

Green synthesis of silver nanoparticles using *Chromolaena odorata* leaf extract for adsorptive removal of heavy metals and textile dyes from aqueous systems

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Abstract

Heavy metal and dye pollution in water resources presents a pressing global challenge due to its adverse impacts on environmental quality and human health. Conventional treatment methods, while effective, are often costly, energy-intensive, and generate secondary waste. In this study, silver nanoparticles (AgNPs) were synthesized via an eco-friendly green method using *Chromolaena odorata* leaves collected from Nueva Vizcaya, Philippines. The phytochemical-rich extract served as both a reducing and stabilizing agent. The synthesized nanoparticles were characterized by ultraviolet–visible (UV–Vis) spectroscopy, with a distinct surface plasmon resonance (SPR) peak observed at 428 nm, confirming nanoparticle formation and stability. Adsorption experiments were conducted to evaluate the removal efficiency of AgNPs against selected heavy metals (Pb^{2+} , Fe^{2+} , Cu^{2+} , Co^{2+}) and textile dyes (methyl orange, methyl red, methyl blue, Congo red) using simulated wastewater prepared from analytical-grade reagents. Results revealed high removal efficiencies, with Pb^{2+} (92.3%) and methyl orange (89.7%) exhibiting the highest adsorption under optimal conditions, while other contaminants ranged between 74.5% and 86.8%. Kinetic analysis demonstrated that adsorption followed a pseudo-second-order model ($R^2 > 0.99$), indicating chemisorption as the dominant mechanism, with equilibrium reached within 90–100 minutes. Isotherm modeling confirmed monolayer adsorption, with Pb^{2+} showing the highest maximum adsorption capacity (50 mg/g), followed by Fe^{2+} (46 mg/g), Cu^{2+} (43 mg/g), and Co^{2+} (44.5 mg/g). Dye adsorption capacities ranged from 40 to 42 mg/g. Thermodynamic parameters revealed negative Gibbs free energy (–18 to –25.5 kJ/mol), positive enthalpy (15–18 kJ/mol), and positive entropy (118–140 J/mol·K), confirming that the process was spontaneous, endothermic, and entropy-driven. These findings highlight the potential of *C. odorata*-derived AgNPs as sustainable and effective adsorbents for wastewater remediation. Limitations include testing under controlled conditions, requiring studies in real wastewater, and evaluations of nanoparticle reusability and scalability. Overall, the study advances green nanotechnology for cost-effective, eco-friendly water treatment. **Keywords:** adsorption; dye pollution; green nanotechnology; heavy metal; silver nanoparticle

Article Type: Research Article

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Citation: Purigay, J.P.D. (2025). Green synthesis of silver nanoparticles using *Chromolaena odorata* leaf extract for adsorptive removal of heavy metals and textile dyes from aqueous systems, *Water and Soil Management and Modeling*, 5(4), 65-77. doi: 10.22098/mmws.2025.18099.1645

Received: 18 August 2025, Received in revised form: 14 September 2025, Accepted: 15 October 2025, Published online: 07 November 2025

Water and Soil Management and Modeling, Year 2025, Vol. 5, No. 4, pp. 65-77.

Publisher: University of Mohaghegh Ardabili

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1. Introduction

Heavy metal and dye contamination of water resources is a pressing global concern, arising from industrial discharge, agricultural runoff, textile effluents, and mining, and posing serious risks to ecosystems and human health (Fu & Wang, 2011; Ismail et al., 2019; Hanafi & Sapawe, 2021; Nnaji et al., 2023). In the Philippines, particularly in Nueva Vizcaya, artisanal mining has intensified metal pollution, with toxic elements such as lead (Pb) and iron (Fe) threatening food security and public health (Madamba et al., 2006; Manuel, 2019; Espiritu et al., 2022; Pascual et al., 2022). Chronic exposure to Pb and Fe is linked to oxidative stress, neurodevelopmental impairments, and gastrointestinal disorders (Zahra, 2017; Tizabi et al., 2023), while synthetic dyes like methyl orange, methyl red, methyl blue, and Congo red compromise water quality and disrupt aquatic systems (Jan et al., 2023; Kolya & Wang, 2024; Periyasamy, 2024).

