RASĀYAN *J. Chem.*
Vol. 19 | No. 4 | 2345-2354 | October-December | 2026
ISSN: 0974-1496 | e-ISSN: 0976-0083 | CODEN: RJCABP
http://www.rasayanjournal.com
http://www.rasayanjournal.co.in

ECO-FRIENDLY SYNTHESIS OF *Simarouba glauca*-ASSISTED ZINC OXIDE NANOPARTICLES WITH ENHANCED BIOLOGICAL EFFICACY

J. Senthil Kumar[1]✉, M. Shanthi[2], N. V. Sithara[1], and P. Rajiv[1]
[1]Department of Biotechnology, PSG College of Arts & Science,
Coimbatore-641 014, Tamil Nadu, India
[2]Department of Physics, Kamaraj College of Engineering & Technology,
K. Vellakulam-625 701, Tamil Nadu, India
✉Corresponding author: senthil.btjeyaraj@gmail.com

ABSTRACT

The current research on *Simarouba glauca* leaf extracts could serve as an eco-friendly and sustainable stabilizing and reducing agent used for the green synthesis approach of zinc oxide nanoparticles (ZnO NPs) having promising biological properties. A novel, eco-friendly, feasible technique for the synthesis of zinc oxide nanoparticles (ZnO NPs) using the *S. glauca* aqueous leaf extract is known as green synthesis. The characterization of the nanoparticles was performed through UV-vis spectroscopy, FTIR, XRD, FESEM, DLS, TGA, and Zeta potential. UV-Vis spectroscopy confirmed the characteristic absorption peak at 280 nm. XRD analysis revealed their crystalline hexagonal wurtzite structure. The nanoparticles obtained from *S. glauca* exhibited needle-shaped morphology and a nanoparticle size of 12.934 nm. DLS results indicated good dispersion stability of the nanoparticles. The thermal stability of prepared ZnO NPs from the aqueous extract of *S. glauca*, with the total mass reduction of about 35.6 %, is due to the evaporation of volatile compounds. The biosynthesized ZnO NPs from *S. glauca* exhibited significant antibacterial activity, with a maximum zone of inhibition of 27 mm against *Bacillus* spp. and 28 mm against *E. coli.* Cell viability was reduced at higher concentrations in cytotoxicity studies using the MTT assay with *S. glauca*-mediated ZnO NPs, indicating progressive impairment of cellular metabolic activity and concentration-dependent cytotoxicity. The progressive closure of the scratch with high concentrations of *S. glauca*-mediated ZnO NPs indicated a dose-dependent effect, with optimal concentrations enhancing wound-healing efficiency without causing excessive cytotoxicity, as determined by a scratch assay. The research emphasized the usage of SDG-3 and 7 for the betterment of the society and the researchers. This study focuses on the potential applications of *S. glauca*-mediated ZnO NPs as multifunctional nanomaterials, with the biological assays highlighting the potential significance as antibacterial and antioxidant agents, for the biomedical and pharmaceutical industries.

Keywords: *Simarouba glauca*, ZnO NPs, Antimicrobial Activity, MTT Assay, Wound Healing, SDGs.
RASĀYAN*J. Chem.*, Vol. 19, No.4, 2026

INTRODUCTION

A multidisciplinary scientific domain that merges with the core concepts of nanotechnology and biotechnology to design and develop innovative materials and systems for applications in medicine, agriculture, biology, and environmental management.[1] By combining nanoscale technologies with biological systems, researchers have advanced biosensing, targeted drug delivery, tissue regeneration, and therapeutic diagnostics. The emerging transformative field of nanotechnology in biomedical applications, combined with the oxides of metals such as ZnO NPs, plays a vital role in wound healing, anticancer, and antimicrobial applications due to their multifunctional and biocompatible properties.[2] An approach to green synthesis using plant extracts offers economic and environmental advantages by eliminating toxic reagents in conventional methods and exploiting phytochemicals as stabilizing and reducing agents. *Simarouba glauca (S. glauca*) DC., also known as Paradise Tree, Lakshmi Taru, or Oil Tree, has a rich botanical and historical background spanning centuries and continents. The species *S. glauca* belongs to the kingdom *Plantae*, which includes all green plants, and is an angiosperm, a flowering plant that produces seeds enclosed within fruits. *Simaroubaceae* is a diverse family of flowering plants comprising approximately 30 genera and 150 species.[3] Members of this family are distributed across tropical and

This work is licensed under a CC BY 4.0 license.

