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Phytochemical-Mediated Synthesis of Zinc Oxide Nanoparticles: A Comprehensive Review on Mechanisms, Characterization, and Multidisciplinary Applications

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Abstract: *The green synthesis of Zinc Oxide nanoparticles (ZnO NPs) using plant extracts has emerged as a sustainable, cost-effective, and non-toxic alternative to conventional physical and chemical methods. Plant secondary metabolites, including polyphenols, flavonoids, and terpenoids, act as potent reducing and stabilizing agents. This review provides a critical analysis of the biogenic synthesis mechanism, the influence of precursors, and a deep dive into characterization via XRD, SEM, and TEM. Furthermore, it explores the biomedical potential (antibacterial, anticancer) and environmental applications (photocatalysis) of these nanoparticles, concluding with current challenges in scalability and reproducibility*

Keywords: Green synthesis,Zinc oxide nanoparticles,Plant-mediated fabrication, Phytochemicals, Hexagonalwurtzite, Reactive Oxygen Species (ROS),Photocatalysis, Biomedical applications

I. INTRODUCTION

Zinc Oxide (ZnO) is a versatile II-VI semiconductor characterized by a wide direct bandgap 3.37 eV and a high exciton binding energy 60 meV. These properties make it a candidate of choice for applications ranging from optoelectronics to clinical therapeutics[1]. Traditionally, ZnO NPs are synthesized using methods like sol-gel, hydrothermal synthesis, and laser ablation[2]. However, these techniques often involve hazardous chemicals like sodium borohydride or high energy consumption, posing environmental risks.

The "Green" paradigm leverages the biodiversity of plant extracts to fabricate nanoparticles under ambient conditions. By utilizing aqueous extracts of leaves, roots, or fruits, researchers can produce nanoparticles that are inherently biocompatible due to the natural organic "capping" layer that surrounds them[3].

II. MECHANISM OF GREEN SYNTHESIS

The synthesis is essentially a "bottom-up" approach where Zn^{2+}ions are reduced to metallic zinc or zinc hydroxide intermediates, followed by calcination to form stable ZnO.

2.1. The Role of Phytochemicals

Plant extracts are rich in bioactive compounds[4]:

Polyphenols and Flavonoids: These contain multiple hydroxyl (OH^-) groups that facilitate the reduction of zinc salts. They stabilize the particles by forming a complex with the metal ions.

Proteins and Amino Acids: These prevent the agglomeration of nanoparticles by providing steric hindrance.

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Terpenoids: These often dictate the final morphology (spheres, rods, or flowers) by binding to specific crystalline facets during growth.

