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Green Synthesis of Stable and Reusable Zinc Nanoparticle Adsorbents for the Removal of Carcinogenic Heavy Metals in Aqueous Solution

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Abstract

Heavy metals like Chromium (Cr), Lead (Pb), and Cadmium (Cd) are recognized as potent toxic substances and known carcinogens that pose significant health risks to humans. The proliferation of these heavy metals in diverse industrial applications led to an alarming rise in their presence, heightening the potential for contamination in various environmental mediums. In order to mitigate the adverse impacts of these heavy metals, it is imperative to reduce their concentrations in environmental samples. Therefore, this study aimed to produce zinc nanoparticles employing *Diospyros chloroxylon* (Roxb.) to effectively eliminate carcinogenic metals from water. The produced nanoparticles were subjected to comprehensive characterization using FT-IR, XRD, SEM, and EDX techniques. The XRD data indicated the emergence of a hexagonal wurtzite structure. SEM images illustrated the spherical morphology of the synthesized particles, with an average diameter measuring 53 nm and having elemental zinc accounting for 69.4% of the composition. The subsequent heavy metal sorption experiments encompassed a range of variables, remarkably, the nanoparticles displayed exceptional adsorption capabilities, achieving maximum removal rates of 95.81%, 90.13%, and 91.25% within an equilibrium time of 90 minutes for Cr, Pb, and Cd, respectively. The adsorption process adhered to a pseudo-first-order reaction kinetics model, with high correlation coefficients of 0.9561, 0.99058, and 0.98481, along with respective rate constants (K) of 0.483, 0.233, and 0.328 for Cr, Pb, and Cd. The outcomes highlight that the synthesized zinc nanoparticles exhibit biocompatibility, stability, and reusability, making them a promising tool for effectively removing carcinogenic heavy metals from polluted water sources.

Keywords: Adsorption Studies, Characterisation, Carcinogenic Heavy Metals, *Diospyros chloroxylon*, Green Synthesis, Zinc Nanoparticles

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1. Introduction

With the growing demand for waste reduction and the pursuit of sustainable development goals through the principles of green chemistry, there arises an evident necessity for innovative eco-friendly techniques in the synthesis of nanoparticles[1]. The adoption of environmentally friendly processes into various technologies has gained remarkable traction, driven by the global environmental challenges linked to conventional harmful chemical methodologies[2]. Nanotechnology has garnered significant attention for its advanced character and its expansive applicability across diverse scientific and technological domains, including biomedical sciences[3]. Traditionally, nanoparticles have been produced through diverse chemical and physical means, which not only incur substantial costs but also pose environmental and human health risks. In this context, plants have emerged as a favored and straightforward avenue for nanoparticle synthesis, as they facilitate the scalable production of stable nanoparticles in assorted shapes and sizes[4]. The utilization of natural plant extracts presents an eco-conscious, uncomplicated, and economical strategy[5]. These extracts often harbor phytochemical compounds such as phenols, flavonoids, alkaloids, terpenes, saponins, and tannins, which serve as both reductive agents and agents for capping or stabilizing nanoparticles[6].

Among the various nano metal oxides, zinc oxide nanoparticles stand out for their recognized antimicrobial, anti-inflammatory, and anticancer properties[7]. Moreover, they find application in sunscreens due to their ability to scatter ultraviolet rays, as well as in drug delivery and wound-healing applications. Zinc nanoparticles exhibit multiple traits as biocompatible and versatile nanomaterials, a designation upheld by the U.S. Food and Drug Administration (FDA), which deems zinc nanoparticles a 'Generally Recognized As Safe' (GRAS) substance[8]. Numerous studies have unveiled methodologies for environmentally benign synthesis of zinc nanoparticles employing diverse plant extracts[9]. Curiously, the *Diospyros chloroxylon* (Roxb.), remains unexplored in the context of zinc nanoparticle synthesis. The plant *Diospyros chloroxylon* (Roxb.) was commonly called as green ebony persimmon of Ebenaceae family. It was native to Indian subcontinent and a wild fruit-bearing plant. The fruits of this plant were cherry size which possess various minerals and phytochemicals that shows significantly high pharmacological properties[10]. In literature, one author reported the synthesis of silver nanoparticles using fruit pulp of *Diospyros chloroxylon* and further, the anti-microbial activity of synthesised nanoparticles was reported[11]. No other works reported for the synthesis of nanoparticles using *Diospyros chloroxylon*.

The main objective of this study includes the synthesis of zinc nanoparticles utilizing leaf extract of *Diospyros chloroxylon* (Roxb.) as a reducing and capping agent. The characterization of *Diospyros chloroxylon*-mediated zinc nanoparticles was conducted with different characterization techniques. Further, the synthesised zinc nanoparticles were applied as catalysts for the removal of carcinogenic pollutants such as chromium, lead, and cadmium in aqueous solution.

2. Materials and Methods

2.1 Collection of Plant Material

Leaves of *Diospyros chloroxylon* (Roxb.) plant were gathered from the Addateegala forest in the East Godavari district of Andhra Pradesh. The collected leaves underwent a cleaning process to eliminate sand and dirt, employing sterile cotton and subsequently rinsing with distilled water. Afterward, any residual water on the cleaned material was blotted using tissue paper. The plant material was then divided into smaller pieces and allowed to air dry under shade. The resulting dried leaf material was carefully stored separately for future use.

2.2 Extractions of Plant Materials

An accurately weighed 10 grams of plant powder was added to a 250mL beaker containing 100mL of double distilled water. The plant material with water was boiled on a hot plant at 40°C for 80min to extract the phytochemical constituents. Subsequently, the extract underwent filtration, with the plant material sediment being discarded, and the resulting clear filtrate was adjusted to a final volume of 100mL using distilled water. This resulting clear filtrate was utilized for the subsequent synthesis of nanoparticles[12].

