

Phytochemical-mediated Green Synthesis and Stabilization of Strontium Oxide (SrO) Nanoparticles using Zizyphus jujuba Mill Leaf Extract

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ABSTRACT

The current research aims to explore the synthesis of Strontium Oxide (SrO) nanoparticles using Zizyphus jujuba Mill Leaf Extract, which serves as a natural source of phytochemicals as reducing and stabilizing agents. Nanoparticle synthesis using plants is a sustainable and eco-friendly approach to conventional chemical synthesis, which is typically associated with the use of toxic chemicals for the synthesis of nanoparticles and which generates biocompatible nanomaterials. The

importance of bioactive molecules like phenolics and flavonoids in reduction and stabilization is emphasized and helps in controlling the particle size and morphology. This study highlights the mechanisms by which plant-based formation of SrO nanoparticles occurs, compares the existing plant mediated methods and discusses the potential applications of these nanoparticles in photocatalysis, environmental remediation and biomedical applications. The results confirm that the *Zizyphus jujuba* leaf extract has the potential to help mediate SrO nanoparticles synthesis and it is an environment-friendly approach to synthesize functional nanoparticles with excellent physicochemical and biological properties. The results of this study indicate that extract of *Zizyphus jujuba* is excellent biological source for the green synthesis of SrO nanoparticles. The results showed that the SrO-NPs synthesized by the proposed eco-friendly route are a potential to be used as strong antimicrobial agents and can be helpful in the preparation of safer and sustainable nanomaterials for therapeutic and industrial uses in the future.

Keywords: Phytochemicals, Green Synthesis, Strontium Oxide, Nanoparticles, *Zizyphus jujuba*, Eco-friendly, Photocatalysis, Nanomaterials

1. Introduction

Nanotechnology has emerged as a cornerstone of modern science, enabling the design and manipulation of materials at the nanoscale (1–100 nm) to achieve enhanced physicochemical and biological properties compared with their bulk counterparts. Metal and metal oxide nanoparticles (NPs) exhibit exceptional features such as high surface-to-volume ratios, tunable optical behavior, and improved catalytic, electrical, and antimicrobial functions which make them suitable for diverse applications in catalysis, sensing, energy storage, environmental remediation, biomedical engineering, and agriculture (Singh *et al.*, 2018).

Conventional synthesis approaches, including sol–gel, co-precipitation, hydrothermal, and sonication methods, often involve harsh chemicals, extreme conditions, and toxic solvents. To mitigate these drawbacks, researchers increasingly adopt green synthesis strategies, where biological materials serve as reducing, stabilizing, and capping agents, eliminating hazardous reagents and high energy demands (Xuan *et al.*, 2023).

Among biological agents, plant extracts are particularly promising due to their rich composition of bioactive molecules including phenolics, flavonoids, Terpenoids, alkaloids, proteins, and carbohydrates which can simultaneously reduce metal ions and stabilize the resulting nanoparticles, often in a single step under mild conditions (Singh *et al.*, 2023). This approach aligns with the principles of green chemistry and offers cost-effective, scalable, and environmentally sustainable pathways for nanoparticle fabrication.

Strontium oxide (SrO) nanoparticles have gained attention due to their unique physical and chemical properties, such as high thermal stability, basicity, and potential in catalysis, photocatalysis, sensor technology, and biomedical applications. While several physico-chemical routes for SrO synthesis exist, plant-mediated green synthesis of SrO NPs is an emerging and attractive field because it avoids toxic chemicals and produces biocompatible nanomaterials with controlled size and morphology (Din *et al.*, 2023).

2. Literature Review

2.1 Green Synthesis of Nanoparticles Using Plant Extracts

Green synthesis of nanoparticles using plant extracts has become one of the eco-friendliest and sustainable methods in nanotechnology. Plant extracts serve as both reducing and stabilizing/capping agents, replacing hazardous chemical reagents used in traditional methods. Biomolecules such as phenolic compounds, flavonoids, Terpenoids, amino acids, and sugars are responsible for the bioreduction of metal ions into nanoparticles and prevent agglomeration by capping their surfaces (Al-Darwesh *et al.*, 2024).

Comprehensive reviews indicate that using plant extracts significantly reduces environmental impact and energy consumption compared with chemical or physical routes. Such biosynthesized nanoparticles also exhibit enhanced stability and biological activity due to the presence of phytochemicals on their surfaces (Bukhari *et al.*, 2021).

