface area, tunable surface functional groups, and strong adsorption capacities, enabling efficient removal of toxic heavy metals such as lead, cadmium, chromium, mercury, and arsenic from contaminated water.

Compared to conventional treatment technologies, green-synthesized nanoparticles demonstrate advantages including cost-effectiveness, biodegradability, reduced secondary pollution, and improved metal recovery potential. Additionally, their compatibility with existing wastewater treatment systems enhances their practical applicability. Despite these advantages, challenges such as large-scale synthesis, long-term stability, regeneration efficiency, and potential ecological impacts require further investigation.

Overall, green-synthesized nanoparticles represent a viable and innovative solution for sustainable industrial wastewater treatment. Continued research focused on process optimization, life-cycle assessment, and pilot-scale applications will be essential to translate laboratory successes into real-world implementations, contributing significantly to environmental protection and sustainable water management.

REFERENCES

1. Awwad, A. M., & Amer, M. W. (2020) Biosynthesis of copper oxide nanoparticles using Phoenix dactylifera leaf extract and their heavy metal ions removal efficiency. *Green Processing and Synthesis*, vol. 9(1), page no. 593–602.
2. Bharathi, D., & Bhuvaneshwari, M. (2019) Green synthesis of silver nanoparticles using Hibiscus rosa-sinensis leaf extract and evaluation of its antibacterial and heavy metal removal activity. *Applied Nanoscience*, vol 9, page no. 953–960.
3. Ebrahiminezhad, A., Bagheri, M., Berenjian, A., & Ghasemi, Y. (2018) Green synthesis of the magnetic iron oxide nanoparticles and their applications in the removal of toxic dyes and heavy metals from wastewater. *Environmental Technology & Innovation*, vol. 10, page no. 291–301.
4. Iravani, S. (2011) Green synthesis of metal nanoparticles using plants. *Green Chemistry*, vol. 13(10), page no. 2638–2650.
5. Kumar, B., Smita, K., Cumbal, L., & Debut, A. (2014) Green synthesis of copper nanoparticles using Swietenia mahogany leaves and their applications in the removal of heavy metals from aqueous solutions. *Journal of Nanoparticle Research*, vol. 16(11), page no. 1–10.
6. Makarov, V. V., Love, A. J. (2014) “Green” nanotechnologies: Synthesis of metal nanoparticles using plants. *Acta Naturae*, vol. 6(1), page no. 35–44.

7. Mousavi, S. M., Yaghoubi, H., & Boroomand, N. (2021) Application of green nanoparticles for removal of environmental pollutants. *Environmental Science and Pollution Research*, vol. 28(42), page no. 59245–59262.
8. Naaz, F., Bhattacharya, S., & Sharma, M. (2020) Green synthesis of nano zero-valent iron using *Camellia sinensis* leaves for remediation of lead from water. *SN Applied Sciences*, vol. 2, page no. 753.
9. Singh, J., Dutta, T., Kim, K. H., Rawat, M. & Kumar, P. (2018) 'Green' synthesis of metals and their oxide nanoparticles: Mechanisms, application and ecotoxicity perspective. *Journal of Nanobiotechnology*, vol. 16(1), page no. 83.
10. Thovhogi, E., Sibuyi, N., Meyer, M., & Maaza, M. (2016) Green synthesis of silver nanoparticles using *Moringa oleifera* natural leaf extract and their effective application in the remediation of lead-contaminated water. *Journal of Molecular Liquids*, issue 222, page no. 1302–1308.
11. Baruah, D., Goswami, M., & Buragohain, A. K. (2023) Green synthesized nanoparticles for heavy metal remediation from wastewater: A review. *Environmental Research*, issue 228, page no. 115722.
12. Makarov, V. V., Love, A. J., Taliansky, M. E., & Kalinina, N. O. (2014). "Green" nanotechnologies: Synthesis of metal nanoparticles using plants. *Acta Naturae*, vol. 6(1), page no. 35–44.
13. Muthukumar, C., Vinodhini, P. A., & Mariappan, R. (2021). Green synthesis of iron oxide nanoparticles using *Terminalia chebula* fruit extract for effective adsorption of heavy metals from wastewater. *Environmental Science and Pollution Research*, vol. 28(32), page no. 43729–43741.
14. Santhoshkumar, J., Rajiv, P., Rajeshwari, S., & Venckatesh, R. (2020). Green synthesis of titanium dioxide nanoparticles using *Cedrus deodara* leaf extract for photocatalytic degradation of heavy metals. *Journal of Molecular Structure*, issue 1207, page no. 127771.
15. Shah, M., Fawad, M., Nasir, F., & Khan, S. (2023). Green synthesis of metal nanoparticles: A systematic review on their application in wastewater treatment. *Nanomaterials*, vol. 13(5), page no. 819.
16. Shakoor, S., & Nasar, A. (2020) Synthesis of green iron oxide nanoparticles and their application for the removal of toxic heavy metals from water. *International Journal of Phytoremediation*, vol. 22(9), page no. 877–888.
17. Siddiqi, K. S., Husen, A., & Rao, R. A. K. (2019). Green synthesis of metal nanoparticles using plants: A review. *International Journal of Analytical Chemistry*, 2019, Article 6272432.
18. Singh, J., Dutta, T., Kim, K.-H., Rawat, M., Samddar, P., & Kumar, P. (2018). 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology*, vol. 16(1), page 83.

19. Vijayan, S., Praseetha, P. K., & Rejani, P. (2018). Green synthesis of silver nanoparticles using Hibiscus rosa-sinensis leaf extract for effective removal of Pb(II) from aqueous solution. *Journal of Environmental Chemical Engineering*, vol. 6(5), page no. 5596–5605.
20. Zafar, M., Iqbal, M., & Firdous, S. (2022). Green synthesis of zinc oxide nanoparticles and their application for the removal of heavy metals from wastewater. *Sustainable Water Resources Management*, vol. 8(5), page no. 1–12.
21. Mangnale, V. (2025). Research as discovery: Unlocking new knowledge across disciplines. *myresearchgo*, 1(9), 1. <https://doi.org/10.64448/myresearchgo..vol.1.issue.9.01>
22. Ahiwale, A., & Ranpise, G. (2025). AI as a catalyst for human discovery: Redefining research, ethics, and lifelong learning in the digital era. *myresearchgo*, 1(9), 5. <https://doi.org/10.64448/myresearchgo..vol.1.issue.9.02>