2.3 Synthesis of Nanoparticles

The aqueous leaf extract and zinc acetate solution in 10:90 (v/v) was mixed and the homogenous mixture was prepared by stirring the solution in a magnetic stirrer for 4h without heating. Then 20mL of ethanolic sodium hydroxide solution was added and stirred for

5 min. The precipitate at the bottom of the flask was collected by removing the excess mother liquid and then obtained precipitate washed with excess distilled water to remove the extract particles on the precipitate. Then the precipitate was purified by heating at 300^{0}C for 45min in a muffle furnace. The obtained particles were preserved for further study.

2.4 Characterization of Synthesised Nanoparticles

The synthesized zinc nanoparticles were characterized using TEM (Transmission Electron Microscopes), EDX (Energy-Dispersive X-ray Spectroscopy), SEM (Scanning Electron Microscopy), FTIR (Fourier-Transform Infrared Spectroscopy), and UV-visible spectroscopy. The TEM analysis was carried out on Jeol JEM 2100 (Japan) instrument which was operated at 120 keV. Prior to the analysis, the nanoparticles were washed thoroughly with methanol and mounted on copper grids coated with carbon. The Jeol 6390LA SEM instrument coupled with OXFORD XMX-N EDX was utilized to evaluate the crystal size and elemental composition of synthesized nanoparticles. The instrument was equipped with a Tungsten lamp and was operated with an accelerating voltage of 0.5 to 30 kV. The nanoparticles were spread on adhesive tapes made of carbon and were supported with metal disks. The images and elemental composition of the coated nanoparticles were recorded at various magnifications. The XRD analysis was conducted on Bruker D8 Advance EDX instrument which was operated at an energy resolution of < 380 eV @ 8 KeV and Cu K_α radiation as the source. The nanoparticles were washed multiple times with ethanol prior to analysis to avoid the crystallization of sodium chloride. The samples were scanned with a scan 2θ of 20-100° range. The phyto-chemical groups responsible for the formation of nanoparticles were evaluated by performing FTIR analysis which was carried out on Bruker (USA) instrument operated in the range of 500-4000 cm^{-1} range. The initial formation of nanoparticles was identified based on the colour change in the initial reaction and the change in colour was confirmed using UV-visible spectral analysis which was carried out on a Double bean UV visible spectrophotometer (JASCO, Japan) in the scan range of 800-300 nm.

2.5 Adsorption Methodology

The adsorption isotherm equilibrium was established by performing batch experiments for all the heavy metals (chromium, lead, cadmium) studied. The heavy metal adsorption experiment was performed in a 250mL conical flask by utilizing 50mL each metal solution at 50mg/L concentration and an adsorption dose of 0.05g. The initial pH and temperature of the experimental solution were maintained at 6.0 and 25 °C respectively. The reaction mixture was kept in an orbital shaker for 24h while stirring at 250rpm. Then the supernatant was collected by centrifuging for 5 min at 6000 rpm and the supernatant was used for quantification of metal content and subsequently evaluated the adsorption efficiency of synthesized zinc nanoparticles. The metal concentration was evaluated using a UV-visible spectrophotometer as per the method reported in the literature. The diphenylcarbazide method[13], Dithizone method[14] and 5, 7 Dibromo-8-Hydroxyquinoline (DBHQ) method[15] respectively were utilized for quantification of chromium, lead, and cadmium during the adsorption studies. The variables such as adsorbent dosage (0.01-0.15 g), metal concentration (25-300 mg/L), contact time (5-300 min), and agitation rate (100-300 rpm) were tested for evaluation of adsorption capacity equilibrium (q_e) and metal removal (R in %) which were calculated using formula

$$q_e = \frac{Ci - Ce \times V}{m}$$

$$R(\%) = \frac{Ci - Ce \times V}{Ci} \times 100$$

Ci = initial metal solution concentration; Ce = equilibrium metal solution concentration; V = metal solution volume in L and m = nanoparticles weight taken as adsorbent.

2.6 Stability and Recyclability of Nanoparticles

The stability of synthesized nanoparticles was evaluated chemically by mixing 0.1g of synthesized nanoparticles with 200mL of aqueous solution at a wide pH range i.e., from 2.0 to 10. Subsequently, the reaction mixture was placed within an orbital shaker and maintained at 75°C for a duration of 24 hours. The zinc ions dissolved in the solution were evaluated using atomic absorption spectrophotometer.

The recyclability of the synthesized nanoparticles plays a significant role as the particles were recyclable, it will reduce the experimental cost. The nanoparticles after completion of the metal reduction study were washed with 0.01M hydrochloric acid, EDTA separately and then

washed with purified water. The particles were dried 24 h at 60°C and then were utilized for adsorption study and the same procedure was repeated for 5 times and based on the results, the reusability was evaluated.

3. Results and Discussion

The zinc nanoparticles were synthesized using leaf aqueous extract and zinc acetate solution. The formation of nanoparticles was initiated with the addition of the aqueous leaf extracts of *Diospyros chloroxylon* and zinc metal solution. Initially, various concentrations of zinc acetate such as 0.01M, 0.1M and 1.0M was studied for the effective formation of nanoparticles. Among the metal ion concentrations studied, the metal ion at 0.1 M concentration was noticed to be effective for the fabrication of nanoparticles. The presence of various secondary metabolites in the aqueous leaf extract of *D. chloroxylon* can reduce the zinc ions in the zinc acetate solution and hence nanoparticles were formed. The addition of the plant aqueous extract and the zinc acetate solution, the formation of nanoparticles was initiated and the initial color of the reaction mixture was light yellow. As the nanoparticles formed, the color of the mixture transitioned from light yellow to a deep brown. This alteration in color within the reaction mixture serves as a visual indicator of the nanoparticles' formation process.

