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Eco-friendly Synthesis of Strontium Oxide Nanoparticles using *Solanum nigrum* Leaf Extract: Characterization and Antibacterial Potential

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ABSTRACT

In this study, strontium oxide nanoparticles (SrO NPs) were successfully synthesized using *Solanum nigrum* leaf extract. The extract acted as a stabilizing agent during the synthesis process. Characterization techniques such as FTIR spectroscopy confirmed the existence of functional groups of the nanoparticles. Photon Correlation Spectroscopy analysis revealed an average particle size of 94.8 nm with a polydisperse distribution. SEM images showed the morphology of the nanoparticles, ranging from individual particles to agglomerates. XRD analysis indicated a cubic crystal structure for the SrO NPs. Importantly, the synthesized SrO NPs exhibited significant antibacterial activity against *Mycobacterium TB*, *Candida albicans*, and *E. coli*, highlighting their potential as antimicrobial agents. This eco-friendly approach utilizing *Solanum nigrum* extract opens up possibilities for the green synthesis of SrO NPs with promising biomedical applications.

Keywords: Strontium oxide nanoparticles, *Solanum nigrum*, Characterization, FTIR spectroscopy, Antibacterial activity

INTRODUCTION

Biomedical research, food processing, electrochemical systems, beauty and personal care, pharmaceutical development, catalytic reactions, sensor technology and other nanotechnology fields have advanced greatly in the past decade. These advances pollute the environment[1] and continue. Toxic waste is a byproduct of conventional synthesis, but today's technology emphasizes green synthesis as a trustworthy, cost-efficient, sustainable, and environmentally conscious means of processing various materials. Green synthesis plays a pivotal role in mitigating the adverse impacts associated with conventional synthesis methods employed in laboratory and industrial settings, encompassing sectors such as paint production, tanneries, textiles, plastics manufacturing, rubber processing, cosmetics formulation, and beyond. Due to rising interest in nanotechnology, several researchers are developing metal oxide nanoparticles for various purposes [2,3]. Novel chemical and physical features characterise nanomaterial production advances. Physical Sciences, chemical engineering, and materials science use metal oxides[4]. Nanotechnology's magnetic, electrical, mechanical, thermal, and optical properties have made scientific material production easier.

Due to their structural variety and wide range of uses, nanoparticles from transition metal oxides like strontium oxide (SrO) are important. Doped dye-sensitive solar cells, chip electrodes, supercapacitors, gas detectors, rechargeable lithium-ion batteries, catalyst supports, biodiesel production, transistors, and photovoltaic cells represent a range of potential applications that have been extensively explored for SrO nanoparticles. In research studies, the synthesis of SrO nanoparticles via the sol-gel method has been documented, with a focus on examining their optical and thermal properties[5]. However, these synthetic approaches typically entail the use of extreme conditions, such as high temperatures, toxic reducing agents, and hazardous solvents. SrO nanoparticles are used in cathode ray tubes as an aluminium alloy to protect eyes from X-ray radiation from old-style colour television[6]. Industrial wastewater contains toxic dyes like rhodamine B, methylorange, methylene blue, and heavy metal ions which can cause serious diseases like contact dermatitis, breathing diseases, cancer, and other health issues in humans. Different methods can be employed for the treatment of polluted water, including biodegradation, adsorption[7], chemical precipitation, oxidation kinetics[8], chlorination, ozonation, sedimentation, and others. But these methods need an enormous amount of energy and chemicals. In recent years, green technology is employed to eliminate environmental pollution problems.

Current approaches for SrO NP synthesis have limitations and insufficient literature.

Plant extracts are safer and more easily available than manufactured chemicals. Many researchers synthesise nanoparticles from plant (or herbal) extracts like Lantana Camara, Acacia Nilotica[9], *Ocimum sanctum*, *Albizia julibrissin*, *Vitis vinifera*, *Cimin*, *Garica papaya*, and *Trigonella foenum-graecum*, to overcome this disadvantage. Plant chemicals as reducing agents in nanoparticle production are of tremendous interest. Synthesised nanoparticles with diverse shape and nanoscale size have better physical and electrical characteristics[10]. Due to its prospective uses in biomedicine, agriculture, and environmental remediation, SrO NPs synthesised from *Solanum nigrum* leaf extract have garnered interest. Biomedical applications benefit from their non-toxicity and cell safety. These nanoparticles fight bacteria and fungus well. They make medical device and surface antibacterial coatings. SrO NPs from *Solanum nigrum* leaf extract catalyse several processes, including wastewater organic pollutant degradation[11]. These nanoparticles may clean up polluted water and soil by eliminating heavy metals and organic contaminants[12,13]. SrO NPs made from *Solanum nigrum* leaf extract boost plant development and kill pests[14].

