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ZINC OXIDE NANOPARTICLES FROM VARIOUS FLORA SOURCES AND THEIR APPLICATIONS - A REVIEW

Abstract : With the advent of nanotechnology, the world now has a wider view of what is possible for humans in terms of manipulating materials at the nanoscale. In this, Zinc oxide nanoparticles and wide range of uses in environmental remediation, electronics and medicine. Different plant sources, metal precursors, characteristics (size & shape) and benefits related to the biosynthesis of ZnO NPs are examined in this paper. Additionally, possible cytotoxicity issues and future research approaches are also discussed. The review emphasizes that in order to fully utilize biogenic ZnO NPs for industrial and biomedical applications, standardized procedures and large-scale manufacturing techniques are required.

Keywords : ZnO NPs, Biogenic synthesis, Green chemistry.

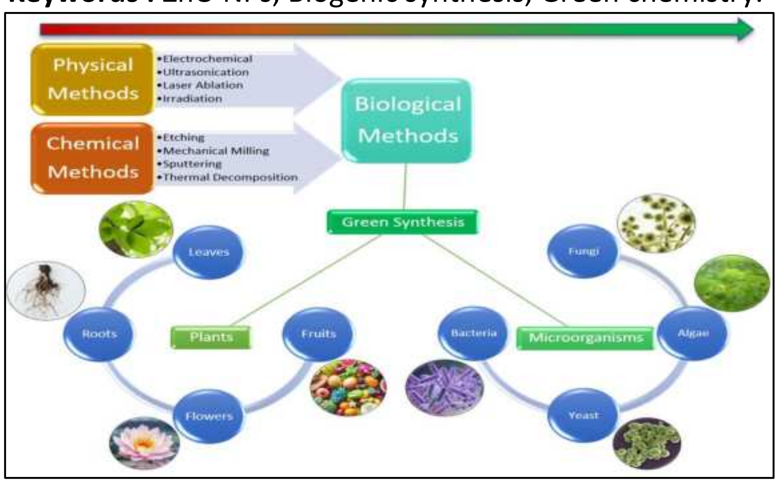

Figure 1. Different types of methods for Metal Oxide Nanoparticles synthesis.

Introduction : Nanomaterials, particularly metal oxide nanoparticles, have gained increasing attention in recent years because of their wide applications across biotechnology, medicine, and material science[1]. Traditional synthesis approaches for zinc oxide nanoparticles (ZnO NPs), such as chemical precipitation, sol–gel, and hydrothermal methods, often involve hazardous reagents, high energy requirements, and the generation of toxic byproducts. These drawbacks raise serious safety and environmental concerns and have encouraged a shift toward more sustainable alternatives.

Biogenic or green synthesis methods are now seen as promising solutions. In these approaches, plants, microbes, and other biological systems act as natural reducing and stabilizing agents. This not only improves cost-effectiveness and reduces ecological impact but also enhances biocompatibility. Moreover, the choice of biological source strongly influences the size, morphology, surface properties, and functionality of the nanoparticles, which directly affects their performance in diverse applications. Despite these advantages, challenges such as scalability, stability, reproducibility, and toxicity still need to be addressed before large-scale commercialization can be achieved[2].

Nanotechnology as a whole has reshaped modern science by enabling the design of materials with novel physicochemical properties at the nanoscale. Among metal oxides, ZnO NPs are especially important. They are considered safe, widely used in daily life, and rank third in global production volume after SiO_2 and TiO_2[3]. Their unique optical, catalytic, electrical, and antimicrobial properties make them valuable in fields ranging from electronics and food packaging to environmental remediation and biomedical research.

From Conventional to Green Synthesis of Nanoparticles : Conventional chemical and physical methods for producing zinc oxide nanoparticles (ZnO NPs) are well-established and can yield precise, uniform particles. However, these approaches often rely on hazardous chemicals, costly reagents, and high energy consumption, creating significant environmental and safety concerns [4].

