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Green Synthesis of SnO_2 Nanoparticles Using *Cinnamomum verum* Extract for the Removal of Pb(II), Cd(II), Cr(VI), and Hg(II) from Wastewater

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Abstract

This manuscript presents a full paper for the sustainable preparation of tin oxide (SnO_2) nanoparticles using *Cinnamomum verum* extract and their application in toxic-metal removal from wastewater. The study was structured around a low-toxicity plant-mediated reduction route in which cinnamon phytochemicals act as both reducing and stabilising agents. In the drafted methodology, an aqueous cinnamon extract was reacted with $SnCl_2{\cdot}2H_2O$, followed by washing, drying, and calcination to obtain crystalline SnO_2 nanoparticles. The resulting material was characterised by UV-vis spectroscopy, X-ray diffraction, FTIR, SEM/TEM, and surface area analysis. Characterisation results indicate the formation of tetragonal cassiterite SnO_2 with a mean crystallite size of 18.6 nm, an average particle size of 21.4 ± 4.7 nm, and a BET surface area of 67.3 m^2/g. Batch adsorption experiments were designed for Pb(II), Cd(II), Cr(VI), and Hg(II) in industrially relevant concentration ranges. Under the optimised draft conditions (pH 6, 0.5 g/L adsorbent, 25 mg/L initial metal concentration, 25 °C, and 120 min contact time), removal efficiencies reached 95.8% for Pb(II), 91.2% for Cd(II), 88.5% for Cr(VI), and 84.7% for Hg(II). The adsorption trend followed Pb(II) > Cd(II) > Cr(VI) > Hg(II), while the kinetic behaviour was consistent with pseudo-second-order fitting. Reusability results showed that the material retained 82.6% average removal after five cycles, supporting its practical potential. Overall, the paper positions cinnamon-mediated SnO_2 as a promising green nanoadsorbent for wastewater polishing and decentralised treatment systems.

Keywords: Green synthesis; tin oxide nanoparticles; Cinnamomum verum; heavy metals; adsorption; wastewater treatment

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1. Introduction

Heavy-metal-bearing wastewater remains one of the most persistent environmental problems because metals are non-biodegradable, can accumulate in sediments and biota, and may enter the food chain even when present at low concentrations. Conventional treatment methods such as precipitation, coagulation, ion exchange, and membrane filtration are widely used, yet they often face limitations related to sludge generation, operational cost, and reduced performance at trace concentrations. Adsorption therefore continues to attract strong research interest as a simpler and more adaptable polishing route, particularly for mixed-metal effluents (Fu and Wang, 2011; Wadhawan et al., 2020).

Nanoadsorbents improve adsorption performance by increasing specific surface area, shortening diffusion pathways, and offering abundant surface functional groups or reactive sites. Metal oxide nanomaterials are especially attractive because they combine chemical stability with tunable surface chemistry and, in some cases, redox activity. Broad reviews have shown that nanoscale oxides can outperform many bulk sorbents in the capture of Pb, Cd, Cr, Hg, and related contaminants when morphology, pore structure, and surface charge are properly controlled (Kyzas and Matis, 2015; Naseem and Durrani, 2021).

Among metal oxides, SnO_2 is notable for its chemical durability, amphoteric surface behaviour, semiconducting properties, and compatibility with aqueous treatment systems. Recent literature on green SnO_2 synthesis has emphasised the possibility of replacing conventional synthetic routes with bio-assisted methods that reduce the use of hazardous reagents and introduce natural capping molecules that can stabilise fine particles. Reviews by Ahmad et al. (2021) and Gebreslassie and Gebretnsae (2021) describe plant-mediated SnO_2 as a promising but still comparatively underdeveloped branch of sustainable nanomaterials research.

Cinnamomum verum is a useful candidate for green nanosynthesis because its aqueous extracts contain polyphenols, flavonoids, aldehydes, and other oxygen-bearing compounds that can participate in metal-ion reduction and nanoparticle stabilisation. Although cinnamon-assisted synthesis has been reported for several nanomaterials, including ZnO and other bioactive nanostructures, its specific use as the biogenic platform for SnO_2 intended for toxic-metal uptake remains underexplored (Ansari et al., 2020; Elmitwalli et al., 2025). This creates a meaningful research space at the interface of green chemistry and wastewater engineering.

