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Green Fabrication of Magnesium Nanoparticles via *Emblica officinalis* Extract: A Promising Route for Heavy Metal Remediation

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Abstract

This study explores the green synthesis of magnesium nanoparticles (Mg NPs) using Emblica officinalis extract and their application in heavy metal degradation. UV-Visible spectroscopy confirmed the successful synthesis of Mg NPs, evidenced by a characteristic surface plasmon resonance (SPR) peak at 301.87 nm, indicating the presence of well-formed nanoparticles. The absorption intensity peak at approximately 1.8 AU suggests a high concentration of Mg NPs, with a broad peak reflecting a polydisperse size distribution. The particle size, estimated using Mie theory, ranged from 20 to 50 nm. Additionally, the Mg NPs demonstrated significant catalytic activity in the degradation of cadmium chloride ($CdCl_2$), as observed from the reduction in absorption intensity at 245.9 nm over time. The most rapid degradation occurred within the first 30 minutes, while the process slowed after 60 minutes, ultimately leading to substantial metal ion removal after 24 hours. The catalytic efficiency is attributed to the high surface area of the Mg NPs, promoting interaction with metal ions. The use of plant-based synthesis offers an eco-friendly alternative, highlighting the potential of Mg NPs in environmental remediation, particularly in heavy metal removal. Further studies utilizing advanced characterization techniques are recommended to better understand the structural and catalytic properties of the synthesized nanoparticles.

Keywords: MgNPs; Cadmium; Metal degradation; Green synthesis

Introduction

Heavy metals are a group of elements characterized by their high atomic weights and densities significantly greater than that of water. Typically, elements such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), and nickel (Ni) are classified as heavy metals (Tchounwou *et al.,* 2012). These metals occur naturally in the Earth's crust and are released into the environment through natural processes like volcanic eruptions, weathering of rocks, and forest fires (Briffa *et al.,* 2020). However, human activities such as mining, industrial operations, agriculture, and urban development have drastically increased the concentration of heavy metals in various ecosystems (Haghighizadeh *et al.,* 2024). Their unique physicochemical properties, including high conductivity, malleability, and resistance to corrosion, have made heavy metals indispensable in various industrial, technological, and medical applications. Despite their utility, heavy metals are also associated with severe environmental and health risks due to their toxicity, persistence, and tendency to bioaccumulate in living organisms (Kondakindi *et al.*, 2024).

Heavy metals find extensive uses across multiple sectors, largely because of their versatile chemical and physical properties. In the industrial sector, heavy metals are essential for the production of batteries, pigments, alloys, electronics, and catalysts (Angon *et al.,* 2024). For instance, lead is used in lead-acid batteries, radiation shielding, and cable sheathing; mercury is employed in thermometers, fluorescent lamps, and dental amalgams; and chromium is crucial for stainless steel production and leather tanning. In the electronics industry, metals like nickel, cadmium, and mercury are components of semiconductors, circuit boards, and display devices. The construction industry uses heavy metals in the form of reinforced steel structures and corrosion-resistant materials (Wei *et al.,* 2015). Furthermore, agriculture utilizes heavy metals in the form of pesticides and fertilizers, particularly arsenic-based compounds, which were historically common in pest control. The medical field also benefits from heavy metals; for example, certain radioactive heavy metals are used in cancer radiotherapy, and metals like silver possess antimicrobial properties utilized in wound dressings and medical devices (Alengebawy *et al.,* 2021).

The applications of heavy metals extend into more specialized and advanced technologies. In renewable energy, heavy metals such as cadmium and tellurium are key components in photovoltaic cells used for solar energy conversion (Preet & Smith, 2024). Heavy metals like tungsten are vital in the aerospace and military industries due to their high melting points and strength. The automotive industry uses platinum, palladium, and rhodium in catalytic converters to reduce vehicle emissions (Zimmermann & Sures, 2004). Additionally, heavy metals are employed in research laboratories for analytical procedures, including spectroscopy and chromatography, where specific metal-based reagents are used (Fisher & Gupta, 2025).