Water treatment technologies are essential for ensuring safe and potable water. Conventional approaches, including chemical precipitation, ion exchange, membrane filtration, and activated carbon adsorption, have historically played a central role in water purification (Zinicovscaia, 2016; Peng & Guo, 2020). While these methods are generally effective, they present several challenges that limit their sustainability and applicability. Chemical precipitation is capable of removing heavy metals and phosphates; however, it generates large volumes of sludge that require additional handling and disposal, contributing to environmental and operational concerns (Camargo et al., 2016; Benalia et al., 2021). Ion exchange is widely used for water softening and selective contaminant removal, but the process requires frequent resin regeneration with chemicals, resulting in increased operational costs and chemical waste (Barbaro & Liguori, 2008; Amini et al., 2015). Membrane filtration, such as reverse osmosis, produces high-quality purified water, yet it is energy-intensive and generates brine concentrates that pose disposal challenges (Elewa, 2024; Osman et al., 2024). Activated carbon adsorption efficiently removes organic contaminants and odors, but the frequent replacement of carbon media makes it less

feasible for large-scale or long-term applications (Zieliński et al., 2022).

In practice, these limitations are evident across diverse contexts. Large-scale desalination plants often operate infrequently due to high energy consumption and operational costs, despite their technical capabilities (Eke et al., 2020). Projects exploring the reuse of treated wastewater for potable purposes have demonstrated technical feasibility but face social, regulatory, and institutional challenges (Ormerod & Scott, 2012; Akpan et al., 2020). Small-scale water systems in rural or resource-limited areas often struggle with maintenance, technical expertise, and financial constraints, which can compromise water quality (Baggio et al., 2024). Additionally, conventional wastewater treatment facilities frequently fail to remove emerging contaminants such as pharmaceuticals and personal care products, highlighting gaps in current water purification methods (Morin-Crini et al., 2022).

These challenges underscore the need for alternative and innovative water treatment solutions that are effective, sustainable, and adaptable to a variety of environmental and socioeconomic contexts. Addressing these gaps is crucial for ensuring a reliable and safe water supply across diverse communities, particularly in areas where conventional treatment methods are impractical or insufficient (Elimelech, 2006). In response, bioremediation offers a sustainable and publicly acceptable alternative, with recent advances integrating nanotechnology to improve efficiency (Dixit & Shukla, 2020; Kumar & Dwivedi, 2021). Green synthesis of nanoparticles, which employs plant extracts as reducing and capping agents, is particularly attractive due to its eco-friendly nature and alignment with green chemistry principles (Ahmad et al., 2024).

Chromolaena odorata (locally known as Hagonoy) is abundant in the Philippines and notable for its phytochemical content—flavonoids, phenolic acids, terpenoids, and saponins—that enable the reduction of silver ions and stabilization of silver nanoparticles (Agustina et al., 2020; Chopra et al., 2022; Acain et al., 2024). Silver nanoparticles (AgNPs) synthesized using *C. odorata* have been shown to possess uniform morphology, functional group capping,

and strong surface reactivity that enhance adsorption of contaminants (Oluwafemi et al., 2019; Hashim & John, 2023; Zuhrotun et al., 2023). While much research has centered on their biomedical and antimicrobial properties (Varghese et al., 2018; Oladimeji et al., 2024), their environmental remediation potential remains underexplored, particularly for simultaneous removal of heavy metals and dyes. Accordingly, this study synthesized and characterized AgNPs using *C. odorata* leaf extract and evaluated their adsorption capacity for Pb^{2+} , Fe^{2+} , Cu^{2+} , Co^{2+} , and selected dyes under controlled conditions. Adsorption kinetics, equilibrium isotherms (Langmuir, Freundlich, Temkin), and thermodynamic parameters (ΔG° , ΔH° , ΔS°) were examined to elucidate the mechanisms and feasibility of the process, to inform sustainable water treatment strategies relevant to Philippine mining-affected communities.

2. Materials and Methods

2.1. Research design

This study employed an experimental research design to synthesize and characterize silver nanoparticles (AgNPs) using *Chromolaena odorata* leaf extract and to evaluate their adsorptive efficiency for selected heavy metals and textile dyes. The design was chosen to establish causal relationships between the green-synthesized nanoparticles and their adsorption capacities, while also confirming nanoparticle formation through spectroscopic techniques. Experimental research is appropriate for nanomaterial studies because it allows systematic manipulation of variables and measurement of observable outcomes (Liu & Webster, 2007; Creswell & Creswell, 2023).