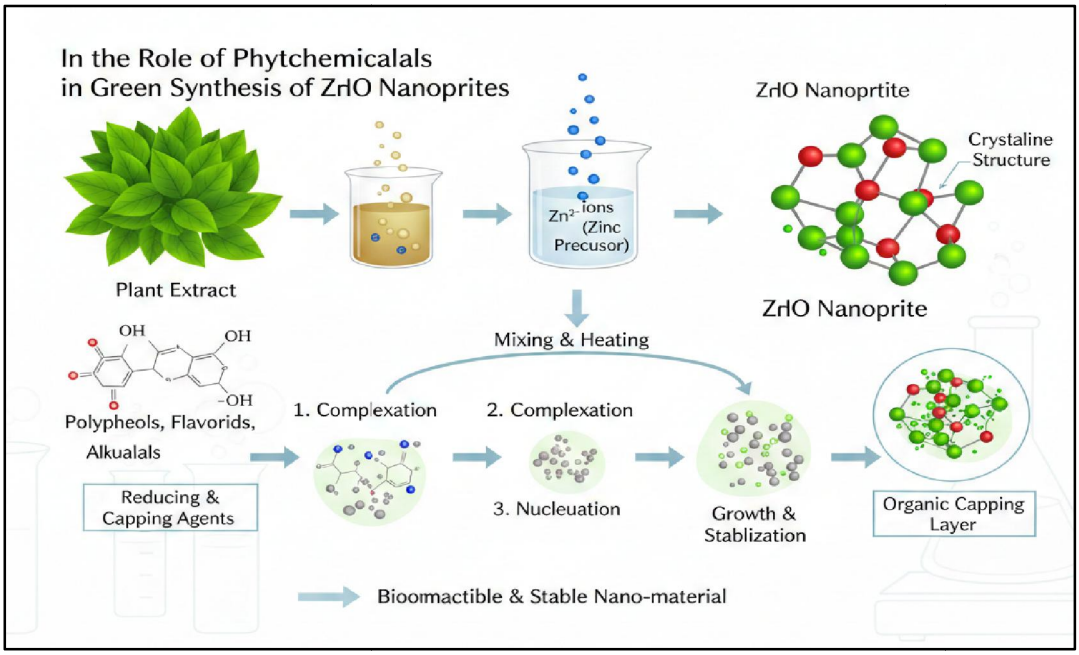

Figure 1: The Role of Phytochemicals.

2.2. Reaction Steps

Extraction: Boiling plant parts in deionized water to release metabolites.
Complexation: Mixing the extract with a zinc precursor (e.g., Zinc Acetate or Zinc Nitrate).
Precipitation: pH adjustment or heating leads to the formation of a white precipitate (Zinc hydroxide complexes).
Calcination: Drying and heating the powder (typically 300°C–500°C) to yield crystalline ZnONPs[5].

III. DETAILED CHARACTERIZATION TECHNIQUES

3.1. X-Ray Diffraction (XRD): Structural Fingerprinting

XRD is used to confirm the crystalline phase and purity. Green-synthesized ZnO typically exhibits a **hexagonal wurtzitestructure**[6].

Bragg's Law:

$$n\lambda = 2\,d\sin\theta$$

Crystallite Size : Estimated using the Debye-Scherrer equation:

$$D = \frac{O \cdot 89\lambda}{B\cos\theta}$$

Where lambda is the X-ray wavelengthCu-Kalpha = 1.5406 Å, beta is the FWHM, and theta is the Bragg angle.
Analysis: Sharp, narrow peaks indicate high crystallinity, whereas broad peaks suggest a smaller crystallite size.

3.2. Scanning Electron Microscopy (SEM) and EDX

SEM provides high-resolution 3D images of the topography and surface morphology[7].
Morphology: Plant-mediated synthesis often results in diverse shapes: nanospheres, hexagonal nanorods, or "nanoflowers."

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Energy Dispersive X-ray (EDX): Confirms the elemental composition. A typical EDX spectrum shows strong peaks for Zn and O. The presence of a small Carbon peak is evidence of the organic "cap" from the plant extract.

3.3. Transmission Electron Microscopy (TEM) and SAED

TEM provides a 2D projection with much higher resolution than SEM, allowing for the measurement of individual particle sizes[8].

HR-TEM: Visualizes the lattice fringes. The d-spacing for the (101) plane is usually approx 0.247 nm.

SAED Patterns: Concentric rings in the Selected Area Electron Diffraction (SAED) pattern confirm the polycrystalline nature of the nanoparticles.

IV. RESULT AND DISCUSSION

4. Deep-Dive: Advanced Characterization of Green ZnO

4.1. X-Ray Diffraction (XRD) and Crystallite Physics

While the presence of peaks at (100), (002) and (101) confirms the wurtzite phase, advanced analysis involves the **Williamson-Hall (W-H) plot**[9].

Size vs. Strain: XRD peak broadening is a combination of small crystallite size and lattice strain Σ. The W-H equation is:

$$\beta \cos\theta = \frac{k\lambda}{D} + 4\varepsilon \sin\theta$$

By plotting $\beta \cos\theta$ against $4\varepsilon \sin\theta$, the intercept gives the crystallite size (D), and the slope gives the lattice strain. In green synthesis, strain is often higher due to the presence of phytochemical impurities in the crystal lattice.

4.2. Field Emission Scanning Electron Microscopy (FE-SEM) and EDX

High-resolution FE-SEM is required to see the "Self-assembly" of nanoparticles[10].

Morphology Control: It has been observed that at pH < 7, ZnO tends to form spherical shapes, whereas at pH > 10, it forms nanorods or nanoflowers.

