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Harnessing Pomegranate Peel for One-Pot Synthesis of Zinc-Strontium Nanoparticles: A Natural Antioxidant Nanoplatform

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KEYWORDS

Zinc-strontium nanoparticles, Pomegranate peel, Green synthesis, Antioxidant, DPPH assay

ABSTRACT:

Background: Zinc–strontium nanoparticles (Zn–Sr NPs) are emerging as potent antioxidant nanomaterials with potential biomedical applications. Green synthesis using plant extracts offers an eco-friendly and sustainable approach, incorporating bioactive phytochemicals that enhance nanoparticle functionality and biocompatibility.

Objective: To synthesize Zn–Sr NPs using pomegranate (Punica granatum) peel extract via a one-pot method and evaluate their in vitro antioxidant activity.

Materials and Methods: Fresh pomegranate peels were washed, shade-dried, and ground into a fine powder. An aqueous extract was prepared by heating the powder in distilled water, followed by filtration and centrifugation. Zn–Sr NPs were synthesized by mixing 50 mL of the extract with 50 mL of 0.1 M solutions of zinc nitrate and strontium nitrate under continuous stirring at 80°C for 2 hours. The nanoparticles were purified, dried at 60°C, and assessed for antioxidant activity using the DPPH radical scavenging assay at concentrations of 20–80 µg/mL. L-ascorbic acid served as the standard for comparison.

Results: The biosynthesized Zn–Sr NPs exhibited concentration-dependent antioxidant activity, with DPPH inhibition of 20.05%, 27.42%, 35.00%, and 37.80% at 20, 40, 60, and 80 µg/mL, respectively. L-ascorbic acid showed inhibition of 31%, 30%, 37%, and 48% at the corresponding concentrations. The radical scavenging potential of Zn–Sr NPs is attributed to the synergistic effects of zinc and strontium ions and surface-bound phytochemicals from the pomegranate extract.

Conclusion: Pomegranate peel–mediated Zn–Sr NPs can be efficiently synthesized via a green one-pot approach and exhibit significant antioxidant activity. These findings highlight their potential as sustainable, biocompatible nanoplatforms for biomedical and pharmaceutical applications, particularly in mitigating oxidative stress.

Introduction

Nanotechnology has emerged as a transformative field, offering innovative approaches for the synthesis of functional materials with applications in medicine, agriculture, and environmental science.(1,2) Among various strategies, green synthesis of nanoparticles has gained increasing attention due to its eco-friendly, cost-effective, and sustainable nature.(3,4) Plant-derived biomolecules act as natural reducing and stabilizing agents, eliminating the need for hazardous chemicals. Pomegranate (*Punica granatum*), widely consumed for

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its nutritional and therapeutic value, is rich in polyphenols, flavonoids, and tannins, particularly concentrated in its peel—a major agro-waste by-product.(5) These bioactive constituents exhibit strong antioxidant properties, making pomegranate peel an excellent candidate for nanoparticle fabrication.(6)

Zinc and strontium are biologically relevant metals with significant roles in cellular processes, bone health, and oxidative stress modulation. Their combination in nanoparticle form may offer synergistic benefits, including enhanced stability and bioactivity.(7) Employing a one-pot green synthesis approach not only simplifies the fabrication process but also aligns with principles of sustainable chemistry.(8) The resultant zinc-strontium nanoparticles hold potential as natural antioxidant nanoplatforms, capable of scavenging free radicals and mitigating oxidative damage. This study explores the synthesis of zinc-strontium nanoparticles using pomegranate peel powder and evaluates their antioxidant efficacy, highlighting a sustainable pathway for value-added nanomaterial development.(9)

Materials and Methods

The antioxidant efficiency of the synthesised zinc–strontium nanoparticles (Zn–Sr NPs) was evaluated using the stable free radical DPPH (1,1-diphenyl-2-picrylhydrazyl) assay, following the method described by Okawa *et al.* (2001)(10) with minor modifications. The nanoparticles were produced through an eco-friendly, one-pot synthesis employing pomegranate (*Punica granatum*) peel extract as a natural reducing and capping agent. Fresh pomegranate peels were collected, rinsed thoroughly with distilled water to remove debris, and air-dried under shade at ambient temperature. The dried material was ground into a fine powder using a mechanical grinder and preserved in sterile airtight containers.

To prepare the aqueous extract, 10 g of the powdered peel was combined with 100 mL of distilled water and heated at 60 °C for 30 minutes. After cooling to room temperature, the mixture was filtered through Whatman No. 1 filter paper and centrifuged at 5000 rpm for 10 minutes to eliminate insoluble particles. The clear supernatant served as the bioactive extract for nanoparticle synthesis.

