



ORIGINAL RESEARCH ARTICLE

Green synthesis of ZnO nanoparticles using *Ixora coccinea* leaf extract for efficient removal of Co (II) from water

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ABSTRACT

The research described in this text uses leaf extract from *Ixora coccinea* as a natural reducing agent to produce zinc oxide nanoparticles (ZnO NPs) in an environmentally friendly way. Instead of traditional chemical synthesis methods, the study highlights the potential of an eco-friendly approach. To create ZnO NPs sustainably, the researchers used leaf extract from *Ixora coccinea*, a plant native to parts of South Asia and grown in Nigeria. The leaf extract from *Ixora coccinea* served as the reducing and stabilizing agent in nanoparticle production, with zinc acetate acting as the precursor. UV-Visible absorption spectroscopy was employed to confirm the formation of ZnO NPs. Multiple analytical techniques characterized the synthesized nanoparticles. Fourier transform infrared spectroscopy (FTIR) was used to identify the functional groups involved in synthesis. Scanning electron microscopy (SEM) analyzed the size and shape of the nanoparticles. X-ray diffraction (XRD) determined the crystalline structure. The ZnO NPs were then used as an adsorbent to extract cobalt (II) ions from water. Atomic absorption spectroscopy (AAS) evaluated the effectiveness of the ZnO NPs in removing cobalt ions from aqueous solutions. Maximum Co(II) removal of 83.8% was achieved at pH 10.3 using 0.01 g/100 mL ZnO NPs. This study demonstrates how plant-mediated synthesis can produce ZnO NPs for heavy metal removal in water purification. By combining environmentally safe, sustainable nanoparticle production with their application in environmental cleanup, this work contributes to the growing field of green nanotechnology.

ARTICLE HISTORY

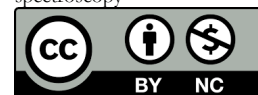
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KEYWORDS

Ixora coccinea, SEM, XRD, FTIR, and UV-visible spectroscopy



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INTRODUCTION

Nanotechnology, which involves the design, construction, and application of structures and systems by manipulating atoms and molecules at the nanoscale (<100 nm), has rapidly developed across scientific and engineering fields (Prathna *et al.*, 2011). At this scale, materials exhibit unique physicochemical properties, such as a high surface-to-volume ratio and size-dependent phenomena, which distinguish them from their bulk counterparts. These characteristics have fueled wide applications of nanomaterials in electronics, energy, healthcare, biotechnology, and environmental remediation (Dada *et al.*, 2017; Ahmed *et al.*, 2016).

Among nanomaterials, metal oxide nanoparticles, particularly zinc oxide (ZnO), have attracted significant attention due to their distinct optical, catalytic, and antimicrobial properties, which can be tailored by modifying their structural attributes (Dagdeviren *et al.*, 2013; Rasmussen *et al.*, 2014; Waseem and Divya, 2020). ZnO nanoparticles have been applied in biosensing, drug delivery, labelling, personal care products, environmental

management, and pharmaceuticals (Zhang *et al.*, 2016). However, conventional synthesis methods, including sol-gel (Hasnidawani *et al.*, 2016), chemical vapour deposition (Lobiak *et al.*, 2020), laser ablation (Cho *et al.*, 2009), solvothermal synthesis (Wang *et al.*, 2006), and thermal decomposition (Ling *et al.*, 2009), are often costly, energy-intensive, and may involve toxic chemicals that pose risks to human health and the environment (Narayanan *et al.*, 2012; Kharissova *et al.*, 2013). These drawbacks highlight the need for sustainable and eco-friendly alternatives.

Green synthesis, which utilizes plant extracts and other biological resources as reducing and stabilizing agents, has emerged as a promising alternative that aligns with green chemistry principles (Noorjahan *et al.*, 2015; Yedurkar *et al.*, 2016). Plants inherently contain phytochemicals such as flavonoids, terpenoids, alkaloids, and phenolic compounds that facilitate the reduction of metal ions and stabilization of nanoparticles (Nilavukkarasi *et al.*, 2020; Sayeed *et al.*, 2020). This approach avoids hazardous chemicals, requires lower energy inputs, and is cost-

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effective, making it particularly attractive for biomedical and environmental applications (Appierot *et al.*, 2009; Sharma *et al.*, 2010). Several plants, including *Aloe barbadensis* (Sangeetha *et al.*, 2011), *Physalis alkekengi* (Qu *et al.*, 2011), *Parthenium hysterophorus* (Rajiv *et al.*, 2013), *Zingiber officinale* (Anand *et al.*, 2015), *Azadirachta indica* (Bhuyan *et al.*, 2015), and *Ocimum basilicum* (Ravij *et al.*, 2013), have been reported for ZnO nanoparticle biosynthesis.

One critical environmental application of ZnO nanoparticles is the removal of toxic heavy metals from wastewater. Heavy metals are naturally occurring elements with densities at least five times greater than water and include cobalt, lead, and others (Fu and Wang, 2011). While trace cobalt is essential for biological processes and has industrial applications in nuclear medicine, semiconductors, electroplating, and vitamin B12 production (Netzer *et al.*, 2002), excessive exposure can be harmful. Lead, by contrast, is extremely toxic to vital organs, including the kidneys, liver, brain, and reproductive system (Naseem and Tahir, 2001). Conventional heavy metal removal methods, such as ion exchange, electrodialysis, chemical precipitation, reduction, reverse osmosis, and ultrafiltration, often face limitations like sludge generation, high operational costs, and low efficiency under variable conditions. Adsorption, however, stands out as an effective, flexible, and regenerable method (Fu and Wang, 2011).

Traditional heavy metal removal adsorbents, such as zeolites and activated carbons, exhibit low selectivity and efficiency. Recent developments in nanotechnology have enabled the creation of nano-adsorbents with enhanced adsorption capacity, stability, and adaptability. Various physical, chemical, and environmentally friendly techniques produce these materials (Al-Mur, 2023). Numerous nano-adsorbents (metal oxides), such as ferric, manganese, aluminium, titanium, zinc, silicon oxide, and selenium nanoparticles, have been produced to remove heavy metals from industrial effluent (Tan *et al.*, 2021).

Since metal oxides like ZnO have special properties, including high electron mobility, remarkable transparency, and strong room-temperature luminescence, it has long been expected that they will make efficient nano-adsorbents. Due to their unique physical, chemical, and biological characteristics—such as their non-toxicity, biocompatibility, affordability, and environmental friendliness—zinc oxide nanoparticles are among the most significant metal oxide materials that have been used extensively in material research (Shaba *et al.*, 2021).