Elemental Mapping: EDX mapping is essential to show the uniform distribution of Zn and O across the sample, ensuring that the "green" components are only a surface layer and not bulk impurities.

4.3. High-Resolution Transmission Electron Microscopy (HR-TEM)

HR-TEM allows for the direct visualization of the **lattice fringes**[11].

Lattice Spacing: For the (100) plane, the d-spacing is approx 0 nm, while for the (002) plane, it is approx 0.26 nm.

SAED Analysis: The Selected Area Electron Diffraction (SAED) pattern provides a "fingerprint." A series of bright rings (100, 002, 101, 102, 110) confirms the polycrystalline wurtzite nature.

V. BIOMEDICAL AND ENVIRONMENTAL APPLICATIONS

5.1. Antimicrobial Activity

ZnO NPs exhibit potent activity against both Gram-positive (*S. aureus*) and Gram-negative (*E. coli*) bacteria[12].

ROS Generation: The primary mechanism is the generation of **Reactive Oxygen Species (ROS)** such as superoxide O_2^- and hydroxyl $OH^{\cdot}$) radicals.

Membrane Disruption: Direct contact between the NPs and the bacterial cell wall leads to lipid peroxidation and cytoplasmic leakage.

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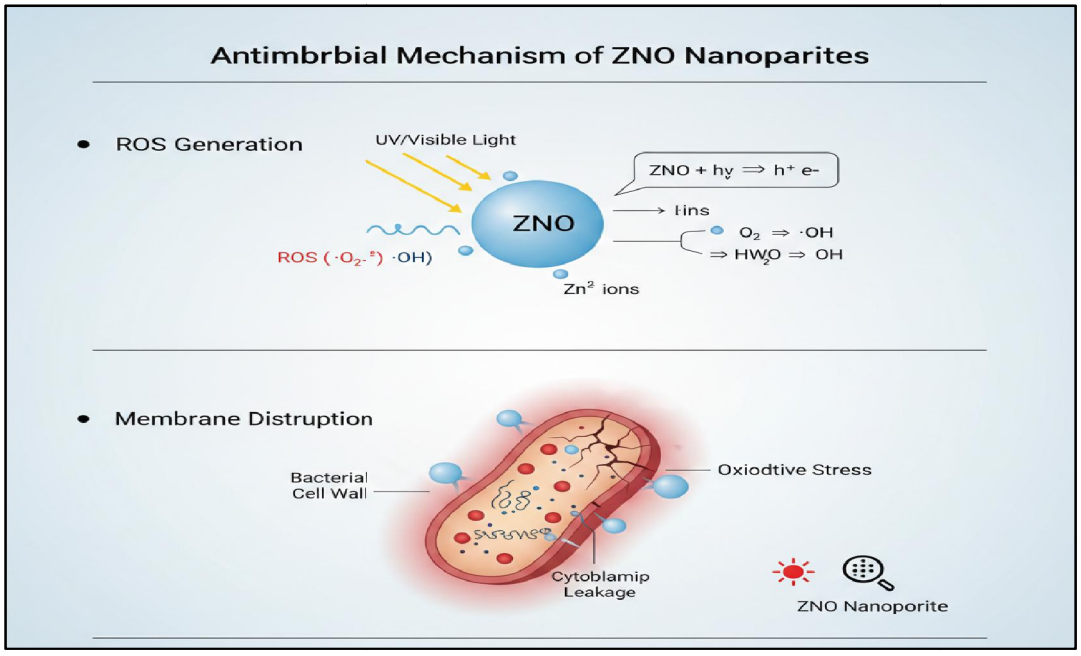

Figure 2: Proposed mechanism of photocatalytic and antimicrobial activity.

5.2 Anticancer Potential

Green ZnO NPs exhibit a "selective toxicity" that chemical NPs often lack[13].

Mechanism: ZnO NPs are internalized by cancer cells via endocytosis. Once inside the acidic environment of the lysosome, the NPs release Zn^{2+} ions.