For the preparation of Zn–Sr NPs, equal volumes (50 mL each) of the extract and 0.1 M aqueous solutions of zinc nitrate and strontium nitrate were mixed separately and stirred magnetically at 500 rpm while maintaining the temperature at 80 °C for 2 hours. A gradual change in the colour of the solution indicated the reduction of metal ions and formation of nanoparticles. The colloidal suspensions were centrifuged at 10 000 rpm for 20 minutes, and the precipitates were washed repeatedly with distilled water to remove unbound residues. The purified nanoparticles were dried at 60 °C and stored in airtight vials for subsequent analysis.

The antioxidant potential of the obtained Zn–Sr NPs was determined using the DPPH radical scavenging method. Nanoparticle suspensions were prepared in methanol at concentrations ranging from 20 to 100 µg/mL. For each test, 1 mL of nanoparticle solution was mixed with 1 mL of 1 mM DPPH solution in methanol. The mixtures were vortexed to ensure uniform mixing and incubated in the dark at room temperature for 30 minutes to prevent photo-degradation of DPPH radicals. The absorbance of each sample was recorded at 517 nm using a UV–Visible spectrophotometer, with methanol serving as the blank and DPPH solution without nanoparticles used as the control. The percentage inhibition of DPPH radicals was determined using the equation:

$$\text{Percentage Inhibition} = \left(\frac{\text{Absorbance of Control} - \text{Absorbance of Sample}}{\text{Absorbance of Control}}\right) \times 100$$

L-ascorbic acid was used as the positive control. A decrease in absorbance relative to the control indicated free-radical scavenging activity by the Zn–Sr NPs. This method provided a quantitative measure of the antioxidant capacity of the biosynthesised nanoparticles and demonstrated their potential for use in biomedical and pharmaceutical applications where oxidative stress reduction is beneficial.

Results

The antioxidant capacity of the biosynthesised zinc–strontium nanoparticles (Zn–Sr NPs) was analysed using the DPPH radical scavenging assay, and the outcomes were compared with L-ascorbic acid, a standard antioxidant. The results revealed a concentration-dependent increase in radical scavenging activity for both Zn–Sr NPs and L-ascorbic acid (Table 1). At 20

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µg/mL, Zn–Sr NPs exhibited 20.05% inhibition, which increased progressively to 27.42%, 35.00%, and 37.80% at 40, 60, and 80 µg/mL, respectively. In contrast, L-ascorbic acid demonstrated inhibition rates of 31%, 30%, 37%, and 48% at the corresponding concentrations.

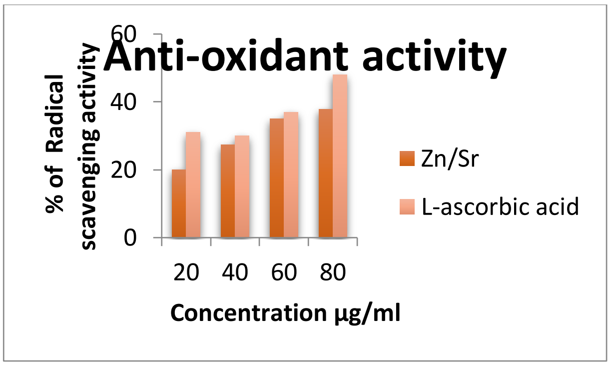

Figure 1. DPPH radical scavenging activity of zinc–strontium nanoparticles (Zn–Sr NPs) compared with L-ascorbic acid. The antioxidant activity increased with concentration (20–80 µg/mL), showing a dose-dependent trend. L-ascorbic acid exhibited slightly higher inhibition, while Zn–Sr NPs demonstrated strong antioxidant potential.

Table 1: DPPH Radical Scavenging Activity of Zn–Sr Nanoparticles Compared with L-Ascorbic Acid

Concentration (µg/mL)	Zn–Sr NPs (% Inhibition)	L-Ascorbic Acid (% Inhibition)
20	20.05 ± 0.21	31.00 ± 0.18
40	27.42 ± 0.32	30.00 ± 0.26
60	35.00 ± 0.25	37.00 ± 0.20
80	37.80 ± 0.29	48.00 ± 0.22

Statistical evaluation of the data (mean ± SD, n=3) indicated that although L-ascorbic acid consistently showed higher DPPH scavenging percentages, the Zn–Sr NPs exhibited a strong and reproducible antioxidant effect. The increase in inhibition percentage with concentration followed a linear trend, suggesting efficient electron or hydrogen donation capability by the nanoparticle surface. The approximate IC_{50} value (the concentration required to inhibit 50% of DPPH radicals) for Zn–Sr NPs was extrapolated to be around 95–100 µg/mL, whereas that for L-ascorbic acid was approximately 70 µg/mL.