Chemical synthesis methods generally provide excellent control over particle size, shape, and uniformity, ensuring high purity and reproducibility. They allow for large-scale production and can be fine-tuned through variations in temperature, pH, and reagent concentration. However, these advantages come at the cost of environmental sustainability. The use of toxic reducing and capping agents, along with organic solvents, often leads to the generation of harmful by-products and chemical waste that are difficult to dispose of safely. Furthermore, many of the stabilizers and surfactants employed in these processes may remain adsorbed on the nanoparticle surface, potentially limiting their biocompatibility and restricting their use in biomedical applications.

Similarly, physical synthesis methods such as laser ablation, thermal evaporation, and sputtering deposition offer high purity and uniformity of ZnO NPs without the use of complex chemical reagents. These methods are fast and can produce nanoparticles of controlled size with consistent physical characteristics. Nonetheless, they require sophisticated instruments and consume large amounts of energy, making them economically and environmentally less feasible for large-scale production. Additionally, the resulting nanoparticles may exhibit lower stability and limited functional versatility unless further modified chemically, which adds additional processing steps and costs.

To address these issues, green or biogenic synthesis methods have emerged as eco-friendly and sustainable alternatives. By employing plants, microbes, or other biological resources as natural reducing and stabilizing agents, these approaches minimize chemical hazards and reduce production costs. The biomolecules present in plant extracts or microbial secretions—such as proteins, phenolics, flavonoids, and enzymes—act simultaneously as reducing and capping agents, promoting nanoparticle formation under mild conditions without the need for harsh chemicals or high temperatures. This makes the process safer, energy-efficient, and more compatible with green chemistry principles.

Additionally, nanoparticles produced through green synthesis are often more biocompatible and exhibit properties that make them suitable for biomedical applications, including targeted drug delivery, antimicrobial treatments, and anticancer therapies[5]. Such nanoparticles tend to possess functional groups derived from biological molecules on their surface, which enhance their stability in physiological environments and allow easy functionalization for specific biomedical uses. This combination of safety, efficiency, and functional performance highlights the growing importance of green-synthesized nanoparticles in both research and industry.

Table 1. Comparison Methods of Nanoparticles

Method	**Advantages**	**Limitations**
Chemical Synthesis	• Controlled size and morphology of nanoparticles • High purity and uniformity of products • Scalable for industrial production • Fast reaction rate and reproducible results • Enables surface functionalization using different reagents	• Involves toxic and hazardous chemicals • Requires organic solvents and stabilizing/capping agents • Some capping agents are toxic or non-biodegradable • Generates harmful by-products causing environmental pollution • High cost of chemicals and waste disposal • May require inert atmosphere or strict conditions
Physical Synthesis	• No use of toxic chemical reagents • Produces nanoparticles of uniform size and shape • High-speed and rapid production • High purity and crystallinity • Suitable for large-scale continuous production • No need for complex chemical reduction steps	• Requires sophisticated and expensive equipment • High energy consumption (laser, evaporation, sputtering, etc.) • Limited control over particle size at nanoscale • Low stability of produced nanoparticles • May cause irreversible environmental pollution due to energy use • Not suitable for biological applications directly
Green Synthesis	• Eco-friendly and sustainable • Safe and non-toxic – uses plants, algae, fungi, or bacteria • Biocompatible and suitable for biomedical applications • Simple, cost-effective, and low energy requirement • Uses water as solvent and mild	• Difficult to control particle size, morphology, and uniformity • Reaction mechanisms are complex and not fully understood • Limited scalability and reproducibility • Relatively less stable nanoparticles • Requires optimization of biological extract composition and pH

	reaction conditions • No generation of hazardous by-products • Can integrate renewable resources	• Slower reaction time compared to chemical methods

Mechanism of Plant-Mediated ZnO-NP Synthesis : The green synthesis of ZnO-NPs using plant extracts generally involves three main steps:

a. *Preparation of Plant Extract*

- Fresh plant parts (leaves, flowers, roots, stems, or fruits) are collected, thoroughly washed, dried, and ground into fine powder.
- The powdered material is boiled or soaked (macerated) in distilled water, ethanol, or methanol to extract bioactive compounds.
- The extract is filtered and directly used as a reducing and stabilizing agent in the synthesis process.
  This approach is preferred since plant-based substrates are cost-effective, simple, and less harmful compared to microorganisms[6].