Recent research has explored the potential of green-synthesized ZnO nanoparticles in heavy metal removal. Plant-based synthesis using *Ixora coccinea*, also known as jungle geranium, is particularly promising. This plant contains bioactive compounds such as flavonoids, ursolic acid, and lupeol, which exhibit antibacterial, antioxidant, and therapeutic properties (Baliga *et al.*, 2012). Previous studies have demonstrated the ability of *I. coccinea* extracts to facilitate nanoparticle synthesis, including gold nanoparticles (Baliga *et al.*, 2012). Building on this, ZnO

nanoparticles synthesized using *I. coccinea* leaf extract have been investigated for cobalt (II) adsorption from aqueous solutions, with process efficiency influenced by factors such as extract concentration, reaction time, and pH (Kowshik *et al.*, 2002; Rautary *et al.*, 2003; Kumar *et al.*, 2014).

This study, therefore, focuses on the green synthesis of ZnO nanoparticles using *Ixora coccinea* leaf extract, the optimization of synthesis parameters, and the evaluation of their effectiveness in removing cobalt (II) from aqueous solutions, offering a cost-effective and environmentally sustainable approach.



Figure 1: *I. Coccinea* leaves

MATERIALS AND METHODS

Collection and Preparation of Samples

A taxonomist from Federal University Dutse's Department of Botany recognized *I. coccinea* leaves that were gathered from the Faculty of Art and Social Sciences, located at 11°42'14.7"N 9°22'11.1"E in Jigawa State, Nigeria. To remove any remaining dust or debris, the leaves were cleaned and rinsed with distilled water before being allowed to air dry at room temperature. In this research work, a mortar and pestle were used to chop and grind the leaves into little pieces. 10 g of leaf extract and 100 mL of distilled water were combined in a 250 mL beaker to create the *I. Coccinea* aqueous extract. The mixture was heated to 60 °C and swirled for 2 hours using a magnetic stirrer. The solution was placed in the refrigerator for additional analysis after being cooled to 25 °C and filtered using a Whatman no. 1 filter paper (Shakeel *et al.*, 2016).

Nanoparticle Synthesis of Zinc Oxide

50 mL of aqueous extract of *I. coccinea* was mixed with 50 mL of a 0.45 M solution of Zn (OAc)₂·2H₂O. The mixture was agitated with a magnetic stirrer in a water bath maintained at 70°C for a duration of 2 hours. Pale yellow pellets started to develop, and their quantity increased progressively. Subsequently, 50 mL of 0.45 M NaOH was added gradually, drop by drop. The mixture was stirred for one hour until a solid with a subtle yellow hue was achieved. ZnO-NPs underwent centrifugation following three rinses with deionised distilled water. The pale-yellow powder represented the final product, which underwent drying overnight in an oven at 85°C and was subsequently stored in airtight vials for future research purposes. Sharmila and Gayathri (2014) indicated that the powder was ultimately prepared for characterisation.

Properties of ZnO nanoparticles

The maximum absorbance of the produced zinc oxide nanoparticles was determined by UV-Vis spectrophotometry. The optical characteristics of zinc oxide nanoparticles were assessed using visible and ultraviolet absorption spectroscopy in the 200–400 nm range. A scanning electron microscope (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were used to examine the morphology and functional groups of the synthesized zinc oxide nanoparticles within the scanning range of 4000 cm to 1000 cm. A scanning electron microscope (SEM) with model PROX: 800-07334 Phenom World and serial number MVE01570775, was used in the Central Research Laboratory at Umaru Musa Yar'adua University in Katsina State, Nigeria. Before the SEM machine was used for analysis, it was turned on and allowed 23 hours to load, while the computer system was set up correctly. An EDX-ray detector, a sample holder, and an X-ray tube make up its three main parts. In order to create X-rays, a cathode ray tube heated a filament to create electrons, then used a voltage to accelerate the electrons towards a target and direct them onto the target material. After being placed on a holder, the sample was put into the machine. To create a highly detailed image, the monitor first displayed an image of a typical compound microscope. The brightness and contrast were then adjusted to create a scanning electron microscope. The image was finally taken at 50 and 100 μm magnifications.

Doppler X-ray (XRD)

X-ray diffraction is a valuable technique for researching semi-crystalline and amorphous polymers. According to Bergström (2015), it can be used to examine a wide range of material microstructure characteristics, such as lattice parameters, the existence of flaws, crystallographic orientations (texture), and the degree of crystallinity.

The Spiked Solution Preparation

By dissolving 0.403 g of CoCl_2 in 100 mL of distilled water to a final concentration of 0.1 M, which was then adjusted with 0.1M HNO_3 , the spiked water was created. The pH meter was calibrated using buffer solutions with pH values of 4.0, 7.0, and 10 to determine the solution's pH.

Studies on Adsorption

By standardizing a fixed quantity of 0.5 g of ZnO NPs with 0.1 mL of 0.1M solution of CoCl_2 at room temperature for 10 minutes, the adsorption was investigated. The pH of 6 was maintained during the adsorption tests in this investigation to assess the quality of the synthesized adsorbent's (ZnO NPs) adsorption on the cobalt ion concentrations in the solutions. The metal ion's concentrations at room temperature were changed from 10.0 to 50.0 mg/L. A cobalt ion concentration in the residues was then measured using an atomic absorption spectrophotometer (AAS).

ASSESSMENT AND RESULTS

The analysis of UV-visible spectrum

A substance's ability to absorb ultraviolet and visible light is evaluated using UV-visible spectroscopy. Using a UV model UV-VIS 752N WL range of 200-1000 nm, the optical absorption spectra of zinc oxide nanoparticles were captured. Figure 2 displays the zinc oxide nanoparticles' UV-visible absorption spectra. A recording of the sample's absorption spectrum was made between 280 and 420 nm. A prominent absorption peak at 340 nm was visible in the UV-Vis spectra, which corresponds to the distinctive band of zinc oxide nanoparticles. The synthetic results are confirmed to be pure ZnO NPs if there isn't another absorbance peak in the spectra. Zinc oxide band gap electronic transitions are typically indicated by the absorption peak of ZnO NPs at 340 nm in the UV-visible spectrum. The main cause of this absorption is zinc oxide's presence. When it comes to electronic transitions within the zinc oxide band gap, the energy needed is 340 nm.