EXPERIMENTAL

Solanum nigrum

Solanum contains about 2,000 tropical and subtropical plant species that thrive worldwide. Ganake soppu, Makoi, Kachchipandu, Munatakali, Piludi, and Black Night Shade are all names for *Solanum nigrum* Linn. Kannada names for this plant include Ganake soppu and Kamuni. Shrubby perennial black nightshade is short-lived. It occasionally appears purple- green. Its glandular or non-glandular hairs will not have prickles. Due to its antibacterial and antidysenteric properties, India uses the "plant" internally to treat cardalgia and gripe[15-17]. Glycoproteins, steroidal saponins (C=H=O) tannin proteins, phytosterols, steroidal alkaloids (C=H=N=O), flavonoids (C_nH_nN), carbohydrates, coumarins, and other elements make up the primary constituents and it iss anti-diabetic, cytoprotective, and anticancer.

Plant Extract

Solanum nigrum leaves were extracted in multiple phases. First, mature leaves were cleaned with distilled water. To preserve active components, the leaves were air-dried in the shade. A mortar and pestle pounded the dried leaves into a powder[18]. To extract bioactive chemicals from the leaves, the powder was weighed and combined with methanol or ethanol. To maximise extraction, the mixture soaked several hours. After filtering out solids, the solvent was evaporated using a rotary evaporator to produce a concentrated extract. A freeze-dryer was used to powder the concentrated extract.

Materials and SrO nanoparticle synthesis

Analytical grade strontium nitrate hexahydrate and *Solanum nigrum* extract were utilised to synthesise SrO samples. Proteins, vitamins, carbohydrates, flavonoids, phenols, and coenzyme-based intermediates are some of the biomolecules and metabolites found in *Solanum nigrum*. The nanoscale particle size of such plant chemicals is reduced by metal ions interacting with carbonyl, hydroxyl, and amino functional groups. For stability and biocompatibility, these chemicals cap nanoparticles. Metal ions are converted to metal oxide nanoparticles by flavonoids and phenolic compounds in the extract. 10 g of leaf extract powder was added to a weak solution of strontium nitrate hexahydrate salt (0.1M) and stirred for an hour at 70°C in a magnetic stirrer. After an hour, strontium oxide nanoparticles formed and the mixture became dark green. It was cooled, centrifuged, and dried in a 500°C hot air oven. The powder was stored in a sealed container for succeeding examination.

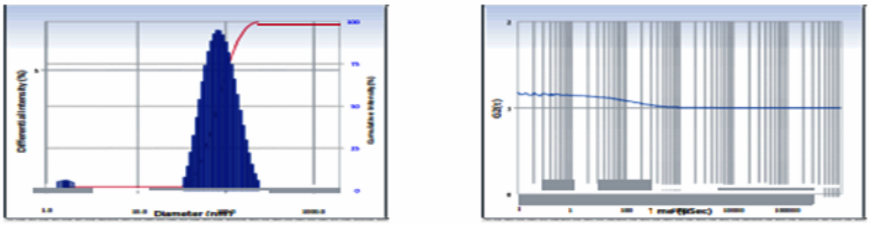
RESULTS AND DISCUSSION

Characterization methods

In order to evaluate the functional group, chemical bonding, particle diameter, and morphological features of the bio-synthesized SrO NPs, they were subjected to characterization. Using KBr pellets and a Fourier Transform Infrared equipment in a wavelength range of 4000–400 cm^{-1}, the functional groups were investigated.

Photon Correlation Spectroscopy (PCS)

The photon correlation spectroscopy (Beckman Delsa Nano C series, USA) was utilised in order to determine the particle dimension of the nanoparticles that were generated from the extract of the leaf of the plant *Solanum nigrum*. The research of particle size is helpful in carrying out an analysis of the molecules that are suspended in the colloidal dispersion that is undergoing Brownian motion[19,20]. The polydispersity index (PDI) is utilized to assess the sample's dispersity in solution, indicating the degree of particle non-uniformity. In the case of the *Solanum nigrum* leaves extract, which serves as a stabilizing agent for strontium oxide nanoparticles (SrONPs), the average particle size, as determined by dynamic light scattering, is found to be 94.8 nm in diameter. The particle distribution demonstrates significant polydispersity, with a polydispersity index (PDI) value of 0.219.