b. *Reaction with Zinc Precursor*

- A zinc precursor such as zinc nitrate [$Zn(NO_3)_2$] or zinc acetate [$Zn(CH_3COO)_2$] is dissolved in distilled water.
- The plant extract is then added dropwise to the precursor solution under constant stirring.
- Bioactive compounds present in the extract (flavonoids, phenols, alkaloids, terpenoids, tannins, and proteins) reduce Zn^{2+} ions and initiate the formation of ZnO nanoparticles.

c. *Precipitation, Calcination, and Characterization*

- The reaction mixture is heated, stirred, or sometimes sonicated to promote nanoparticle formation.
- The resulting ZnO precipitate is collected, thoroughly washed, and calcined at 300–600 °C to improve crystallinity and remove residual organic matter.

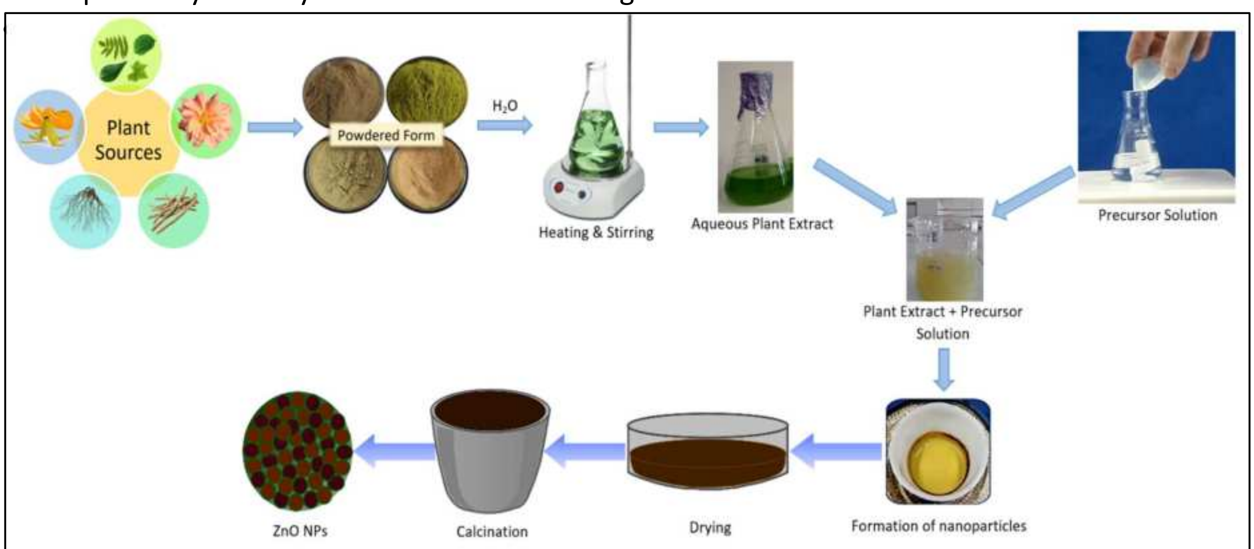

Figure 2. Flow diagram illustrating the mechanism of green synthesis of ZnO nanoparticles (ZnO NPs).

Role of Plant Extract in ZnO-NP Synthesis :

Plant extracts play a multifunctional role in nanoparticle formation:

- *Reduction of Zn^{2+} Ions:* Flavonoids, phenols, and alkaloids act as reducing agents, converting Zn^{2+} ions into ZnO.
- *Stabilization and Capping:* Proteins, tannins, and polysaccharides cap the nanoparticles, preventing aggregation and enhancing stability.
- *Control of Size and Shape:* Different plant species and their phytochemical composition influence the morphology of ZnO-NPs, which may be spherical, rod-like, or hexagonal.

Many plant sources that are used to produce ZnO NPs with their applications are compiled in Table 2.

Table 2. Summary of various plant-mediated methods used for the green synthesis of ZnO nanoparticles along with their reported applications.

