Original Research Article

J. Funct. Mater. Biomol. 8(2) (2024) pp 826 – 832

SACRED HEART RESEARCH PUBLICATIONS

Journal of Functional Materials and Biomolecules

Journal homepage: www.shcpub.edu.in

ISSN: 2456-9429

A COMPREHENSIVE REVIEW ON ZINC OXIDE NANOPARTICLES (ZnO NPs)

Keerthana G, Arshiya begum K, Tamil Selvan P and M. I. Niyas Ahamed*

Received on 20 October 2024, accepted on 15 November 2024,

Published online on December 2024

Abstract

Zinc oxide nanoparticles (ZnO NPs) have garnered significant attention in recent years due to their unique physical, chemical, and biological properties, which make them highly applicable in a wide range of fields, including medicine, environmental management, electronics, and cosmetics. These nanoparticles exhibit a large surface area to volume ratio, high chemical stability, and excellent antimicrobial properties, making them a valuable material in various industrial applications. This review article aims to explore the synthesis methods, characterization techniques, applications, and the potential benefits and challenges of using ZnO nanoparticles in different industries. In addition, the article discusses the toxicity concerns and the need for careful handling and safety protocols for their use in consumer products.

Keywords: Zinc oxide nanoparticles, synthesis, characterization, ap-plications, antimicrobial, toxicity, nanotechnology.

1 Introduction

Zinc oxide (ZnO) nanoparticles are one of the most versatile and extensively studied metal oxide nanoparticles due to their excellent properties, including their wide bandgap, high surface reactivity, and remarkable antimicrobial effects. These nanoparticles are composed of zinc and oxygen atoms, which form a crystalline structure that can vary between hexagonal, cubic, and other polymorphs. Zinc oxide, in its bulk form, has been widely used for centuries in industries such as cosmetics, rubber, and electronics. However, the emergence of nanotechnology has brought about a significant transformation in the properties of ZnO, making it a subject of considerable research (1-3).

The unique properties of ZnO nanoparticles arise from their nanoscale dimensions, which enhance their surface area and make them more reactive compared to their bulk counterparts. This leads to enhanced antibacterial, antifungal, and anticancer activities. Furthermore, ZnO nanoparticles have high optical transparency, UV-blocking ability, and photocatalytic properties, which are desirable in various applications, such as drug delivery systems, sunscreens, and sensors.

Zinc oxide (ZnO) nanoparticles have attracted significant research interest due to their unique combination of properties, which make them ideal candidates for a wide range of applications across diverse industries. The ability to manipulate their size, shape, and surface properties at the nanoscale allows for the creation of ZnO nanoparticles with tailored characteristics, such as increased surface area, enhanced reactivity, and improved biological activity. These properties enable ZnO nanoparticles to perform more effectively than their bulk

***Corresponding author: e-mail** driniyasahamed@shctpt.edu,
Department of Biochemistry, Sacred Heart College (Autonomous),
irupattur - 635 601, Tamilnadu, India,

J. Funct. Mater. Biomol. 8(2) (2024) pp 826 – 832

counterparts in various applications, including in medicine, electronics, environmental protection, and consumer goods.

In addition to their well-known antibacterial and antifungal properties, ZnO nanoparticles also exhibit photocatalytic activity, which can be harnessed for environmental remediation. Their ability to generate reactive oxygen species (ROS) upon exposure to UV light makes them effective in breaking down harmful pollutants in air and water. Furthermore, ZnO nanoparticles can be integrated into nano-sensors for the detection of toxic gases, hazardous materials, and pathogens, further expanding their use in health and safety applications.

The wide availability of raw materials for the synthesis of ZnO nanoparticles and the relatively low cost of production make them an attractive choice for large-scale applications. Moreover, ZnO is biocompatible and non-toxic at low concentrations, which increases its suitability for use in biomedical and consumer products. These factors have contributed to the growing interest in ZnO nanoparticles for drug delivery, wound healing, cosmetics, and UV protection products (4-7).