subtropical regions, particularly in Central and South America, Africa, and Asia. The *Simaroubaceae* family is known for shrubs and medium-sized trees.[4] The plant-mediated synthesis includes minimal processing, no risk of pathogenic contamination, and rapid nanoparticle formation.[5] It enables better control over nanoparticle shape, size, and surface properties, thereby improving their functional efficiency and expanding their applicability in medicine, agriculture, environmental remediation, and catalysis.[6] Many plants have been identified for these applications but *S. glauca* has been identified with certain rare characteristics of wound healing. Nanoparticles produced through biological methods are being cost-effective, non-toxic, and environmentally sustainable, aligning with global efforts toward green chemistry.[7] To mitigate with environmental and health challenges, researchers are in analysis of metallic materials such as silver (Ag) and gold (Au), metal oxides including zinc oxide (ZnO)[8], cerium oxide (CeO_2)[9], titanium dioxide (TiO_2)[10], nickel oxide (NiO)[11], copper oxide (CuO)[12], zirconium oxide (ZrO_2)[13]. Among these, metal oxide nanoparticles attracted particular attention owing to their diverse physicochemical and biological functionalities.[14] Wound healing mediated by nanoparticles is often associated with improvements in cell adhesion, migration, and proliferation, potentially through modulation of reactive oxygen species (ROS) and growth factor expression.[15] The development of eco-friendly sustainable nanomaterials through green synthesis approach has minimized the hazardous chemicals used by enhancing the biological potential of nanomaterials. This study on *S. glauca* explored a sustainable, eco-friendly approach to the synthesis of *S. glauca*-mediated ZnO NPs using aqueous extract of leaves as a natural reduction and agent for stabilization. Also, very few studies have been carried out for evaluation of both synthesis of nanoparticles with its biological efficacy. The integration of green synthesis with characterization techniques such as UV-visible spectroscopy, XRD, FTIR, EDX, TGA, and DLS further establishes the functional properties and structural stability of the green synthesized nanoparticles. The systematic evaluation of the phytochemical contents and antibacterial efficacy thereby proves the biomedical relevance of the ZnO NPs. The anticancer activity and wound-healing efficiency demonstrate the potential of *S. glauca*-mediated ZnO NPs in biomedical applications. The sustainable development goal of the present study is for better health care, in particular by the development of certain eco-friendly antimicrobial and antioxidant materials.

EXPERIMENTAL

Collection and Extraction of Plant

Fresh, healthy *S. glauca* leaves have been collected from Kerala, India's Palakkad district. In order to get rid of contaminants, they were thoroughly cleaned using both tap and distilled water. To extract the bioactive components, 5 g of cleaned leaves were ground with the distilled water of 100 mL and boiled for roughly 30 min to separate bioactive compounds. The extracts were cooled and filtered at 4 °C for further studies.

Phytochemical Screening

Phytochemical analysis of aqueous leaf extracts detected flavonoids, alkaloids, saponins, phenols, proteins, glycosides, amino acids, tannins, and carbohydrates using standard biochemical tests.[16]

Synthesis of *S. glauca* Mediated ZnO NPs

About 5 % aqueous extracts of *S. glauca* were combined with 100 mL of sterile distilled water. The plant extract was heated in a water bath at 100 ˚C for 10 min. $ZnSO_4 \cdot 7H_2O$ of 0.1 M solution was prepared using distilled water. Equal volumes of *S. glauca* leaf extract and zinc sulfate solution were mixed and stirred continuously. The solution was adjusted to pH 9. The solution mixture was kept in a magnetic stirrer at 90 ˚C for 30 min. The brown solution obtained was centrifuged at 10,000 rpm for 10 min. The pellet was dried and the powder was stored under sterile conditions for further characterization.[17]

Characterization of ZnO NPs

The optical property of ZnO NPs was determined by UV-visible spectroscopy (Shimadzu, Kyoto, Japan) over the range of 200-800 nm. The functional groups of *S. glauca* leaf extract were analyzed, showing that it acted as both a capping and stabilizing agent. Both ZnO NPs and KBr pellets (1% w/w) were ground, and the scan was performed from 400 to 4000 cm^{-1}. The size of ZnO NPs was determined using

X-ray diffraction (X'Pert Pro Panalytical). Field-emission scanning electron microscopy (FESEM) analysis (Shimadzu miracle 10 models) conducted to examine the morphology of the ZnO NPs. Dynamic light scattering (DLS) (Horiba SZ-100) was used to measure the particle size of the nanoparticles. The thermal stability (TGA) (EXSTAR/6300) of the biologically synthesized ZnO NPs was observed from 30 to 900 °C.[18]

Antibacterial Activity

The evaluation of antibacterial activity was evaluated using the agar plates by agar well diffusion method against *Escherichia coli,* and *Bacillus spp*. Concentrations of 40 µg, 60 µg, 80 µg, and 100 µg of ZnO NPs suspension were added to the wells.[19] Amoxicillin is considered as a positive control, and incubation was carried out at 37 °C for 24 h. The zone of inhibition was measured in millimeters.