This visualized colour change was monitored instrumentally using a spectrophotometer in the can range of 800-300 nm whereas the absorption spectra of aqueous leaf extract was measured in the scan range of 800-200 nm. The high intense absorption maxima noted in the UV scanning spectra of synthesized zinc nanoparticles at its characteristic absorption maxima at 381 nm due to the presence of zinc nanoparticles and the similar absorption maxima was reported in literature[16,17]. The spectra of dilute solution of the leaf extract prior to the reaction visualize a single large absorption peak at 252 nm (Figure 1B) presumably corresponding to phytochemical constituents in the leaves of *D. chloroxylon*.

Figure 2 depicts the FTIR spectrum of zinc nanoparticles synthesized using an aqueous leaf extract of *D. chloroxylon* which suggest the involvement of plant-derived compounds in the fabrication of zinc nanoparticles. The bands at 3565cm^{-1} and 3295cm^{-1} correspond to free and intra-molecular bonded O-H stretching in alcohols whereas the presence of N-H stretching in primary amine was confirmed by observing the band at 3528cm^{-1}. A week band at 1551 cm^{-1} confirms the presence of aromatic C=C bonds whereas a band at 1740cm^{-1} suggests the presence of C-H bonds in aromatic compounds. In the spectrum, the medium band was noticed in the range of 1650-1580 cm^{-1}confirms the presence of N-H bending vibrations in the amine group. The involvement of aldehyde groups in the fabraction of nanoaprticles was confirmed by identifying band at 2663cm^{-1} and 1740cm^{-1} that represents C-H stretching and C=O stretching vibrations respectively in the aldehyde group. The functional groups noticed in the FTIR spectrum of synthesized zinc nanoparticles proved that the phytochemicals in the leaf extract contain these functional groups such as flavonoids, phenolic compounds, and alkaloids are actively involved in the formation of nanoparticles.

The SEM analysis of zinc nanoparticles synthesized using aqueous leaf extract of *D. chloroxylon* provides insights into their shape and size (Figure 3A). The

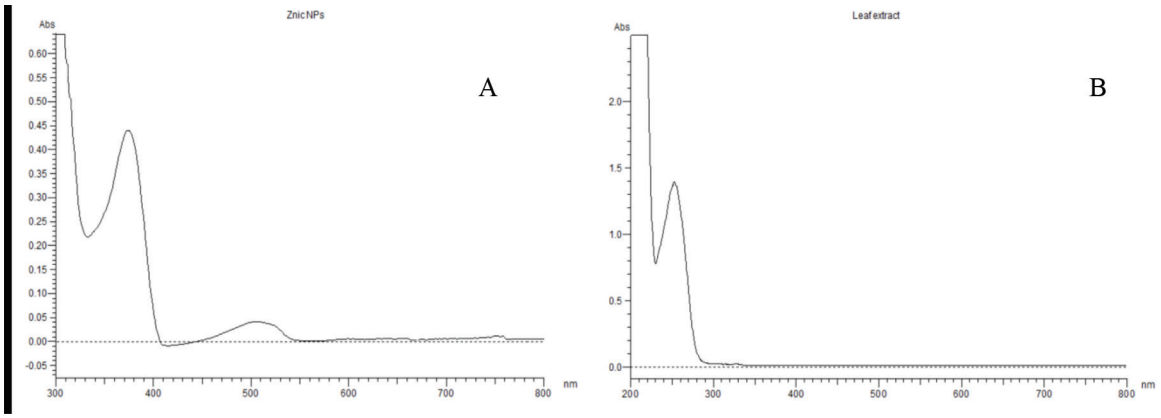


Figure 1. UV-visible absorption spectra of *D. chloroxylon* leaf extract mediated nanoparticles **(A)** and leaf extract **(B)**.

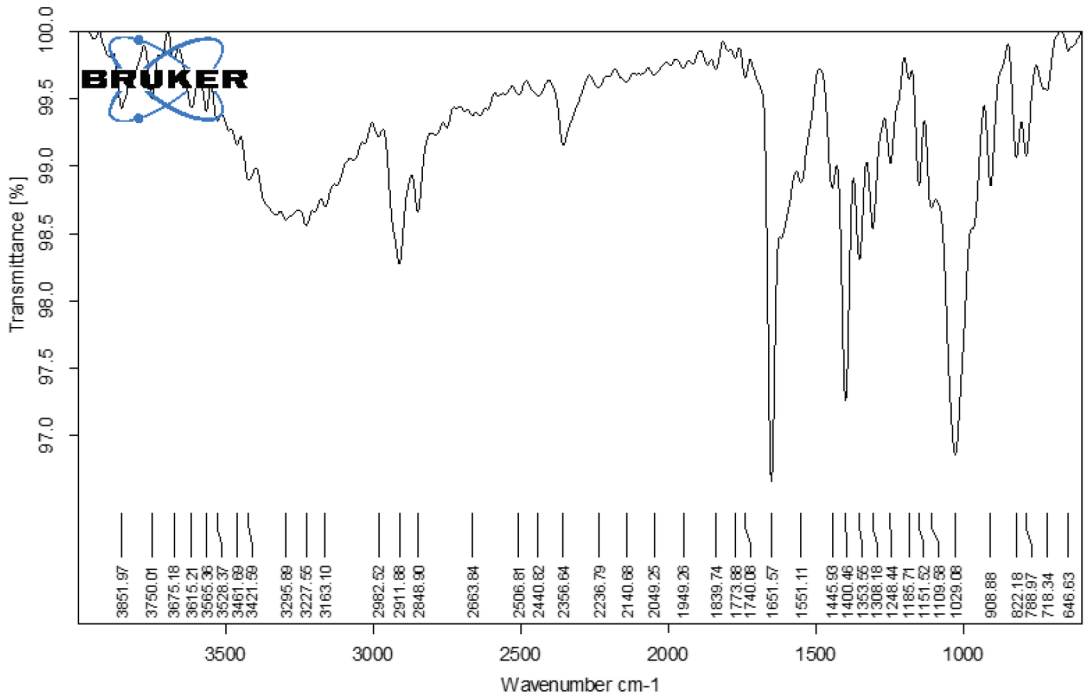


Figure 2. FTIR spectrum of zinc nanoparticles synthesized in the study.