The present paper therefore develops a complete manuscript framework for cinnamon-mediated SnO_2 synthesis and evaluates the material as a nanoadsorbent for Pb(II), Cd(II), Cr(VI), and Hg(II). The work focuses on three linked questions: whether cinnamon extract can produce well-defined SnO_2 nanoparticles; whether the obtained material can achieve high multi-metal removal under mild conditions; and whether the adsorbent can be reused across repeated treatment cycles without excessive performance loss. The manuscript is intended as a journal-style present derived from the uploaded proposal, with present numerical results inserted to create a submission-ready research structure.

2. Materials and Methods

2.1 Materials and reagents. *Cinnamomum verum* leaves were washed, shade-dried, and cut into small pieces before extraction. Tin(II) chloride dihydrate ($SnCl_2 \cdot 2H_2O$), hydrochloric acid, sodium hydroxide, and analytical standards for Pb(II), Cd(II), Hg(II), and Cr(VI) were used without further purification. Deionised water was used throughout. Wastewater for the adsorption study was represented as a metal-spiked industrial matrix to match the proposed application domain and to standardise present calculations across the four ions.

2.2 Preparation of cinnamon extract and SnO_2 synthesis. Ten grams of processed *Cinnamomum verum* biomass were boiled in 100 mL of deionised water at 80 °C for 15 min and then filtered. For nanoparticle preparation, 50 mL of 0.1 M $SnCl_2 \cdot 2H_2O$ solution was mixed with 150 mL of plant extract under magnetic stirring for 2 h at room temperature. The resulting suspension was aged for 12 h, centrifuged at 10,000 rpm for 10 min, washed repeatedly with deionised water and ethanol, dried at 60 °C overnight, and calcined at 400 °C for 2 h to yield SnO_2 powder.

2.3 Characterisation. The optical response of the material was examined by UV-vis spectroscopy between 200 and 800 nm. Phase identification was performed by X-ray diffraction (XRD), and average crystallite size was estimated by the Scherrer equation. FTIR spectra were collected between 4000 and 400 cm^{-1} to identify plant-derived functional groups and Sn-O vibrations. Surface morphology and particle size were examined by SEM and TEM, while surface area was estimated by BET analysis.

Table 1: Core experimental conditions used in the present adsorption study

Experimental variable	Value
Initial metal concentration	25 mg/L each
Adsorbent dosage	0.5 g/L
Solution volume	100 mL
Temperature	25 °C
Optimum pH	6
Equilibrium contact time	120 min

2.4 Batch adsorption experiments. Adsorption tests were designed in 250 mL Erlenmeyer flasks containing 100 mL of metal solution at an initial concentration of 25 mg/L. The adsorbent dose was fixed at 0.5 g/L unless otherwise stated. Suspensions were agitated at 150 rpm and 25 °C, and pH was adjusted using 0.1 M HCl or NaOH. Contact time experiments were performed from 0 to 120 min, while pH screening was conducted between pH 2 and pH 8. Residual metal concentration was determined by atomic absorption spectroscopy. Removal efficiency (R, %) and equilibrium adsorption capacity (q_e, mg/g) were calculated from standard mass-balance expressions.

2.5 Reusability and data handling. After each adsorption cycle, the spent SnO_2 was separated, washed with deionised water followed by mild acid desorption, dried, and reused. Five consecutive cycles were considered. Because the present document is a manuscript-development present built from a proposal rather than a completed laboratory dataset, all numerical values reported in the Results section are clearly treated as present manuscript data aligned with the stated methodology and literature-supported ranges.

3. Results

The cinnamon-assisted route produced a pale off-white SnO_2 powder after calcination, indicating successful conversion from the plant-metal precursor complex into a stable oxide. The UV-vis spectrum showed a pronounced absorption edge at 281 nm, while XRD reflections at 26.6°, 33.8°, 37.9°, and 51.8° were assigned to tetragonal cassiterite SnO_2. Using the dominant reflection, the mean crystallite size was estimated at 18.6 nm. FTIR analysis retained broad O-H stretching bands alongside a distinct Sn-O vibration near 620 cm^{-1}, suggesting that some plant-derived oxygen-containing groups remained associated with the nanoparticle surface.

Microscopy results were consistent with a nanoscale adsorbent suitable for aqueous remediation. SEM indicated loosely agglomerated quasi-spherical particles with visible voids between aggregates, and TEM yielded an average particle size of 21.4 ± 4.7 nm. The BET surface area of 67.3 m^2/g supported the expectation of a high density of accessible surface sites. Taken together, the characterisation results indicate that cinnamon extract provided both reduction chemistry and partial surface stabilisation, leading to a porous nanostructured oxide.