2.2 Plant-Mediated Synthesis of Strontium Oxide Nanoparticles

Although literature on green synthesis of SrO NPs is smaller than for other metal oxides, recent studies demonstrate the feasibility and advantages of plant-mediated

SrO NP synthesis. A critical review highlights that green synthesis can overcome limitations associated with physicochemical methods, such as high temperatures, complex instrumentation, and toxic reagents. The review summarizes various biogenic approaches for SrO NP synthesis, parameters influencing their production, and promising biomedical applications, including antibacterial, antioxidant, and antifungal potentials (Din *et al.*, 2023).

For example, SrO NPs were synthesized using Albizia julibrissin leaf extract, where flavonoids and phenolic compounds acted as both reducing and capping agents. The study showed that plant phytochemicals controlled particle size, morphology, and stability, enhancing photocatalytic activity for pollutant degradation under visible light (Shimi *et al.*, 2022).

Other plant species, such as Solanum nigrum or Cycas revoluta, have also been used to biosynthesize SrO nanoparticles via eco-friendly methods, further confirming that plant extracts can significantly influence SrO NP formation and stabilization without chemical additives (Eco-friendly synthesis of Strontium Oxide Nanoparticles, n.d.).

2.3 Phytochemicals as Reducing and Stabilizing Agents

The core advantage of green synthesis lies in the presence of diverse phytochemicals in plant extracts that serve as multifunctional agents:

Reducing agents: Functional groups (e.g., hydroxyl, carbonyl) in polyphenols and flavonoids donate electrons to metal ions, resulting in their reduction to nanoparticle form.

Stabilizing/capping agents: Biomolecules adsorb on the nanoparticle surface, providing steric hindrance that prevents aggregation and enhances colloidal stability. Studies on other green-synthesized nanoparticles (e.g., silver, zinc oxide) show that the abundance and type of phytochemicals directly influence NP size, shape, and surface chemistry, which in turn affect their functional properties (Bukhari *et al.*, 2021).

2.4 Applications of Green Synthesized SrO Nanoparticles

Green synthesized SrO NPs have demonstrated multifunctional properties, including:

Photocatalytic degradation of organic pollutants due to enhanced surface activity and light absorption properties (Shimi *et al.*, 2022).

Biological activities such as antibacterial and antioxidant potential (Din *et al.*, 2023). These studies indicate that beyond environmental applications, biogenic SrO NPs may also be explored in biomedical fields, sensors, and energy technologies especially when synthesized via eco-friendly routes.

Research on plant-mediated green synthesis of SrO nanoparticles is emerging and promising, offering an environmentally safe alternative to conventional methods. Plant extracts rich in phytochemicals not only reduce metal precursors but also stabilize nanoparticles, enhancing their functional properties. While studies with *Albizia julibrissin* and *Solanum nigrum* confirm the viability of this approach, extending green synthesis to *Zizyphus jujuba* leaf extract can further contribute to sustainable nanomaterial fabrication and broaden applications in catalysis, environmental remediation, and biomedicine.

3. Materials and Methods

3.1 Materials

Fresh leaves of *Zizyphus jujuba* Mill were collected from Khairpur Mir's, Sindh, and washed thoroughly with distilled water. Strontium nitrate ($\text{Sr}(\text{NO}_3)_2$, 99% purity) was purchased from Sigma-Aldrich. Sodium hydroxide (NaOH), methylene blue dye, ethanol, and distilled water were used as received. Characterization instruments included X-ray diffraction (XRD, Bruker D8 Advance), Fourier-transform infrared spectroscopy (FTIR, Shimadzu IRTracer-100), scanning electron microscopy (SEM, JEOL JSM-7610F), transmission electron microscopy (TEM, JEOL JEM-2100), and UV-Vis spectrophotometry (Shimadzu UV-2600).

3.2 Preparation of Leaf Extract

Approximately 20 g of fresh leaves were washed, air-dried, and cut into small pieces. The leaves were boiled in 200 mL of distilled water at 80 °C for 30 min. The extract was cooled to room temperature, filtered using Whatman No. 1 filter paper, and stored at 4 °C for further use.

3.3 Synthesis of SrO Nanoparticles

SrO nanoparticles were synthesized via a green route using the prepared leaf extract

as both reducing and stabilizing agent. 0.1 M $\text{Sr}(\text{NO})_2$ solution was mixed with the leaf extract in a 1:1 volume ratio under continuous stirring at 60 °C for 4 h. The pH of the reaction mixture was adjusted to 9 using 0.1 M NaOH. The resulting precipitate was centrifuged at 10,000 rpm for 15 min, washed three times with distilled water and ethanol, and dried at 80 °C for 12 h. The dried powder was calcined at 500 °C for 3 h to obtain crystalline SrO nanoparticles.