Distribution Results (Contin)

Peak	Diameter (nm)	Std. Dev.
1	1.6	0.2
2	96.9	40.7
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
Average	94.8	42.7
Residual	7.9692.003	(O.K)

Cumulants Results

Diameter	(d)	: 110.9	(nm)
Polydispersity Index	(P.I.)	: 0.219	
Diffusion Const.	(D)	: 4.437e-008	(cm^2/sec)

Measurement Condition

Temperature	: 25.0	(°C)
Diluent Name	: WATER	
Refractive Index	: 1.3328	
Viscosity	: 0.8878	(cP)
Scattering Intensity	: 28737	(cps)
Attenuator 1	: 65.58	(%)

Intensity Distribution Table

d (nm)	f(%)	f(cum.%)	d (nm)	f(%)	f(cum.%)	d (nm)	f(%)	f(cum.%)	d (nm)	f(%)	f(cum.%)
1.0	0.0	0.0	6.7	0.0	2.3	45.3	2.3	7.7	304.7	0.0	100.0
1.1	0.0	0.0	7.3	0.0	2.3	48.9	3.0	10.7	328.9	0.0	100.0
1.2	0.0	0.0	7.8	0.0	2.3	52.7	3.8	14.5	354.9	0.0	100.0
1.3	0.0	0.0	8.5	0.0	2.3	56.9	4.5	19.0	383.1	0.0	100.0
1.4	0.4	0.4	9.1	0.0	2.3	61.4	5.2	24.2	413.4	0.0	100.0
1.5	0.4	0.8	9.9	0.0	2.3	66.3	5.8	30.0	446.2	0.0	100.0
1.6	0.4	1.2	10.6	0.0	2.3	71.6	6.2	36.2	481.5	0.0	100.0
1.7	0.4	1.6	11.5	0.0	2.3	77.2	6.5	42.7	519.7	0.0	100.0
1.8	0.4	2.0	12.4	0.0	2.3	83.3	6.6	49.3	560.9	0.0	100.0
2.0	0.3	2.3	13.4	0.0	2.3	90.0	6.6	56.0	605.3	0.0	100.0

Fig. 1. Dynamic Light Scattering Results of SrONPS FTIR spectrum analysis

The peak at 3342.93 cm^{-1} is indicative of the O-H stretching vibration, likely originating from hydroxyl groups (-OH) on the nanoparticle surface or absorbed water molecules. The peak at 2360.11 cm^{-1} corresponds to alkynes, while the peak at 1636.35 cm^{-1} indicates the stretching vibration of C=O bonds found in carboxylic acid functional groups (-COOH) present on the nanoparticle surface. The peak observed at 435.28 cm^{-1} is likely due to the bending vibration of the metal-oxygen (M-O) bonds present in the strontium oxide nanoparticles. This peak is typically used to identify the presence of metal oxides[21,22].

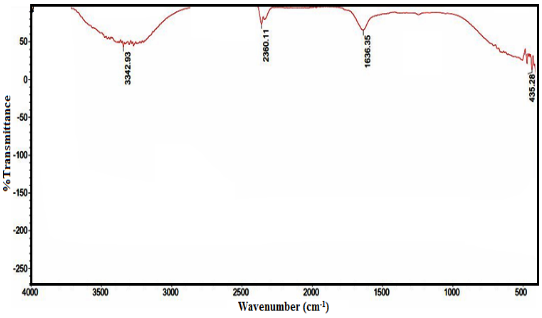


Fig. 2. FTIR spectrum of SrO NPs

Nanoparticle optical characteristics are often investigated using UV-Vis spectroscopy. UV- Vis absorption spectra reveal nanoparticle size, shape, and composition. Particle size increases UV-Vis absorption peak wavelength. Nanoparticle chemical composition affects absorption peak. UV-Vis spectroscopy can evaluate strontium oxide nanoparticles synthesised from leaf extracts. UV-Vis spectroscopy can reveal nanoparticle size, shape, and content. Leaf extract-derived strontium oxide nanoparticles had absorbance maxima between 250 and 350 nm. However, findings may vary based on nanoparticle size, shape, content, and experimental circumstances.

DLS uses Brownian motion to quantify particle size distribution in liquid suspensions. DLS results for leaf extract strontium oxide nanoparticles (NPs) would reveal their size distribution and stability. DLS data with a restricted size distribution and a single peak imply stable, homogenous NPs in suspension. If the DLS findings reveal a broad size range with many peaks, the NPs may be agglomerating in the suspension. DLS data can provide NP zeta potential as well as size distribution. The zeta potential, which measures NP surface charge, can alter suspension stability and behaviour. High zeta potential makes NPs stable and less prone to combine. Low zeta potential increases NP aggregation[23].