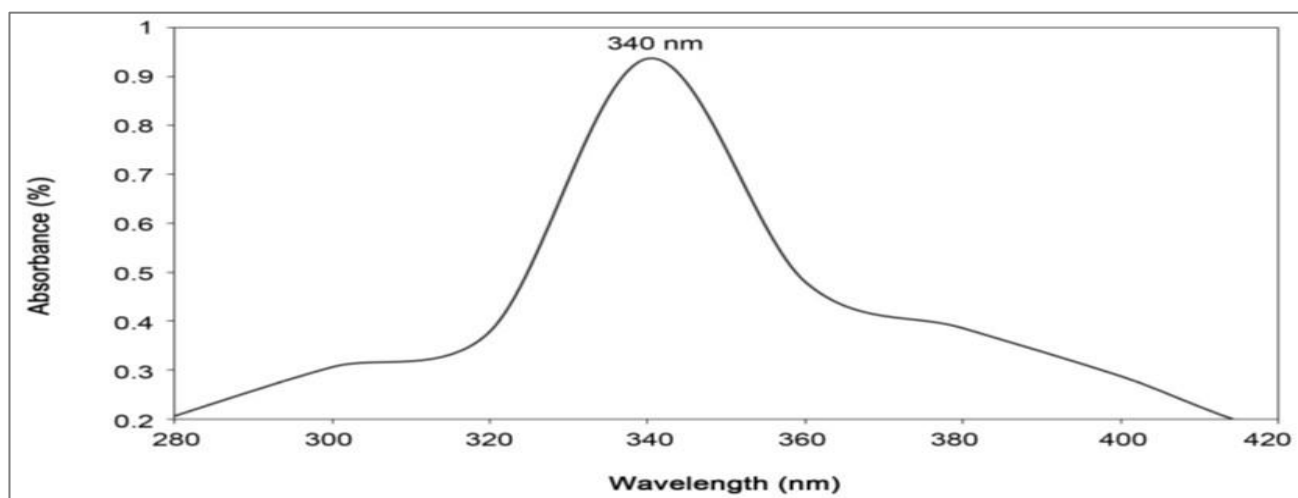


Figure 2. UV-Vis spectrum of synthesized zinc oxide nanoparticles (Yedurkar *et al.*, 2016)

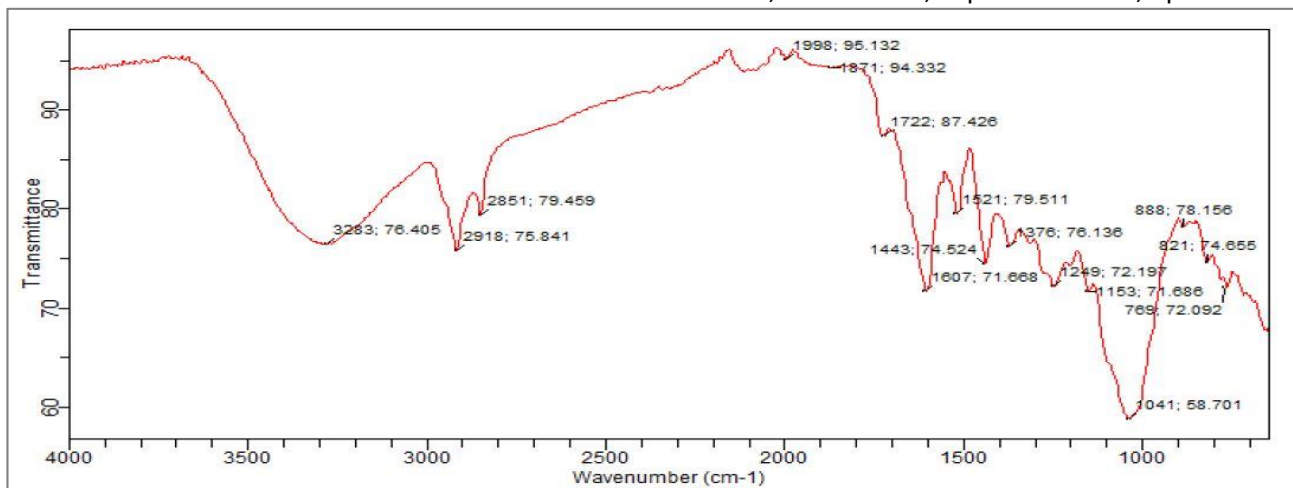


Figure 3: FTIR of *I. Coccinea* powder

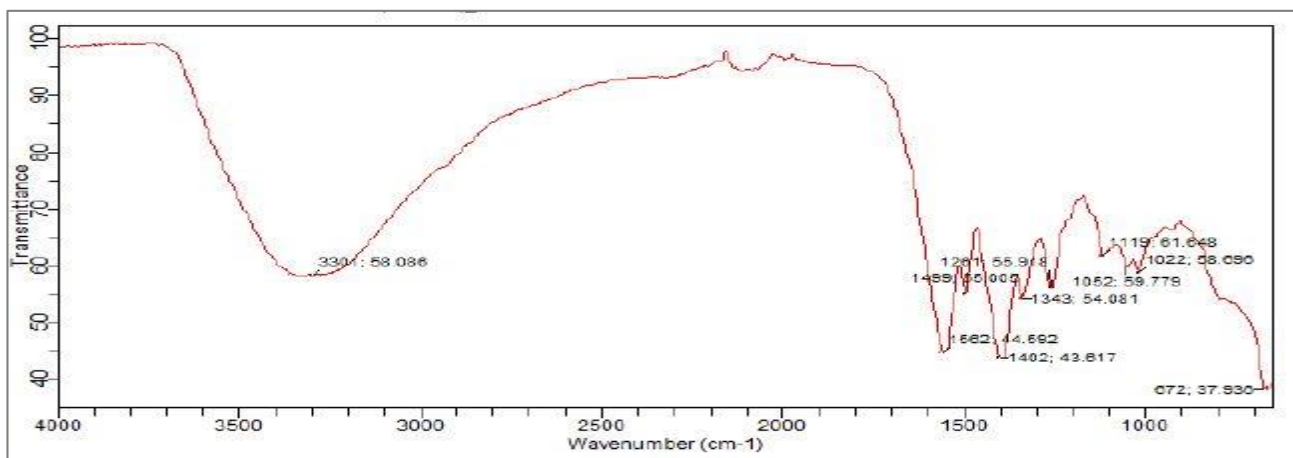


Figure 4: FTIR of ZnO NPs

Infrared Fourier Transform (FTIR) Analysis

FTIR is a useful technique for determining the makeup of a product. Figures 3 and 4, respectively, present the results of FTIR analyses of the finely powdered plant leaves and the synthesized ZnO NPs. A comparison of the plant and ZnO NPs' FTIR spectra was made in order to determine which functional group was responsible for the stabilizing and capping effects. The plant and ZnO NPs' infrared spectra were captured for various functional groups throughout the 1000–4000 cm range, as seen in Figures 3 and 4. The IR spectra of ZnO NPs show a very broad peak at 3301 cm, and a peak indicates the presence of O-H (alcohol) at 3283 cm in *I. Coccinea*. The stretching of alkanes C-H is shown by the peak at 2918 cm, the presence of an aldehyde H-C=O is indicated by the peak at 2851 cm, the bending of amines N-H is indicated by the peak at 1607 cm in the plant's infrared spectrum moved to 1582 cm in the ZnO NPs, and the presence of alkyl ether C-O is indicated by the peak at 1521 cm in the plant's infrared spectrum (The reason for the nanoparticles' shift to 1402 cm is aliphatic C=C stretching in an aromatic ring).