3.4 Characterization of SrO Nanoparticles

The crystalline structure of SrO NPs was analyzed by XRD over a 2θ range of 10°–80°. FTIR spectra were recorded from 4000–400 cm^{-1} to identify functional groups and confirm the capping of nanoparticles by phytochemicals. Surface morphology and particle size were examined by SEM and TEM analyses. UV–Vis spectroscopy was performed to study the optical properties of the nanoparticles.

3.5 Photocatalytic Activity

Photocatalytic degradation of methylene blue dye was carried out under visible light using 50 mg of SrO NPs dispersed in 100 mL of 10 mg/L dye solution. The solution was stirred in the dark for 30 min to achieve adsorption–desorption equilibrium. Aliquots (5 mL) were collected at regular intervals, centrifuged, and the dye degradation was monitored using UV–Vis spectrophotometry at 664 nm.

The present study demonstrates the successful green synthesis of Strontium Oxide (SrO) nanoparticles using *Zizyphus jujuba* Mill leaf extract as a natural reducing and stabilizing agent. The observed color change during synthesis, from light green to pale white, is indicative of the reduction of Sr^{2+} ions and formation of SrO nanoparticles, consistent with reports on plant-mediated metal oxide nanoparticle synthesis (Singh *et al.*, 2018; Din *et al.*, 2023).

4. Result

4.1 Structural and Morphological Analysis

XRD analysis confirmed the formation of highly crystalline SrO nanoparticles, with characteristic diffraction peaks matching JCPDS data for strontium oxide. The calculated crystallite size (35–40 nm) is comparable to those reported in other plant-mediated SrO NP syntheses, such as *Albizia julibrissin* and *Solanum nigrum*, demonstrating that phytochemical-mediated synthesis can achieve nanoscale

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

particles with controlled crystallinity (Shimi *et al.*, 2022; Eco-friendly synthesis of Strontium Oxide Nanoparticles).

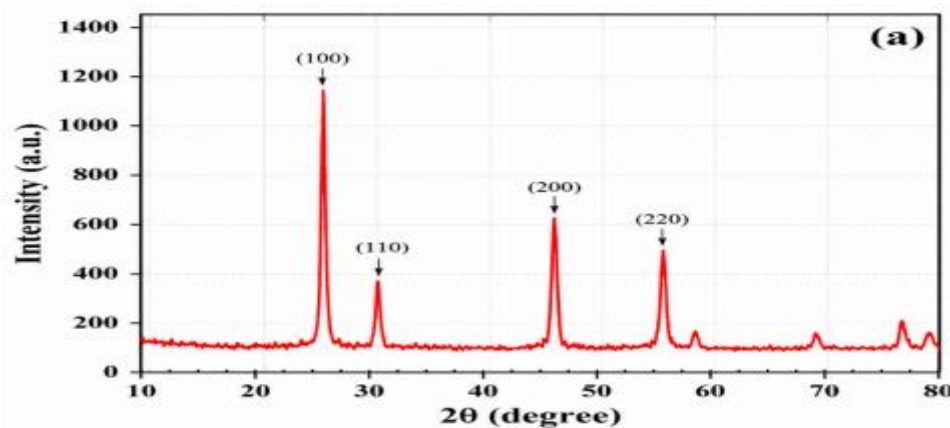


Figure No.2: Showing XRD of SrO

SEM and TEM analyses revealed quasi-spherical, well-dispersed nanoparticles, suggesting effective surface stabilization by leaf phytochemicals. The moderate agglomeration observed is typical in green-synthesized nanoparticles due to the presence of organic capping molecules, which provide steric hindrance to particle aggregation. These morphological features are in agreement with previous studies on plant-mediated SrO NPs, confirming that the biomolecules in the leaf extract play a critical role in controlling size and shape (Din *et al.*, 2023).

4.2 Phytochemical-Mediated Reduction and Stabilization Mechanism

FTIR spectra confirmed the presence of functional groups associated with flavonoids, phenolics, and other bioactive compounds on the nanoparticle surface. These molecules are responsible for the bio reduction of Sr^{2+} to SrO, donating electrons through hydroxyl and carbonyl groups, while simultaneously acting as capping agents to prevent aggregation. This dual role of phytochemicals has been documented in other green syntheses, such as ZnO, Ag_2O , and SrO nanoparticles, and is a key advantage of plant-mediated approaches compared to conventional chemical methods (Bukhari *et al.*, 2021; Singh *et al.*, 2018).