Despite their widespread applications, the environmental issues associated with heavy metals are profound and multifaceted. Heavy metals are non-biodegradable, meaning they persist in the environment for extended periods once released (Das *et al.*, 2023). They can contaminate soil, water, and air, leading to widespread ecological disruption. In soil, heavy metals can alter microbial community structures, reduce soil fertility, and impair plant growth through phytotoxic effects (Angon *et al.*, 2024). In aquatic environments, heavy metals accumulate in sediments and bioaccumulate through the food chain, affecting fish, aquatic plants, and eventually human consumers (Ray & Vashishth, 2024). Airborne heavy metal particles, often originating from industrial emissions and vehicular exhaust, contribute to air pollution and pose inhalation risks. Chronic exposure to heavy metals can cause severe health issues in humans, including neurological disorders, kidney damage, bone deformities, and cancers (Shetty, *et al.*, 2023). For instance, mercury exposure can impair cognitive function, while lead exposure is particularly harmful to children's brain development. Furthermore, the remediation of heavy metal pollution is challenging and expensive, often requiring advanced technologies such as phytoremediation, soil washing, chemical immobilization, and thermal treatment (Liu & Lewis, 2014).

Among heavy metals, cadmium holds a particularly controversial position due to its useful applications and significant environmental and health hazards. Cadmium is a soft, bluish-white metal primarily obtained as a by-product from the refining of zinc, lead, and copper ores. It has numerous industrial applications, most notably in rechargeable nickel-cadmium (Ni-Cd) batteries, which have been widely used in consumer electronics like mobile phones, laptops, and power tools (Genchi *et al.*, 2020). Cadmium's high electrochemical stability and ability to operate over a wide temperature range make it an ideal component for battery production. In addition to batteries, cadmium is used in coatings and plating to protect iron and steel from corrosion, particularly in aerospace and military equipment. Cadmium pigments, such as cadmium sulfide (yellow) and cadmium selenide (red), are renowned for their brilliant and stable colors and have been used in paints, plastics, ceramics, and glass manufacturing. Furthermore, cadmium compounds serve as stabilizers in polyvinyl chloride (PVC) production and as neutron-absorbing materials in nuclear reactors, playing a crucial role in maintaining reactor safety.

Despite its beneficial applications, cadmium poses serious environmental and health risks. Cadmium is highly toxic even at low concentrations, and its release into the environment primarily occurs through industrial discharges, improper disposal of cadmium-containing products, and the use of phosphate fertilizers, which often contain cadmium as an impurity (Wang *et al.,* 2019). Once introduced into the environment, cadmium persists for decades, contaminating soil and water. In agricultural settings, cadmium uptake by crops leads to the accumulation of the metal in the food chain, posing dietary risks to humans and animals (Hamid *et al.,* 2019). Long-term exposure to cadmium through ingestion or inhalation can lead to severe health issues, including kidney damage, bone demineralization (leading to diseases like Itai-itai disease observed in Japan), lung cancer, and cardiovascular diseases. Cadmium is classified as a human carcinogen by the International Agency for Research on Cancer (IARC) (Rasin *et al.,* 2025).

The environmental contamination by cadmium is particularly troubling in aquatic systems. Industrial effluents containing cadmium can result in bioaccumulation in aquatic organisms, adversely affecting fish reproduction, growth, and survival (Liu *et al.,* 2022). Cadmium exposure can impair the osmoregulatory abilities of fish, leading to disturbances in ion balance and enzyme functions. Moreover, cadmium in sediments can remain a long-term source of contamination, slowly releasing into the water column and perpetuating exposure risks. In soils, cadmium reduces microbial diversity, inhibits enzymatic activities essential for nutrient cycling, and can lead to reduced crop yields and quality (Soegianto *et al.,* 2023). Human activities such as mining, metal smelting, waste incineration, and the indiscriminate use of cadmium-containing fertilizers exacerbate environmental cadmium levels, making it a persistent threat to ecological and human health (Du *et al.,* 2020).

Addressing cadmium pollution requires comprehensive strategies encompassing regulatory control, technological innovation, and public awareness. Many countries have established strict regulations to limit cadmium emissions and restrict its use in consumer products (Wang *et al.,* 2024). For example, the European Union's Restriction of Hazardous Substances (RoHS) directive limits cadmium content in electrical and electronic equipment.

