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Synthesis, Characterization and Application of *Azadirachta Indica* Leaf-Derived Zinc Oxide Nanoparticle for Remediation of Heavy Metals in Dumpsite-Contaminated Soil

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ABSTRACT
Azadirachta indica (neem) leaf extract-mediated synthesis of zinc oxide nanoparticles (ZnO NPs) provides an eco-friendly, cost-effective, and sustainable approach for heavy metal remediation in contaminated environments. This study evaluated the potential of *A. indica*-derived green nanoparticles for remediating dumpsite-contaminated soil. Soil samples were collected at a depth of 0–10 cm using a soil auger along the Gujba Road dumpsite in Damaturu, Yobe State, Nigeria. Physicochemical parameters were determined using standard procedures, and heavy metal concentrations were analysed via Atomic Absorption Spectroscopy (AAS). Aqueous extract from 200 g of *A. indica* leaf powder in 1,000 mL of distilled water was mixed with zinc salt under heated conditions to synthesize ZnO NPs. Characterization by UV-Visible spectroscopy and Fourier-Transform Infrared (FTIR) spectroscopy confirmed the successful green synthesis of ZnO NPs. Phytoremediation efficacy on the contaminated soil was evaluated at 0, 7, 14, 21, and 28-days post-application. Data were analysed using Analysis of Variance (ANOVA) at $p < 0.05$. Results indicated that the dumpsite soil exhibited alkaline pH, elevated electrical conductivity, and high organic carbon and nutrient contents. Prior to treatment, arsenic (As) and cadmium (Cd) concentrations exceeded World Health Organization permissible limits. Application of synthesized ZnO NPs led to a progressive reduction in arsenic, cadmium, and lead (Pb) concentrations across the sampling intervals.

Keywords: Neem, Nanoparticle, Physicochemical, Synthesis, Remediation

INTRODUCTION

Soil is an essential component of the Earth's biosphere, playing a crucial role not only as a geochemical sink for contaminants but also as a natural buffer that regulates the movement of chemical elements and compounds across ecosystems. Beyond these roles, the most significant function of soil is its capacity to support plant growth, forming the foundation of food production and human survival (Kataba-Pendias, 2021).

However, soil contamination with heavy metals (HMs) has emerged as a pressing global issue. Human activities, such as industrial emissions, traffic pollution, and improper disposal of municipal waste, have significantly increased the concentration of heavy metals in soils (Zeb et al., 2020; Wu et al., 2021). These metals are persistent pollutants with low transferability and long-term retention, posing serious threats to plants, animals, and humans through food chain accumulation (Hu et al., 2020). While certain metals, like copper (Cu), zinc (Zn), manganese (Mn), and iron (Fe), are vital for biological functions, others, such as cadmium (Cd), nickel (Ni), and mercury (Hg), have no beneficial physiological role and can be harmful at elevated concentrations (Xiang et al., 2021). Excessive exposure to toxic metals like Hg, Cr, Pb, and Cd has been linked to severe health issues, including kidney damage, liver dysfunction, and bone degeneration (Liu et al., 2021; Yin et al., 2021).

Although soil has physical, chemical, and biological mechanisms to filter and degrade contaminants such as adsorption, precipitation, and organic matter decomposition, its capacity to handle heavy metals is often insufficient (Singh et al., 2019a). Unlike air pollution, which directly impacts human health, soil pollution tends to exert its harmful effects indirectly through the food chain.

Heavy metals, broadly defined as elements with metallic properties, include both essential nutrients and harmful pollutants. Zinc, copper, and chromium are critical for metabolic processes while lead, cadmium, and mercury are highly toxic even at low concentrations (Rehman et al., 2021). The accumulation of heavy metals in soil depends on various factors, including the soil's physical and chemical properties, as well as the ability of plants to absorb and remove these metals. Parameters such as pH and texture play a significant role, influencing the mobility of metals and nutrient availability for plants (Lwin et al., 2019; Kome et al., 2019).

