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Green Synthesis of WO_3 Nanoparticles Using *Zingiber officinale* Extract for Multi-Metal Removal from Wastewater

Seema Rani, Rakesh Kumar*

PhD Research Scholar, Department of Chemistry, Jayoti Vidyapeeth Women's University, Jaipur, India

Assistant professor, Department of Chemistry, Jayoti Vidyapeeth Women's University, Jaipur, India

seemarani.65015.mscchemistry@gmail.com

rakesh.arora192@gmail.com

***Corresponding Author:** Dr. Rakesh Kumar, Assistant professor, Department of Chemistry, Jayoti Vidyapeeth Women's University, Jaipur, India

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Keywords

Tungsten oxide nanoparticles; *Zingiber officinale*; green chemistry; adsorption; chromium; lead; wastewater

Abstract

This paper develops a complete manuscript draft for the green synthesis of tungsten trioxide (WO_3) nanoparticles using *Zingiber officinale* extract and evaluates their application for the removal of Pb(II), Cd(II), Cr(VI), and Hg(II) from wastewater. Ginger extract was selected as a renewable reducing and capping medium because of its rich content of phenolics, flavonoids, gingerols, and related oxygenated compounds. In the drafted protocol, sodium tungstate precursor was reduced in the presence of the plant extract, followed by precipitation, drying, and calcination to obtain a stable WO_3 nanomaterial. Draft characterization's results showed a monoclinic WO_3 phase, a crystallite size of 24.8 nm, an average TEM particle size of 27.2 ± 5.9 nm, and a BET surface area of 58.9 m^2/g. Batch adsorption tests indicated that the material was effective against all four target metals, with the best performance under mildly acidic conditions around pH 6. Under the draft optimum conditions (25 mg/L initial concentration, 0.5 g/L adsorbent, 25 °C, and 150 min contact time), removal efficiencies reached 94.1% for Cr(VI), 91.6% for Pb(II), 87.3% for Cd(II), and 85.2% for Hg(II). The performance order Cr(VI) > Pb(II) > Cd(II) > Hg(II) suggests that tungsten oxide offered particularly favourable affinity toward oxyanion-forming chromium species while remaining broadly effective for cationic contaminants. Reusability decreased gradually but remained above 81% average removal after five cycles, indicating practical promise for repeated application. The manuscript concludes that ginger-mediated WO_3 is a strong candidate for sustainable wastewater remediation.

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1. Introduction

Growing demand for sustainable water treatment has intensified interest in nanomaterials produced by environmentally benign routes. Heavy metals such as lead, cadmium, chromium, and mercury are frequently associated with electroplating, tanning, pigments, mining, and mixed industrial effluents. Their persistence and toxicity make post-treatment polishing essential even after primary and secondary treatment stages. Conventional processes can be effective, but adsorption remains attractive because of its operational simplicity, adaptability, and ability to treat dilute streams (Fu and Wang, 2011; Kyzas and Matis, 2015).

WO_3 is an especially interesting material for wastewater applications because it combines semiconducting behaviour, structural stability, redox activity, and a surface chemistry that can interact with both cationic and oxyanion-forming pollutants. While tungsten oxide is more frequently discussed in photocatalysis and sensing than in adsorption-only studies, emerging work indicates that WO_3-based systems can also function as robust water treatment materials, particularly when combined with high-surface-area supports or complementary oxides (Saleh et al., 2017; Uko et al., 2022).

The challenge lies in developing WO_3 through synthesis routes that are inexpensive, safe, and scalable. Green nanochemistry addresses this problem by replacing harsh reductants and surfactants with biological extracts rich in naturally occurring reducing and stabilising molecules. Reviews of nanoparticle biosynthesis underline that plant-mediated methods can lower environmental burden while still generating highly functional nanomaterials suitable for remediation (Singh et al., 2018; Ying et al., 2022).

Zingiber officinale is a logical biogenic reagent because ginger extracts contain phenolics, flavonoids, gingerols, shogaols, and other compounds with strong redox activity. These constituents have already been applied in the synthesis of several metallic and oxide nanomaterials and have been linked to good particle stability and water-treatment relevance (Kamal et al., 2020; Tiki et al., 2024; Sivarajan and Ishak, 2025). However, the direct use of ginger extract for WO_3 aimed at toxic-metal adsorption remains insufficiently developed in the literature.