MTT ASSAY

The cytotoxicity evaluation using the MTT colorimetric assay, assesses cell metabolic activity. Fibroblast cells (L929) were kept under standard culture conditions and plated to 96 sterile well plates at a density of 1×10^6 cells per well in fresh DMEM. After allowing cells to attach, they were treated with *S. glauca* ZnO NPs at concentrations of 20, 40, 60, 80 and 100 µg/mL, and incubation was done at 37 °C for 24 h. MTT solution (5 mg/mL) after incubation, were added to each well, the plates were placed in the dark for 3 h to form crystals of formazan. The medium was removed after this period, and the crystals were dissolved with the addition of dimethyl sulfoxide (DMSO) of 100 µL per well. The plates were shaken and absorbance measured for each well at 570 nm using a microplate reader[20].The calculation of cell viability using the formula:

$$\text{Cell viability (\%)} = 100 \times (\text{Sample absorbance} / \text{Control absorbance})$$

Wound Healing-Scratch Assay

Cells were seeded into multiwell plates and allowed to grow until a confluent, uniform monolayer formed. Once the monolayer was ready, a slight scratch was made across it using a sterile micropipette tip. After creating the scratch, the monolayers were washed with Phosphate Buffer Saline (PBS) that removes detached cells, and test samples were added to the wells in increasing concentrations. Proper controls were maintained for comparison. Images of the wound area were recorded using a phase-contrast microscope, taken immediately at time 0 and 24 h.[21]

RESULTS AND DISCUSSION

Phytochemical Analysis

The preliminary phytochemical analysis of *S.glauca* leaf extract showed the presence of secondary metabolites, including alkaloids, flavonoids, phenolics, tannins, saponins, terpenoids, and glycosides. It also contains, steroids and anthraquinones were absent or detected in trace amounts. Similar results were obtained from the earlier reports of *S. glauca* leaves.[22,23] Dash *et al.* (2017) analyzed phytochemicals using methanolic leaf extracts of *Azadirachta indica*, with the presence of flavonoids, alkaloids and saponins, compared with aqueous leaf extracts of the plant.[24]

UV- vis Spectroscopy

The optical characteristics of UV peak 280 nm (200-400 nm) with its gap energy as 3.36 eV, *S. glauca* leaf extract, and the biosynthesized ZnO NPs evaluation was carried out using UV–Visible spectroscopy (Fig.- 1). UV–Visible spectrum confirms the formation of green-synthesized ZnO NPs from *S. glauca* leaf extract. The behavior on absorption in association with the transition of electrons between the conduction bands and valence bands in reflection to the optical properties of the synthesized nanoparticles.

According to Asghar *et al*. (2021)[25], the colloidal suspension of *S. glauca* mediated ZnO NPs was scanned in the ranges of wavelength of 200–800 nm, and a distinct absorption peak was observed between 360–380 nm which may be due to the specific feature of intrinsic band gap.[26]

Fourier Transform Infrared Spectroscopy (FTIR) analysis of *S. glauca*-mediated ZnO NPs

The FTIR spectrum of *S. glauca* leaf-mediated ZnO NPs exhibited characteristic absorption peaks confirming the presence of phytochemicals, along with metal-oxygen vibrations responsible for ZnO formation.

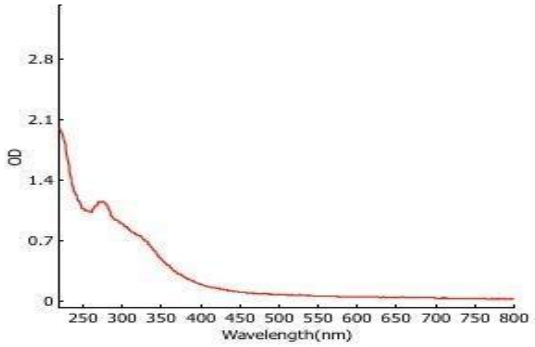


Fig.-1: UV vis spectral analysis of *S. glauca*-mediated ZnO NPs

The broad absorption band at 3341 cm^{-1}, representing O–H/N–H stretching, confirmed the presence of hydrogen-bonded alcohols, phenols, and aliphatic primary amines, which participate in capping the nanoparticles. The peaks obtained at 1569 cm^{-1} and 1370 cm^{-1} are due to nitrogenous biomolecules, namely nitro compounds, which stabilize the nanoparticles at the surface. Characteristic absorption bands at 1072 cm^{-1} correspond to the presence of metal oxides, as observed with reducing agents such as carbohydrates and polyphenols. Finally, the peaks detected at 401 cm^{-1} were attributed to C–Cl/C–Br stretching or C=C bending, suggesting the presence of metal oxides (Fig.-2). The presence of bioactive functional groups acts as a reducing and stabilizing agents during the formation of nanoparticles.

