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"Spectroscopic Investigation of Plant-Derived Metal Nanoparticles for the Adsorptive Removal of Hazardous Compounds from Wastewater"

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Abstract

Hazardous dyes, dissolved metals and persistent organic substances in wastewater require treatment technologies that are effective without creating additional environmental burdens. Plant-mediated synthesis of metal and metal-based nanoparticles offers an appealing route because naturally occurring phytochemicals can participate in reduction, nucleation and surface stabilization. This paper critically examines the relationship between synthesis chemistry, spectroscopic signatures and adsorption of wastewater contaminants. Particular attention is given to silver nanoparticles and iron-based particles, with gold nanoparticles included as a useful optical reference rather than a preferred large-scale adsorbent. A comparative experimental protocol is proposed involving aqueous plant extraction, nanoparticle synthesis, ultraviolet–visible spectroscopy, Fourier-transform infrared spectroscopy, X-ray diffraction, microscopy and controlled batch adsorption. The discussion addresses pollutant speciation, adsorption kinetics, equilibrium models, interference by wastewater constituents, particle recovery and potential metal leaching. Published literature supports the feasibility of plant-assisted synthesis but does not establish universal superiority over conventional adsorbents. Accordingly, this manuscript distinguishes evidence-based interpretation from experiments that remain to be performed. The study concludes that reproducible synthesis, rigorous separation of adsorption from degradation and careful assessment of environmental safety are prerequisites for practical wastewater applications.

Keywords: Plant extract; metal nanoparticles; green synthesis; UV–Vis; FTIR; XRD; adsorption; wastewater.

1. Introduction

Wastewater from textile finishing, metal processing, electroplating, chemical manufacture and other activities can contain dyes, dissolved metals and organic compounds that remain problematic after inadequate treatment. Even where pollutant concentrations are low, repeated discharge can produce chronic exposure and ecological damage. Selection of a treatment technology must therefore consider both contaminant removal and the environmental consequences of the treatment material itself.

Adsorption is attractive because it transfers dissolved contaminants to a recoverable solid phase and can be implemented in batch or continuous systems. Activated carbon, mineral sorbents, polymeric resins and biomass-derived materials are widely studied. Nanoscale materials introduce additional possibilities through their accessible surface chemistry, short diffusion distances and ability to be combined with larger supports. Nevertheless, nanoscale dimensions alone do not ensure excellent adsorption: aggregation, insufficient binding sites and poor recovery can offset the theoretical surface-area advantage.

Plant-mediated synthesis has gained attention as a way to replace some conventional reducing and stabilizing chemicals. Extracts contain mixtures of phenolic compounds, carbohydrates, proteins and other metabolites whose behavior depends on plant species, extraction conditions and storage. These constituents may reduce appropriate metal precursors, coordinate metal ions or cap particle surfaces. As a result, the botanical route can alter both particle formation and subsequent pollutant interactions.

Spectroscopic investigation provides a bridge between preparation and application. Optical absorption may indicate formation of silver or gold nanoparticles; infrared spectra reveal functional groups; diffraction identifies crystalline phases; and complementary microscopy helps evaluate particle morphology. A convincing adsorption study combines these observations with accurate aqueous concentration measurements and

mass balances rather than relying on a color change or a single spectral feature.

The purpose of this paper is to present a coherent, chemically grounded framework for examining plant-derived metal nanoparticles as wastewater adsorbents. It focuses on measurable structure–property relationships, experimentally testable mechanisms and realistic barriers to deployment.

2. Review of Literature

Vilchis-Nestor et al. (2008) investigated the green synthesis of gold and silver nanoparticles using Camellia sinensis (green tea) extract. The study demonstrated that naturally occurring compounds in plant extracts could support nanoparticle formation without conventional chemical reducing agents. The researchers examined the optical properties of the synthesized nanoparticles and highlighted the importance of plant-derived compounds in controlling nanoparticle formation. Their findings provided an early foundation for developing environmentally friendly methods of preparing metallic nanoparticles.

Kumar and Yadav (2009) discussed the plant-mediated synthesis of silver and gold nanoparticles and their potential applications. The study explained how biological compounds present in plant materials can participate in the reduction of metal ions and stabilization of nanoparticles. The authors highlighted the advantages of plant-based synthesis, including simpler preparation methods and reduced dependence on hazardous chemicals. Their work contributed to the growing interest in using biological resources for sustainable nanomaterial development.

Iravani (2011) reviewed the green synthesis of metal nanoparticles using different plant species and examined the role of plant metabolites in nanoparticle formation. The study described how compounds such as flavonoids, proteins, and polyphenols could act as reducing and stabilizing agents. It also discussed the influence of reaction conditions on nanoparticle size, shape, and stability. The research emphasized the potential of plant-based synthesis as an environmentally responsible alternative to conventional chemical methods.

Narayanan and Sakthivel (2011) examined the biological synthesis of metallic nanoparticles using terrestrial and aquatic organisms, including photosynthetic and non-photosynthetic biological systems. Their review discussed the mechanisms involved in nanoparticle formation and the contribution of biological molecules to particle stabilization. The authors highlighted the importance of controlling synthesis conditions to obtain nanoparticles with suitable structural and physicochemical properties. The study provided valuable information for understanding biological nanoparticle synthesis and its potential technological applications.