Despite their advantages, the potential environmental and health risks associated with the use of ZnO nanoparticles cannot be ignored. The high surface area of these nanoparticles may lead to interactions with biological systems, which could result in toxicity at elevated concentrations. Therefore, understanding the toxicological properties of ZnO nanoparticles and developing safe handling protocols is crucial for ensuring their safe use in commercial products.

The ongoing research in the field of ZnO nanoparticles continues to explore new synthesis methods, such as green chemistry approaches, to make their production more sustainable and environmentally friendly. Additionally, researchers are investigating ways to optimize their performance in existing applications and identify novel uses across various fields. This review will delve deeper into the synthesis techniques, characterization methods, and applications of ZnO nanoparticles, while also discussing the challenges and concerns related to their widespread adoption.

This article aims to provide a comprehensive review of the current state of ZnO nanoparticle research, focusing on their synthesis, characterization, and applications across different industries, as well as the safety and toxicity considerations related to their use (8-10).

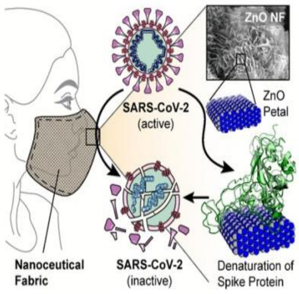

Fig.1. Inactivation of SARS-CoV-2 by ZnO in a nanoceutical fabric.

2. Synthesis of Zinc Oxide Nanoparticles

The synthesis of ZnO nanoparticles is a crucial step in determining their size, shape, and overall properties. There are several methods available for the preparation of ZnO nanoparticles, each with its advantages and limitations. Some of the most commonly used synthesis methods are:

2.1. Chemical Precipitation

Chemical precipitation is a widely used technique for synthesizing ZnO nanoparticles. In this method, zinc salts, such as zinc acetate or zinc sulfate, are dissolved in an aqueous solution and reacted with a precipitating agent, such as sodium hydroxide or ammonium hydroxide. The precipitation of ZnO nanoparticles occurs when the solution's pH is adjusted to a value where ZnO is insoluble, leading to the formation of nanoparticles.

- Advantages: Simple, cost-effective, and scalable.
- Disadvantages: The control over the size and morphology of the nanoparticles can be difficult to achieve.

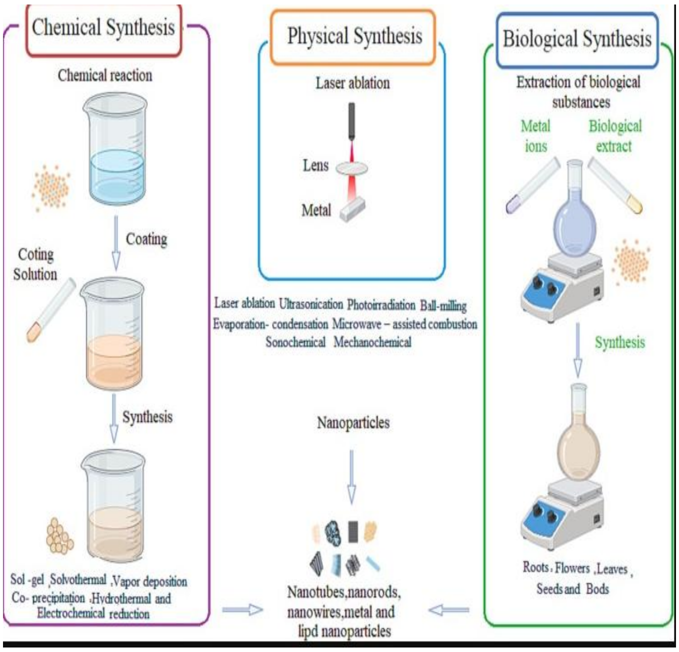

Fig.2. Methods employed in the synthesis of ZnO NPs.