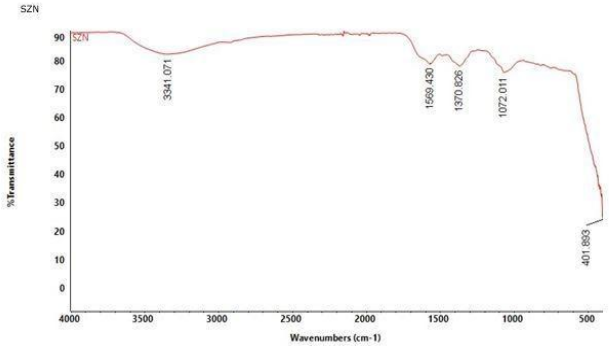


Fig.-2: FTIR analysis of *S. glauca*-mediated ZnO NPs

These prove that phytochemicals not only forms nanoparticles but improves the stability of nanoparticles. According to the studies carried out by Alamdari *et al*. (2020), on the leaf extracts of *S.glauca* in the synthesis of ZnO NPs the FTIR results revealing the presence of alkaloid, flavonoids and phenolic whereas the stretching band at 3429 cm^{-1} indicating broader peak with the presence of bonded hydrogen groups. The two peaks at 700 and 2212-2230 cm^{-1} indicated that ZnO NPs have C-H and C=C. A sharp band at 546 cm^{-1} indicated the existence of Zn-O vibrations.[27]

X-ray Diffraction (XRD)

The XRD patterns of *S. glauca* leaf-mediated ZnO NPs exhibited several intense and sharp diffraction peaks, confirming the formation of a well-crystalline nanoparticle. The particle size with JCPDS Number 96-900-4180 yields an average size of 12.934 nm (Fig.-3).

High crystallinity improves the structural stability, antibacterial performance and optical behavior of ZnO NPs. Prominent diffraction peaks were observed, showing the characteristic of hexagonal ZnO NPs and are consistent with previous reports on *Taraxacum officinale* extract-mediated ZnO NPs synthesis.[28] The peak dominant to the corresponding 36.2° peak based on the full width at half maximum (FWHM) of the crystallite size of the biosynthesised ZnO NPs of *Cymbopogon citrates* was determined to be approximately 24-35 nm.[29]

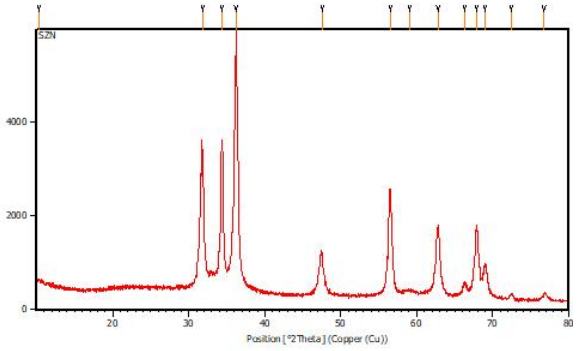


Fig.- 3: XRD analysis of *S. glauca-mediated ZnO NPs*

Field Emission Scanning Electron Microscope (FESEM)

According to Fig.-4, *S. glauca*-mediated ZnO NPs have a needle shape and a uniformly distributed, nearly isotropic nature, attributed to the anisotropic wurtzite crystal structure of ZnO.

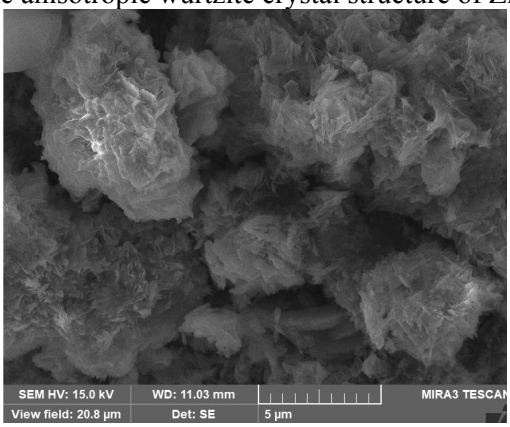


Fig.-4: FESEM analysis of *S. glauca*-mediated ZnO NPs

The observed size of the particle and its shape demonstrate the successful synthesis of ZnO NPs, indicating the controlled particle agglomeration and growth due to the phytochemicals present in *S. glauca*. According to Nandhini *et al.* (2023), FESEM micrographs revealed that the *S. glauca*-mediated ZnO NPs exhibited a spherical to quasi-spherical morphology.[6] Agglomerated spherical architectures are typical for plant-mediated ZnO NPs and have been similarly reported in previous FESEM investigations of biosynthesized ZnO NPs.[30]

Thermogravimetric Analysis (TGA)

The thermal stability of ZnO NPs mediated by the aqueous extract of *S. glauca* was assessed, and a total of 35.6 % mass reduction was observed due to evaporation of volatile compounds. The TGA curve displayed an initial weight loss for *S. glauca*-mediated ZnO NPs between 29-200 °C, corresponding to 11.6 % mass reduction. A second major weight loss was observed in the range of 200-600 °C, with a 19.2 % mass reduction, attributed to the thermal degradation of organic phytoconstituents, such as polyphenols, flavonoids, and proteins (Fig.-5).