Phytoremediation has emerged as an environmentally friendly and cost-effective solution for cleaning up contaminated soils. This method uses plants to absorb, accumulate, and detoxify pollutants, including heavy metals, from the soil. Different types of plants have varying levels of efficiency in this process. (Lange et al., 2019; Rocha et al., 2021; Vander et al., 2023).

In addition, advances in nanotechnology have opened new pathways for sustainable soil remediation. Nanoparticles (NPs), materials ranging from 1–100 nanometers in size, exhibit unique properties, such as high mechanical strength and a large surface area, making them effective in various scientific applications (Liu et al., 2020).

The aim of this research is to synthesize characterize, and assess the application of A. *indica* leaf-derived zinc oxide nanoparticle for remediation of heavy metals in dumpsite-contaminated Soil.

MATERIALS AND METHODS

Soil Collection and Preparation

Soil samples were collected at a depth of 0–10 cm using a soil auger along the Gujba Road dumpsite in Damaturu, Yobe State. The samples were taken at three designated locations: Point A (entry point), Point B (midpoint of the dumpsite), and Point C (apex point). Each sample was placed in a clean polythene bag, labeled appropriately, and transported to the laboratory (Iyaka, 2019). Samples were prepared in triplicate following the method outlined by Bako et al. (2014). In the laboratory, the samples were crushed and sieved through a 2.0 mm mesh to ensure uniformity (Iyaka, 2019).

Heavy Metals Analysis of the Contaminated Soil from Dump Site

Approximately 5.0 g of dried soil samples was digested separately. Each sample was placed in a 25 mL conical flask, and 10 mL of concentrated HNO_3 and 5 mL of concentrated HCl (2:1 ratio) was added (Parker *et al*., 2022). The mixture was heated on a hot plate to avoid boiling until the volume reduced to 15 mL. After cooling, the digested samples were filtered and quantitatively transferred into a 100 mL volumetric flask, topped with distilled water, and analyzed using Atomic Absorption Spectroscopy (AAS). Some heavy metals of interest were analyzed including Arsenic (AS), Cadmium (Cd), and Lead (Pb) using the AAS after the digestion. *Azadirachta indica* leaf sample was equally analyzed for the heavy metal's presence.

Plant Material Collection

Fresh leaves of *A. indica* were collected in Ganye-uku Gujba Road Damaturu. The collected leaves were transported to the herbarium unit in Biology Department, Yobe State University for identification by a botanist and was issued a voucher number. The samples were prepared and processed in the laboratory. Initially, the neem leaves were thoroughly washed with tap water followed by distilled water to remove debris and impurities. The washed leaves were air-dried for 2–3 hours and then oven-dried at 65°C for 24 hours. Once dried, the leaves were crushed using a porcelain mortar and pestle and sieved through a 2.0 mm mesh and a fine powdered form was obtained, following the of Iyaka (2019).

Extraction of Plant Bioactive Compounds

200g of the grinded leaves sample were macerated with 1000 mL of water. The solvent was left in contact with the powered plant sample for 24 hours with intermittent shaking by an electric shaker (MaxiShake MS-FT-100A). The extract was decanted and allowed to stand, after which the marc was filtered through a Whatman No. 42 filter paper. The extracts was then concentrated using water bath (76-B0066/A model) at 40 ^{0}C until a paste form of the extract was obtained, weighed, and stored in a refrigerator at 4 °C until when required (Arya *et al.,* 2020).

The percentage yield of the extracts was determined as:

$$\% \text{ Yield} = \frac{Weight\ of\ sample\ extracted}{Weight\ of\ dry\ extract} \times 100.$$

Zinc Oxide Nano-particle Synthesis

Aqueous extract of *A. indica* was used for the synthesis. 40 ml of extract was measured into a beaker. Two grams (2 g) of Zinc oxide (ZnO) was measured and added into the beaker. The mixture was stirred for 4 hr at 100 rpm under the heating condition. The reaction solution was centrifuged at 10,000 rpm for 20 min. The supernatant was discarded, and the precipitation was collected. The precipitate obtained was washed with distilled water and dried to obtain Zn NP (Xiang *et al*., 2023).