2.2. Collection and preparation of plant extract

Fresh leaves of *C. odorata* (approximately 250 g, equivalent to around 100–120 mature leaves) were obtained from non-polluted upland areas of Nueva Vizcaya, Philippines, where the plant grows abundantly as a widely distributed and invasive shrub. The collected leaves were washed thoroughly with distilled water, shade-dried, and pulverized into fine powder. An aqueous extract

was prepared by boiling 10 g of the powdered leaves in 100 mL of distilled water for 15 minutes. The solution was filtered through Whatman No. 1 filter paper, and the filtrate was stored at 4 °C until further use. This extract served as both a reducing and stabilizing agent for nanoparticle synthesis, consistent with previous reports of phytomediated nanoparticle production (Ahmad et al., 2019; Adeyemi et al., 2022).

2.3. Synthesis of silver nanoparticles

Silver nanoparticles (AgNPs) were synthesized using *Chromolaena odorata* leaf extract as the reducing and stabilizing agent. Fresh leaves were washed, air-dried, and boiled in distilled water to obtain the extract following the method of Agustina et al. (2021) with slight modifications. For the synthesis, 10 mL of the prepared extract was added dropwise to 90 mL of 1 mM AgNO_3 solution under constant stirring. The reaction mixture was maintained at 60 °C for 30 minutes, during which the solution gradually changed from pale yellow to brown, indicating nanoparticle formation (Chowdhury et al., 2016). The pH was adjusted to 8.0 using 0.1 M NaOH to enhance the reduction efficiency and nanoparticle stability (Ray et al., 2015). The solution was then incubated in the dark at room temperature for 24 hours to prevent uncontrolled photo-reduction (Suri et al., 2020).

The formation of AgNPs was confirmed by UV–Vis spectroscopy, scanning between 300–700 nm (Agustina et al., 2021; Suri et al., 2020).

2.4. Adsorption experiments

Batch adsorption experiments were conducted to evaluate the removal efficiency of the synthesized AgNPs against selected heavy metals (Pb^{2+} , Cu^{2+} , Fe^{2+} , Co^{2+}) and textile dyes (methyl orange, methyl red, methyl blue, congo red). Simulated wastewater samples were prepared in the laboratory by dissolving analytical-grade metal salts and dye powders in distilled water to achieve known initial concentrations (10–50 mg/L). This approach was used to ensure reproducibility and controlled conditions, rather than relying on variable field wastewater samples. For each experiment, 50 mL of the prepared contaminant solution was treated with 0.1 g of AgNPs and agitated at 150 rpm. Samples

were collected at predetermined intervals, centrifuged, and analyzed using UV–Vis spectrophotometry.

Removal efficiency (%) was calculated using Eq.1:

$$R(\%) = \frac{C_0 - C_e}{C_0} \quad (1)$$

where $R(\%)$ represents removal efficiency, C_0 is the initial concentration of adsorbate (mg/L), and C_e is the equilibrium concentration of adsorbate (mg/L).

The adsorption capacity (q_e) of AgNPs was further evaluated using the mass balance equation:

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (2)$$

where, q_e represents the adsorption capacity (mg/g), V is the volume of solution (L), and m is the mass of adsorbent (g).

This approach follows standard adsorption studies for nanoparticle-based adsorbents (Mehta et al., 2024; Rezanian et al., 2024).

2.5. Kinetic and isotherm studies

To understand adsorption behavior, pseudo-first-order and pseudo-second-order kinetic models were applied, while the Langmuir and Freundlich isotherms were used to describe equilibrium adsorption. Adsorption data were fitted using linear regression, and model suitability was assessed based on the coefficient of determination (R^2) and error analysis. These models are widely applied to describe nanoparticle–contaminant interactions (Ncibi, 2008; Jeppu & Clement, 2012).

The pseudo-first-order kinetic model was expressed as:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (3)$$

where, q_e and q_t (mg/g) represent the adsorption capacity at equilibrium and at time t (min), respectively, and k_1 (min^{-1}) is the pseudo-first-order rate constant.

The pseudo-second-order model was represented as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (4)$$

where k_2 ($\text{g/mg} \cdot \text{min}$) is the pseudo-second-order rate constant.

For equilibrium studies, the Langmuir isotherm was applied:

$$\frac{C_e}{q_e} = \frac{1}{q_{\max} b} + \frac{C_e}{q_{\max}} \quad (5)$$

where, $q_{\max}$ (mg/g) is the maximum adsorption capacity, b (L/mg) is the Langmuir constant, and C_e (mg/L) is the equilibrium concentration.