Moisture evaporation corresponds to the weight loss occurring initially, whereas phytochemical residues are attributed to degradation with the subsequent losses. The weight loss in limited amount at increase in temperature indicates good thermal stability of ZnO NPs, which is needed for thermal resistance that includes catalytic materials and biomedical coatings. A gradual and smaller mass loss between 600–886 °C at 4.8 % mass reduction, representing the breakdown of strongly bound carbonaceous residues, indicating the final removal of organic components. According to Aldeen *et al.* (2022)[31], ZnO NPs synthesized from the leaf extract of *Phoenix roebelenii* TGA indicated a stable temperature of 500°C that required calcination in order to form stable ZnO NPs.

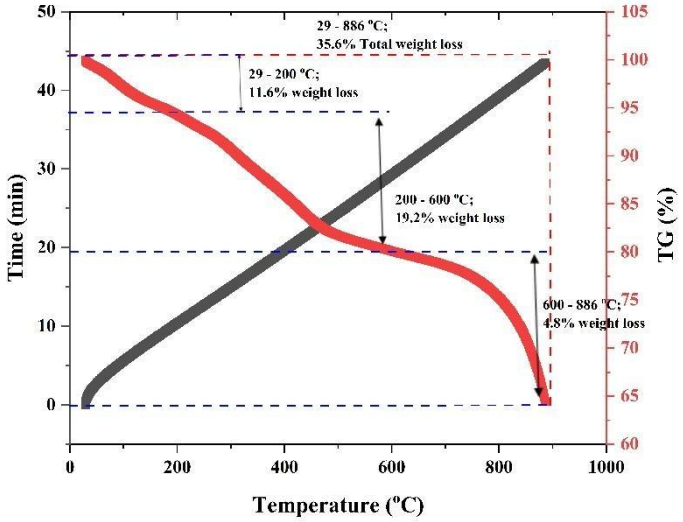


Fig.-5:TGA analysis of *S. glauca*-mediated ZnO NPs

Dynamic Light Scattering (DLS)

The average hydrodynamic diameter was measured at 840 nm from the DLS spectrum, which showed a prominent peak and a uniform size distribution for the colloidal nanoparticles (Fig.-6).

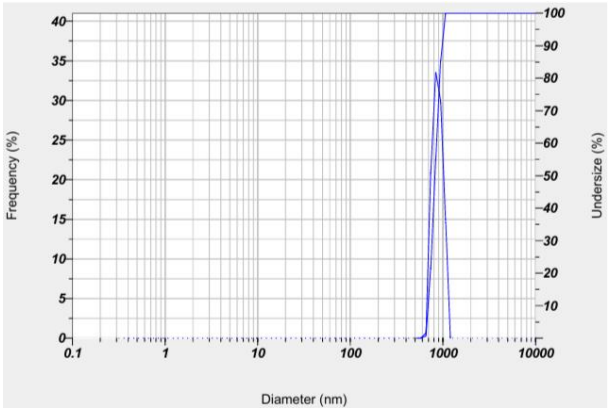


Fig.-6: DLS analysis of *S. glauca*-mediated ZnO NPs

A relatively narrow size of the particle indicates a good colloidal nanoparticle which is used in biological interactions and biomedical applications. The size distribution based on intensity confirmed that the majority of particles were within the nanorange, indicating the successful synthesis of ZnO NPs using *S. glauca* leaf extract. González *et al.* (2022)[32] evaluated the particle size of the nanoparticle as 47.2 nm as a mean hydrodynamic diameter and corresponding standard deviation as 3.2 nm in the *M. oleifera* leaf extract mediated green synthesis of ZnO NPs.

Zeta Potential

The *S. glauca* leaf-mediated ZnO NPs possessed a zeta potential with a surface charge of –11.4 mV (Fig.-7). A negative zeta potential on the nanoparticle surface indicates the presence of negatively charged functional groups indicating strong electrostatic repulsion between particles by reducing aggregation during applications and storage. According to Chandramohan *et al*. (2022)[33], synthesized ZnO NPs mediated by *Oxalis stricta* exhibited a zeta potential value of approximately –22.6 mV, indicating that the particles possess a moderately high negative surface charge. This negative charge attracts the phytochemical constituents, such as phenolics, flavonoids, and carboxyl-containing biomolecules present in the *S. glauca* extract, which coat the nanoparticle surface during biosynthesis.