S. No.	Plant Source	Bio component Extract	Precursor	Size & Shape	Application	Ref.
1	*Azadirachta indica* (Neem)	Flower extract	Zinc sulfate	30 nm to 60 nm Distorted spherical	Antibacterial, anti-biofilm; room-temperature gas sensor coatings	[7]
2	*Monoon longifolium* (Ashoka tree)	Leaf extract	Zinc nitrate hexahydrate	49.25 nm Hexagonal shape	Antimicrobial, wound healing	[8]
3	*Cissus quadrangularis*	Stem extract	Zinc acetate	88 nm to 182 nm Spherical shape	Antimicrobial, wound healing, antioxidant, agriculture	[9]
4	*Punica granatum* (Pomegranate)	Peel extract	Zinc acetate dihydrate	10 nm to 45 nm Spherical, well arranged, and crystallographic	Antimicrobial, antioxidant, anticancer	[10]
5	*Grewia flavescens*	Leaf extract	Zinc nitrate hexahydrate	20 nm to 30 nm Spherical	Antimicrobial, photocatalysis	[11]
6	*Cymbopogon citratus* (Lemongrass)	Grass extract	Zinc nitrate hexahydrate	20 nm to 24 nm Wurtzite structure	Antimicrobial, antioxidant, sunscreen, photocatalysis	[12]
7	*Corchorus olitorius*	Leaf extract	Zinc acetate dihydrate	22 nm Hexagonal wurtzite crystalline	Wound healing, agriculture, antimicrobial	[13]
8	*Plantain* (A type of banana)	Fruit Peel extract	Zinc acetate	20 nm Spherical	Food preservation, antimicrobial	[14]
9	*Musa paradisiaca* (Aanana peel)	Leaf extract	Zinc nitrate hexahydrate	20–60 nm Rod-shaped	Antibacterial; photocatalysis; antifungal.	[15]

10	*Dysphania ambrosioides*	Leaf extract	Zinc nitrate hexahydrate	7 nm to 130 nm Hexagonal prism, and quasi-spherical	Pesticidal, antimicrobial	[16]
11	*Annona muricata* (Soursop)	Leaf extract	Zinc nitrate hexahydrate	37 nm Quasi-spherical	Anticancer, antioxidant, anti-inflammatory	[17]
12	*Daphne oleoides*	Leaf extract	Zinc nitrate hexahydrate	38 nm Spherical	Photocatalysis, antimicrobial	[18]
13	*Coffea Arabica* (Coffee plant)	Leaf extract	Zinc nitrate hexahydrate	~40 nm	Photocatalysis, antimicrobial	[19]
14	*Acacia caesia*	Bark extract	Zinc nitrate hexahydrate	32.32 nm Hexagonal	Electronics, sensors	[20]
15	*Zingiber officinale* (Ginger)	Root extract	Zinc acetate dihydrate	17 nm to 40 nm Spherical	Anticancer, anti-inflammatory, antimicrobial	[21]
16	*Cratoxylum formosum*	Leaf extract	Zinc acetate	150 nm to 900 nm Spherical or sheet-like structures (depending on synthesis process and concentration of crude extract)	Photocatalysis, electronics	[22]
17	*Ailanthus altissima*	Fruit extract	Zinc nitrate hexahydrate	5 nm to 40 nm Spherical shape	Photocatalysis, heavy metal removal	[23]
18	*Matricaria chamomilla L.*	Flower extract	Zinc oxide	48.2 nm Crystalline shapes	Antioxidant, anti-inflammatory, sunscreen	[24]
19	*Cassia alata*	Leaf extract	Zinc acetate	60–80 nm Spherical shaped	Antibacterial	[25]
20	*Garcinia mangostana*	Fruit pericarp extract	Zinc nitrate hexahydrate	21 nm Spherical	Anticancer, antioxidant, cosmetic	[26]
21	*Camellia sinensis* (Green/black tea)	Leaf extract	Zinc acetate dihydrate	88 nm Spherical shape	Antibacterial; photocatalysis	[27]
22	*Lycopersicon esculentum* (Red tomatoes)	Fruit extract	Zinc nitrate	40 nm to 100 nm Spherical shape	Food preservation, antimicrobial	[28]

Applications of ZnO Nanoparticles : Green synthesized zinc oxide nanoparticles (ZnO NPs) exhibit unique physicochemical and biological properties that make them highly versatile. Their eco-friendly synthesis, improved biocompatibility, and tunable surface characteristics allow for a wide range of applications in biomedical, environmental, agricultural, and food sectors.