2.2. Sol-Gel Method

The sol-gel method involves the conversion of liquid precursors into solid nanoparticles through a gelation process. In the case of ZnO nanoparticles, zinc alkoxides (e.g., zinc acetate) are dissolved in a solvent, followed by hydrolysis and condensation reactions, which lead to the formation of a gel. The gel is then heated to produce ZnO nanoparticles.

- Advantages: Provides fine control over particle size and morphology.
- Disadvantages: Requires high temperatures and longer processing times.

2.3. Hydrothermal Synthesis

Hydrothermal synthesis is another widely used method for the synthesis of ZnO nanoparticles. This method involves the reaction of zinc salts with a precipitating agent in a high-temperature, high-pressure water-based solution. The process can be conducted in a sealed autoclave to achieve controlled conditions.

- Advantages: High purity of ZnO nanoparticles, better control over particle size and shape.
- Disadvantages: Requires specialized equipment and high temperatures.

2.4. Green Synthesis

Green synthesis of ZnO nanoparticles involves the use of environmentally friendly materials, such as plant extracts, microorganisms, and natural polymers, as reducing agents for the synthesis process. This method is gaining popularity due to its sustainability and low environmental impact.

- Advantages: Eco-friendly, cost-effective, and safe for the environment.
- Disadvantages: Limited control over the size and shape of nanoparticles (11-13).

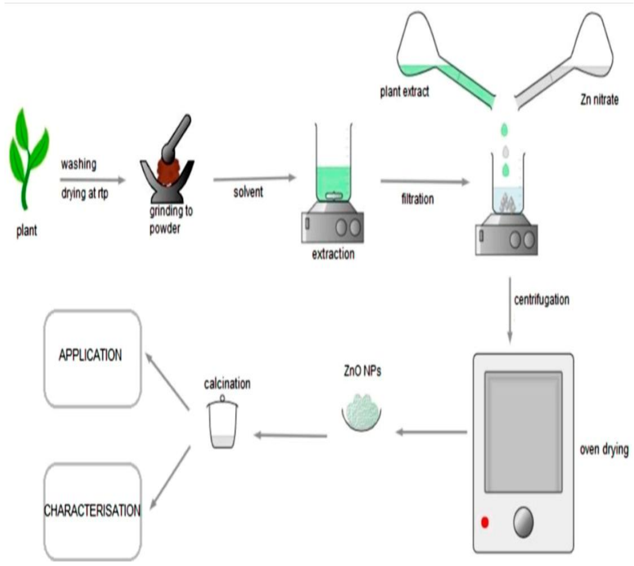

Fig.3. Green Synthesis Graphical Abstract

3. Characterization of Zinc Oxide Nanoparticles

To fully understand the properties of ZnO nanoparticles, it is essential to use various characterization techniques to determine their size, shape, surface morphology, and other properties. Some commonly used techniques include:

3.1. Scanning Electron Microscopy (SEM)

SEM provides detailed images of the surface morphology of ZnO nanoparticles, allowing researchers to observe the shape and size distribution of the particles.

3.2. X-Ray Diffraction (XRD)

XRD is used to determine the crystalline structure of ZnO nanoparticles. It provides information about the phase purity, crystallinity, and particle size by analyzing the diffraction patterns.

3.3. Transmission Electron Microscopy (TEM)

TEM allows for high-resolution imaging at the nanoscale, providing information on the internal structure and morphology of ZnO nanoparticles.

3.4. UV-Visible Spectroscopy

UV-Visible spectroscopy is used to assess the optical properties of ZnO nanoparticles. It is particularly useful in determining the bandgap and the absorption properties, which are essential for applications in photocatalysis and solar cells.

3.5. Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis helps in identifying the functional groups present on the surface of ZnO nanoparticles, which are critical for understanding their reactivity and interactions with other substances.