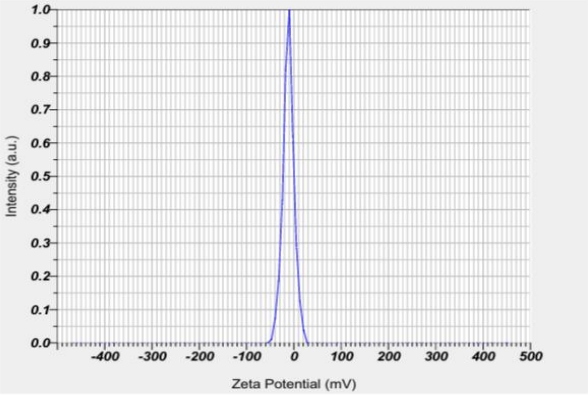


Fig.-7: Zeta potential of *S. glauca*-mediated ZnO NPs

Antibacterial Properties

The ZnO NPs exhibited antibacterial activity, evidencing clear zones of inhibition around the wells of *E. coli* and *Bacillus* spp. The diameter of the zone of inhibition increased with increasing nanoparticle concentration, indicating a dose-dependent antibacterial effect. A concentration of 100 µg/mL, the maximum zone of inhibition observed was 27 mm against *Bacillus* spp and 28 mm against *E. coli* (Table-1). The concentration-dependent increase in antibacterial activity observed in this study is consistent with earlier research on ZnO NPs synthesized using *Capparis zeylanica* leaf extracts.[34]

Table-1: Antibacterial activity of *S. glauca* -mediated ZnO NPs

Concentration (µg)	Diameter in mm	
	Bacillus spp	*E. coli*
Control	27	25
40	20	22
60	23	24
80	26	26
100	27	28

Cytotoxicity Studies

The demonstration of results from *S. glauca*-mediated ZnO NPs using the MTT assay showed a dose-dependent cytotoxic response after 24 h of exposure. The untreated control cells with 100 % viability in comparison with *S. glauca*-mediated ZnO NPs treated cells retaining the viability of 88.51 %, 76.59 %, 64.01 %, 56.92 %, and 48.25 % with concentration of 20, 40, 60, 80, and 100 µg, corresponding the 11.49 %, 23.41 %, 35.99 %, 43.08 %, and 51.75 % of cytotoxicity values. The reduction in cell viability with increasing concentration indicates that ZnO NPs progressively impair cellular metabolic activity, as evidenced by the decrease in MTT reduction. Moderate toxicity is observed at intermediate concentrations, and at 100 µg, treatment reduces viability to below 50 % (Fig.-8). The dose-dependent decline in MTT-based viability has been widely reported in treated nanoparticle cell systems, with increased nanoparticle concentration, which enhances metabolic suppression, membrane damage, mitochondrial dysfunction, and oxidative stress. The present findings reveal that *S. glauca-mediated* ZnO NPs exert significant concentration-dependent cytotoxicity. Selim *et al*. (2020) studied *Deverra tortuosa* mediated ZnO NPs from *Deverra tortuosa* with the values of IC_{50} 902.83 and 434.60 µg/mL obtained by the epithelial lung cell treatment (WI38), indicating potential anticancer activity with the investigations against cell lines causing cancer, human colon adenocarcinoma and human lung adenocarcinoma "A549" in comparison with the activities on the fibroblast cell line of human lung (WI38) using the MTT assay. ZnO NPs mediated by *Deverra tortuosa* exhibited high cytotoxicity against cancer cell lines.[35]

Wound Healing-Scratch Assay

Treatment of *S. glauca* with ZnO NPs resulted in a clear enhancement in cell migration over 24 h, suggesting a potential role in promoting cellular repair processes. Initial conditions were confirmed to be consistent at 0 h, with a uniform scratch width.

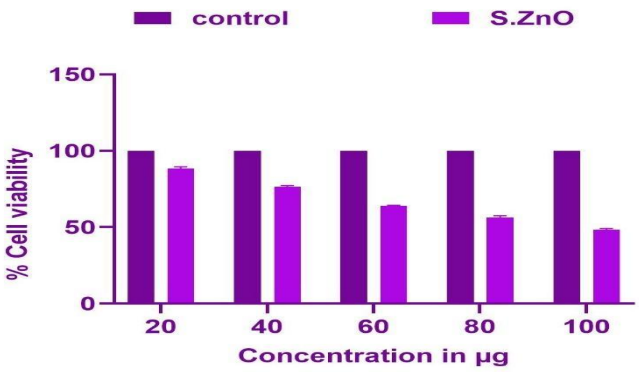


Fig.-8: Cytotoxicity of *S. glauca*-ZnO NPs

The treated groups after 24 h showed a significant reduction in wound area compared to the control, with higher concentrations of *S. glauca*-mediated ZnO NPs indicating faster scratch closure. This indicates that *S. glauca*-mediated ZnO NPs stimulate cell migration and tissue proliferation in tissue regeneration. Moalwi *et al.* (2024) reported the wound healing potential of ZnO NPs from *Wodyetia bifurcata* fruit peel extract in vivo with the scratched cell layers and incubation at different time intervals, including 0 h and 24 h showing the effective healing of skin wounds.[36]