nanoparticles exhibited predominantly spherical shapes, with a few adopting oval forms. These nanoparticles aggregated within a size range spanning 35nm to 68nm, with an average size of approximately 53nm.

The EDX analysis spectra of the zinc nanoparticles mediated by the aqueous leaf extract revealed the presence of key elements zinc and oxygen (as shown in Figure 3B). Notably, the EDS spectra of the synthesized nanoparticles displayed characteristic peaks representing elemental zinc at 8.60 keV (Kα) and 1.07 keV (Lα), while a peak corresponding to oxygen was observed at 0.49 keV. This elemental analysis established that the nanoparticles contained approximately 69.4% metallic zinc content. Additionally, the spectra exhibited a characteristic peak associated with elemental carbon, possibly attributed to bioactive phytochemical constituents derived from the aqueous plant leaf extract of *D. chloroxylon*.

TEM was the perfect analytical tool for the chemical and structural characterization of the nanoscale materials. Diffraction, imaging, and microanalytical information were obtained from the TEM analysis, and the combination of these results produces the behavior of the nanosized and nanostructured materials. Hence TEM analysis of zinc nanoparticles synthesised using aqueous leaf extract of *D. chloroxylon* was evaluated. The findings indicate that the nanoparticles exhibited a predominantly spherical shape with a generally smooth surface texture on each particle. The average particle size was determined to be approximately 53 nm (depicted in Figure 3(C)). The results obtained from TEM analysis were consistent with the observations previously reported for the same sample using SEM.

The crystal phases and crystallinity along with the particle size of the nanoparticles were further confirmed by XRD analysis (Figure 3(D)). In the XRD spectrum, significantly defined diffraction reflections were noticed at 2θ values representing 100, 002, 101, 102, 110, 103, 200, 112, 201, 004, and 202 planes of the crystal lattice which suggest hexagonal Wurtzite phase structure of the particles. The Bragg reflections noticed in this study were in correlation with the standard JCPDS card no 89-0510. The XRD results suggest that except hexagonal Wurtzite phase structure, there is no sight of other diffraction patterns related to impurities suggesting that the obtained particles were very pure. The Debye-Scherrer equation was applied for the evaluation of the crystal size of the synthesized zinc nanoparticles and the size of the particles were noticed to be 53nm. The crystal size calculated using the Debye-Scherrer equation was well correlated with the size noticed during SEM and TEM analysis.