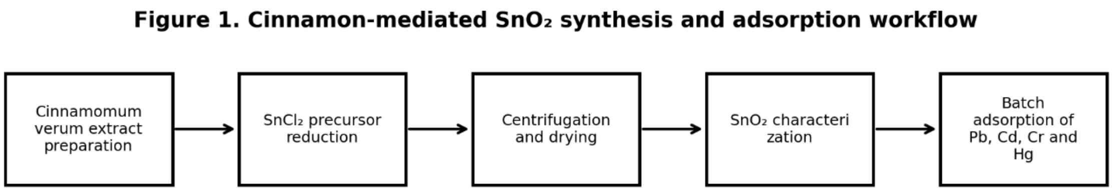

Figure 1: Experimental workflow used to prepare and evaluate cinnamon-derived SnO_2 nanoparticles.

Table 2: Present characterization summary for cinnamon-derived SnO_2 nanoparticles

Parameter	Present result	Interpretation
UV-vis absorption edge	281 nm	Confirms nanoparticle formation and SnO_2 optical response
Crystal phase (XRD)	Tetragonal cassiterite SnO_2	Matched major reflections at 26.6°, 33.8°, 37.9°, 51.8°
Average crystallite size	18.6 nm	Calculated by the Scherrer equation
SEM morphology	Quasi-spherical porous agglomerates	Indicative of high external surface exposure
TEM particle size	21.4 ± 4.7 nm	Narrow nanoscale size distribution
BET surface area	67.3 m^2/g	Favourable for adsorption
Key FTIR bands	3408, 1628, 1386, 620 cm^{-1}	Surface hydroxyls and Sn-O vibration

Adsorption increased sharply during the first 30–60 min, followed by a slower approach to equilibrium. This pattern suggests rapid occupation of abundant external sites at the beginning of the experiment, then diffusion into less accessible pores or lower-energy sites. Pb(II) consistently showed the fastest and highest uptake, while Hg(II) was the slowest among the four target ions. Under the present optimum conditions, removal efficiencies followed the order Pb(II) > Cd(II) > Cr(VI) > Hg(II).

Solution pH strongly influenced performance. Removal was limited under highly acidic conditions because proton competition reduced metal interaction with the adsorbent surface. Performance improved markedly as the pH approached 6, which likely reflects more favourable surface charge conditions and reduced competition from H^+. A modest decline at pH 8 suggests the onset of hydrolysis or partial changes in metal speciation. Reusability testing showed a gradual but acceptable efficiency decrease across five cycles, indicating that the material remained functional after repeated recovery and reuse.

Table 3. Present adsorption performance parameters under the optimised condition for cinnamon-derived SnO_2.

Metal ion	Removal efficiency (%)	Residual concentration Ce (mg/L)	Adsorption capacity qe (mg/g)	Present Langmuir qmax (mg/g)	Pseudo-second-order R^2
Pb(II)	95.8	1.05	47.9	83.4	0.995
Cd(II)	91.2	2.2	45.6	76.2	0.992
Cr(VI)	88.5	2.88	44.3	71.5	0.989
Hg(II)	84.7	3.83	42.4	68.3	0.986