Additionally, technological advances are being made to develop cadmium-free alternatives, such as lithium-ion batteries replacing nickel-cadmium batteries in many applications. Remediation of cadmium-contaminated sites employs a variety of techniques, including soil washing, phytoremediation using cadmium-accumulating plants, and stabilization using chemical amendments to reduce cadmium mobility and bioavailability. Research into nanotechnology-based solutions, such as the use of nanoscale zero-valent iron particles for cadmium removal from water, offers promising avenues for more effective remediation (Li *et al.*, 2024).

Furthermore, sustainable waste management practices, including recycling of cadmium-containing products and proper disposal methods, are critical to minimizing environmental release. Public education and industry accountability are equally important to ensure that cadmium use is managed responsibly, and alternative materials are embraced where possible (Grandhi *et al.*, 2024). Future perspectives in heavy metal management emphasize the development of green technologies that minimize environmental footprints and the implementation of a circular economy approach, wherein materials are continually reused and recycled to reduce the need for virgin heavy metal extraction (Oyejobi *et al.*, 2024).

Heavy metals are essential to modern industry and technology due to their diverse and unique properties. Their applications range from construction and electronics to medicine and agriculture, underscoring their vital role in contemporary society. However, the environmental and health issues associated with heavy metals, particularly cadmium, highlight the need for vigilant management and innovative solutions (Asiminicesei *et al.*, 2024). Cadmium's extensive industrial utility contrasts sharply with its environmental persistence and toxicity, creating a complex challenge for policymakers, industries, and researchers. Through stringent regulations, technological advancements, sustainable practices, and public engagement, it is possible to mitigate the adverse impacts of heavy metals while continuing to benefit from their remarkable properties (Tchounwou *et al.*, 2012).

The present study deals with the preparation of Magnesium nanoparticles using *Emblica officinalis* leaf extract and used heavy metal degradation.

Material and Methods

Plant collection and extraction

Fresh leaves of *Emblica officinalis* were sourced from a cultivated area in the Coutrallam hills. The collected leaves were shade-dried to preserve their phytochemicals and then ground into a fine powder using a mechanical grinder. For extract preparation, 10 grams of the powdered leaves were mixed with 100 mL of distilled water and heated at a temperature range of 60°C to 80°C for approximately 20 minutes. After cooling to room temperature, the mixture was filtered using Whatman No.1 filter paper to obtain a clear aqueous extract for further use.

Synthesis and characterization of Magnesium nanoparticles

For nanoparticle synthesis, a 1 mM magnesium nitrate [$Mg(NO_3)_2$] solution was prepared in distilled water. Then, 90 mL of this magnesium nitrate solution was combined with 10 mL of the *E. officinalis* extract in a clean conical flask. The mixture was stirred continuously at ambient temperature for 2 to 3 hours. A visible color change from pale yellow to brownish indicated the successful formation of magnesium nanoparticles. Characterization of the synthesized Mg NPs was carried out using UV–Visible spectrophotometry. The absorption spectrum was recorded in the wavelength range of 200 to 1000 nm.

Heavy metal degradation

To evaluate the catalytic potential of the green-synthesized magnesium nanoparticles for cadmium degradation, a stock solution of cadmium chloride ($CdCl_2$) was prepared by dissolving the appropriate amount of $CdCl_2$ salt in distilled water to achieve a concentration of 1 mM. For the degradation experiment, 90 mL of the cadmium solution was taken in a conical flask, and 10 mL of the freshly prepared Mg NP suspension was added. The reaction mixture was stirred continuously at room temperature under ambient conditions. Samples were collected at regular time intervals (0, 30, 60 minutes, and up to 24 hours) to monitor the degradation process.

The progress of cadmium ion degradation was assessed using UV–Visible spectrophotometry by recording absorbance values at 245.9 nm, which corresponds to the characteristic absorption peak of Cd^{2+} ions. A gradual decrease in absorbance at this wavelength over time indicated the reduction of cadmium concentration in the solution.

Result and Discussion

The synthesis of magnesium nanoparticles (Mg NPs) using *Emblica officinalis* extract was confirmed through UV-Visible spectroscopy analysis (Figure 1). The absorption spectrum of the Mg NPs exhibited a prominent peak at approximately 301.87 nm, indicative of the surface plasmon resonance (SPR) characteristic of magnesium nanoparticles. The presence of this peak indicates the successful formation of Mg NPs, as SPR arises due to the collective oscillation of conduction electrons when excited by incident light. The intensity of absorption, which peaked around 1.8 AU, suggests a high concentration of nanoparticles, while the broadening of the peak hints at a polydisperse particle size distribution, likely caused by variations in size and morphology.