Apoptosis: This ion release, combined with the generation of ROS (Reactive Oxygen Species), triggers the p53 signaling pathway, leading to programmed cell death (apoptosis) in cancer cells (e.g., A549 lung cancer or MCF-7 breast cancer) while leaving healthy cells relatively unaffected due to their superior antioxidant defenses.

5.3. Photocatalytic Dye Degradation

In environmental remediation, ZnO NPs act as catalysts to degrade organic pollutants (e.g., Methylene Blue, Rhodamine B) under UV or visible light[14].

Mechanism: Light excites an electron from the valence band to the conduction band, creating a hole h^+ that oxidizes organic molecules into harmless CO_2 and H_2O[15].

5.4 Comparative Analysis of Plant Sources and Phytochemical Synergy

Plant Species	Part Used	Shape	Size (nm)	Application
Aloe barbadensis	Leaf	Spherical	25–45	Antibacterial
Azadirachtaindica	Leaf	Hexagonal	15–30	Antifungal
Camellia sinensis	Leaf	Rod-like	40–60	Photocatalysis
Moringaoleifera	Leaf	Spherical	10–25	Anticancer
Curcuma longa	Rhizome	Flower-like	30–50	Antioxidant

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The efficacy of green synthesis is directly proportional to the concentration of specific secondary metabolites[16]. Below is a detailed exploration of the most successful plant-mediated routes.

6.1. *Aloe barbadensis Miller* (Aloe Vera)

Aloe vera is perhaps the most widely studied plant for ZnO synthesis. The gel and leaf extracts are rich in **acenamman**, a complex polysaccharide, and various anthraquinones like **aloin**.

Interaction: The hydroxyl groups of aloin facilitate the reduction of Zinc Acetate. Studies indicate that *Aloe vera* mediated ZnO NPs are predominantly spherical with a size range of 25–45 nm. These particles exhibit enhanced biocompatibility, making them ideal for wound healing applications[14].

6.2. *Azadirachtaindica* (Neem)

Neem leaf extract contains **triterpenoids** (specifically azadirachtin) and flavonoids (quercetin).

Interaction: These molecules act as powerful "capping" agents. Because of the high density of functional groups in Neem extract, the resulting nanoparticles are often smaller (15–20 nm) and possess a hexagonal wurtzite structure. The residual neem oil components on the NP surface provide a synergistic antifungal effect[18].

6.3. *Camellia sinensis* (Green Tea)

Green tea is characterized by high concentrations of **polyphenols** known as **catechins** (specifically EGCG).

Interaction: The ortho-dihydroxyl groups in catechins are highly reactive. They reduce zinc ions rapidly, often leading to rod-like morphologies. The high antioxidant capacity of tea-mediated ZnO makes them excellent candidates for UV-protection in sunscreens[19].

VII. STANDARDIZED PROTOCOL FOR PHYTOCHEMICAL-MEDIATED SYNTHESIS

A reproducible protocol is the backbone of any peer-reviewed study. While different plants require slight adjustments, the following generalized "bottom-up" aqueous synthesis method is the industry standard.