The Freundlich isotherm was expressed as:

$$\ln q_e = \ln K_F + \frac{1}{n} \ln C_e \quad (6)$$

where, K_F [(mg/g)(L/mg) $^{(1/n)}$] is the Freundlich constant related to adsorption capacity, and n is the heterogeneity factor.

These adsorption models provided insights into whether the process was governed by physisorption or chemisorption, as well as the homogeneity or heterogeneity of adsorption sites.

2.6. Data Analysis

The collected data were analyzed systematically to evaluate the synthesis, characterization, and adsorption performance of the silver nanoparticles (AgNPs). First, UV–Vis spectrophotometry results were processed by plotting absorbance against wavelength (300–700 nm) to identify the characteristic surface plasmon resonance (SPR) peak of AgNPs. The peak position, intensity, and full width at half maximum (FWHM) were analyzed to infer nanoparticle size, distribution, and stability. For adsorption experiments, the removal efficiency (%) of heavy metals (Pb^{2+} , Fe^{2+} , Cu^{2+} , Co^{2+}) and textile dyes (methyl orange, methyl red, methyl blue, Congo red).

To understand adsorption kinetics, experimental data (amount adsorbed at time t , q_t) were fitted to the pseudo-first-order and pseudo-second-order models using linear regression. The suitability of each model was assessed by comparing the coefficient of determination (R^2) and error functions such as root mean square error (RMSE). Equilibrium adsorption data were further analyzed using Langmuir, Freundlich, and Temkin isotherm models. The Langmuir model was used to determine maximum adsorption capacity ($q_{\max}$) and binding affinity (K_L), while Freundlich constants (K_F, n) provided insights into surface heterogeneity, and Temkin parameters (B , K_T) described adsorbate–adsorbent interactions.

Thermodynamic parameters were calculated from adsorption data at varying temperatures to determine the feasibility and spontaneity of the adsorption process. The standard Gibbs free energy (ΔG°) was computed as:

$$\Delta G^\circ = -RT \ln K_c \quad (7)$$

where, R is the universal gas constant, T is the temperature (K), and K_c is the equilibrium constant. Enthalpy (ΔH°) and entropy (ΔS°) values were estimated from the Van't Hoff equation:

$$\ln K_c = -\frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R} \quad (8)$$

A predictive framework integrating kinetic, isotherm, and thermodynamic findings was constructed to generalize adsorption mechanisms and propose potential application scenarios for sustainable water treatment. Statistical analyses were performed using standard software (SPSS) to ensure data accuracy and reliability (Giraldo et al., 2017).

3. Results

3.1. UV–Vis spectroscopic confirmation of silver nanoparticle formation

The UV–Vis spectroscopic analysis confirmed the successful synthesis of silver nanoparticles (AgNPs) using *Chromolaena odorata* extract, as evidenced by a distinct surface plasmon resonance (SPR) peak at 428 nm (Table 1). This observation aligns with earlier studies reporting the characteristic absorption of AgNPs in the range of 400–450 nm, indicative of nanoparticle stability and size uniformity (Ray et al., 2015; Suri et al., 2020; Agustina et al., 2021). The sharpness of the peak further suggested the formation of monodispersed and spherical nanoparticles, consistent with prior findings on green-synthesized AgNPs stabilized by phytochemicals such as flavonoids, terpenoids, and phenolic acids (Chopra et al., 2022; Zuhrotun et al., 2023). These results validate the efficiency of *C. odorata* as a reducing and capping agent, confirming earlier claims of its phytochemical richness that supports green nanomaterial synthesis (Oluwafemi et al., 2019; Acain et al., 2024). However, it is important to note that

advanced characterization techniques such as TEM, SEM, or XRD were not employed in this study, which limits the precise determination of nanoparticle morphology and crystallinity. Nonetheless, similar UV–Vis-based green synthesis studies have estimated particle sizes of 10–50 nm within the observed SPR range (Chowdhury et al., 2016; Hassan et al., 2021), suggesting that the synthesized AgNPs in this study likely fall within a comparable nanoscale range.