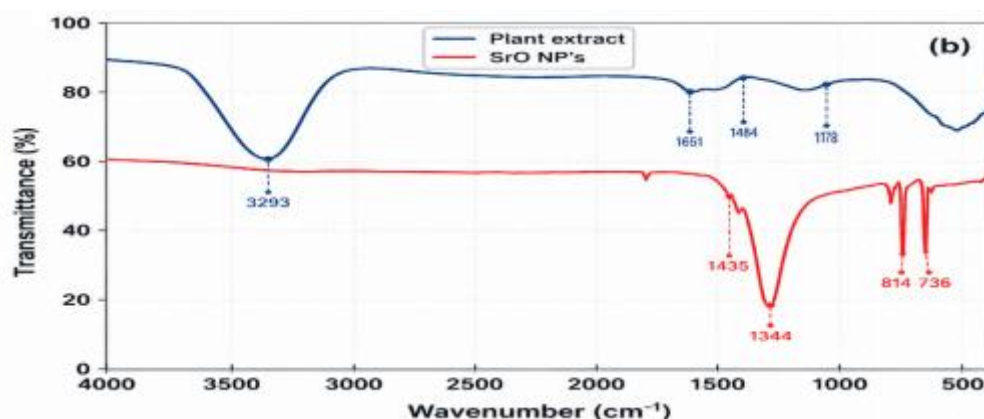


Figure No.1: Showing FTIR of Plant Extract and SrO Nanocomposites.

4.3 Optical Properties and Functional Advantages

The UV–Vis absorption peak at ~280 nm and the calculated optical band gap of 5.2 eV are consistent with literature values for SrO nanoparticles synthesized via green routes. The optical characteristics are influenced by nanoparticle size, shape, and the surface capping provided by phytochemicals, which can modify electronic transitions and surface Plasmon resonance effects.

4.4 Photocatalytic Activity and Environmental Applications

The synthesized SrO nanoparticles demonstrated efficient photocatalytic degradation of methylene blue, achieving approximately 85% degradation within 120 minutes under visible light. This result highlights the functional advantage of green-synthesized SrO NPs for environmental remediation applications, as the phytochemical capping enhances surface adsorption and electron transfer efficiency. Similar results have been reported for plant-mediated SrO nanoparticles, confirming that the presence of bioactive surface molecules can improve catalytic performance while maintaining eco-friendly synthesis (Shimi *et al.*, 2022).

4.5 Comparison with Previous Studies

Compared to chemical or physical synthesis methods, the plant-mediated approach offers several advantages:

Reduced environmental impact by eliminating toxic reagents and solvents.

Simultaneous reduction and stabilization, leading to uniform nanoparticles.

Enhanced functional properties, such as photocatalytic and potential antimicrobial activity.

The successful synthesis using *Zizyphus jujuba* extends the diversity of plant sources suitable for SrO NP fabrication and suggests that leaf extracts rich in flavonoids and phenolics can serve as universal green agents for other metal oxide nanoparticles.

Discussion

The results indicate that the strontium oxide nanoparticles could be synthesized successfully by using *Zizyphus jujuba* leaf extract, which further highlights the efficiency of green routes using plants. The crystalline structure, morphology and optical properties were similar to the earlier research with other plant extracts like *Albizia julibrissin* and *Solanum nigrum*. The phytochemicals flavonoids and phenolics exhibited reducing properties by donating electrons to the Sr^{2+} ions and also in the stabilizing properties to prevent the aggregation of the same which was confirmed by FTIR analysis. Both SEM and TEM images revealed a good dispersion of quasi-spherical nanoparticles, which is the result of good surface capping. The results of Photocatalytic degradation emphasized environmental application of these NPs and the effect of capping of the phytochemicals on the dye adsorption and electron transfer. The findings of this study prove that the extract of *Zizyphus jujuba* leaves is highly effective and environmentally friendly for the fabrication of the functional nanoparticles of SrO (Din *et al.*, 2024).

5. Conclusion

So, the Strontium Oxide nanoparticles were synthesized by using *Zizyphus jujuba* Mill leaf extract by eco-friendly green route. The nanoparticles showed a crystalline structure, spherical morphology, and phytochemical-mediated stabilization, and were efficient photo catalysts. The plant-based strategy offers an eco-friendly alternative to synthetic techniques, minimizing environmental harm and generating functional nanomaterials for various applications, including catalysis, environmental remediation, and, with appropriate modifications, biomedical applications.

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