Mittal, Chisti, and Banerjee (2013) reviewed the synthesis of metallic nanoparticles using plant extracts and explored the role of naturally occurring biomolecules in the reduction of metal ions. The authors described the influence of plant species, extract concentration, temperature, and reaction conditions on nanoparticle formation. Their work also emphasized the importance of characterization techniques for evaluating particle size, morphology, and stability. The study supported the development of plant-mediated synthesis as a promising approach for producing functional nanomaterials.

Kuppusamy et al. (2016) investigated developments in the biosynthesis of metallic nanoparticles using plant derivatives and reviewed their potential pharmacological applications. The study described how different plant parts, including leaves, roots, fruits, and seeds, could be used for nanoparticle preparation. The authors discussed the contribution of phytochemicals to particle formation and stabilization, along with the influence of synthesis conditions on nanoparticle properties. Their review highlighted the versatility of plant-derived nanoparticles and the importance of understanding their biological and chemical characteristics.

Ahmed et al. (2016) reviewed the synthesis of silver nanoparticles using plant extracts, with particular attention to their antimicrobial applications. The study explained how plant-

based reducing agents facilitate nanoparticle formation and how different characterization methods help evaluate their properties. The authors discussed the influence of particle size, shape, and surface characteristics on functional performance. Their findings demonstrated the importance of green synthesis and nanoparticle characterization for developing materials with useful biological and environmental properties.

Saratale et al. (2018) reviewed recent developments in the green synthesis of metallic nanoparticles using plant materials and biological waste resources. The study emphasized the potential of agricultural residues and other biomass sources as affordable raw materials for nanoparticle production. The authors examined the influence of biological compounds on nanoparticle formation and discussed their agricultural and environmental applications. Their findings highlighted the importance of sustainable material selection and the possibility of utilizing waste-derived resources for nanotechnology applications.

Yadi et al. (2018) reviewed developments in the green synthesis of metallic nanoparticles using plant extracts and discussed the chemical and biological mechanisms involved in particle formation. The study explained how different phytochemical constituents contribute to the reduction and stabilization of metallic nanoparticles. The authors also discussed characterization methods used to investigate nanoparticle morphology, structural properties, and stability. Their review emphasized the importance of optimizing synthesis parameters to improve nanoparticle quality and reproducibility.

Nasrollahzadeh et al. (2021) examined green-synthesized nanocatalysts and nanomaterials for water treatment, focusing on their potential environmental applications and practical limitations. The study discussed the use of environmentally responsible synthesis methods for producing functional nanomaterials capable of participating in pollutant removal processes. The authors highlighted important challenges, including material stability, recovery, reusability, and large-scale application. Their work emphasized the need for further investigation into the effectiveness and environmental safety of green nanomaterials for wastewater treatment.

Gowda, Goveas, and Dakshayini (2022) investigated the adsorption of methylene blue using silver nanoparticles synthesized from Urena lobata leaf extract. The study examined nanoparticle formation and characterization alongside the adsorption behavior of the prepared material. Adsorption kinetics and equilibrium analysis were used to evaluate interactions between the nanoparticles and dye molecules. Their findings demonstrated the potential of plant-derived silver nanoparticles as adsorbents for dye-containing wastewater and highlighted the importance of adsorption studies in evaluating pollutant removal performance.

3. Objectives of the Study

- To investigate plant-mediated nanoparticle formation and determine optical, functional-group and crystalline characteristics using complementary spectroscopic techniques.
- To assess the adsorptive removal of selected dyes and dissolved metal ions under controlled aqueous conditions.
- To identify how solution chemistry, adsorbent properties and regeneration influence removal efficiency and practical environmental suitability.

4. Materials and Methods (Proposed Experimental Design)

4.1 Research design. This is a literature-informed experimental protocol, not a report of completed laboratory trials. Silver and iron-based nanoparticles are proposed for comparative testing. Gold nanoparticles may be synthesized on a smaller scale as an optical characterization reference, but their cost makes routine wastewater deployment less attractive.

4.2 Plant selection and extraction. Healthy neem or tulsi leaves may be collected with botanical identity documented. After rinsing with deionized water, leaves should be dried under controlled conditions, weighed and extracted in measured volumes of water. Extraction temperature, time, plant-to-water

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ratio and filtrate pH should be recorded. Extract-only blanks and replicate preparations are essential because phytochemical concentration varies naturally.

4.3 Particle preparation. For silver nanoparticles, aqueous silver nitrate may be mixed with plant extract at selected volume ratios while temperature and pH are controlled. A developing visible absorption band can support, but cannot alone prove, nanoparticle formation. For iron-based materials, suitable ferrous or ferric precursors may be reacted under conditions chosen for the intended phase. Metallic iron, magnetite and other iron oxides must not be treated as chemically interchangeable. Precipitates should be washed and recovered using a method appropriate to their composition. Residual precursor and free plant compounds should be quantified where feasible.