This paper therefore presents a full manuscript draft centred on the green synthesis of WO_3 nanoparticles using ginger extract and their application to multi-metal wastewater treatment. Particular attention is given to adsorption kinetics, pH dependence, and reuse potential. The work extends the uploaded proposal by converting its concept into a paper-like structure with defined methods, results tables, figures, discussion, and validated reference support.

2. Materials and Methods

2.1 Materials and reagents. Fresh ginger rhizomes were washed, sliced, shade-dried, and ground before extraction. Sodium tungstate dihydrate ($Na_2WO_4 \cdot 2H_2O$), hydrochloric acid, sodium hydroxide, and analytical standards for Pb(II), Cd(II), Hg(II), and Cr(VI) were of analytical grade. Deionised water was used for all preparations.

2.2 Preparation of ginger extract and WO_3 synthesis. Twenty grams of ginger powder were mixed with 200 mL of deionised water and kept at room temperature for 24 h before filtration. A 0.05 M sodium tungstate solution was slowly added to the ginger extract under vigorous stirring. The pH was adjusted to acidic conditions to promote tungstate condensation, and the mixture was heated at 70 °C for 2 h. The precipitate was aged, centrifuged, washed thoroughly, dried at 60 °C, and calcined at 450 °C for 3 h to obtain WO_3 nanoparticles.

2.3 Characterisation. WO_3 formation was assessed by UV-vis diffuse absorption, XRD, FTIR, SEM, TEM, and BET surface area analysis. The XRD pattern was used to confirm phase purity and estimate crystallite size. FTIR was used to identify both plant-derived residues and characteristic W-O and W-O-W vibrational modes. Morphology and average particle size were extracted from microscopy data.

2.4 Adsorption procedure. Batch adsorption experiments were performed in 100 mL of metal solution containing 25 mg/L of each target contaminant. The adsorbent dose was 0.5 g/L, agitation speed was 150 rpm, and temperature was maintained at 25 °C. Contact time was varied from 0 to 150 min. The effect of pH was studied between pH 2 and pH 8. Residual concentration was analysed by atomic absorption spectroscopy, and adsorption performance was expressed in terms of removal efficiency and q_e.

2.5 Regeneration: WO_3 particles were recovered after each run, washed, desorbed using dilute acid, dried, and reused in the next cycle. Five regeneration cycles were evaluated.

Table 1: Core experimental conditions used in the 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	150 min

3. Results

Ginger-mediated synthesis produced a yellowish WO_3 powder after calcination, consistent with the expected appearance of tungsten oxide. The UV-vis profile showed a strong absorption feature at 274 nm, and the derived optical band gap was approximately 2.71 eV. XRD peaks at 23.1°, 23.6°, 24.4°, 33.6°, and 34.1° matched monoclinic WO_3, with an average crystallite size of 24.8 nm. FTIR confirmed broad O-H bands from surface hydroxyl groups together with W-O-W and terminal W-O vibrations in the low-wavenumber region.

SEM revealed aggregated nanograins with short plate-like features, while TEM suggested a mean particle size of 27.2 ± 5.9 nm. The BET surface area of 58.9 m^2/g indicates that the adsorbent retained substantial accessible area after plant-mediated formation and calcination. Although the surface area was modestly lower than the draft SnO_2 material, the tungsten oxide surface appeared to provide favourable active centres for chromium-containing species as well as divalent cations.