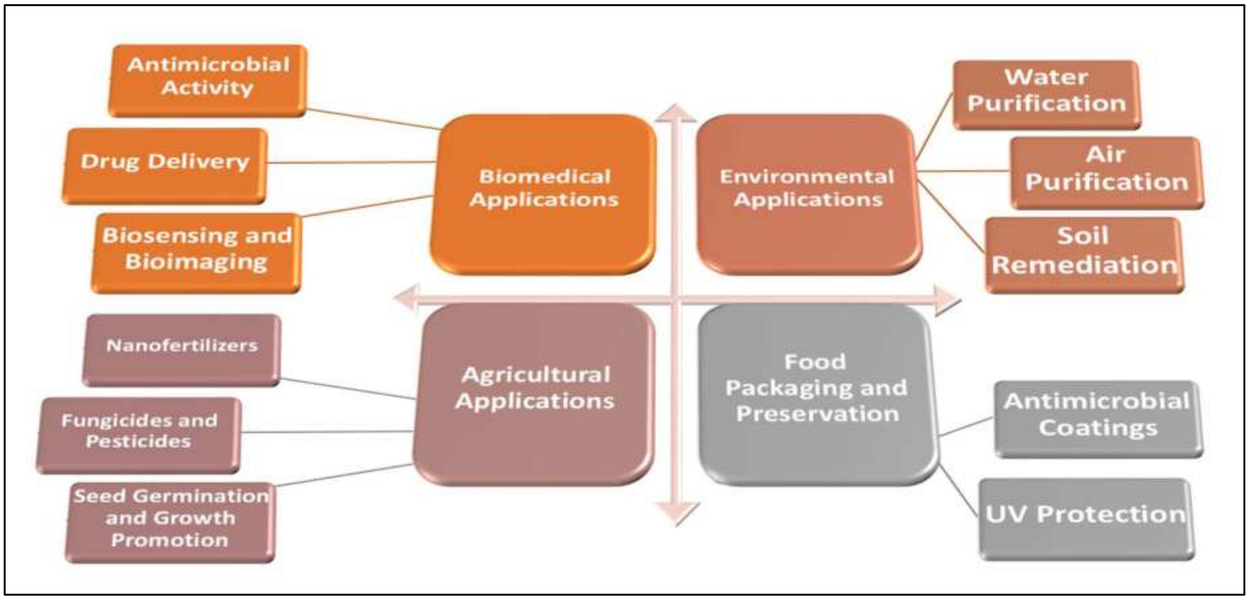

Figure 3. Overview of diverse applications of ZnO NPs in biomedical, environmental, and industrial sectors.

1. Biomedical Applications

- *Antimicrobial Activity:* ZnO NPs generate reactive oxygen species (ROS) and disrupt microbial cell membranes, showing strong antibacterial, antifungal, and antiviral activity. This makes them suitable for antimicrobial coatings, wound healing materials, and infection-resistant packaging.
- *Drug Delivery:* Due to their high surface area and stability, ZnO NPs serve as efficient carriers for controlled and targeted drug release, particularly in cancer treatment and antibacterial therapies.
- *Biosensing and Bioimaging:* Their optical and photocatalytic properties enable applications in biosensors, bioimaging, and diagnostics for detecting pathogens and biomolecules.

2. Environmental Applications

- *Water Purification:* ZnO NPs act as efficient photocatalysts, breaking down organic pollutants, dyes, and heavy metals in wastewater.
- *Air Purification:* Their photocatalytic activity helps degrade airborne pollutants, reducing environmental contamination.
- *Soil Remediation:* At controlled levels, ZnO NPs neutralize soil pollutants and can improve soil health, supporting sustainable agriculture.