Characterization of Synthesized Nanoparticles

UV-Vis Absorption Spectroscopy

UV-Vis spectroscopy was employed to determine the optical properties of the synthesized nanoparticles. The reduction of Zinc Oxide nanoparticles synthesized using *A. indica* extract was monitored by measuring the UV-visible spectra of the reaction mixture. A SHIMAZDU 2600 (TCC) UV-visible spectrophotometer, with a resolution of 1 nm over the 200–600 nm wavelength range, was used. A 300 µL aliquot of the sample was diluted 10-fold with distilled water to minimize errors caused by high optical density (Alkali and Yoriyo, 2022).

Data Analysis

The data collected were analyzed using IBM SPSS Statistics (version 25). The mean values and standard deviations of the parameters (plant height, number of leaves, and metal uptake) were calculated for each treatment group. ANOVA was used to determine if there were significant differences in plant growth parameters and metal uptake across different soil treatments.

RESULTS AND DISCUSSION

The result shows the physicochemical parameters of dumpsite soil. This includes the pH, electrical conductivity (EC), organic carbon, total nitrogen, cation exchange capacity (CEC), available phosphorus and particulate size. One-way ANOVA showed that sampling points (A, B and C) differed significantly in pH ($F(2,6)=6.10$, $p=0.036$), organic carbon ($F(2,6)=15.79$, $p=0.004$) and CEC ($F(2,6)=33.93$, $p<0.001$), but did not differ significantly in EC ($F(2,6)=4.47$, $p=0.065$), total nitrogen ($F(2,6)=4.17$, $p=0.073$) or available phosphorus ($F(2,6)=1.99$, $p=0.217$). (Table 1).

Table 1: **Physicochemical Parameters of Contaminated Soil from Dumpsite**

Sampling Points	pH	EC (dS/m)	Organic Carbon (%)	Total Nitrogen (%)	CEC (cmol/kg)	AP (mg/kg)
A	9.1 ± 0.06^{a}	6.8 ± 1.06^{a}	3.3 ± 0.12^{ab}	0.2 ± 0.00^{a}	34 ± 1.15^{b}	56 ± 4.36^{a}
B	8.4 ± 0.44^{b}	8.47 ± 0.6^{a}	3.6 ± 0.12^{a}	0.3 ± 0.06^{a}	42 ± 2.00^{a}	61 ± 2.08^{a}
C	8.5 ± 0.12^{ab}	8.0 ± 0.10^{a}	3.0 ± 0.15^{b}	0.3 ± 0.06^{a}	42 ± 0.58^{a}	56 ± 3.79^{a}
p value	p=0.036	p=0.065	p=0.004	p=0.073	p=0.001	p=0.217

Key: EC= Electrical conductivity, CEC= Cation Exchange Capacity, AP= Available Phosphorus

Means within a column bearing different superscript letters differ significantly ($p<0.05$); means sharing a letter do not differ significantly.

The result shows the particulate soil size of Gujba road dumpsite. Clay, silt and sandy content were measured. One-way ANOVA showed a significant difference among sampling points for clay content ($F(2,6)=17.29$, $p=0.003$), but no significant difference for silt ($F(2,6)=2.20$, $p=0.192$) or sand ($F(2,6)=0.96$, $p=0.435$). The particulate size of clay ranged from mean values of 7.3% to 10% in points A, B and C, with point B significantly higher than both A and C, which did not differ significantly from each other. (Table 2).

Table 2: Concentration of Heavy Metals in Collected Soil Samples of Gujba Road Dumpsite, Damaturu (Before Treatment)

SN	Metals	WHO Maximum Tolerable Limit (mg/kg)	A	B	C	p value p<0.05
1	Arsenic (As)	10	12.4 ± 0.02^{c}	25.0 ± 0.04^{b}	29.0 ± 0^{a}	p=0.001
2	Cadmium (Cd)	0.8	32.0 ± 0.01^{a}	7.0 ± 0.05^{c}	12.7 ± 1^{b}	p=0.001
3	Lead (Pb)	85	64.0 ± 0.20^{a}	$10.3.0\pm0.04^{c}$	30.1 ± 0^{b}	p=0.001

Means within a row bearing different superscript letters differ significantly across sampling points ($p<0.05$); means sharing a letter do not differ significantly.