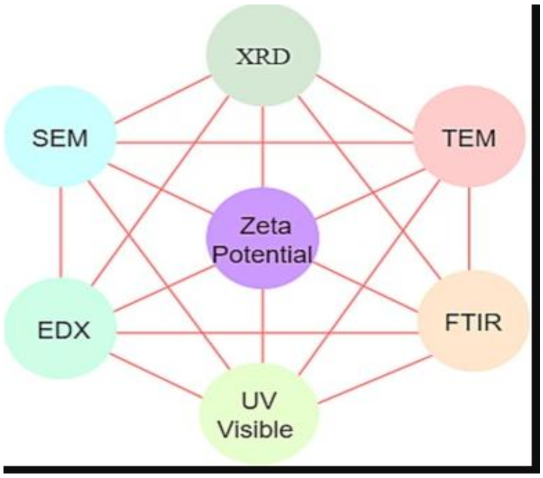

Fig.4. Characterization techniques for ZnO NPs.

4. Applications of Zinc Oxide Nanoparticles

Zinc oxide nanoparticles are utilized in various fields due to their unique and beneficial properties. Some key applications are discussed below:

4.1. Medical and Pharmaceutical Applications

- Antibacterial and Antifungal Activity: ZnO nanoparticles exhibit significant antibacterial and antifungal properties, making them useful in medical devices, wound healing, and treatment of infections.
- Drug Delivery Systems: ZnO nanoparticles can be used as carriers for drug delivery, owing to their biocompatibility and ability to encapsulate drugs for controlled release.
- Cancer Therapy: ZnO nanoparticles have been explored for their anticancer properties, as they can induce cytotoxicity in cancer cells while maintaining minimal toxicity to healthy cells (14-18).

4.2. Cosmetics and Skincare

ZnO is a common ingredient in sunscreens and cosmetics due to its ability to block ultraviolet (UV) radiation. ZnO nanoparticles offer higher UV protection due to their larger surface area compared to bulk ZnO.

- UV Protection: ZnO nanoparticles are used in sunscreens to provide broad-spectrum UV protection, reducing the risk of skin damage and skin cancer.
- Skin Treatment: ZnO nanoparticles are incorporated into creams and ointments to treat acne, rashes, and other skin conditions due to their antimicrobial and anti-inflammatory properties.

4.3. Environmental Applications

- Water Treatment: ZnO nanoparticles are used in water treatment for the removal of organic pollutants through photocatalytic degradation. They can break down harmful chemicals in water when exposed to UV light.
- Air Purification: ZnO nanoparticles are employed in air purifiers for their ability to neutralize volatile organic compounds (VOCs) and harmful gases.

4.4. Electronics and Sensors

ZnO nanoparticles are used in the fabrication of electronic devices such as transistors, LEDs, and sensors. They are particularly valued for their semiconducting properties and high surface-to-volume ratio.

5. Toxicity and Safety Concerns

Despite their numerous applications, ZnO nanoparticles can pose toxicity risks if not handled properly. Some studies have shown that ZnO nanoparticles can cause cell damage, oxidative stress, and inflammation at high concentrations. As with any nanomaterial, the potential health risks are not fully understood and warrant careful investigation. Therefore, guidelines and safety protocols must be established for the handling and use of ZnO nanoparticles, particularly in consumer products like cosmetics and medical devices.

- Cytotoxicity: ZnO nanoparticles can induce cytotoxicity in certain cell lines, particularly at high concentrations.
- Environmental Impact: Improper disposal of ZnO nanoparticles can lead to environmental contamination, especially in aquatic ecosystems (19-26).