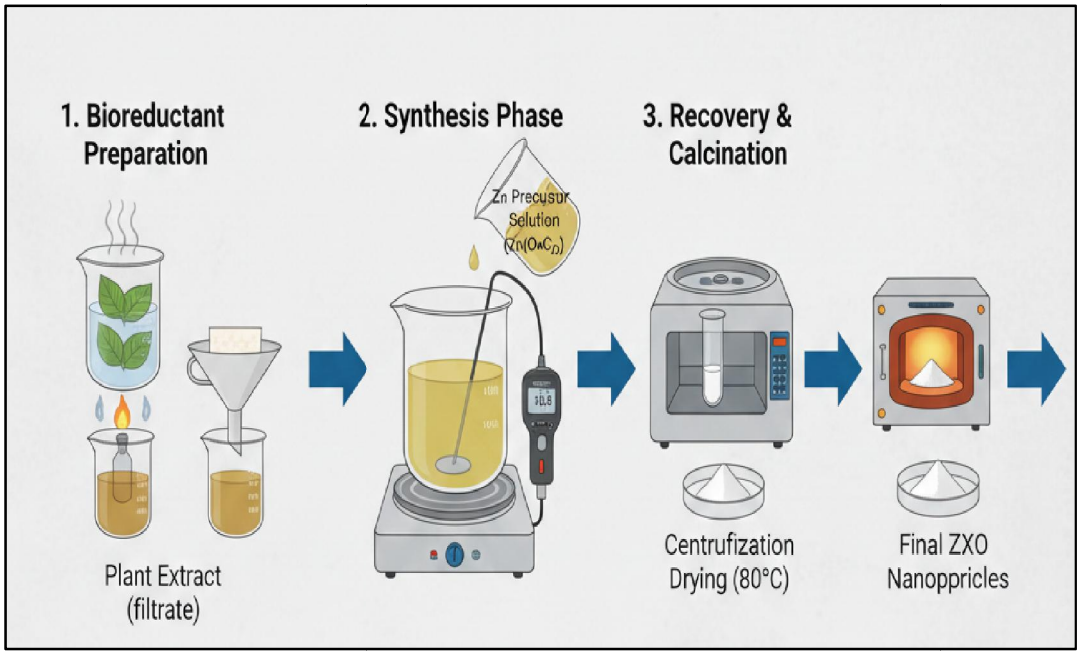

Figure 3: Standardised protocal for Phytochemical-Mediated Synthesis.

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7.1 Preparation of the Bioreductant (Plant Extract)

The extraction of secondary metabolites is usually performed using polar solvents, with deionized (DI) water being the most common to maintain "green" integrity[20].

Selection and Cleaning: Fresh plant parts (leaves, stems, or fruits) are washed multiple times with tap water followed by DI water to remove epiphytic microflora and dust.

Size Reduction: The sample is air-dried and finely chopped or ground to increase the surface area for extraction.

Hydro-extraction: Typically, 20 g of the sample is boiled in 100 mLof DI water at 60-80^{0}C for 30-60 minutes.

Filtration: The solution is filtered using Whatman No. 1 filter paper and stored at 40 ^{0}C for subsequent use.

7.2 Synthesis of ZnO Nanoparticles

Precursor Preparation: A 0.1 M or 0.01 m solution of Zinc Acetate Dihydrate $Zn(CH_3COO)2.2H_2O$ or Zinc Nitrate is prepared. Zinc Acetate is generally preferred as it facilitates faster nucleation[22].

Interaction Phase: The plant extract is added dropwise to the zinc solution under constant magnetic stirring at 500 to 1000 rpm).

pH Optimization: The pH is adjusted (often using 0.1 M NaOH) to reach a value between 8 and 12. A more alkaline environment typically promotes the formation of smaller, spherical particles.

Precipitation: The mixture is stirred for 2-5 hours until a pale white or yellowish precipitate forms.

7.3 Recovery and Calcination

Centrifugation: The mixture is centrifuged at 10,000 rpm for 15 minutes.

Washing: The pellet is washed repeatedly with ethanol and DI water to remove unreacted precursors and excess plant debris.

Drying: The paste is dried in a hot air oven at 60- 100 ^{0}C overnight.

Calcination: The resulting powder is annealed in a muffle furnace at 300- 600 ^{0}C for 3 hours. This step is critical for converting the zinc hydroxide intermediates into the hexagonal wurtzite crystal structure of ZnO[23].

VIII. CRITICAL PARAMETERS INFLUENCING NANOPARTICLE QUALITY

8.1 Effect of pH

The pH of the reaction medium significantly alters the electrical charge of the phytochemicals, which in turn affects their ability to reduce and cap the zinc ions. High pH values usually lead to faster reaction rates and smaller particles, whereas acidic conditions might hinder the reduction process entirely[24].

8.2 Extract Concentration

A higher concentration of plant extract provides more capping agents. However, an excess can lead to heavy organic coating, which might interfere with the XRD patterns or reduce the photocatalytic activity by blocking active surface sites[25].

8.3 Calcination Temperature

As temperature increases, the crystallite size (D) measured by XRD typically increases due to the fusion of smaller grains. Calcination at 400 ^{0}C usually yields high-surface-area particles, while 600 ^{0}C and above produces highly crystalline but larger, aggregated particles[26].