CONCLUSION

Recent studies showed the presence of ZnO NPs mediated by the *S. glauca* aqueous extracts and discussed their physicochemical properties. The characterization studies confirmed the formation and occurrence of ZnO NPs. The functional groups identified by FTIR confirmed that the leaf extracts coagulated during the formation of ZnO NPS, resulting in the green synthesis of metal nanoparticles. The XRD patterns of *S. glauca* leaf-mediated ZnO NPs showed a particle size of 12.934 nm. *S. glauca-mediated* ZnO NPs have a needle shape, a uniform distribution, and a nearly isotropic nature, as evidenced by FESEM and EDX, which are attributed to the anisotropic wurtzite crystal structure of ZnO. The thermal stability of ZnO NPs mediated by the aqueous extract of *S. glauca* was assessed, and a total of 35.6 % mass reduction was observed due to evaporation of volatile compounds. Antibacterial activity was observed against selected strains, with increased activity against *E. coli.* The findings from the MTT assay revealed that *S. glauca*-mediated ZnO NPs exert significant concentration-dependent cytotoxicity, with further studies involving ROS generation, membrane integrity, and apoptosis markers clarifying the underlying mode of cell death. The enhanced migration of *S. glauca* mediated by ZnO NPs was associated with increased cellular metabolic activity and the activation of signaling pathways involved in cytoskeletal rearrangement and extracellular matrix remodeling. The biosynthesized *S. glauca*-mediated ZnO NPs were thus shown to be useful for wound-healing applications, providing better health care, by the development of certain environmentally friendly antimicrobial and antioxidant materials.

ACKNOWLEDGMENTS

We would like to thank PSG College of Arts & Science, Coimbatore, for providing the necessary facilities to complete the entire work.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-3:Good Health and Well-Being*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

J. Senthil Kumar https://orcid.org/0000-0002-2272-6414
M. Shanthi https://orcid.org/0000-0002-7988-2979
N. V. Sithara https://orcid.org/0009-0006-7380-4335
P. Rajiv https://orcid.org/0000-0002-5792-818X

Open Access: This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
Cite this article as: J. Senthil Kumar *et al.*, *Rasayan J. Chem.*, 19(4), 2345-2354(2026), https://doi.org/10.31788/RJC.2026.1949891

REFERENCES

1. S. M. Bhavi, A. C. Padti, B. Thokchom, S. R. Singh, M. B. Abbigeri, S. R. Kulkarni, P. Joshi, S. S. Bhat, B. P. Harini, R. B. Yarajarla, *Periodontal and Implant Research*, **9,** 2(2025), https://doi.org/10.1007/s41894-025-00145-y
2. T. Ansari, S. B. Babu, R. Jadhav, C. K. Panigrahi, P. Sharma, S. Poornima, S. Sarangi, G. G. Chaware, *Journal of Scientific Research and Reports*, **31,** 4(2025), https://doi.org/10.9734/jsrr/2025/v31i42983
3. S. Garg, L. R. Singh, *Dev Sanskriti Interdisciplinary International Journal*, **18,** (2021), https://doi.org/10.36018/dsiij.v18i.220
4. H. Veena, N. Navya, G. K. Sandesh, N. B. Thippeswamy, *Journal of Applied Pharmaceutical Science*, **9,** 5(2019), https://doi.org/10.7324/JAPS.2019.90511
5. S. Rudraswamy, G. V. Yashaswini Devi, S. H. Sheshanna, N. Doggalli, S. V. Madhunapantula, *Molecules*, **31,** 3(2026), https://doi.org/10.3390/molecules31030497
6. S. O. Aisida, N. Madubuonu, M. H. Alnasir, I. Ahmad, S. Botha, M. Maaza, F. I. Ezema, *Applied Nanoscience*, **10,** 1(2020), https://doi.org/10.1007/s13204-019-01190-9
7. M. Ramasamy, P. Karuppiah, H. Ranganathan, S. Djearaman, E. Muthukrishnan, S. Kayarohanam, N. Arumugam, A. I. Almansour, L. S. Wong, *Journal of King Saud University Science*, **36,** 11(2024), https://doi.org/10.1016/j.jksus.2024.103533
8. Q. Sun, J. Li, T. Le. *Journal of Agricultural and Food Chemistry*. **66,** 43(2018), https://doi.org/10.1021/acs.jafc.8b04031
9. K. R. Singh, V. Nayak, T. Sarkar, R. P. Singh, *RSC Advances*, **10,** 45(2020), https://doi.org/10.1039/D0RA04067H
10. A. Das, B. Nag Chowdhury, R. Saha, S. Sikdar, J. Sultana, G. Kumar Dalapati, S. Chattopadhyay, *Physica Status Solidi A Applications and Materials Science*, **216,** 2(2019), https://doi.org/10.1002/pssa.201800640
11. S. Sharma, N. M. Dhote, M. S. Wagh, *International Journal of Plant and Environment*, **11,** 2(2025), https://doi.org/10.18811/ijpen.v11i02.13
12. M. Alavi, M. Moradi, *Inorganic Chemistry Communications*, **142,** 109590(2022), https://doi.org/10.1016/j.inoche.2022.109590
13. N. P. Patel, K. V. Chauhan, *Materials Today Proceedings*, **64**, 1(2022), https://10.1016/j.matpr.2022.03.472
14. S. Ramesh, K. K. Annamalai, M. Kaari, T. G. Saravanan, R. Singaraj, A. Baskaran, S. Dharmalingam, K. Prakash Mekala Panneerselvam, S. M. Saravanan, G. Venugopal, K. Parthasarathy, *Mangrove Microbiome: Diversity and Bioprospecting*, (2025), https://10.1007/978-981-97-1234-5_15
15. N.V.Sithara and J.Senthil Kumar, *National Academy Science Letters*, (2026) https://doi.org/10.1007/s40009-026-02145-3
16. M. Ramesh, M. Anbuvannan, G. Viruthagiri, *Spectrochimica Acta Part A Molecular and Biomolecular Spectroscopy*, **136**, B(2015), https://10.1016/j.saa.2014.09.049
17. R. Periakaruppan, N. Chandrasekaran, K. TS, G. Sasthri and N. Al-Dayan, *Biomass Conversion and Biorefinery,* **15**, 22(2025), https://10.1007/s13399-024-05123-8
18. A. Jafari-Sales, P. Bolouri. *Jorjani Biomedical Journal*, **6**, 4(2018). https//:10.29252/jorjanibiomedj.6.4.78
19. J. S. Kumar, R. Raghul, N. V. Sithara, R. Periakaruppan, J. Alagusingam, *National Academy Science Letters,* **48,** (2025), https://10.1007/s40009-024-01456-2