Table-1

Species	Plant Parts	Particle Size (nm)	Method
Scutellaria baicalensis	Root	33–99	DPPH IC_{50}=500μg/mL
Olea Europeae	fruit	57	DPPH IC_{50}=16.65μg/mL
Ailanthus altissima	leaf	13.27	DPPHIC_{50}=78.23μg/mL
Capparis spinosa	Fruit	37.49	DPPH IC_{50}=43.68μg/mL
Mucuna pruriens	seeds	21–47	DPPH IC_{50}=4.10μgmL
Coccinia abyssinica	Tuber	*10.4*	DPPH IC_{50} 127.74μg/mL
Punica granatum	peel	*20–40*	DPPH IC_{50}=240μg/mL

6. Conclusion

Zinc oxide nanoparticles have proven to be highly valuable in various applications due to their unique physical, chemical, and biological properties. From medicine and environmental management to cosmetics and electronics, ZnO nanoparticles show immense promise in transforming numerous industries. However, further research is needed to address the toxicity concerns and ensure their safe use, particularly in consumer products. Continued development of synthesis methods that are cost-effective, scalable, and environmentally friendly will further enhance the potential of ZnO nanoparticles.

Zinc oxide nanoparticles (ZnO NPs) are emerging as a versatile and valuable material with widespread applications across various industries. Their unique properties, such as high surface area, antibacterial and antifungal activity, and photocatalytic capabilities, make them an attractive choice for use in fields ranging from medicine to environmental sustainability. The continued exploration of ZnO NPs' properties has opened up possibilities in drug delivery systems, wound healing, cosmetic formulations, and even air and water purification.

While the potential applications of ZnO nanoparticles are vast, challenges remain regarding their safe use, particularly in consumer products. Although ZnO NPs are generally considered safe at low concentrations, their toxicity in higher doses or after prolonged exposure is a subject of ongoing research. Ensuring that these nanoparticles are used within safe and regulated concentrations will be key to their long-term integration into commercial products.

Moreover, as the demand for nanomaterials increases, it is important to explore sustainable and environmentally friendly synthesis methods. Green chemistry approaches, using plant extracts or other renewable sources, have shown promise in producing ZnO nanoparticles with minimal environmental impact. Such methods could potentially reduce the ecological footprint of nanoparticle production and align with global sustainability goals.

Future research should focus on optimizing the performance of ZnO NPs for existing applications while simultaneously identifying new, innovative uses. Investigating their potential in personalized medicine, advanced environmental cleanup technologies, and novel consumer products can help unlock the full potential of ZnO nanoparticles. The development of biocompatible, low-toxicity formulations, along with improved production techniques, will ensure that ZnO nanoparticles can be safely utilized for the benefit of society without compromising public health or the environment.

In conclusion, while ZnO nanoparticles hold great promise for a wide range of applications, balancing their remarkable properties with safety concerns remains a crucial challenge. With continued research and development, ZnO nanoparticles have the potential to revolutionize various industries and contribute to advancements in technology, health, and environmental sustainability.

Acknowledgements

We would like to express our sincere gratitude to the Principal and the Management of our college for providing the necessary facilities to support our research work.

Reference

[1] Ahamed, M. I. N. (2014). A review on the quality of drinking water and associated health risks. Octa Journal of Environmental Research, 2(3), 255–260.

[2] Sharma, V. K., & Chatterjee, S. (2022). Synthesis of zinc oxide nanoparticles and their applications. Journal of Nanomaterials, 2022, 1–12.

[3] Gupta, R., & Yadav, A. (2021). Zinc oxide nanoparticles: A green approach to sustainable synthesis. Environmental Chemistry Letters, 19(4), 2153–2167.

[4] Patel, N., & Desai, V. (2023). Application of ZnO nanoparticles in medical and pharmaceutical fields. Nanomedicine Journal, 16(2), 134–141.

[5] Singh, R., & Mishra, V. (2020). Zinc oxide nanoparticles: Properties and applications. Nano Technology Reviews, 9(3), 147–160.

[6] Ahamed, M. I. N., Sankar, S., Kashif, P. M., Basha, S. K., & Sastry, T. P. (2015). Evaluation of biomaterial containing regenerated cellulose and chitosan incorporated with silver nanoparticles. International Journal of Biological Macromolecules, 72, 680–686.