Scanning Electron Microscope (SEM)

The synthesized ZnO NPs' sizes, shapes, and morphologies were described using SEM. The ZnO NPs particles' surface morphology was heterogeneous, based on the SEM pictures showing them. Additionally, the Ag-Fe nanoparticles appeared to be pliable in both size and shape, with sharp holes and an uneven or irregular appearance. This shows how the ZnO NPs made using the green approach using *I*'s leaf extract look on the surface. With the use of a scanning electron microscope, coccinea was examined, and the results showed that the plant leaves were quite effective at producing ZnO NPs. Figure 5X, Y, and Z's sizes were 30, 50, and 100 μm, respectively, according to the results, confirming that the synthesized particles are nanoparticles.

Doppler X-ray (XRD)

For the zinc oxide nanoparticles sample ZnONPs, the X-ray diffraction (XRD) data show the existence and ratios of several crystalline phases. The phases listed below were acquired: An interaction or contamination from alumina-based crucibles or supports during high-temperature processing is suggested by this spinel-type impurity.

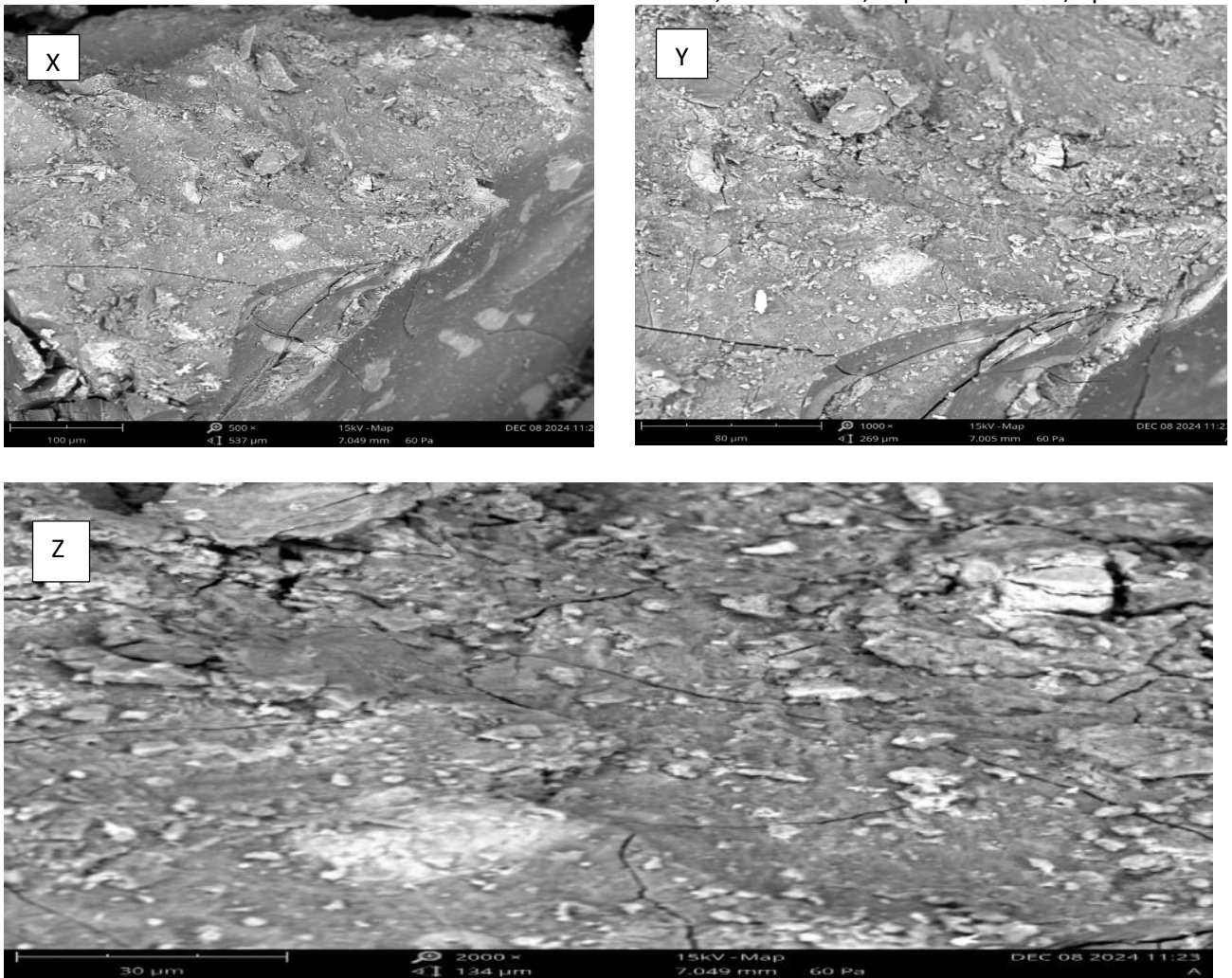


Figure 5: The morphologies, shape and size of the synthesized ZnO NPs

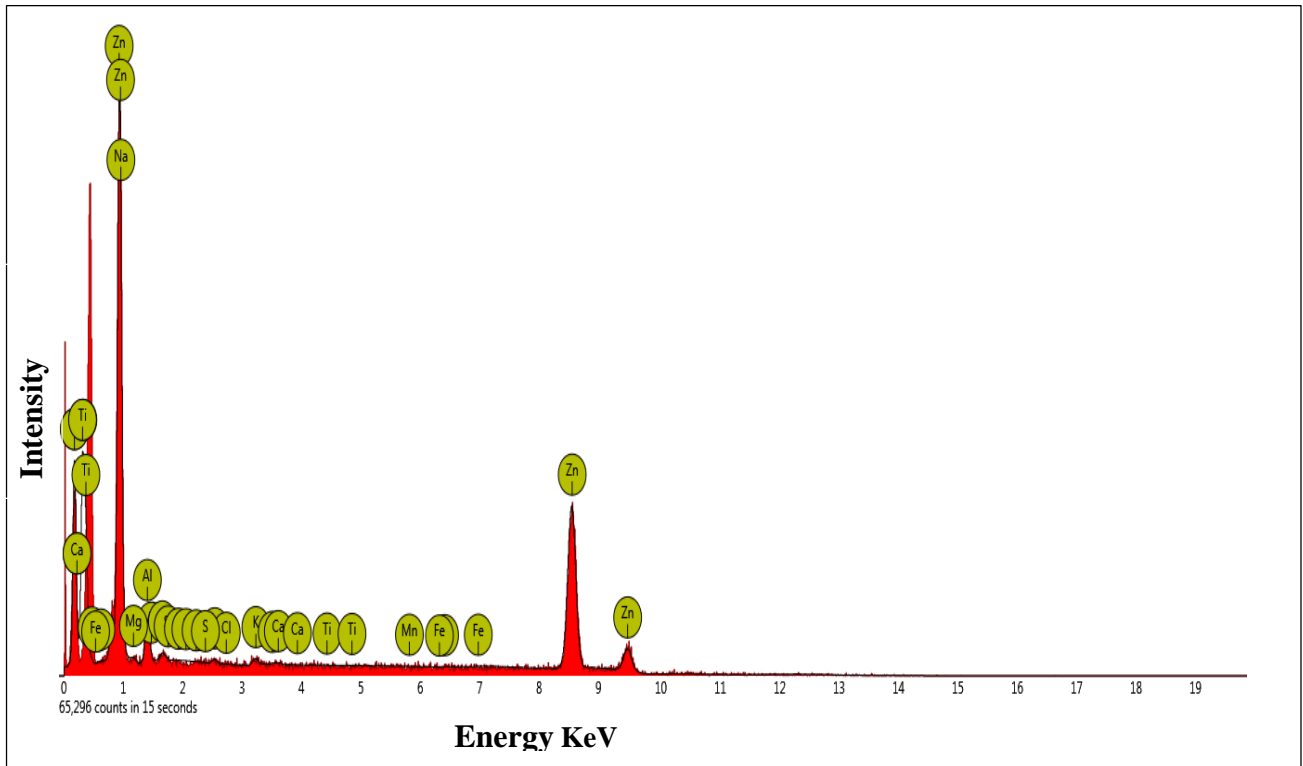


Figure 6: Showing the composition of elements present in ZnO-NPs

Table 1: The EDX of ZnO nanoparticles

Element Symbol	Element Name	Atomic Conc. %	Weight Conc. %
Zn	Zinc	32.1	57.07
Na	Sodium	64.57	40.37
Al	Aluminium	2.68	1.97
K	Potassium	0.21	0.22
Si	Silicon	0.24	0.18
Cl	Chlorine	0.12	0.11
Ca	Calcium	0.07	0.08
Total		99.99	100

Table 2.0 The Presence and Proportions of Crystalline Phases

S/N	Phase	Weight%	Interpretation
1.	Zincite (ZnO)	91	This is the dominant phase in the sample. Zincite is the hexagonal wurtzite crystal form of zinc oxide, which is the expected structure for ZnO nanoparticles. A high percentage like 91% confirms successful synthesis of ZnO nanoparticles.
2.	Zinc, syn (Metallic Zinc)	5	Indicates a minor presence of unreacted or reduced metallic zinc. Could arise from incomplete oxidation during synthesis or excess zinc precursor.