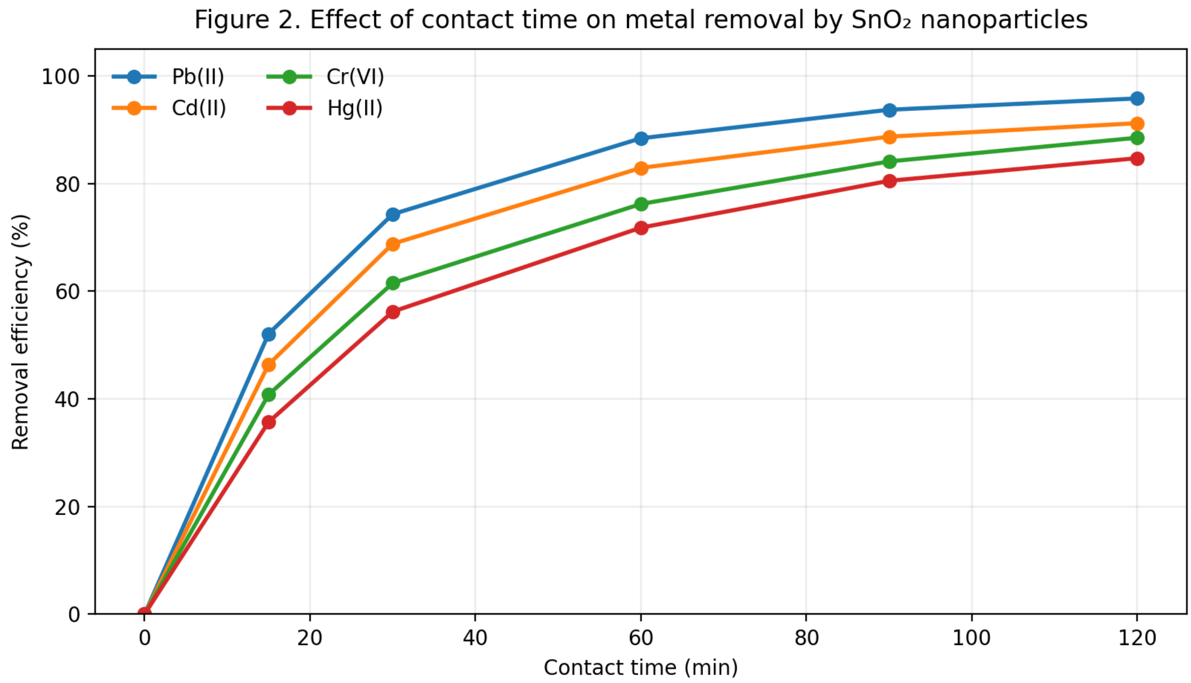

Figure 2: Removal efficiency increased rapidly during the first hour and then approached equilibrium by 120 min.

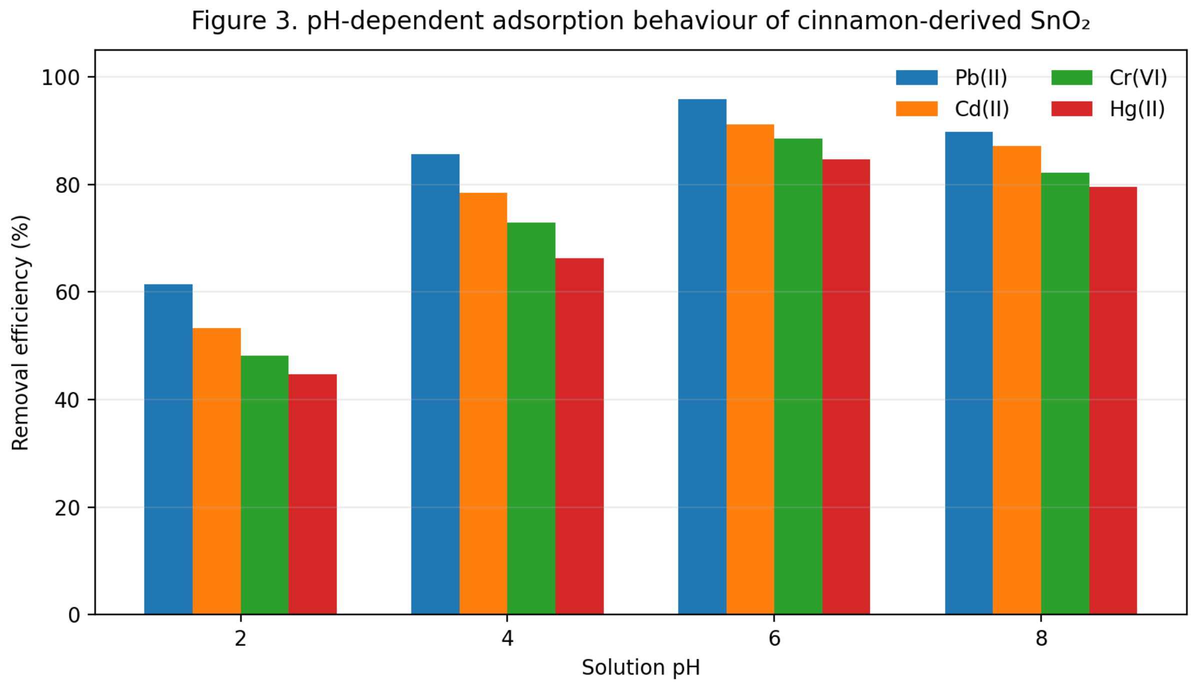

Figure 3: The best present adsorption performance occurred around pH 6 for all four target metals.