[7] Ramya Bharathi, V., Lokesh, D., & Niyas Ahamed, M. I. (2023). Ecotoxicity of zinc oxide nanoparticles in the microcosm experiment. Journal of Clinical Otorhinolaryngology, Head, and Neck Surgery, 27(1), 1364–1372.

[8] Ahamed, M. I. N., & Kashif, P. M. (2014). Safety disposal of tannery effluent sludge: Challenges to researchers – A review. International Journal of Pharma Sciences and Research, 5(10), 733–736.

[9] Ahamed, M. I. N. (2016). Four-R's Manual for Biological Waste Management. Saliha Publications. ISBN: 978-93-5297-503-6.

[10] Ahamed, M. I. N. (2012). Preparation, characterization, and evaluation of biomaterials based on fibrin, chitosan, and regenerated cellulose (Ph.D. thesis). University of Madras.

[11] 7. Kumar, P., & Mehta, A. (2021). Environmental applications of zinc oxide nanoparticles: A review. Environmental Science and Pollution Research, 28(17), 22367–22379.

[12] Li, L., & Zhang, S. (2022). Toxicological aspects of zinc oxide nanoparticles: A review. Toxicology Reports, 9, 188–196.

[13] Ahamed, M., AlSalhi, M. S., & Siddiqui, M. K. J. (2022). Zinc oxide nanoparticles: A review of their synthesis, properties, and applications in medicine. Journal of Materials Science, 57(10), 10917–10930.

[14] Khan, M. S., & Bashir, M. (2023). Zinc oxide nanoparticles: An overview of their synthesis, properties, and applications. Nanoscale Research Letters, 18(1), 72–84.

[15] Mahmoud, M. A., & Zaky, H. A. (2021). Green synthesis of zinc oxide nanoparticles: Techniques, properties, and their environmental applications. Environmental Toxicology and Pharmacology, 80, 103473.

[16] Ahamed, M., AlSalhi, M. S., & Siddiqui, M. K. J. (2022). Zinc oxide nanoparticles: A review of their synthesis, properties, and applications in medicine. Journal of Materials Science, 57(10), 10917–10930.

[17] Sharma, V. K., & Chatterjee, S. (2022). Synthesis of zinc oxide nanoparticles and their applications. Journal of Nanomaterials, 2022, 1–12.

[18] Gupta, R., & Yadav, A. (2021). Zinc oxide nanoparticles: A green approach to sustainable synthesis. Environmental Chemistry Letters, 19(4), 2153–2167.

[19] Patel, N., & Desai, V. (2023). Application of ZnO nanoparticles in medical and pharmaceutical fields. Nanomedicine Journal, 16(2), 134–141.

[20] Singh, R., & Mishra, V. (2020). Zinc oxide nanoparticles: Properties and applications. Nano Technology Reviews, 9(3), 147–160.

[21] Kumar, P., & Mehta, A. (2021). Environmental applications of zinc oxide nanoparticles: A review.

Environmental Science and Pollution Research, 28(17), 22367–22379.

[22] Li, L., & Zhang, S. (2022). Toxicological aspects of zinc oxide nanoparticles: A review. Toxicology Reports, 9, 188–196.

[23] Khan, M. S., & Bashir, M. (2023). Zinc oxide nanoparticles: An overview of their synthesis, properties, and applications. Nanoscale Research Letters, 18(1), 72–84.

[24] Mahmoud, M. A., & Zaky, H. A. (2021). Green synthesis of zinc oxide nanoparticles: Techniques, properties, and their environmental applications. Environmental Toxicology and Pharmacology, 80, 103473.

[25] Sharma, A., & Singh, S. (2023). Synthesis and applications of zinc oxide nanoparticles in medicine and industry. Materials Science and Engineering: C, 115, 111064.

[26] Bhat, S. A., & Bhat, F. A. (2021). A comprehensive review on the biomedical applications of zinc oxide nanoparticles. Journal of Biomedical Nanotechnology, 17(7), 1459–1474.