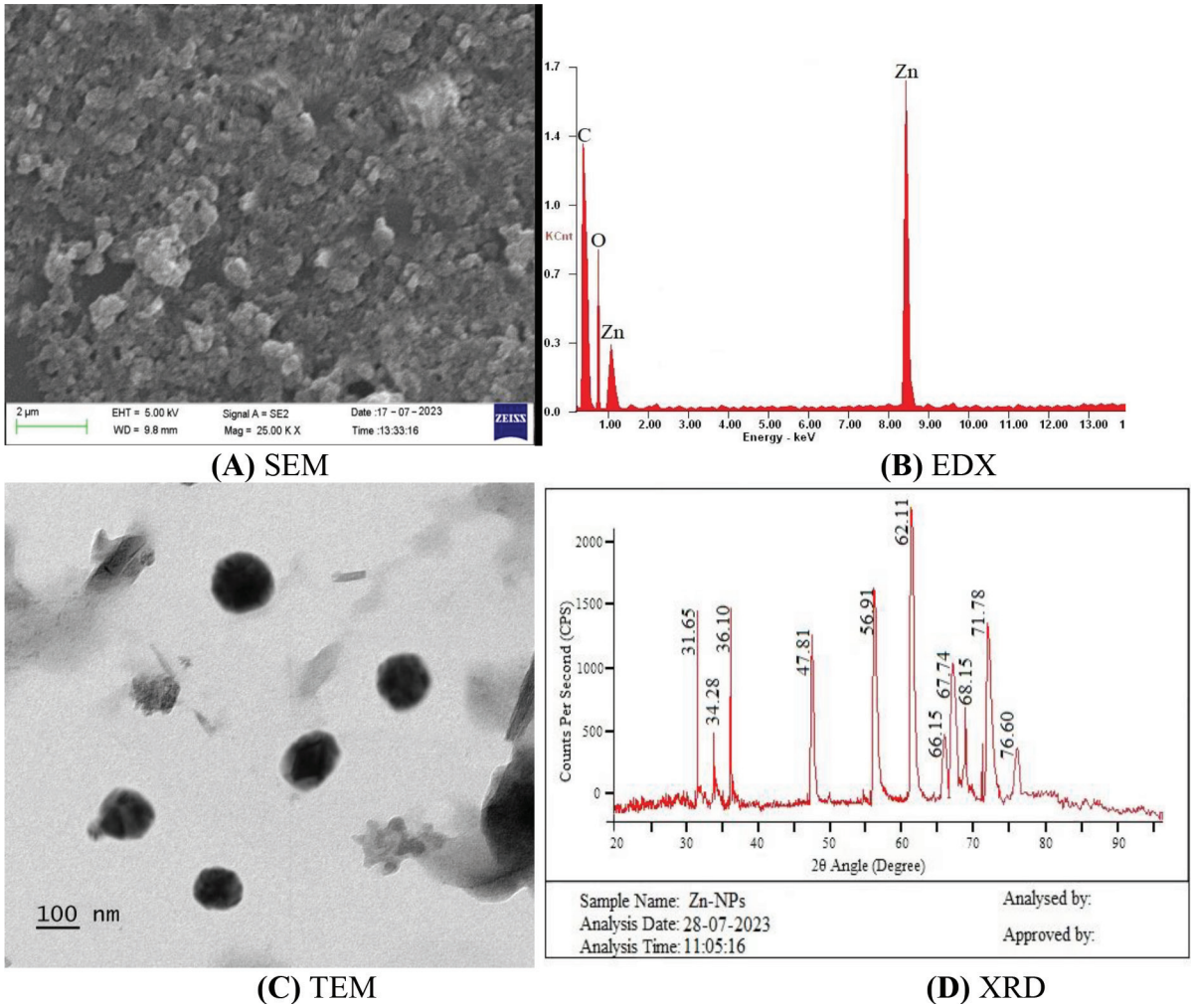


Figure 3. Structural characterization of synthesized zinc nanoparticles.

3.1 Adsorption Study

The utilization of aqueous leaf extract from *D. chloroxylon* for the synthesis of zinc nanoparticles was investigated in the context of their catalytic potential in reducing carcinogenic pollutants like Cr, Pb, and Cd. The efficacy of metal solution strength/concentration in the reduction process was assessed through UV-visible spectrophotometry. To determine the optimal metal concentration, reduction experiments were conducted with varying metal concentrations, while keeping other parameters such as contact time (60 minutes), nanoparticles dosage (0.50g/L), reaction mixture pH (7.0), and agitation rate (100rpm) consistent. The findings indicate that concentrations of 75µg/mL for Pb and 50µg/mL each for Cr and Cd were identified as optimal for the adsorption study. Figure 4(A) visually presents the outcomes observed during the selection of metal concentrations.

The impact of pH on the reduction of the metals under investigation was assessed by optimizing various pH values within the range of 2 to 9. The remaining parameters were held constant, consistent with the optimization of metal concentration, which was employed in this study. The findings reveal that metal adsorption demonstrated a noteworthy increase as the pH of the reaction mixture decreased while elevating pH values led to a decrease in metal adsorption. The introduction of acidic conditions led to an elevated presence of H^+ ions on the adsorbent's surface, enhancing the adsorption of negatively charged metal ions. Extremely low pH levels, however, exhibited a harmful influence on the adsorption process. The optimal pH was identified as 3, 3, and 4 for Cr, Pb, and Cd, respectively (Figure 4(B)).

The agitation rate of the adsorption mixture was optimized to achieve the most efficient adsorption of

the metals under examination. By exploring different agitation rates, while maintaining the optimized metal concentration, pH of the adsorption mixture, and a contact time of 1 hour, a moderate agitation rate of 100 rpm was found to be suitable for Cr whereas 75 rpm was noticed to be optimal for Pb and Cd (Figure 4(C)).

To determine the appropriate nanoparticle dosage for achieving effective adsorption, varying doses of nanoparticles were investigated, including 0.25g/L, 0.50g/L, 0.75g/L, and 1.0g/L. Notably high percentages of adsorption were observed as 81.79% (0.5 g/L dose) for Cr, 91.13% (0.75g/L) for Pb, and 87.76% (0.75g/L) for Cd. These results indicate that a lower nanoparticle dose displays effective adsorption capacity for removing the studied metals

The parameters of optimized adsorbent dose, metal concentration, pH of the reaction mixture, and agitation rate were held constant for investigating the appropriate duration of time needed for the adsorption of metal ions. The amount of adsorbed metal ions was quantified at various time intervals ranging from 15 minutes to 2 hours, employing a UV-visible spectrophotometer. The UV-visible absorption spectra of metal solutions, both untreated and treated with nanoparticles, for the studied metals are depicted in Figure 5. The figure clearly demonstrates a substantial reduction in the concentration of metal ions, implying a decrease in the metal ion concentration within the aqueous solution. Additionally, the EDX spectrum of nanoparticles treated with metals was analyzed to assess the quantity of metals adsorbed onto the nanoparticle surface. As presented in Figure 5, the spectrum exhibits noticeable peaks corresponding to the metals under study, providing evidence that the metal ions were indeed adsorbed onto the surface of the nanoparticles.

Overlay UV scanning of Blank, untreated and nanoparticle-treated metal solution showing a decrease in absorbance after nanoparticle treatment for Cr **(A)**, Pb **(C)**, and Pb **(E)**; EDX spectrum of Cr **(B)**, Pb **(D)** and Pb **(F)** treated zinc nanoparticles synthesized in the study showing the presence of studied meal.