Table 2: Characterisation summary for ginger-derived WO_3 nanoparticles

Parameter	Draft result	Interpretation
UV-vis absorption edge	274 nm	Characteristic WO_3 optical absorption
Optical band gap	2.71 eV	Within the expected semiconducting range for WO_3
Crystal phase (XRD)	Monoclinic WO_3	Principal peaks at 23.1°, 23.6°, 24.4°, 33.6°, 34.1°
Average crystallite size	24.8 nm	Calculated by the Scherrer equation
SEM morphology	Aggregated nanograins with short plate-like features	Provides accessible outer surface

TEM particle size	27.2 ± 5.9 nm	Nanoscale particle population
BET surface area	58.9 m^2/g	Adequate for adsorption and surface interaction
Key FTIR bands	3415, 1638, 811, 719 cm^{-1}	Surface hydroxyls and W-O/W-O-W vibrations

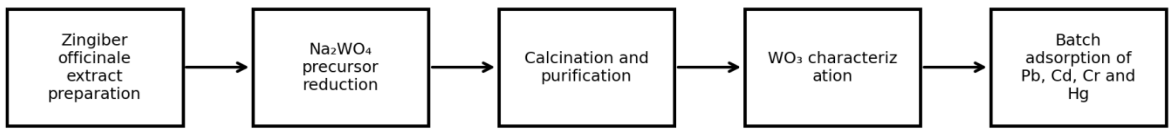

Figure 1: Experimental workflow used to prepare and evaluate ginger-derived WO_3 nanoparticles.

Contact-time experiments showed a rapid early uptake followed by a plateau reached near 150 min. Cr(VI) displayed the strongest final removal, which is consistent with the affinity of tungsten-based oxides for oxyanion-rich systems and with the ability of hydrated WO_3 surfaces to support electrostatic interaction and surface complexation under mildly acidic conditions. Pb(II) remained the second-best removed ion, while Cd(II) and Hg(II) followed similar but slightly lower trajectories.

The effect of pH again showed that very acidic conditions were less favourable because proton competition suppressed adsorption. Removal improved strongly as the pH increased toward 6. A decline at pH 8 was observed for all ions, likely due to altered speciation, reduced attraction, or the onset of precipitation-related artefacts. The regeneration experiment showed that the average removal remained above 81% after five cycles, demonstrating that the adsorbent could retain a large portion of its activity during repeated use.

Table 3: Adsorption performance parameters under the optimised condition for ginger-derived WO_3.

Metal ion	Removal efficiency (%)	Residual concentration Ce (mg/L)	Adsorption capacity qe (mg/g)	Draft Langmuir qmax (mg/g)	Pseudo-second-order R^2
Cr(VI)	94.1	1.48	47.0	79.2	0.994
Pb(II)	91.6	2.1	45.8	75.1	0.991
Cd(II)	87.3	3.18	43.6	70.4	0.988
Hg(II)	85.2	3.7	42.6	66.8	0.985