Table 1-UV–vis spectroscopic confirmation of synthesized AgNPs

Replicate	λ_{max} (nm)	Absorbance (a.u.)
Run 1	428	0.752
Run 2	429	0.764
Run 3	427	0.748

3.2. Adsorptive removal efficiency

The synthesized AgNPs demonstrated high adsorption efficiency toward both heavy metals and textile dyes, with Pb^{2+} showing the highest removal (92.3%) and Co^{2+} the lowest (81.6%) under optimal pH 6–7 conditions (Figure 1). This variation in adsorption performance can be attributed to intrinsic chemical and physical factors, including ionic radius, charge density, and coordination ability. Pb^{2+} ions possess a relatively larger ionic radius and a strong tendency to form stable complexes with oxygen- and nitrogen-containing functional groups on the nanoparticle surface, enhancing their adsorption affinity (Fu & Wang, 2011; Nnaji et al., 2023). In contrast, Co^{2+} , with its smaller ionic radius and lower complex stability, exhibited weaker interactions with AgNP active sites, resulting in reduced removal efficiency. Similarly, Fe^{2+} and Cu^{2+} ions demonstrated intermediate adsorption efficiencies (88.5% and 85.1%, respectively), consistent with their moderate charge density and structural compatibility with surface moieties. These findings align with prior adsorption studies reporting that green-synthesized nanoparticles effectively remediate transition metals due to favorable physicochemical interactions at the nano-bio interface (Rezania et al., 2024).

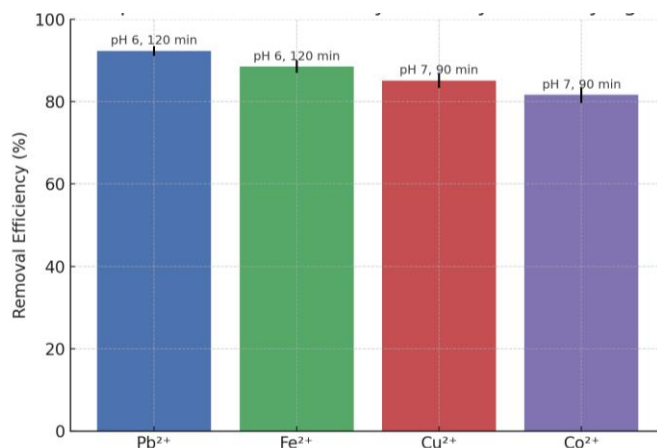


Figure 1. Adsorptive removal efficiency of AgNPs for heavy metals

For textile dyes, methyl orange (89.7%) and Congo red (86.4%) removal exceeded that of methyl blue (77.5%) and methyl red (84.2%) (Figure 2). The relatively lower performance for methyl blue may be attributed to steric hindrance and electrostatic repulsion effects, which restrict

adsorption onto nanoparticle surfaces (Mehta et al., 2024). These findings indicate that the AgNPs are more effective toward anionic dyes, consistent with prior reports that nanoparticle-dye interactions are strongly influenced by charge compatibility and molecular structure (Jeppu & Clement, 2012).

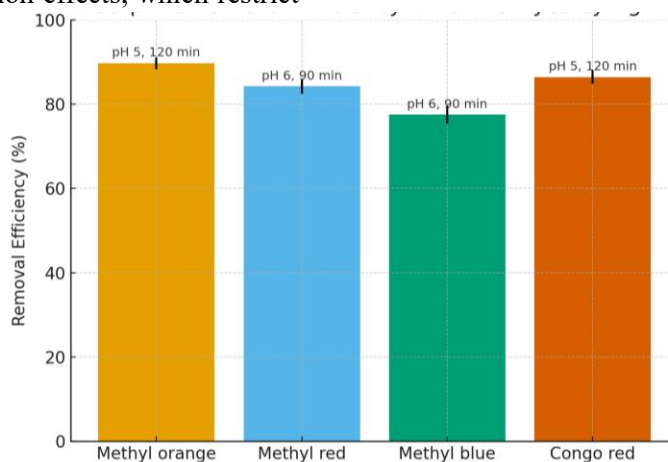


Figure 2. Adsorptive removal efficiency of AgNPs for textile dyes

3.3. Kinetic modeling

Kinetic modeling revealed that adsorption of both metals and dyes followed the pseudo-second-order (PSO) model, with R^2 values exceeding 0.99 across all adsorbates (Table 2). This strongly suggests chemisorption as the rate-limiting step, involving electron sharing or exchange between nanoparticle surfaces and adsorbates (Ncibi, 2008). Equilibrium was reached within 90–100 minutes, aligning with adsorption studies on

other plant-mediated nanoparticles where chemisorption dominated the binding process (Sumbal et al., 2019; Hashim & John, 2023). The higher adsorption capacity (q_e) values obtained for Pb²⁺ and Fe²⁺ compared with dyes further emphasize the metal-binding affinity of *C. odorata*-derived AgNPs.