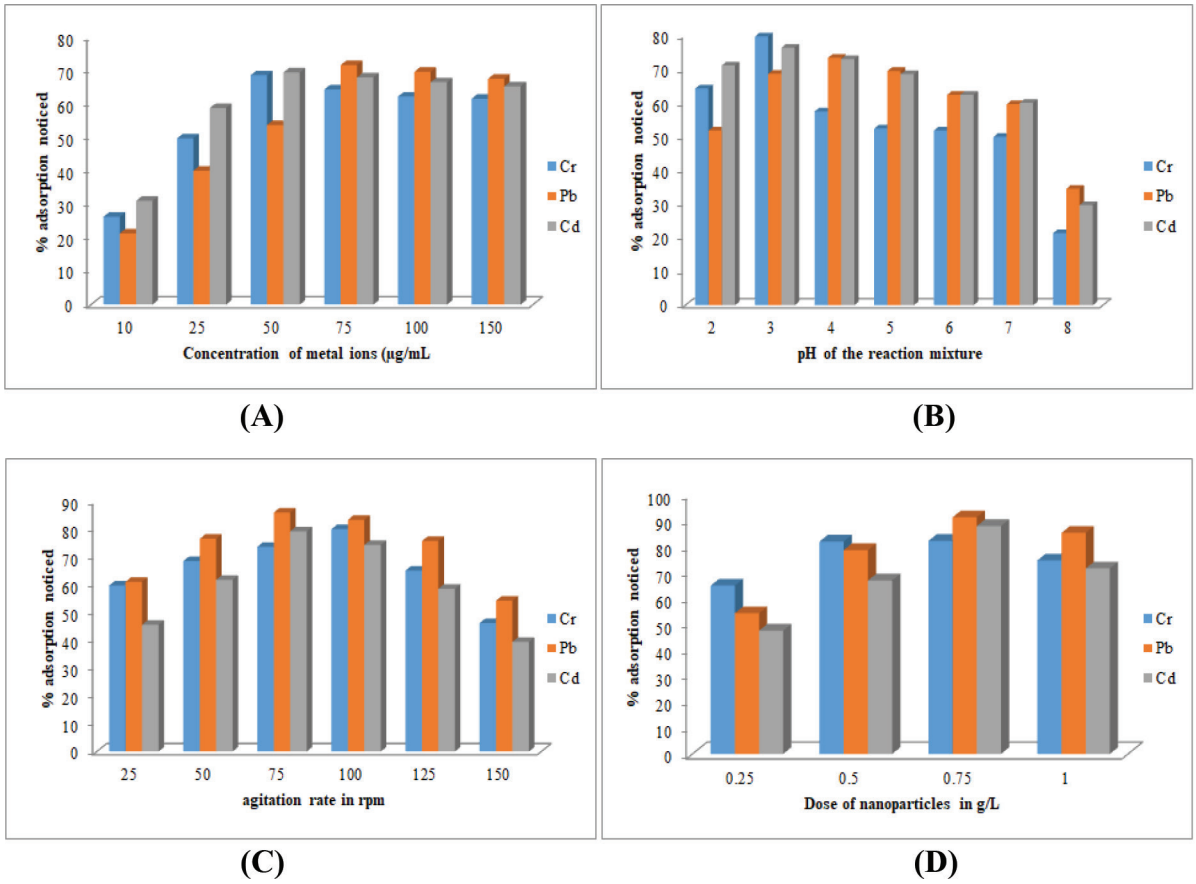


Figure 4. Metal adsorption optimization study. **(A)** metal concentration optimization; **(B)** pH of reaction mixture optimization; **(C)** agitation rate optimization and **(D)** dose of nanoparticles optimization