3. Agricultural Applications

- *Nanofertilizers:* ZnO NPs enhance zinc availability to plants, supporting enzymatic activity, photosynthesis, and overall crop productivity.

- *Fungicides and Pesticides:* Their antimicrobial action helps in plant disease management, reducing dependency on harmful chemical pesticides.
- *Seed Germination and Growth Promotion:* ZnO NPs improve seed germination, root elongation, and plant growth, ultimately contributing to higher yields.

4. Food Packaging and Preservation

- *Antimicrobial Coatings:* Incorporation of ZnO NPs into food packaging materials prevents microbial growth, thereby extending the shelf life of perishable products.
- *UV Protection:* Their strong UV-blocking ability prevents oxidative damage, maintaining food freshness and nutritional quality.

Toxicological Effects of ZnO Nanoparticles

Zinc oxide nanoparticles (ZnO NPs) possess unique physicochemical properties that make them valuable in electronics, food packaging, pharmaceuticals, cosmetics, and other industries. However, with their increasing utilization, concerns regarding their toxicological effects on human health and the environment have gained significant attention.

Mechanisms of Toxicity

The toxicity of ZnO NPs is primarily attributed to the following mechanisms:

- *Oxidative Stress:* Excessive generation of reactive oxygen species (ROS) can damage lipids, proteins, and DNA within cells.
- *Ion Release:* Dissolution of ZnO NPs releases Zn^{2+} ions, disrupting cellular homeostasis and contributing to toxicity.
- *Inflammatory Response:* Activation of inflammatory pathways may cause cell damage and lead to chronic inflammation.
- *Cellular Uptake and Damage:* Internalization of ZnO NPs can trigger apoptosis, mitochondrial dysfunction, and lysosomal rupture.

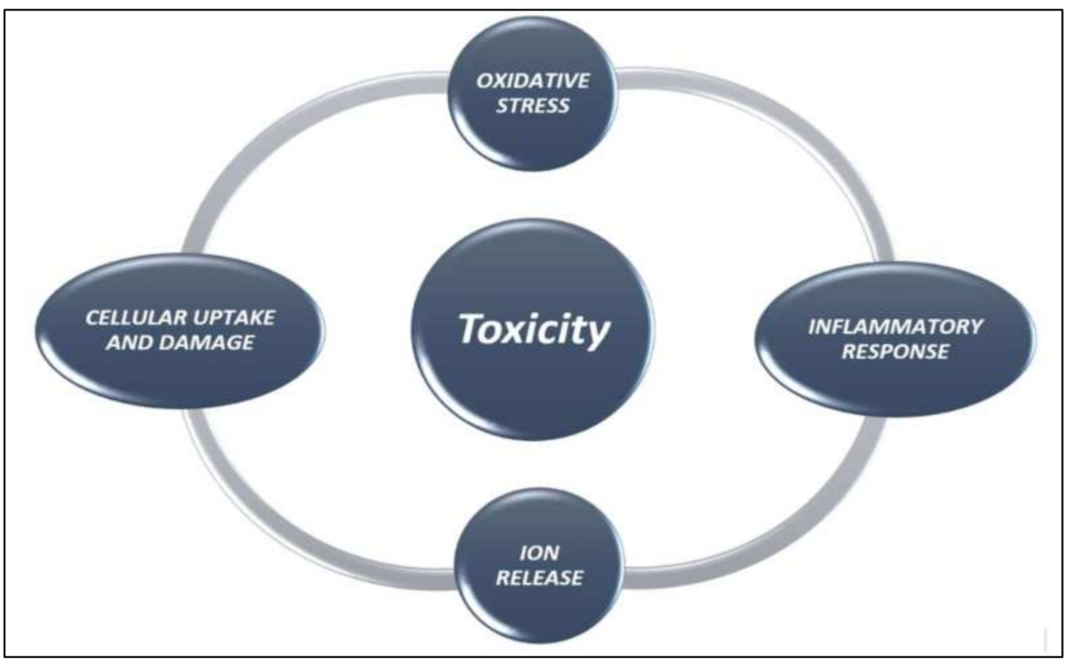

Figure 4. Mechanisms through which ZnO nanoparticles exert toxic effects.