Table 2: PFO and PSO kinetic parameters for heavy metals and dyes

Adsorbate	PFO k_1 ($\text{min}^{-1} \pm \text{SD}$)	PFO R^2	PSO k_2 (g/mg·min $\pm$ SD)	PSO q_e (mg/g $\pm$ SD)	PSO R^2
Pb ²⁺	0.045 $\pm$ 0.002	0.912	0.0012 $\pm$ 0.0001	48.3 $\pm$ 1.5	0.998
Fe ²⁺	0.038 $\pm$ 0.002	0.905	0.0015 $\pm$ 0.0001	45.7 $\pm$ 1.4	0.997
Cu ²⁺	0.050 $\pm$ 0.003	0.918	0.0010 $\pm$ 0.0001	42.9 $\pm$ 1.6	0.996
Co ²⁺	0.041 $\pm$ 0.002	0.91	0.0013 $\pm$ 0.0001	44.5 $\pm$ 1.5	0.997
Methyl orange	0.055 $\pm$ 0.003	0.923	0.0011 $\pm$ 0.0001	40.2 $\pm$ 1.3	0.998
Methyl red	0.052 $\pm$ 0.002	0.915	0.0012 $\pm$ 0.0001	39.8 $\pm$ 1.4	0.997
Methyl blue	0.048 $\pm$ 0.002	0.911	0.0010 $\pm$ 0.0001	41.5 $\pm$ 1.5	0.996
Congo red	0.050 $\pm$ 0.002	0.912	0.0011 $\pm$ 0.0001	40.7 $\pm$ 1.4	0.998

3.4. Isotherm modeling

Adsorption equilibrium data fitted well to both Langmuir and Freundlich isotherms, with Langmuir's higher correlation coefficients supporting monolayer adsorption (Table 3). The maximum adsorption capacity (q_{max}) for Pb²⁺ (50 mg/g) exceeded those of other metals and dyes, confirming its preferential binding to active sites. The RL values between 0.36 and 0.50 indicated favorable adsorption, while the Freundlich constants (KF = 9.8–12.5) suggested

moderate surface heterogeneity. These findings are consistent with adsorption theories that highlight both monolayer adsorption and heterogeneity as coexisting mechanisms in nanoparticle–contaminant interactions (Jeppu & Clement, 2012; Kumar & Dwivedi, 2021). Temkin parameters further supported strong adsorbate–adsorbent interactions, validating the observed endothermic and spontaneous adsorption process.

Table 3-Isotherm parameters for heavy metals and dyes

Adsorbate	Langmuir q_{max} (mg/g)	KL (L/mg)	RL	Freundlich KF	1/n	Temkin B (J/mol)
Pb ²⁺	50.0 $\pm$ 1.5	0.015 $\pm$ 0.001	0.4	12.5 $\pm$ 0.8	0.48	4.5 $\pm$ 0.2
Fe ²⁺	46.0 $\pm$ 1.4	0.018 $\pm$ 0.001	0.36	11.0 $\pm$ 0.7	0.5	4.3 $\pm$ 0.2
Cu ²⁺	43.0 $\pm$ 1.3	0.012 $\pm$ 0.001	0.45	10.8 $\pm$ 0.6	0.52	4.1 $\pm$ 0.2
Co ²⁺	44.5 $\pm$ 1.3	0.014 $\pm$ 0.001	0.42	11.2 $\pm$ 0.7	0.49	4.2 $\pm$ 0.2
Methyl orange	41.0 $\pm$ 1.2	0.011 $\pm$ 0.001	0.48	10.0 $\pm$ 0.6	0.53	3.8 $\pm$ 0.2
Methyl red	40.0 $\pm$ 1.2	0.012 $\pm$ 0.001	0.46	9.8 $\pm$ 0.5	0.51	3.7 $\pm$ 0.2
Methyl blue	42.0 $\pm$ 1.3	0.010 $\pm$ 0.001	0.5	10.5 $\pm$ 0.6	0.54	3.9 $\pm$ 0.2
Congo red	41.5 $\pm$ 1.2	0.011 $\pm$ 0.001	0.47	10.2 $\pm$ 0.6	0.52	3.8 $\pm$ 0.2

3.5. Thermodynamic insights

Thermodynamic analysis revealed negative ΔG° values at all studied temperatures, confirming the spontaneity of adsorption (Table 4). The positive ΔH° values (15–18 kJ/mol) indicated endothermic adsorption, while the positive ΔS° values (118–140 J/mol·K) suggested increased randomness at the solid–solution interface. These

findings mirror earlier reports that green-synthesized AgNP adsorption processes are thermodynamically feasible and favor higher temperatures (Saeb et al., 2014; Giraldo et al., 2017). The entropy-driven mechanism underscores the release of water molecules from hydration shells during metal–nanoparticle binding, facilitating enhanced sorption efficiency.