The result shows the concentration of heavy metals in soil samples collected from the dumpsite (before treatment). Arsenic (As), cadmium (Cd), and lead (Pb) were tested and compared with WHO permissible limits for heavy metals in soil. One-way ANOVA showed highly significant differences among sampling points for all three metals: arsenic ($F(2,6)=337571.21$, $p<0.001$), cadmium ($F(2,6)=1540.96$, $p<0.001$) and lead ($F(2,6)=159549.29$, $p<0.001$), with Tukey HSD confirming that points A, B and C were all significantly different from one another for each metal ($p<0.05$).(Table 3).

Percentage Yield of *A. Indica* Leaf Extract

The result shows Percentage Yield of *A. indica* leaf extract .726 g dry weight was obtained. Using water as solvent, 47 g was extracted with a percentage yield of 6.5 %.(Table 3.).

Table 3: Percentage Yield of *A. Indica* Leaf Extract

Sample	Weight of Dry Sample	Weight of Sample Extracted	Percentage Yield (%)
Azadirachta indica	726 g	47 g	6.5

The result shows the elemental concentrations of heavy metals in dumpsite soil after treatment (0, 7, 14, 21 and 28 days) with Zn nanoparticles, compared with an untreated control. One-way ANOVA showed significant differences among Control, A, B and C for all three metals: arsenic ($F(3,8)=45.83$, $p<0.001$), cadmium ($F(3,8)=24.99$, $p<0.001$) and lead ($F(3,8)=168.84$, $p<0.001$). Arsenic showed bioreduction from 12 to 8 mg/kg in point A, 25 to 21 mg/kg in point B and from 29 to 21 mg/kg in point C; Tukey HSD grouped the Control and point A together as not significantly different from each other, while points B and C were significantly higher than both the Control and point A but not significantly different from each other (Table 4).

Table 4: Heavy metals concentration in dumpsite soil after treatment with Zn nanoparticles

SN	Metals	WHO Maximum tolerable limits of metals in soil (mg/kg)	Control	Mean±SD Concentration of Heavy Metals in Dumpsite (mg/k)			
				A	B	C	p value p<0.05
1	Arsenic (As)	10	8.5 ± 2.0^{b}	10.0 ± 2.0^{b}	23.0 ± 1.6^{a}	24.8 ± 2.9^{a}	p=0.001
2	Cadmium (Cd)	0.8	0.5 ± 1.0^{b}	25.4 ± 6.8^{a}	5.4 ± 1.7^{b}	9.2 ± 2.4^{b}	p=0.001
3	Lead (Pb)	85	74.0 ± 2.1^{a}	58.4 ± 5.5^{b}	7.2 ± 2.3^{d}	22.6 ± 5.3^{c}	p=0.001

Means within a row bearing different superscript letters differ significantly across Control, A, B and C ($p<0.05$); means sharing a letter do not differ significantly.