Toxicological Effects on Humans

- *Lungs:* Inhalation may damage the epithelial lining, induce inflammation, and cause oxidative stress.
- *Liver:* ZnO NPs have been linked to histopathological changes, lipid peroxidation, and elevated enzyme activity, indicating hepatotoxicity.
- *Kidneys:* Nephrotoxicity manifests as oxidative injury and tubular damage.
- *Reproductive System:* Studies suggest hormonal imbalance and reduced sperm motility.
- *Brain:* Limited evidence points to neurotoxicity caused by oxidative stress and neuroinflammation.
- *Cell Lines Affected:* Cytotoxicity has been observed in lung epithelial cells, keratinocytes, HepG2 liver cells, and macrophages, often leading to reduced viability, DNA damage (genotoxicity), necrosis, and altered cell cycle progression.

In addition to their therapeutic properties, ZnO NPs are known to induce ROS production and apoptosis, similar to other metal oxide nanoparticles[29].

Toxicological Effects on the Environment and Ecosystem

- *Aquatic Toxicity:* ZnO NPs can adversely affect aquatic organisms such as fish, algae, and invertebrates by impairing growth, reproduction, and survival.
- *Soil Organisms:* Exposure may disrupt microbial activity and harm earthworms, thereby influencing soil fertility and ecosystem balance.

Regulation and Safe Usage

To minimize toxicity risks, several strategies have been proposed:

- *Surface Modification:* Functionalization or coating of ZnO NPs can reduce their hazardous effects.
- *Dose Management:* Using the minimal effective concentration lowers exposure risks.
- *Regulatory Oversight:* Agencies such as the U.S. Environmental Protection Agency (EPA) and European Chemicals Agency (ECHA) are actively assessing the potential risks associated with ZnO NPs.

Despite their wide-ranging applications, the toxicity of ZnO NPs varies depending on exposure route, particle size, concentration, and surface chemistry. Moreover, their stability in physiological conditions can be compromised, as biological compounds such as enzymes may alter or delay their intended activity at the target site[30]. Therefore, comprehensive toxicological and epidemiological studies are necessary to ensure the safe application of ZnO NPs in consumer and industrial products.

Challenges and Future Perspectives

Challenges in Translating ZnO Nanoparticles from Bench to Market

Zinc oxide nanoparticles (ZnO NPs) hold significant promise due to their multifunctional properties; however, several scientific, regulatory, and financial hurdles limit their successful transition from laboratory research to large-scale commercial applications. These challenges appear at every stage of the innovation pipeline, including synthesis, characterization, scale-up, and commercialization.

One of the foremost issues lies in synthesis reproducibility. The physicochemical properties of ZnO NPs—such as size, shape, and surface charge—are highly sensitive to small variations in reaction conditions. Laboratory-scale methods, while effective for research, are often not robust when scaled up for industrial production. Additionally, the absence of internationally standardized protocols for synthesis and characterization makes it difficult to compare safety and quality across different studies and industries.

From a technological standpoint, many existing synthesis routes, such as sol–gel, hydrothermal, and green synthesis, require expensive precursors, high energy input, and extended processing times. Scaling up production while preserving nanoparticle uniformity, stability, and functional properties remains a key challenge. Storage and transportation further complicate commercialization, as nanoparticles tend to agglomerate without appropriate stabilization strategies.

Safety concerns also present a critical barrier. Although ZnO NPs are generally considered less hazardous than many other metal oxide nanoparticles, uncertainties regarding their dose-dependent cytotoxicity, ROS generation, and bioaccumulation persist—especially for biomedical, cosmetic, and food-related applications. Comprehensive toxicological studies, including *in vitro*, *in vivo*, and long-term exposure assessments, are essential but are costly, time-intensive, and often produce inconsistent findings.