3.	Gahnite (ZnAl ₂ O ₄ or a spinel-type phase)	4	This spinel-type impurity suggests some interaction or contamination possibly from alumina-based crucibles or supports during high-temperature processing.

Table 3.0: The characteristics of two different Peaks obtained

	Peak at 2θ = 34.02°	Peak at 2θ = 59.94°
Phase	Zincite (ZnO)	Gahnite (ZnAl ₂ O ₄)
Miller Index	(002)	(511)
Interplanar spacing (d)	2.634 Å	1.542 Å
Full width at Half Maximum (FWHM)	1.42°	1.2°
Estimated Crystalline Size	~61 Å (≈ 6.1 nm)	~83 Å (≈ 8.3 nm)

Table 4.0: Crystalline Phases Identified

Phase Name	Formula	PDF Card No.	Space Group	Quantity (wt%)
Zincite	ZnO	00-001-1136	P6 ₃ mc	91%
Zinc (metallic)	Zn	00-004-0831	P6 ₃ /mmc	5%
Gahnite	ZnAl ₂ O ₄	00-001-1146	Fd-3m	4%

Table 5.0: The effect of pH changes on cobalt (II) removal from the solution (%)

pH of the metal solution	% Metal removal
2.3	21.5
4.1	35.6
6.2	44.9
8.1	61.3
10.3	83.8

A fixed quantity of ZnO NP (0.01 g) was used in each 100 mL volumetric flask and the concentration of Co²⁺ was varied as shown above.

High Purity ZnO was recovered, and it is the predominant zincite phase (~91%), confirming that ZnO nanoparticles make up the majority of the sample. Additionally, some impurities were found; tiny amounts of metallic gahnite

and zinc may have an impact on optical or electrical characteristics, depending on the application. As is typical of XRD-detectable nanoparticles, the sample appears to have a high degree of crystallinity based on the distinct

identification of crystalline phases. The sample is presumably primarily crystalline because there is no amorphous material present. Notwithstanding the substantial uncertainty in the results for minor phases (5(6), 4(5)), the small standard deviations (in parenthesis) indicate that the phase quantification is reasonably accurate.

XRD Peak Evaluation

The primary phase of zinc oxide (ZnO) exhibits a prominent peak at 34.02°, which is in line with the (002) plane of wurtzite ZnO and verifies high crystallinity (Table 3.0).

Table 6.0: The effects of ZnO NPs on different concentration of Cobalt (II)

Initial concentration (mg/L)	Residual concentration (mg/L)	% Metal removal
0.543 ± 0.008	0.211 ± 0.019	48
1.042 ± 0.015	0.312 ± 0.003	61
1.332 ± 0.009	1.283 ± 0.004	13.7
2.305 ± 0.011	2.032 ± 0.011	5.1
2.421 ± 0.006	2.313 ± 0.004	3.6