UV-Vis and FTIR Spectroscopy of *A. Indica* Leaf

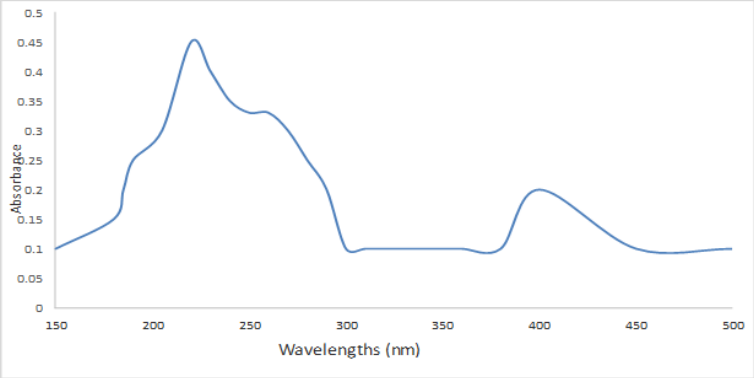

Figure 1: UV-Visible Spectrum of *A. indica of* leaf extract

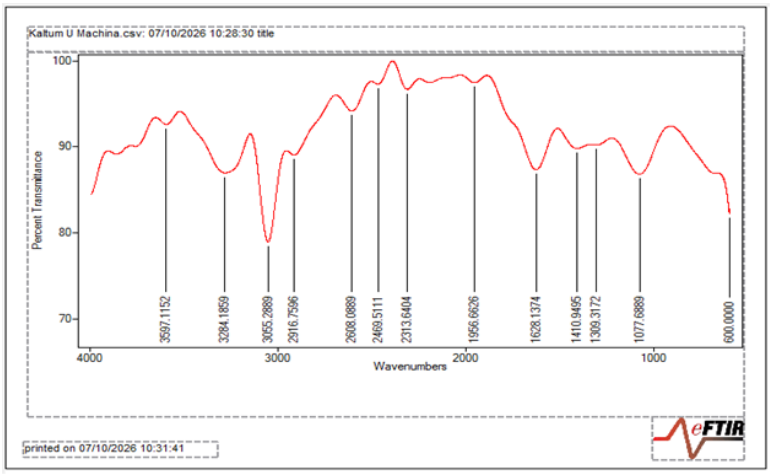

Figure 2: FTIR spectrum of Zinc (Zn) nanoparticles synthesized using *A. indica*

Discussion

The physicochemical properties of the dumpsite soil revealed notable variations across the three-discharge points A, B, and C, reflecting the heterogeneous nature of waste deposition and decomposition at the site. The soil pH ranged from 8.4 to 9.1, indicating alkaline conditions across all sampling points. Such alkalinity is characteristic of dumpsite soils and has been widely attributed to the accumulation of ash, construction debris, decomposing organic matter, and inorganic wastes that release basic cations into the soil matrix (Sharma *et al.,* 2019b; Alloway, 2023).

The variability in pH values among discharge points A, B, and C further suggests differences in waste composition, age, and decomposition stages. Areas receiving higher proportions of construction and demolition wastes typically exhibit elevated alkalinity due to lime, cement dust, and concrete residues (Sharma *et al.,* 2019a). Such spatial heterogeneity is common in unmanaged dumpsites where waste segregation is absent, leading to localized physicochemical variations across short distances.

The percentage yield of *A. indica* leaf extract (6.5%) indicates effective extraction using water as a solvent (Table 4.5). The use of plant extracts in nanoparticle synthesis is advantageous due to the presence of bioactive compounds such as flavonoids, terpenoids, and phenolics, which act as reducing and stabilizing agents (Sangeetha *et al.,* 2022). Neem (*A. indica*) has been widely reported as an effective green synthesis agent due to its rich phytochemical composition and antimicrobial properties (Ahmed *et al.,* 2019).

The UV–visible spectra of the *A. indica* leaf extract and the biosynthesized zinc nanoparticles demonstrated a distinct shift in the absorption maximum from 220 nm in the crude leaf extract to 280 nm after nanoparticle synthesis. The absorption peak at 220 nm in the leaf extract is characteristic of transitions of aromatic rings and phenolic compounds, indicating the abundance of phytochemicals such as flavonoids, tannins, phenolic acids, alkaloids, and terpenoids in the extract. Similar UV–visible absorption bands for *A. indica* leaf extracts have been reported by Shankar *et al.* (2004), Ahmed *et al.* (2016), and Iravani (2011), who attributed these peaks to bioactive phytochemicals involved in nanoparticle synthesis.