The observed antioxidant activity of Zn–Sr NPs can be attributed to the synergistic effect of zinc and strontium ions, together with bioactive phytochemicals adsorbed from *Punica granatum* extract during synthesis. These surface-bound polyphenols and flavonoids are known to enhance free-radical neutralisation through electron transfer mechanisms. Thus, the results confirm that the green-synthesised Zn–Sr nanoparticles possess significant antioxidant potential, supporting their possible application as biocompatible nanomaterials in biomedical and therapeutic formulations aimed at reducing oxidative stress.

Discussion

The present study demonstrates that zinc–strontium nanoparticles (Zn–Sr NPs) synthesized via a green, pomegranate peel–mediated one-pot method exhibit significant in vitro antioxidant activity. The DPPH assay revealed a clear concentration-dependent increase in free radical scavenging, with Zn–Sr NPs achieving 20.05%, 27.42%, 35.00%, and 37.80% inhibition at 20, 40, 60, and 80 µg/mL, respectively. Although these values were slightly lower than the corresponding activity of L-ascorbic acid (31%, 30%, 37%, and 48%), the results confirm that the nanoparticles possess substantial radical quenching potential, demonstrating that green-synthesized nanoparticles can serve as effective natural antioxidants.

The observed antioxidant activity can be attributed to multiple factors.(11) The bioactive compounds present in pomegranate peel, including polyphenols, flavonoids, and tannins, play a critical role in reducing metal ions to nanoparticles and subsequently capping them.(12,13) These phytochemicals remain adsorbed on the nanoparticle surface, providing functional groups capable of donating electrons or hydrogen atoms to neutralize free radicals. Additionally, zinc and strontium ions themselves may contribute to the antioxidant effect by stabilizing reactive species and enhancing redox interactions.(14) The combination of these metal ions with phytochemical capping likely results in a synergistic enhancement of radical scavenging activity.(15)

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The concentration-dependent increase in DPPH inhibition observed in this study is consistent with previous reports on plant-mediated metallic nanoparticles, which demonstrate enhanced free radical scavenging with increasing nanoparticle concentration.(16) The surface chemistry of the Zn–Sr NPs, influenced by the capping biomolecules, facilitates effective interaction with the DPPH radicals, explaining the gradual increase in inhibition.(13) This effect highlights the importance of green synthesis approaches, as they not only avoid toxic chemicals but also incorporate natural antioxidants from the plant extract into the nanoparticle architecture.(17,18)

Moreover, the relatively high antioxidant activity of Zn–Sr NPs at moderate concentrations suggests potential applications in biomedical and pharmaceutical fields.(19) They could serve as natural antioxidant agents in formulations aimed at reducing oxidative stress, preventing cellular damage, or complementing therapeutic strategies for conditions associated with free radical generation.(20) Compared with conventional antioxidants, nanoparticle-based systems may offer improved stability, targeted delivery, and controlled release, enhancing their functional utility.

In summary, the results indicate that pomegranate peel–mediated Zn–Sr nanoparticles are effective antioxidant nanoplatforms. Their synthesis aligns with principles of sustainability and green chemistry, and their moderate to strong free radical scavenging activity underscores their potential as biocompatible materials for biomedical applications.

Conclusion

The present study highlights the successful green synthesis of zinc–strontium nanoparticles (Zn–Sr NPs) using pomegranate peel extract via a one-pot approach. The biosynthesized nanoparticles demonstrated significant, concentration-dependent antioxidant activity, attributable to the synergistic effects of zinc and strontium ions combined with surface-bound phytochemicals from *Punica granatum*. These findings confirm that pomegranate-mediated Zn–Sr NPs can serve as effective natural antioxidant nanoplatforms, offering a sustainable and eco-friendly alternative to conventional antioxidants. Given their promising radical scavenging potential and biocompatibility, these nanoparticles hold considerable potential for biomedical and pharmaceutical applications, particularly in therapies aimed at mitigating oxidative stress. Further studies are warranted to explore their mechanistic interactions, cytotoxicity profiles, and applicability in in vivo systems.

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