To estimate the particle size, Mie theory was applied, which correlates the SPR wavelength with nanoparticle dimensions. According to this theory, the SPR wavelength (301.87 nm) is influenced by factors such as particle size, shape, and the dielectric environment. The Mie theory formula relates the plasmon resonance wavelength to the dielectric constants of the metal and the surrounding medium. The estimated size of the nanoparticles, inferred from the spectral features, ranges between 20 to 50 nm. Additionally, the full width at half maximum (FWHM) of the SPR peak can provide insights into particle size, considering damping effects and interband transitions.

The observed SPR peak around 301.87 nm correlates well with previously reported data for magnesium nanoparticles synthesized through green methods. The use of Emblica officinalis extract as a reducing and capping agent introduces natural variability, resulting in a slightly broader absorption peak. This variability is attributed to the complex mixture of bioactive compounds present in the plant extract, which affects nanoparticle formation and stabilization. Further studies using techniques like Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS) are recommended to acquire more precise data on particle size and morphology. These techniques would complement the UV-Visible analysis and provide a more comprehensive understanding of the synthesized nanoparticles.

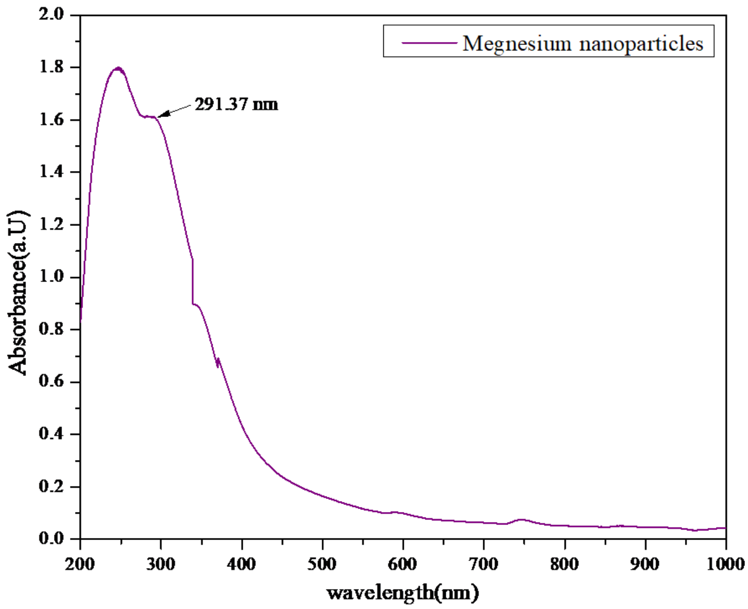

Figure 1: Green synthesized magnesium nanoparticles UV/Vis spectral data.

The degradation of heavy metals using magnesium nanoparticles (Mg NPs) synthesized from Emblica officinalis extract was analyzed using UV-Visible spectroscopy. The absorption spectra presented show the degradation of cadmium chloride ($CdCl_2$) over various time intervals, including 5 minutes, 10 minutes, 15 minutes, 30 minutes, 60 minutes, 120 minutes, and 24 hours. The initial absorption peak for $CdCl_2$ was observed at approximately 245.9 nm. The gradual decrease in absorption intensity with increasing time clearly indicates the effective degradation of $CdCl_2$ by Mg NPs.

The decrease in the absorption peak's intensity at 245.9 nm suggests the breakdown of the cadmium chloride structure due to the interaction with magnesium nanoparticles. The most significant decrease in absorption occurred within the first 30 minutes, indicating a rapid initial degradation phase. After 60 minutes, the rate of degradation slowed down, as observed from the relatively stable absorption spectra, indicating the near-complete reduction of the heavy metal ions.

After 24 hours, the absorption peak became almost negligible, confirming the substantial removal or transformation of cadmium ions into less absorbent species. This gradual decrease in absorbance demonstrates that the Mg NPs facilitate the degradation process through adsorption and possible reduction reactions (Figure 2). The catalytic activity of Mg NPs can be attributed to their high surface area, which promotes interactions with the heavy metal ions.