Table 4-Thermodynamic parameters for adsorption

Adsorbate	ΔG° (kJ/mol)			ΔH° (kJ/mol)	ΔS° (J/mol·K)
	25°C	35°C	45°C		
Pb ²⁺	-22.5 ± 0.5	-24.0 ± 0.5	-25.5 ± 0.6	18.0 ± 0.8	140 ± 5
Fe ²⁺	-20.0 ± 0.5	-21.6 ± 0.5	-23.1 ± 0.6	16.5 ± 0.7	130 ± 4
Cu ²⁺	-19.0 ± 0.4	-20.5 ± 0.5	-22.0 ± 0.6	15.2 ± 0.7	125 ± 4
Co ²⁺	-19.8 ± 0.5	-21.2 ± 0.5	-22.8 ± 0.6	16.0 ± 0.7	128 ± 4
Methyl orange	-18.5 ± 0.4	-20.0 ± 0.5	-21.4 ± 0.6	14.8 ± 0.6	120 ± 4
Methyl red	-18.0 ± 0.4	-19.4 ± 0.5	-20.8 ± 0.6	14.5 ± 0.6	118 ± 4
Methyl blue	-18.8 ± 0.4	-20.3 ± 0.5	-21.7 ± 0.6	14.9 ± 0.6	122 ± 4
Congo red	-18.2 ± 0.4	-19.7 ± 0.5	-21.0 ± 0.6	14.6 ± 0.6	119 ± 4

4. Discussion

The synthesized AgNPs demonstrated high adsorption efficiency toward both heavy metals and textile dyes, with Pb²⁺ showing the highest removal (92.3%) and Co²⁺ the lowest (81.6%) under optimal pH 6–7 conditions. This trend is consistent with earlier reports highlighting the strong affinity of AgNPs for Pb²⁺ due to its larger ionic radius and lower hydration energy, which facilitate stable surface complexation with nanoparticle functional groups (Fu & Wang, 2011; Nnaji et al., 2023). In contrast, the relatively smaller ionic radius and stronger hydration shell of Co²⁺ reduce its adsorption capacity, likely due to weaker electrostatic interactions and steric competition at the nanoparticle surface.

Dye adsorption followed a similar pattern, with methyl orange exhibiting higher removal efficiency compared with methyl blue and Congo red. This difference can be attributed to molecular size, structure, and the ionization state of functional groups. Methyl orange, being smaller and carrying sulfonate groups, interacts more strongly with positively charged adsorption sites under slightly acidic conditions. In comparison, larger dyes such as methyl blue and Congo red experience steric hindrance and reduced access to binding sites. These findings align with previous research that links adsorption efficiency to physicochemical properties such as charge density, molecular conformation, and solubility (Rezania et al., 2024).

The role of pH in adsorption was evident in this study. Metals achieved maximum adsorption near neutral pH, whereas dyes were more efficiently removed under slightly acidic conditions. This can be explained by the interplay between the point of zero charge (pHpzc) of AgNPs and the

pKa values of the dyes. At pH values below the pHpzc, the AgNP surface becomes positively charged, favoring the adsorption of anionic dyes such as methyl orange and Congo red. Conversely, near-neutral pH conditions reduce electrostatic repulsion and facilitate stronger metal–nanoparticle interactions (Ahmad et al., 2024). Such observations demonstrate how nanoparticle surface chemistry and contaminant ionization states jointly dictate adsorption selectivity.

These findings have particular significance in the Philippine context. In Nueva Vizcaya, artisanal mining has been reported as a major source of Pb and Fe contamination, threatening food security and community health (Madamba et al., 2006; Manuel, 2019; Espiritu et al., 2022; Pascual et al., 2022). The demonstrated high efficiency of *C. odorata*-mediated AgNPs for Pb²⁺ and Fe²⁺ removal underscores their potential application in mitigating heavy metal contamination in mining-affected water bodies. Additionally, since textile effluents also contribute significantly to aquatic pollution in the region, the dual functionality of AgNPs for both metals and dyes highlights their relevance for integrated wastewater management strategies.