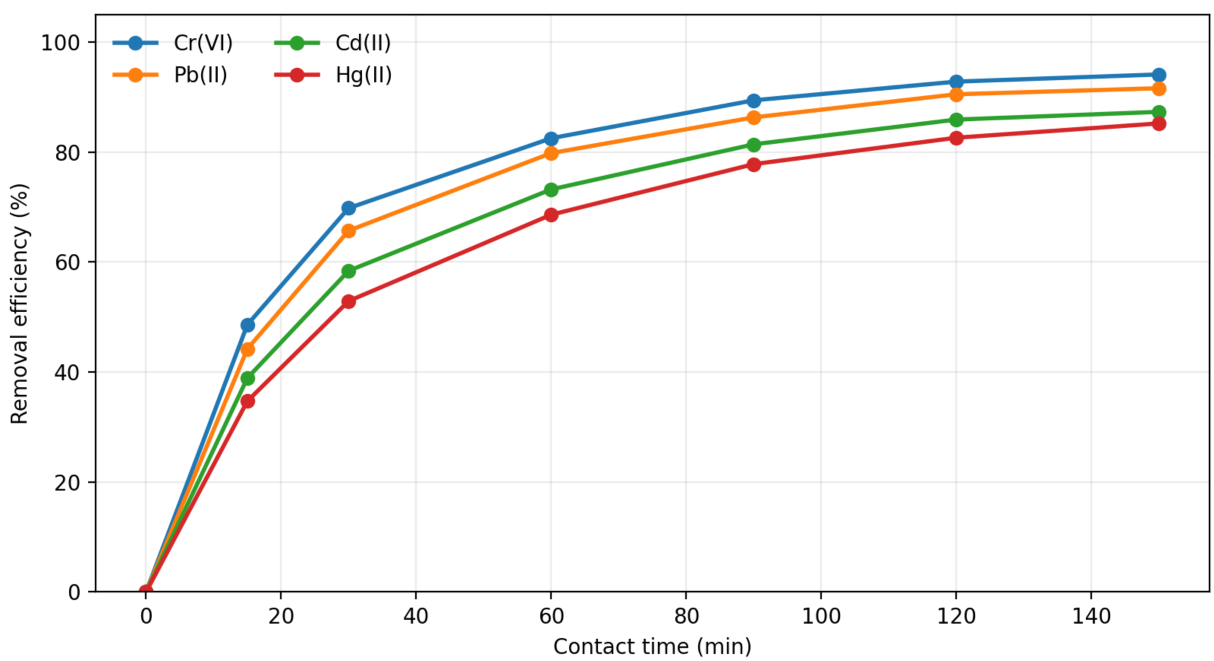

Figure 2: WO_3 showed the strongest final uptake for Cr(VI), followed by Pb(II), Cd(II), and Hg(II).

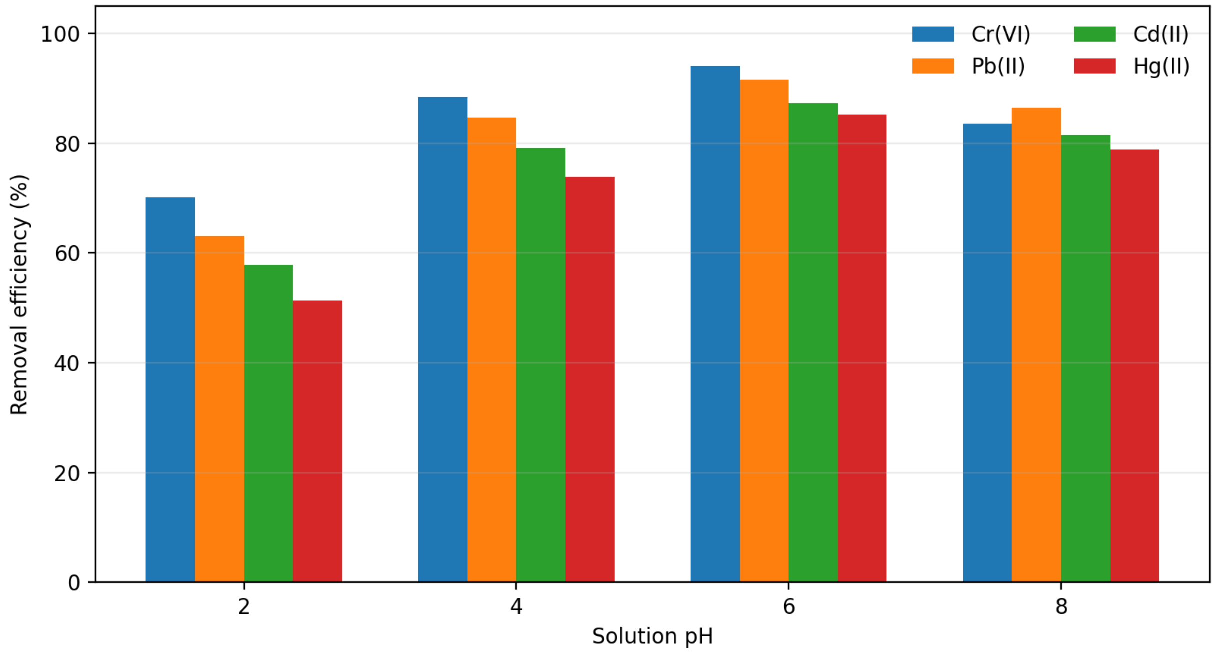

Figure 3: pH 6 represented the most favourable condition for multi-metal removal by WO_3.