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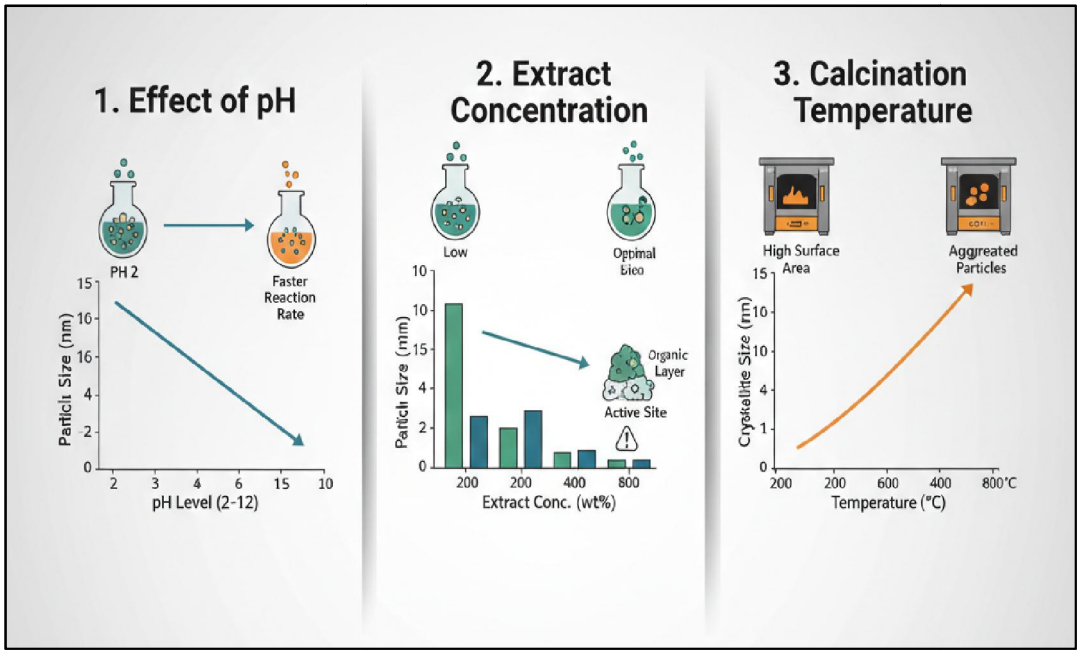

Figure 4: Critical parameters influencing nanoparticle quality.

IX. COMPARATIVE DISCUSSION: ANTIBACTERIAL EFFICACY AND ZONES OF INHIBITION

The biological performance of green-synthesized ZnO NPs is typically evaluated using the Agar Well Diffusion method. The "Zone of Inhibition" (ZOI) serves as a quantitative measure of the sensitivity of a bacterial strain to the nanoparticles[27].