Morphological Analysis

SEM pictures of strontium oxide nanoparticles of plant extract examined using JOEL JSM 6360 machine reveal individual particles or agglomerates with diameters ranging from a one micro meters to a few hundred nanometers, depending on the synthesis technique and circumstances. Spherical or irregular particles may be loosely or tightly packed. Depending on aggregation and surface coatings or functional groups, particles may have rough or smooth surfaces Fig. 4. The particles may also have organic groups or biomolecules that stabilise or functionalize them.

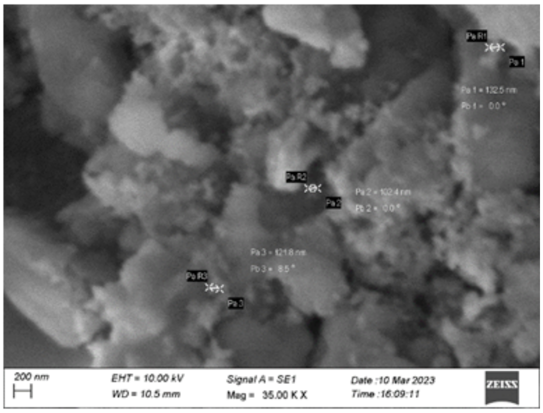


Fig. 3. SEM images of SrO NPs at 200 nm

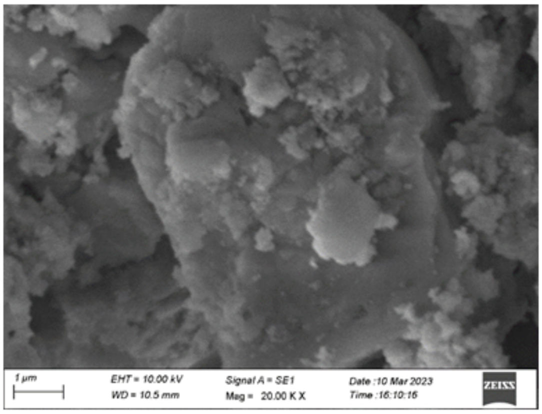


Fig. 4. SEM images of SrO NPs at 1µm Crystallographic Analysis

The XRD pattern in Fig. 1a shows peaks at 28.72°, 36.13°, 59.95°, and 67.36°, corresponding to the crystallographic planes (110), (200), (311), and (400) in the prepared sample. Based on the Miller indices provided, we can infer that the crystal structure of strontium oxide nanoparticles is likely cubic. This is because the Miller indices represent planes that are perpendicular to specific crystallographic directions, and in a cubic crystal system, the crystallographic axes are equivalent. In a cubic crystal structure, the lattice parameters along all three axes (a, b, c) are equal. The presence of planes with Miller indices (110), (200), (311), and (400) suggests that the crystal structure is consistent with cubic symmetry. The obtained results demonstrate a perfect match with the cubic structure of SrO, indicating the successful synthesis of the desired material. Additionally, the parameters obtained suggest that the natural extract derived from the plant leaves serves as an effective stabilizing and capping agent during the synthesis process. An alternative method for determining the average crystallite size (D) involves the utilization of the Debye-Scherrer equation, which relates the peak broadening in the XRD pattern to the crystallite size.

$$D = \frac{K\lambda}{\beta \cos \theta}$$

Equation as where is the full width at half maximum (FWHM), K = 0.94 (shape factor), l = 1.5405° A and θ is the diaravcetriaogne acnrgylset.alTlithee size of the sample is calculated at around 36 nm 24.