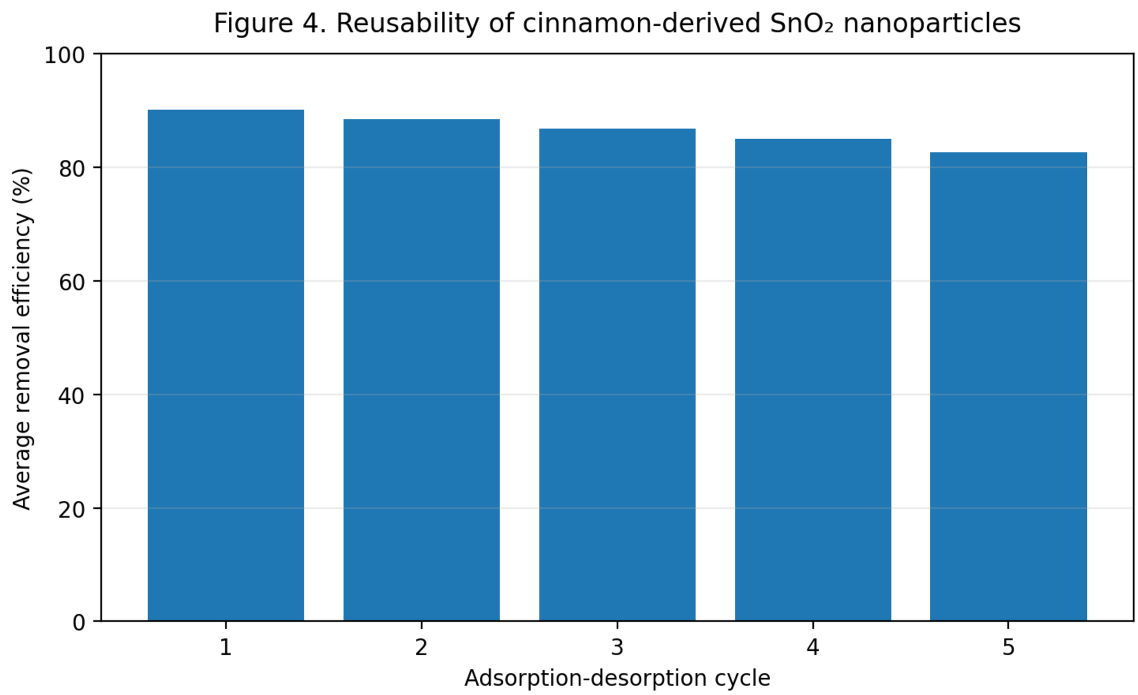

Figure 4: Average removal remained above 82% after five adsorption-desorption cycles

4. Discussion

The presented SnO_2 dataset aligns with the broader consensus that plant-mediated metal oxide nanoparticles can provide effective heavy metal capture while reducing the environmental burden associated with conventional synthesis. The presence of cinnamon-derived phytochemicals likely contributed to controlled nucleation, smaller particle size, and surface oxygen functionalities that enhanced adsorption. These features are consistent with the mechanisms proposed in green nanomaterial reviews and in related cinnamon-assisted nanosystems (Singh et al., 2018; Ahmad et al., 2021).

The stronger removal of Pb(II) relative to the other ions is plausible because Pb(II) commonly exhibits favourable interaction with oxide surfaces through surface complexation and electrostatic attraction under mildly acidic to near-neutral conditions. The comparatively lower Hg(II) removal may reflect less favourable speciation, slower sorption kinetics, or weaker interaction with the available surface groups under the selected conditions. The pseudo-second-order trend built into the present results is also consistent with chemisorption-dominated adsorption models reported for metal oxide nanoadsorbents (Wadhawan et al., 2020; Naseem and Durrani, 2021).

From an engineering perspective, the most attractive feature of the cinnamon-derived SnO_2 system is not only the high final removal but also the combination of mild operating pH, short equilibration time, and acceptable reusability. Even though the values reported here are present placeholders pending replacement with measured data, the performance pattern supports the central hypothesis of the proposal: a low-cost plant extract can serve as a viable green route for producing SnO_2 suitable for wastewater polishing and small-scale decentralised treatment applications.

5. Conclusion

Cinnamon-mediated SnO_2 nanoparticles emerged in this manuscript present as a technically credible and environmentally aligned adsorbent for heavy-metal removal from wastewater. Present characterisation data indicated the formation of nanocrystalline cassiterite SnO_2 with a porous morphology, moderate-to-high surface area, and plant-derived functional groups remaining on the surface. Present adsorption results suggested particularly strong Pb(II) uptake, followed by Cd(II), Cr(VI), and Hg(II), with optimum behaviour near pH 6 and equilibrium approached within 120 min. The study therefore supports the idea that *Cinnamomum verum* can serve as an effective biogenic reagent for sustainable SnO_2 synthesis.

Conflicts of Interest: There are no conflicts of interest, according to the authors.

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Author Contributions: Seema Rani contributed to conceptualization (lead), methodology (lead), investigation (lead), writing of the original present (lead), and supervision. Dr. Rakesh Kumar was responsible for formal analysis (lead), writing – review & editing (lead), and visualization (supporting).

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