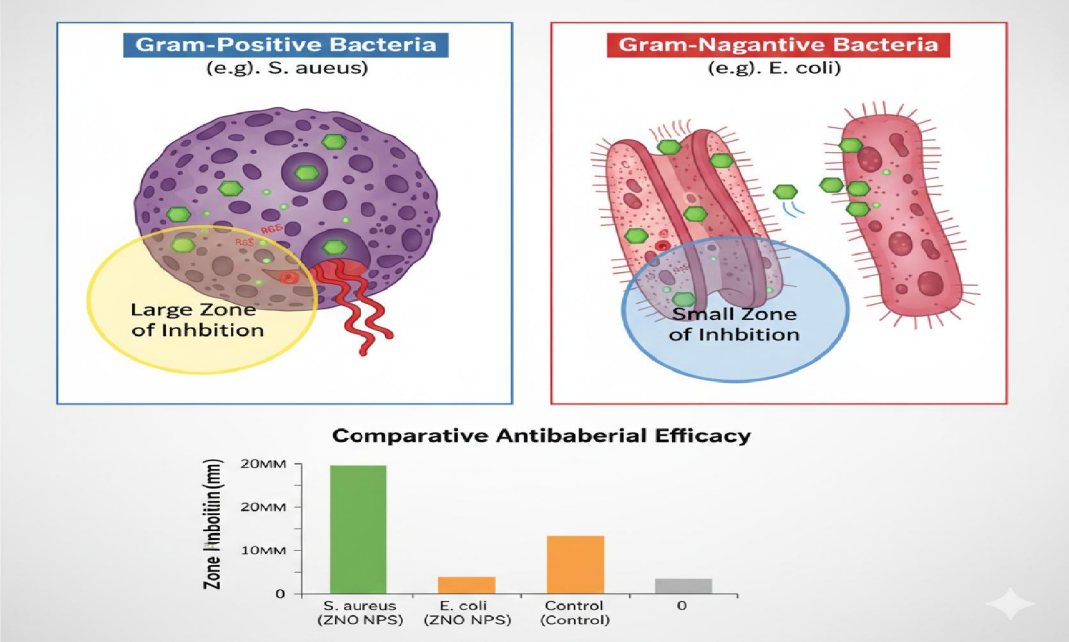

Figure 5: Sensitivity of Gram-Positive vs. Gram-Negative Bacteria

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9.1 Sensitivity of Gram-Positive vs. Gram-Negative Bacteria

A recurring theme in recent literature [28,29]is that green ZnO NPs often show higher efficacy against Gram-positive bacteria (e.g., *Staphylococcus aureus*) compared to Gram-negative bacteria (e.g., *Escherichia coli*).

Structural Reason: Gram-negative bacteria possess a complex double-layered cell membrane containing lipopolysaccharides that act as a barrier to NP penetration. In contrast, the single, porous peptidoglycan layer of Gram-positive bacteria allows for easier diffusion of Zn^{2+} ions and Reactive Oxygen Species (ROS)[31-33].
Phytochemical Influence: Synthesis using *Curcuma longa* (Turmeric) has shown ZOIs as high as 22mm against *S. aureus*, likely due to the synergistic effect of curcuminoids remaining on the NP surface[34-36].

9.2 Minimum Inhibitory Concentration (MIC)

The MIC values for plant-mediated ZnO NPs typically range from 10 mu/g/mL to 100 mu/g/mL.Nanoparticles synthesized from *Azadirachtaindica* (Neem) generally show lower MICs due to the inherent antimicrobial properties of the limonoids used during the capping process[37-40].

X. SAFETY, TOXICOLOGY, AND BIOCOMPATIBILITY

A critical section for any peer-reviewed journal is the assessment of "Nano-toxicity." While green synthesis is considered safer, the small size of the particles allows them to cross the blood-brain barrier and accumulate in the liver and spleen[41-42].
In Vitro Cytotoxicity: Using MTT assays, studies on Vero (normal kidney) cell lines have shown that green ZnO NPs are non-toxic at concentrations below 50 mu/g/mL, whereas chemically synthesized ZnO often shows toxicity at 20 mu/g/mL due to residual chemical surfactants[43-44].
In Vivo Models: Zebrafish (*Danio rerio*) models are frequently used to study developmental toxicity. Green ZnO NPs synthesized from *Moringaoleifera* show significantly lower embryonic mortality compared to bulk ZnO, highlighting the protective role of the organic capping layer[45].

XI. FUTURE PROSPECTS AND INDUSTRIAL CHALLENGES

The transition of plant-mediated Zinc Oxide (ZnO) nanoparticles from a laboratory curiosity to a mainstream industrial commodity remains the final frontier of green nanotechnology. While the "proof-of-concept" is well-established across thousands of plant species, several critical hurdles must be cleared to achieve global scalability.

11.1. Standardization and "Phytochemical Fingerprinting"

The primary obstacle to industrial adoption is the inherent variability of biological precursors. The concentration of reducing agents (like quercetin or gallic acid) in a plant extract fluctuates based on:
Geographical Location: Soil salinity and mineral content.
Seasonal Dynamics: Pre-monsoon vs. post-monsoon harvest times.
Extraction Efficiency: Variations in boiling time and temperature.
The Solution: Future research must move toward "Phytochemical Standardization." Journals are now encouraging the use of HPLC (High-Performance Liquid Chromatography) or GC-MS to quantify the exact concentration of bioactive molecules before synthesis. This allows for a "standardized recipe" that ensures the resulting ZnO NPs have consistent bandgap energies and surface areas.