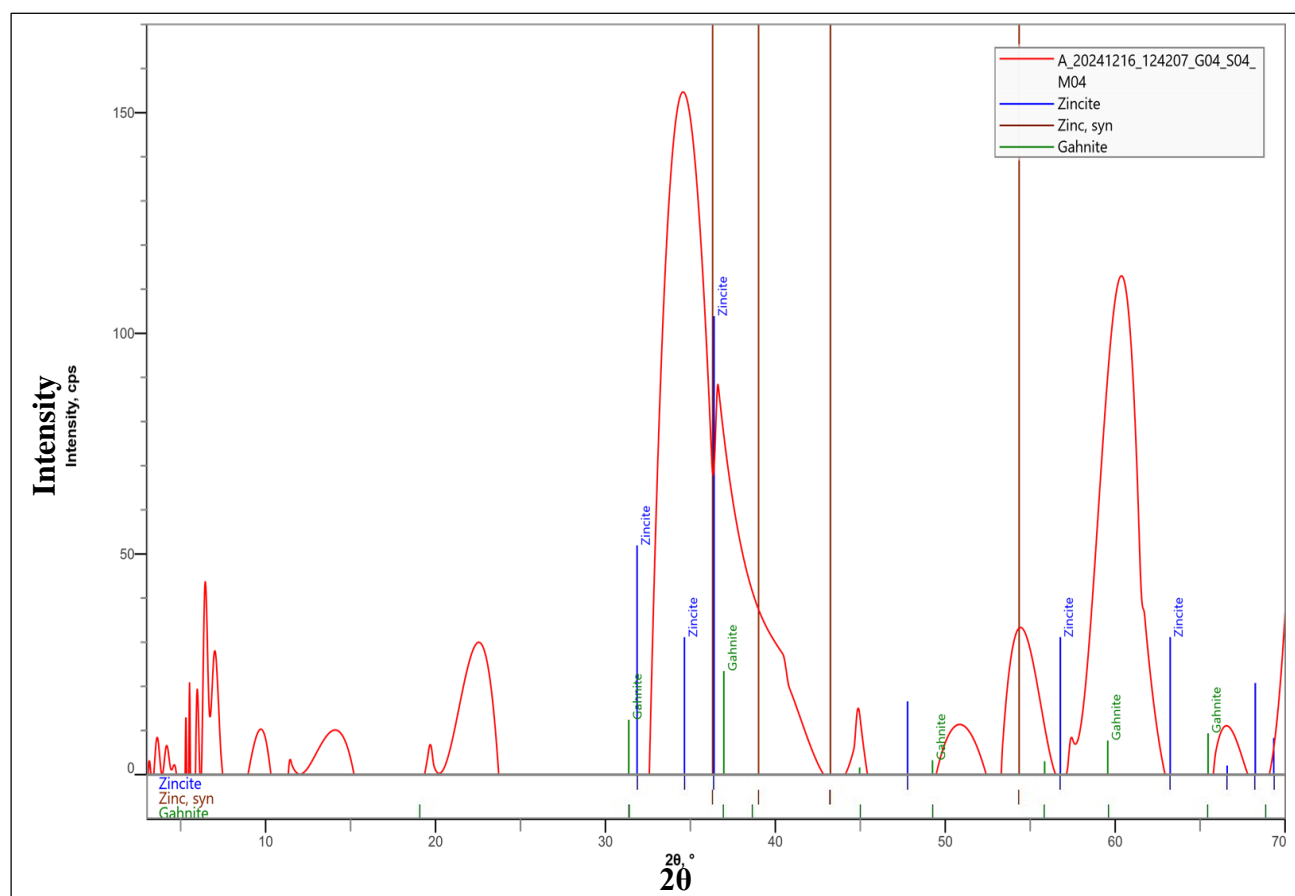


Figure 7: Shows the X-ray Diffraction result of ZnO NPs

This signal indicates an estimated crystallite size of ~6.1 nm, which is consistent with nanoparticle dimensions. The effective synthesis of ZnO nanoparticles with the anticipated crystal structure is demonstrated by this. Metallic zinc and gahnite were minor stages. Gahnite (ZnAlO₄) might have developed as a result of interactions with materials that included aluminum during processing or manufacture. A by-product of partial oxidation or an unreacted precursor could be metallic zinc. The estimated size of the crystallite was 61 Å, which most likely originated from the Scherrer equation. High-purity ZnO nanoparticles, around 6 nm in size, and trace amounts of gahnite and remaining metallic zinc are confirmed by XRD.

The effect of pH on adsorption

The pH of a solution plays a crucial role in determining the efficiency of the adsorption process, as it influences both the ionic form of Mn⁺ and the surface properties of the nanoparticles (Taha *et al.*, 2016). Tables 5.0 and 6.0 show how the pH and metal concentration affect the biosynthesized ZnO NPs' ability to adsorb surface contaminants. ZnO NP (0.01 gram) was added in a set amount to each 100 mL volumetric flask, and the Co²⁺ concentration was adjusted as shown below.

Between 2.3 and 10.3 was the pH range. At lower pH (acidic circumstances), adsorption was limited because of competition between metal ions (Co²⁺) and protons (H⁺) for active sites on the ZnO NPs. It was shown that the

adsorption of Co^{2+} increased with increasing pH. Adsorption greatly increased at higher pH (alkaline settings) because of the creation of metal hydroxides (precipitation) and decreased competition between Co^{2+} and H^+ at pH 10.3, it rose from 21.5% at pH 2.3 to 83.8%. Lower pH levels resulted in reduced metal adsorption, primarily because of the high amount of H^+ ions competing with the metal ions (M^{2+}) for active binding and interchange sites, thereby decreasing the availability of adsorption sites. Furthermore, at lower pH, the adsorbent surface exhibited a positive charge, creating electrostatic repulsion with the positively charged Co^{2+} ions, which further inhibited adsorption (Al-Mur, 2023). The variation in adsorption efficiency across different pH levels highlights the strong influence of pH on the adsorption mechanism.

Adsorption's Reaction with Initial Concentration

The concentration ranged from 0.654 to 2.530 mg/L (with a fixed dosage of 0.01 g of adsorbent). The optimal concentration of 0.421 mg/L was reached as the adsorption capacity rose as the initial concentration of Co^{2+} increased. The ZnO NPs' active sites became saturated, causing the % clearance to drop above 0.421 mg/L.

When the pH is higher and the concentration of metal ions is lower, ZnO NPs are more effective at extracting Co^{2+} from water. Both pH and starting concentration affect the adsorption process; alkaline pH and modest metal ion concentrations are ideal. Higher metal ion concentrations may cause the adsorbent's limited number of active sites to become saturated. It is possible to effectively remove metal ions from water with low concentrations of metal ions by using ZnO NPs. For optimal adsorption efficiency, pH management is essential. Using ZnO NPs as an adsorbent, this work emphasizes how crucial it is to optimize pH and starting concentration for efficient metal ion removal.

CONCLUSION

Finally, zinc oxide nanoparticles were synthesized from I. A viable and sustainable method for the efficient removal of cobalt (II) ions is the extract from coccinea leaves. By using fewer dangerous chemicals, the green synthesis process not only limits the lowering and stabilizing effects of phytochemicals in plant extract but also supports sustainable practices. The resultant zinc oxide nanoparticles exhibit their adsorbent function and show considerable promise for the removal of cobalt (II) ions. The huge surface area and customized characteristics of the nanoparticles are among their distinctive features that boost adsorption performance.

The necessity for effective heavy metal ion removal is met by this environmentally benign approach, which also underscores the importance of sustainable nanotechnology in environmental rehabilitation. Unlocking the full potential of zinc oxide nanoparticles synthesized from I will require further research in this area, with an emphasis on improving synthesis conditions,

understanding adsorption mechanisms, and scaling up production. Coccinea leaf extract for the elimination of cobalt (II) ions. This study presents an eco-friendly method for synthesizing ZnO nanoparticles (ZnO-NPs) using *Ixora coccinea* extract. The synthesized nanoparticles effectively removed Co^{2+} ions from aqueous solutions, demonstrating their potential in mitigating common metal pollutants. This approach is cost-effective, environmentally sustainable, and suitable for metal ion treatment applications.