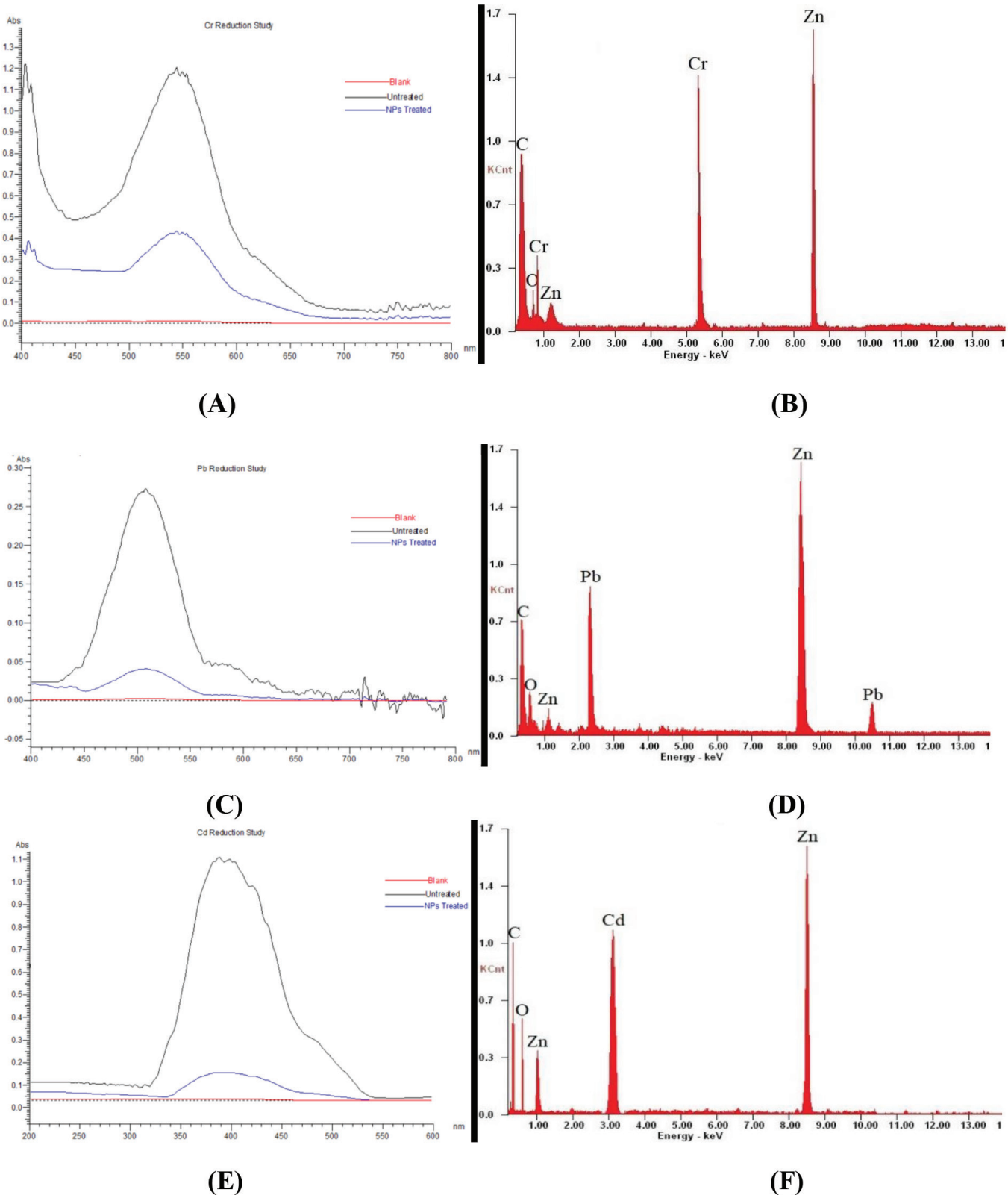


Figure 5. UV and EDX spectral analysis results were observed in the metal reduction study of synthesized nanoparticles.

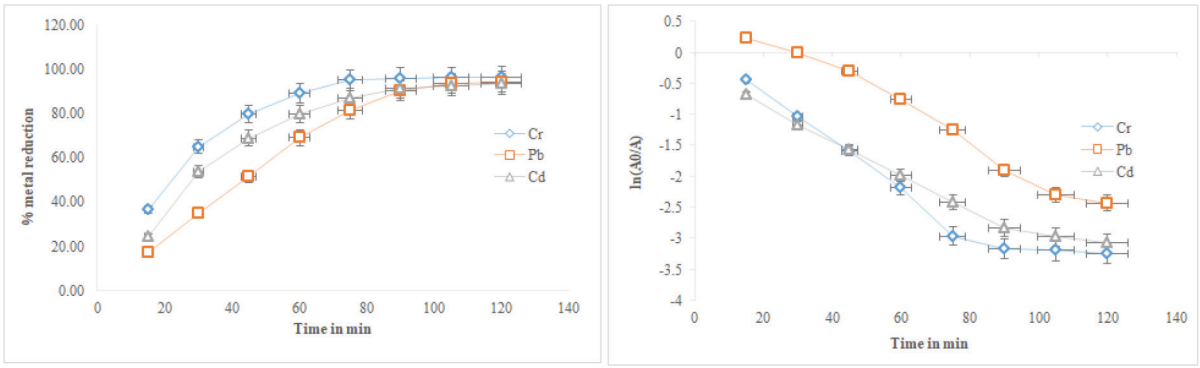
The impact of contact time on the reduction of studied metals using synthesized zinc nanoparticles was presented in Figure 6(A). The plot indicates that the metal reduction increased with an increase in contact time. The % reduction of 88.79, 68.81, and 79.36 was noticed for Cr, Pb, and Cd respectively with a very less contact time of 1 h, whereas at 90 min contact time, the reduction was noticed to be 95.81, 90.13, and 91.25 respectively. The maximum adsorption removal of was 96.13%, 94.15%, and 93.11% within 120 min equilibrium time for Cr, Pb, and Cd respectively suggesting that the nanoparticles possess high adsorption efficiency. The kinetics of the adsorption study was determined by using different equations and as shown in Figure 6(B), the adsorption process follows a pseudo-first order reaction. The kinetic parameters are presented in Table 1.

3.2 Stability and Recyclability of Nanoparticles

The chemical stability of the synthesized zinc nanoparticles was assessed across various pH ranges spanning from 2.0 to 10. The metal content of the nanoparticles in the stability study was compared against the nanoparticles synthesized in the present study, and the percentage stability was computed. As illustrated in Figure 7(A), the synthesized nanoparticles were found to exhibit stability across the explored pH concentrations.

Evaluating the reusability of the prepared nanoparticles was of paramount importance in terms of reducing analysis costs. During the initial cycle, the nanoparticles demonstrated a reusability rate of 98.62%, 96.36%, and 97.87% for Cr, Pb, and Cd, respectively. As the cycles progressed, the reusability declined slightly, with rates of 95.32%, 89.85%, and 90.53% at the fifth cycle for Cr, Pb, and Cd, respectively. This gradual reduction in efficiency could be attributed to the reduction in available active sites within the nanoparticles due to the blocking of these sites by metal ions. Overall, the nanoparticles exhibited notable reusability with a consistently high percentage of adsorption efficiency.

The summary of various metal nanoparticles reported in the literature for the reduction of studied metals is summarized in Table 2. The results clearly illustrated that the nanoparticles synthesized in this study show enhanced metal adsorption activity than the findings reported in the literature. The chitosan-based core shall zinc nanoparticles reported by A.A. Saad, *et al.*,[26] reported higher activity than the present study but the reported method produced