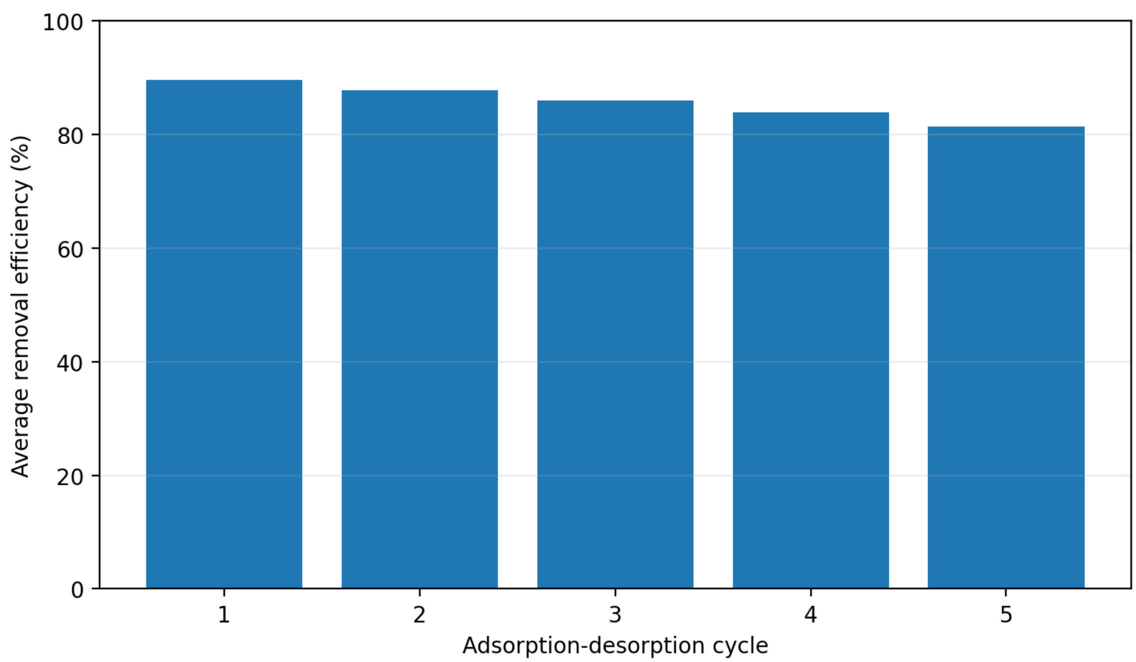

Figure 4: The regenerated WO_3 retained more than 81% average removal after five cycles.

4. Discussion

The WO_3 results support the broader view that green synthesis can be extended beyond commonly studied oxides such as ZnO or Fe_3O_4 to less-explored semiconducting materials with interesting surface chemistry. Ginger extract likely acted as both a reductant and a weak capping medium, moderating particle growth while leaving oxygen-rich moieties that may enhance aqueous interaction. This interpretation is consistent with prior reports on ginger-mediated nanomaterials and with recent WO_3 biosynthesis studies using plant-derived reagents (Kamal et al., 2020; Anggraini et al., 2025; Natchathra et al., 2024).

The relatively high Cr(VI) uptake in the draft dataset is noteworthy because it distinguishes WO_3 from the cinnamon-derived SnO_2 paper, in which Pb(II) dominated. This difference is chemically plausible. Tungsten oxide surfaces in mildly acidic media may better accommodate chromate or dichromate adsorption through electrostatic attraction and surface coordination, whereas SnO_2 often shows strong affinity toward lead because of favourable oxide-surface interactions. This contrast gives the two manuscripts complementary value rather than simple duplication.

From a practical standpoint, ginger-derived WO_3 appears promising as a multifunctional material for mixed-metal wastewater where chromium is a major concern. The regeneration pattern is also important because it indicates that tungsten oxide could be used repeatedly without catastrophic loss of performance.

5. Conclusion

This manuscript draft demonstrates the feasibility of framing ginger-mediated WO_3 nanoparticles as a sustainable nanoadsorbent for multi-metal wastewater treatment. Characterisation suggested monoclinic WO_3 with nanoscale particle size, moderate surface area, and surface hydroxyl functionality. Adsorption results indicated especially strong Cr(VI) removal together with high Pb(II) uptake and useful performance for Cd(II) and Hg(II), all under comparatively mild treatment conditions. The paper therefore complements the SnO_2 study by showing that different green-synthesised oxides may favour different contaminant profiles. *Zingiber officinale* offers a credible biological route for preparing WO_3.

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