The ZnO-NPs exhibited strong ultraviolet absorption at 340 nm. X-ray diffraction analysis revealed crystal sizes ranging between 6.1 and 8.3 nm, with an average size of 7.2 nm. The adsorption behavior of Co^{2+} on ZnO-NPs was also evaluated. The synthesized nanoparticles showed high adsorption capacity and regeneration efficiency exceeding 91%, indicating their suitability for large-scale applications. Under optimal conditions (pH 10.3, at Temperature 28 °C), a maximum adsorption capacity of 0.421 mg/L and a removal efficiency of 48% were achieved.

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AN INTEREST CONFLICTS

No conflicts of interest are disclosed by the authors.

REFERENCES

- Ahmed, S., Ahmad, M., Swami, B. L., Ikram, S. J., & Radiat, S. O. (2016). Green synthesis of silver nanoparticles using plant extract. *Research Application Science*, 9(1), 1–7. [Crossref]
- Al-Mur, B. A. (2023). Green zinc oxide (ZnO) nanoparticle synthesis using mangrove leaf extract from *Avicenna marina*: Properties and application for the removal of toxic metal ions (Cd^{2+} and Pb^{2+}). *Water*, 15(3), 455. [Crossref]
- Anand Raj, L. F. A., & Jayalakshmy, E. (2015). Biosynthesis and characterization of zinc oxide nanoparticles using root extract of *Zingiber officinale*. *Oriental Journal of Chemistry*, 31, 51–56. [Crossref]
- Anbuannana, M., Rameshb, M., Viruthagiria, G., Shanmugama, N., & Kannadasana, N. (2015). Anisochilus carnosus leaf extract mediated synthesis of zinc oxide nanoparticles for antibacterial and photocatalytic activities. *Materials Science in Semiconductor Processing*. [Crossref]
- Appierot, G., Lipovsky, A., Dror, R., Perkas, N., Nitzan, Y., Lubart, R., & Gedanken, A. (2009). Enhanced antibacterial activity of nanocrystalline ZnO due to increased ROS-mediated cell injury. *Advanced Functional Materials*, 19(6), 842–852. [Crossref]
- Bala, N., Saha, S., Chakraborty, M., Maiti, M., Das, S., Basub, R., & Nandyc, P. (2015). Green synthesis of zinc oxide nanoparticles using Hibiscus

- subdariffa leaf extract: Effect of temperature on synthesis, anti-bacterial activity and anti-diabetic activity. *RSC Advances*, 5(7), 4993–5003. [Crossref]
- Baliga, M. S., & Kurian, P. J. (2012). Ixora coccinea Linn: Traditional uses, phytochemistry and pharmacology. *Chinese Journal of Integrative Medicine*, 18(1), 72–79. [Crossref]
- Bergström, J. (2015). Experimental characterization techniques. In *Mechanics of solid polymers: Theory and computational modeling* (pp. 19–114). [Crossref]
- Bhuyan, T., Mishra, K., Khanuja, M., & Prasad, R. (2015). Biosynthesis of zinc oxide nanoparticles from *Azadirachta indica* for antibacterial and photocatalytic applications. *Materials Science in Semiconductor Processing*, 32, 55–61. [Crossref]
- Bogunia-Kubik, K., & Sugisaka, M. (2002). From molecular biology to nanotechnology and nanomedicine. *BioSystems*, 65(2–3), 123–138. [Crossref]
- Cho, J. M., Song, J. K., & Park, S. M. (2009). Characterization of ZnO nanoparticles grown by laser ablation of a Zn target in neat water. *Bulletin of the Korean Chemical Society*, 30(7), 1616–1618. [Crossref]
- Dada, A. O., Adekola, F. A., & Odebunmi, E. O. (2015). A novel zerovalent manganese for removal of copper ions: Synthesis, characterization and adsorption studies. *Applied Water Science*. [Crossref]
- Dagdeviren, C., Hwang, S.-W., Su, Y., Kim, S., Cheng, H., Gur, O., & Rogers, J. A. (2013). Transient, biocompatible electronics and energy harvesters based on ZnO. *Small*, 9(20), 3398–3404. [Crossref]
- Daniel, M. C., & Astruc, D. (2004). Gold nanoparticles: Assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology. *Chemical Reviews*, 104(1), 293–346. [Crossref]
- Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. *Journal of Environmental Management*, 92(3), 407–418. [Crossref]
- Hasnidawani, J. N., Azlina, H. N., Norita, H., Bonnia, N. N., Ratim, S., & Ali, E. S. (2016). Synthesis of ZnO nanostructures using sol-gel method. *Procedia Chemistry*, 19, 211–216. [Crossref]
- Haverkamp, R. G., & Marshall, A. T. (2009). The mechanism of metal nanoparticle formation in plants: Limits on accumulation. *Journal of Nanoparticle Research*, 11(6), 1453–1463. [Crossref]
- Kharissova, O. V., Rasika Dias, H. V., Kharisov, B. I., Pérez, B. O., & Pérez, V. M. J. (2013). The greener synthesis of nanoparticles. *Trends in Biotechnology*, 31(4), 240–248. [Crossref]
- Kowshik, M., Deshmukh, N., Vogel, W., Urban, J., Kulkarni, S. K., & Paknikar, K. M. (2002). Microbial synthesis of semiconductor CdS nanoparticles, their characterization, and their use in the fabrication of an ideal diode. *Biotechnology and Bioengineering*, 78(5), 583–588. [Crossref]
- Kumar, B., Smita, K., Cumbal, L., & Debut, A. (2014). Sacha inchi (*Plukenetia volubilis* L.) shell biomass for synthesis of silver nanocatalyst. *Journal of Saudi Chemical Society*, 18(4), 356–363. [Crossref]
- Lin, C., & Li, Y. (2009). Synthesis of ZnO nanowires by thermal decomposition of zinc acetate dihydrate. *Materials Chemistry and Physics*, 113(1), 334–337. [Crossref]
- Ling, L. T., Yap, S., Radhakrishnan, A. K., Subramaniam, T., Cheng, H. M., & Palanisamy, U. D. (2009). Standardized *Mangifera indica* extract is an ideal antioxidant. *Food Chemistry*, 113(4), 1154–1159. [Crossref]
- Lobiak, E. V., Shlyakhova, E. V., Bulusheva, L. G., Plyusnin, P. E., Shubin, Y. V., & Okotrub, A. V. (2015). Ni-Mo and Co-Mo alloy nanoparticles for catalytic chemical vapor deposition synthesis of carbon nanotubes. *Journal of Alloys and Compounds*, 621, 351–356. [Crossref]
- Nagajothi, P. C., An, T. N. M., Sreekanth, T. V. M., Lee, D. J., & Lee, K. D. (2013). Green route biosynthesis: Characterization and catalytic activity of ZnO nanoparticles. *Materials Letters*, 108, 160–163. [Crossref]
- Naseem, R., & Tahir, S. S. (2001). Removal of Pb(II) from aqueous/acidic solutions by using bentonite as an adsorbent. *Water Research*, 35(16), 3982–3986. [Crossref]
- Netzer, A., & Hughes, D. E. (1984). Adsorption of copper, lead and cobalt by activated carbon. *Water Research*, 18(8), 927–933. [Crossref]
- Nilavukkarasi, M., Vijayakumar, S., & Prathipkumar, S. (2020). *Capparis zeylanica* mediated bio-synthesized ZnO nanoparticles as antimicrobial, photocatalytic and anti-cancer applications. *Materials Science for Energy Technologies*, 3, 335–343. [Crossref]
- Noorjahan, C. M., Jasmine, S. K., Deepika, S., & Rafiq, S. (2015). Green synthesis and characterization of zinc oxide nanoparticles from *Neem* (*Azadirachta indica*). *International Journal of Engineering Research and Development*, 4(3), 5751–5753.
- Prathna, T. C., Chandrasekaran, N., Raichur, A. M., & Mukherjee, A. (2011). Kinetic evolution studies of silver nanoparticles in a bio-based green synthesis process. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 377(1–3), 212–216. [Crossref]
- Qu, J., Yuan, X., Wang, X., & Shao, P. (2011). Zinc accumulation and synthesis of ZnO nanoparticles using *Physalis alkekengi* L. *Environmental Pollution*, 159(7), 1783–1788. [Crossref]
- Rajiv, P., Rajeshwari, S., & Venkatesh, R. (2013). Bio-fabrication of zinc oxide nanoparticles using leaf extract of *Parthenium hysterophorus* L. and its size-dependent antifungal activity against plant