4.4 Characterization. UV–Vis scans of precursor, extract, reaction mixture and washed dispersions should be compared. FTIR spectra of the extract, washed material and pollutant-loaded adsorbent can reveal changes in surface groups. XRD with reference phase matching is required to distinguish crystalline products. TEM or SEM provides particle dimensions and morphology, while dynamic light scattering describes hydrodynamic aggregates rather than primary particle size. Zeta potential across the experimental pH range and BET surface area, when available, strengthen adsorption interpretation.

4.5 Wastewater preparation. Separate stock solutions of methylene blue and selected metal salts may be diluted to known concentrations. Metal experiments should be planned with speciation and solubility limits in mind. Synthetic wastewater allows controlled comparisons; subsequently, filtered and unfiltered real effluents should be assessed to examine matrix effects. All metal-containing solutions and nanoparticle residues require hazardous-waste management.

4.6 Batch adsorption. Measured adsorbent masses may be contacted with fixed wastewater volumes in capped vessels under controlled mixing. Samples should be collected at predefined times, separated using a validated method and analyzed against calibration standards. Methylene blue may be quantified spectrophotometrically if spectral interferences are excluded. Lead or cadmium requires validated elemental analysis, for example AAS or ICP–OES. Replicates, instrument blanks, matrix spikes and recovery checks should be incorporated.

4.7 Essential controls. Each series should include contaminant-only blanks, extract-only controls, precursor-only controls and adsorption vessels without nanoparticles. Light and dark experiments are valuable when photochemical degradation is possible. Dissolved metal released from the adsorbent should be measured in treated water. These controls establish whether the observed decrease represents adsorption rather than unrelated chemical transformation or sampling loss.

4.8 Calculations

The adsorption performance of plant-derived metal nanoparticles was evaluated using percentage removal and equilibrium adsorption capacity.

1. Percentage Removal

The percentage removal of pollutants was calculated using the following equation:

$$\text{Removal Efficiency (\%)} = \left(\frac{C_0 - C_t}{C_0}\right) \times 100$$

Where:

- C_0= Initial pollutant concentration (mg/L)
- C_t= Pollutant concentration at time t (mg/L)

2. Equilibrium Adsorption Capacity

The equilibrium adsorption capacity was calculated using the following equation:

$$q_e = \frac{(C_0 - C_e) \times V}{m}$$

Where:

- q_e = Equilibrium adsorption capacity (mg/g)
- C_0= Initial pollutant concentration (mg/L)
- C_e= Equilibrium pollutant concentration (mg/L)
- V= Volume of wastewater solution (L)
- m= Mass of adsorbent (g)

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5. Results:

Table 1. Characterization techniques

Method	Primary evidence	Important limitation
UV–Vis	Optical absorption; plasmon response	Not sufficient for phase identification
FTIR	Surface functional groups	Overlapping bands and ambiguous assignments
XRD	Crystalline phase and crystallite estimate	Weak sensitivity to amorphous coatings
SEM/TEM	Morphology and particle dimensions	Limited field of view
Zeta potential	Electrokinetic surface behavior	Depends on pH and ionic strength

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Table 2. Material comparison

Material	Potential advantage	Key concern
Silver nanoparticles	Convenient optical characterization	Silver leaching and recovery
Iron-based nanoparticles	Potentially lower cost; possible magnetic recovery	Oxidation and competing removal pathways
Gold nanoparticles	Well-defined optical behavior	High precursor cost

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Table 3. Adsorption variables

Variable	Expected influence	Recommended control
pH	Surface charge and contaminant speciation	No-adsorbent pH blanks
Contact time	Kinetics and equilibration	Multiple timed samples
Dose	Number of available binding sites	Report both % removal and mg/g
Ionic strength	Competition and aggregation	Controlled salt series
Reuse cycles	Surface aging and material losses	Leaching and mass recovery

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6. Conclusion

Spectroscopic characterization techniques such as UV–Visible spectroscopy, Fourier Transform Infrared (FTIR) spectroscopy, and X-ray Diffraction (XRD) provide essential information about nanoparticle formation, surface functional groups, and crystalline structure. These analytical techniques contribute to understanding the relationship between nanoparticle properties and adsorption mechanisms. The comparative

analysis suggests that adsorption performance is influenced by several operational parameters, including solution pH, contact time, adsorbent dosage, initial pollutant concentration, and nanoparticle stability.

The study further identifies the importance of evaluating adsorption efficiency, equilibrium adsorption capacity, and regeneration potential when assessing the suitability of plant-derived nanoparticles for environmental applications. Although published research demonstrates encouraging pollutant removal performance, practical challenges remain concerning nanoparticle aggregation, recovery, metal leaching, and large-scale production. Therefore, further experimental validation using actual industrial wastewater is necessary to establish treatment efficiency, environmental safety, and economic feasibility.

Overall, the study concludes that plant-derived metal nanoparticles represent a promising approach to wastewater remediation by combining green synthesis principles with advanced material characterization and adsorption-based pollutant removal. Continued research focusing on improved nanoparticle stability, adsorption selectivity, reusability, and scalable treatment technologies may support the development of cost-effective and environmentally responsible wastewater purification systems.

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