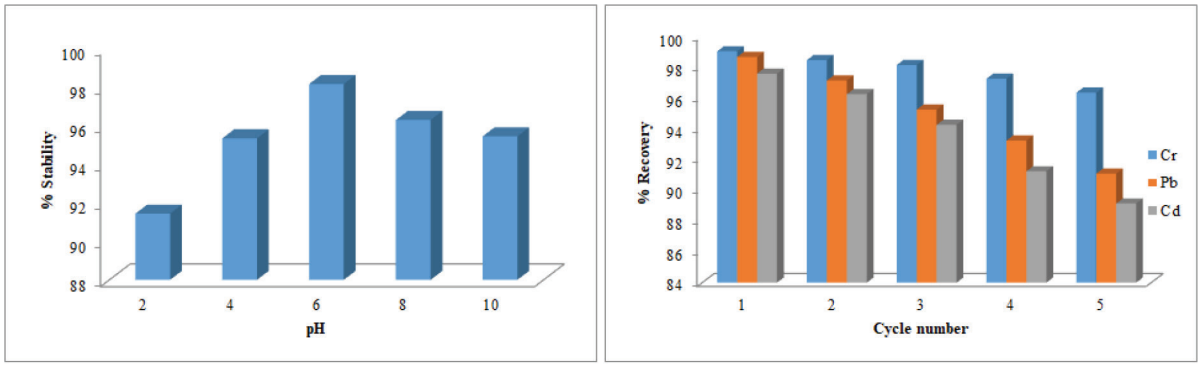


(A) % metal reduction with time **(B)** kinetic linear plots

Figure 6. Results were noticed in metal adsorption study using synthesized zinc nanoparticles.

Table 1. Isotherm parameters noticed in the adsorption study of metals using zinc nanoparticles

S. No.	Parameter	Results noticed for the reduction study of		
		Cr	Pb	Cd
1	q_{max} (mg/g)	125.71	97.46	115.8
2	Rate constant (K)	0.483	0.233	0.328
3	R^2	0.9561	0.99058	0.98481



(A) **(B)**

Figure 7. Stability and recyclability results of synthesized zinc nanoparticles. **(A)** Stability of synthesized zinc nanoparticles in different pH ranges; **(B)** recyclability study of zinc nanoparticles at 5 cycles using EDTA as wash solution

Table 2. Summary of various adsorbents reported for the adsorption of metals in the study

S. No.	Adsorbent	Metal studied	q_{max} (mg/g)	Reference
1	Eggshell-based nanocrystalline chlorapatite	Cr	63.47	[18]
2	Guar gum-mediated zinc nanoparticles	Cr	55.56	[19]
3	Eucalyptus leaf extract-mediated iron nanoparticles	Cr	20.05	[20]
4	Eggshell-mediated based zinc nanoparticles	Cr	38.32	[21]
5	*Azolla pinnata* extract-mediated zinc nanoparticles	Cr	60.13	[22]
6	Acacia catechu extract-mediated iron nanoparticles	Cr	29.8	[23]
7	bamboo extract-mediated zinc nanoparticles	Cr	22.93	[24]
8	*D. chloroxylon* leaf extracted mediated Zn nanoparticles	Cr	125.71	This work
9	Mangrove Leaf extract-mediated Zn nanoparticles	Cd	7.66	[25]
10	Chitosan core-shell Zn nanoparticles	Cd	135.1	[26]
11	Graphene oxide and polyaniline-based Zn nanoparticles	Cd	12.033	[27]
12	Yeast treated with EDTA-based iron nanoparticles	Cd	41.55	[28]
13	Mint leaf extract-mediated copper nanoparticles	Cd	15.60	[29]
14	*D. chloroxylon* leaf extracted mediated Zn nanoparticles	Cd	115.8	This work
15	Mangrove Leaf extract-mediated Zn nanoparticles	Pb	2.02	[25]
16	Chitosan core-shell Zn nanoparticles	Pb	476.1	[26]
17	Yeast treated with EDTA-based iron nanoparticles	Pb	88.16	[28]
18	Mint leaf extract-mediated copper nanoparticles	Pb	88.80	[29]
19	Nano-ZnO/yeast composites	Pb	38.47	[30]
20	Baker's yeast biomass-mediated iron nanoparticles	Pb	16.26	[31]
21	Honey-mediated cobalt-zinc ferrite nanoparticles	Pb	289	[32]
22	*D. chloroxylon* leaf extracted mediated Zn nanoparticles	Pb	97.46	This work

nanoparticles using thermal de-carbonation, and the procedure was not a green methodology. On comparison of q_{max} (mg/g) of this study's findings with the literature as shown in Table 2, it was confirmed that nanoparticles synthesized in the study were considered as best choice for removal of pollutant carcinogenic metals in aqueous solution. Further study needs to be performed to evaluate the synthesized nanoparticles for the reduction of selected metal in real-time samples.

4. Summary and Conclusion

This study underscores the effectiveness of the utilization of the aqueous extract of *Diospyros chloroxylon* (Roxb.) as a multifunctional agent for the reduction, capping, and stabilization of zinc nanoparticles. This approach facilitated the successful fabrication of zinc nanoparticles characterized by spherical morphology and a hexagonal Wurtzite phase structure, with an average particle size of 53 nm. Notably, this research represents a groundbreaking achievement, as it marks the first endeavor to environmentally synthesize zinc nanoparticles using the aqueous extract derived from this particular halophytic plant species, and notably employs zinc acetate as the precursor. The produced nanoparticles were investigated for their potential as efficient adsorbents for the elimination of carcinogenic heavy metals, notably Cr, Pb, and Cd. The Langmuir adsorption isotherm and the pseudo-second-order kinetic model exhibited strong correlation coefficients (R^2) of 0.9561, 0.99058, and 0.98481 respectively, offering suitable frameworks for assessing the adsorption kinetics concerning the reduction of Cr, Pb, and Cd using the synthesized zinc nanoparticles. Calculations indicated impressive removal rates of 95.81, 90.13, and 91.25 for Cr, Pb, and Cd respectively. Based on the empirical findings, it is evident that zinc nanoparticles synthesized through environmentally conscious methods can be effectively employed as economical, eco-friendly adsorbents for the eradication of carcinogenic metals such as Cr, Pb, and Cd. Future research endeavors should focus on assessing the nanoparticles' potential in real-time sample pollutant removal, alongside a thorough exploration of their toxicological properties.

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