- fungal pathogens. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 112, 384–387. [[Crossref](#)]
- Rajiv, P., Rajeshwari, S., & Venckatesh, R. (2013). Bio-fabrication of zinc oxide nanoparticles using leaf extract of Parthenium hysterophorus L. and its size-dependent antifungal activity against plant fungal pathogens. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 112, 384–387. [[Crossref](#)]
- Rasmussen, J. W., Martinez, E., Louka, P., & Wingett, D. G. (2010). Zinc oxide nanoparticles for selective destruction of tumor cells and potential for drug delivery applications. *Expert Opinion on Drug Delivery*, 7(9), 1063–1077. [[Crossref](#)]
- Samat, N. A., & Nor, R. M. (2013). Sol-gel synthesis of zinc oxide nanoparticles using Citrus aurantifolia extracts. *Ceramics International*, 39, S545–S548. [[Crossref](#)]
- Sangeetha, G., Rajeshwari, S., & Venckatesh, R. (2011). Green synthesis of zinc oxide nanoparticles by aloe barbadensis miller leaf extract: Structure and optical properties. *Materials Research Bulletin*, 46(12), 2560–2566. [[Crossref](#)]
- Seyyed, M., Tabrizi, H. M., Behrouz, E., & Vahid, J. (2020). Biosynthesis of pure zinc oxide nanoparticles using Quince seed mucilage for photocatalytic dye degradation. *Journal of Alloys and Compounds*, 821, 153519. [[Crossref](#)]
- Seyyed, M., Tabrizi, H. M., Behrouz, E., & Vahid, J. (2020). Biosynthesis of pure zinc oxide nanoparticles using Quince seed mucilage for photocatalytic dye degradation. *Journal of Alloys and Compounds*, 821, 153519. [[Crossref](#)]
- Shaba, E. Y., Jacob, J. O., Tijani, J. O., & Suleiman, M. A. T. (2021). A critical review of synthesis parameters affecting the properties of zinc oxide nanoparticle and its application in wastewater treatment. *Applied Water Science*, 11(2), 48. [[Crossref](#)]
- Shakeel, A., Saifullah, M. A., Swami, B. L., & Saiqa, I. (2016). Green synthesis of silver nanoparticles using Azadirachta indica aqueous leaf extract. *Journal of Radiation Research and Applied Sciences*, 9(1), 1–17. [[Crossref](#)]
- Sharma, D., Rajput, J., Kaith, B. S., Kaur, M., & Sharma, S. (2010). Synthesis of ZnO nanoparticles and study of their antibacterial and antifungal properties. *Thin Solid Films*, 519(3), 1224–1229. [[Crossref](#)]
- Sharmila, D. R., & Gayathri, R. (2014). Green synthesis of zinc oxide nanoparticles by using Hibiscus rosa-sinensi. *International Journal of Current Engineering and Technology*, 4(1), 1137.
- Taha, A. A., Shreadah, M. A., Ahmed, A. M., & Heiba, H. F. (2016). Multi-component adsorption of Pb (II), Cd (II), and Ni (II) onto Egyptian Na-activated bentonite; equilibrium, kinetics, thermodynamics, and application for seawater desalination. *Journal of Environmental Chemical Engineering*, 4(1), 1166–1180. [[Crossref](#)]
- Tan, W. K., Muto, H., Kawamura, G., Lockman, Z., & Matsuda, A. (2021). Nanomaterial fabrication through the modification of sol-gel derived coatings. *Nanomaterials*, 11(1), 181. [[Crossref](#)]
- Wang, C., Shen, E., Wang, E., Gao, L., Kang, Z., Tian, C., Lan, Y., & Zhang, C. (2006). Controllable synthesis of ZnO nanoparticles via a surfactant assisted alcohol thermal process at low temperature. *Current Applied Physics*, 6(3), 499–502. [[Crossref](#)]
- Wang, X. X., Wu, L., Zhou, P., Li, C., Zhao, L. B., An, W., & Chen, Y. (2014). Effect of ZnO nanoparticles on Medicago Sativa at the germination stage. *Applied Mechanics and Materials*, 665, 583–586. [[Crossref](#)]
- Waseem, A., & Divya, K. (2020). Green synthesis, characterization and anti-microbial activities of ZnO nanoparticles using Euphorbia hirta leaf extract. *Journal of King Saud University - Science*, 32(4), 2358–2364. [[Crossref](#)]
- Yedurkar, S., Maurya, C., & Mahanwar, P. (2016). Biosynthesis of zinc oxide nanoparticles using Ixora coccinea leaf extract—A green approach. *Open Journal of Synthesis Theory and Applications*, 5(1), 1–14. [[Crossref](#)]
- Zhang, X. F., Liu, Z. G., Shen, W., & Gurunathan, S. (2016). Silver nanoparticles: Synthesis, characterization, properties, applications, and therapeutic approaches. *International Journal of Molecular Sciences*, 17(9), 1534. [[Crossref](#)]
- Zharov, V. P., Kim, J. W., Curiel, D. T., & Everts, M. (2005). Self-assembling nanoclusters in living systems: Application for integrated photothermal nanodiagnostics and nanotherapy. *Nanomedicine: Nanotechnology, Biology, and Medicine*, 1(4), 326–345. [[Crossref](#)]