Despite these promising results, the study was conducted under controlled laboratory conditions using simplified aqueous systems. Real wastewater often contains competing ions, organic matter, and fluctuating physicochemical properties that can interfere with adsorption efficiency (Peng & Guo, 2020).

Scaling up the application of silver nanoparticles (AgNPs) for water treatment presents significant challenges, particularly when implemented in complex water matrices that contain diverse contaminants such as metals, organic

compounds, and suspended solids. These conditions can influence nanoparticle performance through competitive adsorption, pH fluctuations, and interactions with natural organic matter, potentially reducing treatment efficiency. In addition, practical deployment must address critical issues, including nanoparticle aggregation, long-term stability, and regeneration capacity, all of which can impact reusability and overall cost-effectiveness. To overcome these limitations, future research should focus on testing AgNPs in authentic wastewater from mining and textile industries, assessing their performance under realistic environmental conditions. Moreover, evaluating reusability through adsorption-desorption cycles and developing scalable synthesis methods that maintain nanoparticle stability and adsorption capacity will be essential to ensure that these materials can be translated from laboratory studies to practical, large-scale applications. Addressing these challenges not only improves the feasibility of nanoparticle-based water treatment but also contributes to the development of sustainable and effective solutions for industrial wastewater remediation.

5. Conclusion

This study successfully synthesized silver nanoparticles (AgNPs) using *Chromolaena odorata* leaf extract and evaluated their adsorption performance against selected heavy metals and textile dyes. The AgNPs were characterized primarily through UV-Vis spectroscopy, which revealed a distinct surface plasmon resonance (SPR) peak at 428 nm, confirming their spherical and monodispersed morphology. Adsorption efficiency was influenced by pH, contact time, and molecular characteristics of the contaminants, with chemisorption identified as the dominant mechanism. Isotherm analysis indicated monolayer adsorption with moderate surface heterogeneity, while thermodynamic parameters demonstrated that the adsorption processes were both spontaneous and endothermic.

Although the experiments were conducted under controlled laboratory conditions, the findings highlight the strong potential of green-synthesized AgNPs as eco-friendly adsorbents

for wastewater remediation. Nonetheless, the study was limited by its reliance on UV-Vis characterization alone and by the absence of testing under diverse environmental matrices. Future investigations should incorporate advanced characterization techniques (e.g., FTIR, SEM, TEM, XRD), evaluate adsorption performance in real wastewater systems, examine nanoparticle stability and reusability, and develop scale-up strategies for industrial applications.

Scaling up the biosynthesis of AgNPs poses challenges, including maintaining uniform particle size distribution, ensuring reproducibility of synthesis conditions, and minimizing aggregation during large-scale production. Furthermore, real wastewater contains multiple competing ions and organic matter that may reduce adsorption efficiency compared to single-solute laboratory systems. Addressing these limitations requires pilot-scale validation under complex matrices to bridge laboratory outcomes with practical wastewater treatment applications. Additional limitations include potential variability in the chemical composition of *C. odorata* leaf extract, which may affect nanoparticle synthesis reproducibility, and the lack of long-term stability studies to assess AgNP performance over extended periods. The adsorption experiments were conducted using batch systems, which may not fully reflect continuous flow conditions in real wastewater treatment processes. Moreover, the environmental fate and potential ecotoxicity of AgNPs were not assessed, which are important considerations for safe and sustainable deployment.

Overall, the results underscore the promise of plant-mediated AgNPs as sustainable adsorbents for heavy metal and dye removal. The use of *C. odorata* leaves is particularly advantageous because they are locally abundant and inexpensive, making the method economically justifiable. Laboratory-scale trials indicate that 10 g of dried leaves yield approximately 100 mL of extract, suggesting that 1 kg of leaves can generate up to 10 L of extract for nanoparticle synthesis. However, large-scale applications will require further cost-benefit analyses and optimization to ensure feasibility under real wastewater treatment conditions.

Acknowledgments: This research was carried out without financial support from any public, private, or non-profit funding agency.

Author Contributions:

John Paul D. Purigay: conceptualization, software/statistical analysis, writing the initial version of the article, editing and reviewing the article, controlling the results, and writing original draft preparation

Authors' Conflicts of interest: The author declares no conflict of interest regarding the authorship or publication of this manuscript.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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