Following synthesis, the absorption maximum shifted to 280 nm, indicating the formation of zinc nanoparticles and confirming that the phytochemicals present in the extract actively participated in the reduction and stabilization of zinc ions. Such shifts in absorption wavelength after nanoparticle synthesis have been widely reported and are attributed to changes in the electronic environment resulting from nanoparticle formation and the interaction of plant metabolites with the nanoparticle surface. Although ZnO nanoparticles are frequently reported to exhibit absorption bands between approximately 330 and 380 nm depending on synthesis conditions, particle size, crystallinity, and instrument settings, absorption in the ultraviolet region around 270–300 nm has also been reported for biosynthesized zinc nanoparticles, particularly for smaller particles and partially oxidized zinc nanomaterials (Jayaseelan *et al.,* 2012; Singh *et al.,* 2018; Sangeetha *et al.,* 2022).

The FTIR spectra further support the transformation from plant extract to nanoparticle. In the A. indica leaf extract, broad absorption bands at 3597 and 3284 cm^{-1} correspond to

O–H stretching vibrations of phenols and alcohols, while the band at 2916 cm^{-1} represents aliphatic C–H stretching. The absorption band at 1628 cm^{-1} is attributed to C=O stretching or H–O–H bending vibrations, whereas the bands at 1309 cm^{-1} and 1077 cm^{-1} correspond to C–O stretching vibrations of alcohols, ethers, and carboxylic acids. These functional groups are typical of phenolic compounds, flavonoids, proteins, and polysaccharides found in *an.indica* leaves, all of which are known to possess strong reducing and metal-chelating properties (Ahmed *et al.,* 2016; Mittal *et al.,* 2023). After nanoparticle synthesis, notable changes were observed in both the position and intensity of these absorption bands. The O–H stretching band shifted from 3597 to 3447 cm^{-1}, while the C–H stretching vibration shifted from 2916 to 2985 cm^{-1}. Similarly, the carbonyl-related band shifted slightly from 1628 to 1638 cm^{-1}, and the C–O stretching band changed from 1077 to 1085 cm^{-1}. These spectral shifts indicate the interaction of hydroxyl, carbonyl, and carboxyl functional groups with zinc ions during nanoparticle formation, suggesting that these biomolecules served as both reducing agents and stabilizing (capping) agents. Comparable FTIR shifts have been reported in numerous studies on the green synthesis of zinc nanoparticles using plant extracts, confirming the participation of polyphenols, flavonoids, proteins, and other phytochemicals in nanoparticle biosynthesis (Singh *et al.,* 2018; Iravani, 2021; Mittal *et al.,* 2023).

The application of synthesized ZnO nanoparticles to the contaminated dumpsite soil resulted in a significant reduction in Arsenic, Cadmium, and Lead concentrations over the 28-day treatment period. Arsenic reduction observed across all sampling points suggests effective adsorption and immobilization by the nanoparticles. ZnO nanoparticles possess high surface area and reactive sites, enabling efficient binding of metalloid species such as arsenic (Wang *et al.,* 2019).

Cadmium exhibited substantial reduction, particularly at sampling point A, where concentrations decreased from 32 to 14 mg/kg. This reduction can be attributed to surface complexation, ion exchange, and precipitation mechanisms facilitated by ZnO nanoparticles (Zhang *et al*., 2019a). Similar findings have been reported by Prasad et al. (2020b), who demonstrated the effectiveness of metals oxide nanoparticles in removing cadmium from contaminated soils. Lead concentrations also decreased markedly across all sampling points, with the most pronounced reduction observed at point B. The affinity of ZnO nanoparticles for lead ions has been linked to electrostatic attraction and the formation of stable Pb–O bonds on nanoparticle surfaces (Reddy *et al*., 2019).

The significant decline in Cadmium concentration suggests that ZnO nanoparticles provided abundant reactive surface sites capable of binding Cd^{2+} ions efficiently. Due to their high surface area-to-volume ratio and enhanced surface reactivity, nanoparticles offer more adsorption sites compared to bulk materials, thereby increasing immobilization capacity (Kumar *et al.,* 2021). Cadmium ions may have been immobilized through chemisorption processes involving hydroxyl functional groups present on ZnO nanoparticle surfaces, resulting in the formation of stable inner-sphere complexes (Zhang *et al*., 2019b). In addition, the introduction of ZnO nanoparticles can influence soil pH, often shifting it toward slightly alkaline conditions, which favor the precipitation of cadmium as cadmium hydroxide or carbonate species (Alloway, 2023).