Interestingly, ZnO NPs also exhibit antifungal, antiviral, antiparasitic, and anti-inflammatory properties, which expand their potential use in biomedical formulations, including sunscreen lotions for UV/visible light protection and topical treatments for acne and blemishes[31].

Future Perspectives : ZnO NPs are emerging as a versatile nanomaterial with potential applications across biomedical, environmental, energy, and electronic domains. Moving forward, several strategies are expected to overcome current limitations and drive innovation:

- *Green and Biogenic Synthesis:* Environmentally friendly synthesis routes remain a top priority. Microbial, plant-mediated (phyto-synthesis), and other biological approaches are being developed to improve sustainability, reduce toxicity, and enhance biocompatibility. Bio-synthesis of metal and metal oxide nanoparticles using marine algae and marine plants is one promising but largely underexplored area[32].
- *Biomedical Applications:* ZnO NPs are being widely explored for antimicrobial treatments, targeted cancer therapy, biosensing, and drug delivery. Their ability to selectively generate ROS in cancer cells is particularly attractive for oncological applications. Surface functionalization with ligands, antibodies, or peptides enables targeted delivery and reduced off-target effects. Additionally, their intrinsic luminescence properties are being exploited for diagnostic fluorescence imaging and theranostic systems. Notably, green-synthesized ZnO NPs have also demonstrated antidiabetic potential by improving glucose regulation and acting as antioxidant agents with enhanced radical scavenging activity.
- *Smart and Stimuli-Responsive Systems:* ZnO NPs show potential in advanced applications such as self-cleaning coatings, intelligent drug release systems, and multifunctional nanocomposites. Their semiconducting and piezoelectric properties make them attractive for next-generation electronics, sensors, and energy harvesting devices.
- *Environmental Applications:* With excellent photocatalytic properties, ZnO NPs are ideal for degrading organic pollutants and removing heavy metals from water and air, supporting sustainable environmental remediation technologies.

- *Hybrid Nanomaterials and Composites:* Combining ZnO NPs with other nanomaterials (e.g., graphene, silver, TiO_2) can enhance their mechanical, optical, and photocatalytic properties, opening up new possibilities for multifunctional materials.

Finally, establishing comprehensive safety guidelines and regulatory frameworks will be critical to ensure responsible development and commercialization. Future progress will rely not only on technological innovation but also on addressing public health, environmental safety, and market acceptability.

Conclusion : Zinc oxide nanoparticles (ZnO NPs) can be synthesized economically, sustainably, and in an eco-friendly manner through biogenic routes. The use of plants, algae, fungi, and bacteria as natural reducing and stabilizing agents not only enhances the functional and biocompatible properties of ZnO NPs but also reduces the dependence on hazardous chemicals. Importantly, the synthesis method significantly influences particle size, morphology, and surface chemistry, which in turn determine their efficiency in various applications.

Biogenic ZnO NPs have demonstrated significant potential across diverse sectors. In biomedicine, they serve as antimicrobial agents, drug delivery carriers, and bioimaging tools. In environmental science, they contribute to water and air purification as well as soil remediation. In agriculture, they function as nanofertilizers and growth enhancers, while in food packaging and cosmetics, they offer antimicrobial and UV-protective properties. Their photocatalytic activity, antibacterial potential, and biocompatibility also make them attractive for applications in nanoelectronics and other advanced technologies.

Despite these advantages, certain challenges remain before their widespread commercialization. Issues such as variability in synthesis parameters, limited scalability, long-term stability, and potential cytotoxicity must be carefully addressed. Future research should focus on optimizing synthesis conditions, improving yield reproducibility, and conducting comprehensive toxicological and environmental risk assessments. Strong interdisciplinary collaborations among material science, nanotechnology, biomedical engineering, and microbiology will be essential to ensure the safe and effective utilization of biogenic ZnO NPs.

In conclusion, biogenic ZnO NPs represent a promising green nanomaterial with broad industrial and clinical potential. With further advancements in synthesis methods and safety evaluations, they could significantly transform multiple sectors while minimizing environmental impact. This efficient, low-cost, and chemical-minimized approach paves the way for the development of other environmentally sustainable nanoparticle synthesis strategies[33].

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