20. I. Roy, K. T. Magesh, M. Sathyakumar, A. Sivachandran, D. Purushothaman, R. Aravindhan, *Journal of Pharmacy and Bioallied Sciences*, **15**, 1(2023), https://10.4103/jpbs.jpbs_221_22
21. R. K. Sharma, R. Bandichhor, V. Mishra, S. Sharma, S. Yadav, S. Mehta, B. Arora, P. Rana, S. Dutta, K. Solanki, *Materials Advances,* **4**, 8(2023). https://10.1039/D3MA00045A
22. A. K. Singh, H. K. Rana, T. Tshabalala, R. Kumar, A. Gupta, A. R. Ndhlala, and A. K. Pandey, *South African Journal of Botany*, **129**, 1(2020), https://10.1016/j.sajb.2019.11.021
23. S. P. Dash, S. Dixit, S. Sahoo, *Biochemistry and Analytical Biochemistry*, **6**, 323(2017), https://10.4172/2161-1009.1000323
24. M. Asghar, S. Z. Khan, F. Ahmad, M. S. Athar, *Pakistan Journal of Medical and Cardiological Review,* **5,** 1(2026), https://doi.org/10.66021/pakmcr663
25. S. Rani, N. Kumari, V. Sharma, *BioNanoScience*, **15,** 2(2025), https://doi.org/10.1007/s12668-025-01858-x
26. H. B. Boppudi, Y. S. Rao, C. Kuchi, *Results in Chemistry*, **6,** (2023), https://doi.org/10.1016/j.rechem.2023.101227
27. M. S. Sudhanva, S. M. Anush, K. S. Sharathkumar, *Washington DC: American Chemical Society*, 2025, https://doi:10.1021/bk-2025-1432.ch010.
28. K. Kasthuri, J. K. Kumar, P. Rajkumar, *Inorganic Chemistry Communications*, **170,** 3(2024), https://doi.org/10.1016/j.inoche.2024.113409
29. R. Prakash, P. Saravanan, P. Kumar, S. N. Omer, R. Rajeshkannan, *Sustainable Chemistry for One World*, **8**, Article 100144(2025), https://doi.org/10.1016/j.scowo.2025.100144
30. G. K. Prashanth, A. S. Giresha, H. S. Lalithamba, *Inorganic Chemistry Communications*, **171**, Article 113592(2025), https://doi.org/10.1016/j.inoche.2024.113592
31. R. Verma, A. Chauhan, S. Kumari, *Chemical Papers*, **77,** 9(2023), https://doi.org/10.1080/02757540.2024.2425284
32. N. A. Idris, H. M. Yusoff, N. H. Idris, *Arabian Journal for Science and Engineering*, **49,** 1(2024), https://doi.org/10.1007/s13369-023-08300-y
33. S. Faisal, H. Jan, S. A. Shah, *ACS Omega*, **6,** 14(2021)**,** https://doi.org/10.1021/acsomega.1c00310
34. K. K. Samanta, M. Kumar, H. P. Mamgain, *RSC Advances*, **15,** 42(2025), https://doi.org/10.1039/d5ra05670e
35. Y. A. Selim, M. A. Azb, I. Ragab, M. H. Abd El-Azim. *Scientific Reports*, **10,** 1(2020), https://doi.org/10.1038/s41598-020-60541-1
36. A. Moalwi, K. Kamat, U. M. Muddapur, *Frontiers in Pharmacology*, **15,** (2024), https://doi.org/10.3389/fphar.2024.1435222

[RJC-9891/2026]