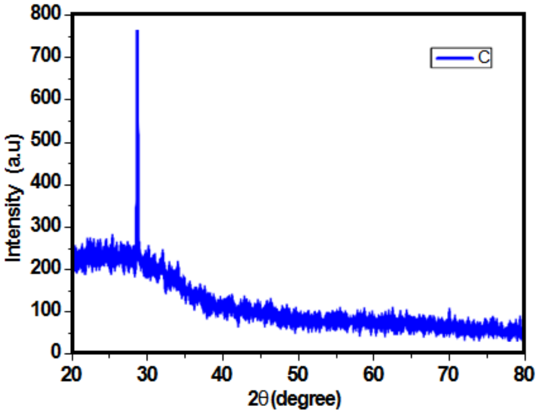


Fig. 5. XRD of strontium oxide nanoparticles

Antibacterial assay

Plant extract-derived SrO NPs are assessed for antibacterial activity utilising well diffusion. Bacteria are cultivated on well-agar plates. The plates are incubated with synthesised nanoparticles. Nanoparticles antibacterial activity is shown by the wells' zone of inhibition. SrO NPs synthesised from plant extracts inhibited bacterial growth for a number of *Gram-positive* and *Gram-negative* strains, depending on nanoparticle concentration and strain. A loop brush infected a cooled sterile nutritional agar plate. The inoculated agar plate was dried for 10-15 min and agar wells were made with a sterile cork borer or pipette tip. Well size was determined experimentally. 20-50 µL of nanoparticle solution was pipetted into each well. Agar plates were incubated at the right temperature. The agar plate was inspected after incubation for zones of inhibition surrounding the wells, indicating bacterial or fungal growth suppression.

Plant extract-derived SrO NPs displayed a zone of inhibition of 12-18 mm, indicating moderate to high antibacterial activity against *Mycobacterium TB*. *Candida albicans* inhibited 12-18 mm more than the control. *E.coli* inhibited the most (33 mm). The plant extract utilised to synthesise SrO NPs contains phytochemicals that give them antibacterial and antifungal properties. Alkaloids, flavonoids, tannins, phenolic chemicals, and saponins in plant extracts are antibacterial. These phytochemicals damage microbe cell walls/membranes, preventing growth and replication. Slow-growing, acid-fast *Mycobacterium tuberculosis* produces TB. SrO NPs show moderate to high antibacterial activity against this pathogen with a zone of inhibition of 12-18 mm. Broad-spectrum antibiotic gentamicin treats bacterial infections. Gentamicin's 20 mm zone of inhibition at 100 µL shows that it is more effective than synthesised SrO NPs against the tested bacteria. Fungal pathogen *Candida albicans* causes several infections. The synthesised SrO NPs suppress this fungus with a 12-18 mm inhibition zone. *Gram-negative E. coli* is present in the intestines. This bacterium has the maximum inhibition zone of 33 mm against the synthesised SrO NPs. *Gram-negative* bacteria are more vulnerable to antimicrobial harm because their cell walls are thinner and more complicated than those of *Gram-positive* bacteria. The synthesised SrO NPs' size and form may have increased their activity against *E. coli*.

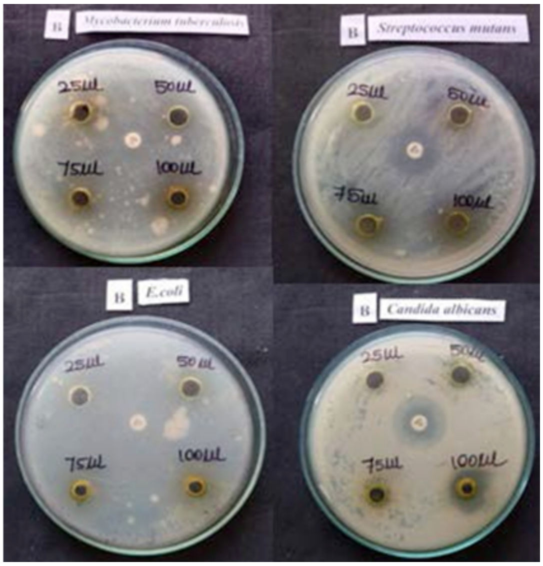


Fig. 6. Inhibition zones of strontium oxide nanoparticles

CONCLUSION

The synthesis of SrO NPs using *Solanum nigrum* leaf extract as an eco-friendly approach was successfully achieved. The analysis of the nanoparticles revealed a cubic crystal structure based on XRD analysis, with an average particle size of 94.8 nm as determined by PCS. The SEM images showed the morphology of the nanoparticles, ranging from individual particles to agglomerates. The bio-synthesized SrO NPs exhibited notable antibacterial activity against *Mycobacterium TB*, *Candida albicans*, and *E. coli*, indicating their potential as effective antimicrobial agents. This suggests that *Solanum nigrum* leaf extract, with its bioactive compounds, can coordinate with the SrO NPs, enhancing their antibacterial properties.The study demonstrates the feasibility of using *Solanum nigrum* leaf extract for the eco-friendly synthesis of SrO NPs with promising antimicrobial properties.The approach presents opportunities for the development of environmentally friendly nanomaterials for various biomedical applications.

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Conflict of interest

There is no conflict of interest.

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