The pronounced reduction of Lead at sampling point B further highlights the strong binding affinity between Pb^{2+} ions and ZnO nanoparticle surfaces. Lead ions readily interact with negatively charged surface sites through electrostatic attraction, forming stable coordination bonds that enhance adsorption stability (Reddy *et al*., 2019b). The formation of Pb–O bonds on nanoparticle surfaces contributes to the creation of relatively insoluble complexes, which are less susceptible to leaching under normal soil conditions (Prasad *et al.,* 2020a). Furthermore, co-precipitation processes between zinc and lead compounds may occur, strengthening immobilization and reducing lead bioavailability in the soil matrix (Kumar *et al*., 2021).

Differences in reduction efficiency among sampling points A, B, and C may be influenced by variations in soil texture, organic matter content, cation exchange capacity, and initial contaminant concentrations. Soils rich in clay minerals and organic matter typically provide additional adsorption sites, enhancing the overall retention of heavy metals (Alloway, 2023). Organic functional groups such as carboxyl and phenolic groups may interact synergistically with nanoparticle surfaces, forming stronger metals–ligand complexes.

Overall, the observed decreases in Cadmium and Lead concentrations demonstrate the effectiveness of ZnO nanoparticles in mitigating heavy metals contamination in soils. Through adsorption, surface complexation, ion exchange, precipitation, and co-precipitation mechanisms, nanoparticles reduce metals mobility and bioavailability. However, long-term environmental stability of immobilized metals remains a critical consideration, as changes in soil pH, redox conditions, or organic matter dynamics may influence remobilization potential (Alloway, 2023). Continuous monitoring is therefore essential to ensure sustainable remediation outcomes. Although, the concentrations did not fall below permissible limits in all cases, the observed reductions highlight the potential of green-synthesized ZnO nanoparticles as an eco-friendly and efficient soil remediation agent.

Overall, the findings of this study demonstrate that *A. indica*-mediated ZnO nanoparticles are effective in reducing heavy metals contamination in dumpsite soils. This aligns with the growing body of literature supporting nanotechnology-based remediation as a sustainable alternative to conventional physicochemical methods, which are often costly and environmentally disruptive (Karn *et al.,* 2019a)

Conclusion

The findings revealed that the Gujba road dumpsite soils across the three sampling points exhibited alkaline pH, elevated electrical conductivity, and appreciable organic carbon and nutrient contents, reflecting significant influence from waste deposition and leachate infiltration. Particle size distribution showed that the soils were predominantly sandy with moderate proportions of clay and silt, a texture that enhances contaminant mobility while still permitting some level of metals retention through adsorption to fine particles and organic matter. The concentrations of arsenic and cadmium in the dumpsite soil before treatment exceeded World Health Organization (WHO) permissible limits, while lead concentrations, though within limits, were relatively higher than the control values. This confirms that the dumpsite poses a considerable environmental and public health risk if left unmanaged.

The successful green synthesis of ZnO nanoparticles using *A. indica* leaf extract was confirmed through UV–visible spectroscopy and FTIR analysis. The presence of functional groups associated with plant biomolecules indicated their role in the reduction, stabilization, and capping of the

nanoparticles, validating the effectiveness of the eco-friendly synthesis approach. Application of the synthesized ZnO nanoparticles to the contaminated soil resulted in a progressive reduction in arsenic, cadmium, and lead concentrations over the 28-day treatment period. Although complete remediation to permissible limits was not achieved for all metals, the substantial decrease recorded highlights the potential of green-synthesized ZnO nanoparticles as an effective, sustainable, and environmentally benign soil remediation strategy. This study establishes that *A. indica*–mediated ZnO nanoparticles can serve as a promising tool for mitigating heavy metals contamination in dumpsite soils, contributing to safer land use and environmental sustainability.

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