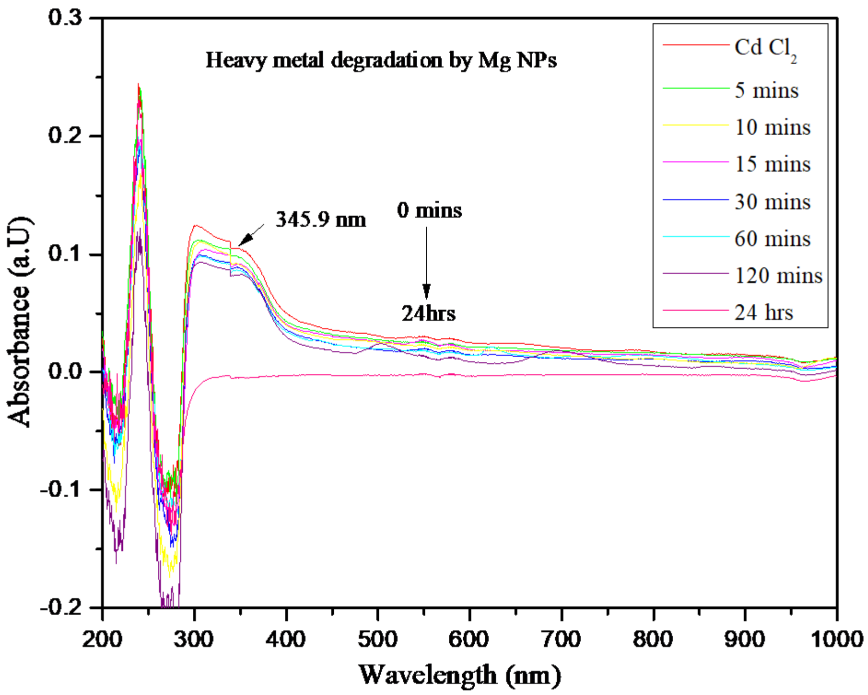

Figure 2: Heavy metal degradation by MgNPs.

The efficiency of degradation is influenced by several factors, including the concentration of Mg NPs, the nature of the metal ions, and the time of exposure. The use of green-synthesized Mg NPs is particularly advantageous, as it minimizes the use of hazardous chemicals and enhances the sustainability of the process. The results align with previous studies indicating the potential of metal nanoparticles in environmental remediation, specifically in heavy metal removal. Further studies focusing on the mechanistic aspects of degradation and the role of bioactive compounds from the extract could provide deeper insights into the process.

Conclusion

The study demonstrated the successful synthesis of magnesium nanoparticles (Mg NPs) using Emblica officinalis extract, confirmed by the characteristic surface plasmon resonance (SPR) peak observed at 301.87 nm in the UV-Visible spectrum. The prominent absorption peak indicates the efficient formation of Mg NPs with a high concentration, while the broadening of the peak suggests a polydisperse size distribution, potentially caused by natural variability inherent to the plant extract. The particle size estimation, based on Mie theory, indicates that the nanoparticles range from 20 to 50 nm. This size distribution aligns with other reports on biosynthesized magnesium nanoparticles.

Furthermore, the degradation studies demonstrated the potential of Mg NPs to effectively reduce cadmium chloride ($CdCl_2$) concentrations over time, as evidenced by the significant decrease in the absorption peak at 245.9 nm. The rapid degradation phase within the first 30 minutes highlights the nanoparticles' strong catalytic activity, while the slower rate after 60 minutes suggests that most cadmium ions had already interacted with the nanoparticles. After 24 hours, the near absence of the absorption peak confirms substantial metal ion removal or transformation. The degradation efficiency can be attributed to the high surface area and reactive nature of the Mg NPs, which facilitate adsorption and reduction reactions.

Overall, the green synthesis of Mg NPs using Emblica officinalis extract offers an eco-friendly approach to nanoparticle production, with promising applications in environmental remediation. The study highlights the potential of Mg NPs for heavy metal degradation, emphasizing the need for further investigation into the mechanistic pathways involved. Advanced characterization techniques, including Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS), would help elucidate the structural attributes and size distribution, enhancing the understanding of their catalytic properties.

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