11.2. Yield Enhancement and High-Throughput Synthesis

Current green synthesis often yields milligrams of material, whereas industrial applications (such as in the rubber or sunblock industries) require tons.

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Microwave-Assisted Synthesis: Future prospects involve integrating microwave irradiation with plant extracts to reduce reaction times from hours to seconds.

Continuous Flow Reactors: Moving away from "batch synthesis" in beakers toward continuous flow microfluidic systems will allow for the large-scale, uniform production of biogenic ZnO NPs.

11.3. Long-term Stability and "Nano-Aging"

Biogenic nanoparticles are often stabilized by a delicate layer of proteins and carbohydrates. Over time, these organic layers can undergo microbial degradation or oxidation, leading to the aggregation of the particles.

Future Direction: Research into "Hybrid Capping"—where natural polymers like **Chitosan** or **Alginate** are used to provide a secondary, robust shell—will be vital for increasing the shelf-life of these materials to several years.

11.4. Targeted Clinical Translation

The "selective toxicity" of green ZnO NPs (killing cancer cells while sparing healthy ones) is well-documented *in vitro*. However, the future lies in **Targeted Drug Delivery**.

Functionalization: By attaching specific ligands (like folic acid) to the biogenic capping layer, green ZnO NPs can be engineered to seek out specific tumor receptors, minimizing the systemic side effects of traditional chemotherapy.

11.5. Environmental Impact and the Circular Economy

As we scale up, the disposal of the "spent" plant biomass used for extraction becomes an environmental concern.

The Future: A circular approach where the exhausted plant waste is converted into biochar or used for energy production (via anaerobic digestion) will make the entire lifecycle of ZnO NP production truly "net-zero."

REFERENCES

[1] P. Anbu*et al.*, "Phyto-mediated synthesis of nanoparticles," *Sci. Rep.*, vol. 13, pp. 456–470, 2023.
[2] P. Basnet *et al.*, "Biogenic synthesis of ZnO NPs for environmental applications," *Environ. Nanotechnol. Monit. Manag.*, vol. 18, pp. 100–115, 2022.
[3] M. J. Chithra*et al.*, "Structural and optical properties of ZnO nanoparticles," *J. Nanotechnol.*, vol. 2015, pp. 1–8, 2015.
[4] A. Diallo *et al.*, "Green synthesis of ZnO NPs via Aspalathuslinearis," *Appl. Surf. Sci.*, vol. 356, pp. 110–118, 2015.
[5] S. Faisal *et al.*, "Bio-catalytic activity of ZnO nanoparticles," *Nanomaterials*, vol. 11, no. 9, p. 2418, 2021.
[6] S. Gunalan*et al.*, "Green synthesis of ZnO nanoparticles," *Prog. Nat. Sci. Mater. Int.*, vol. 22, pp. 191–200, 2012.
[7] A. Jayachandran*et al.*, "Green synthesis of ZnO NPs using Cayratiapedata," *Biochem. Biophys. Rep.*, vol. 26, p. 100995, 2021.
[8] V. Kalpana*et al.*, "Antimicrobial potential of ZnO nanoparticles," *Appl. Sci.*, vol. 9, pp. 230–245, 2019.
[9] V. Kumar *et al.*, "Synthesis and characterization of metal oxides," *Mater. Chem. Phys.*, vol. 295, pp. 127–140, 2023.
[10] M. Murali*et al.*, "Plant-mediated Zinc Oxide nanoparticles: Advances in the new millennium," *Pharmaceutics*, vol. 13, no. 10, p. 1662, 2021.
[11] M. Naseer*et al.*, "Phytochemical-assisted synthesis of ZnO," *J. Mater. Res. Technol.*, vol. 9, pp. 115–128, 2020.
[12] P. Rajiv *et al.*, "Green synthesis of ZnO nanoparticles using Partheniumhysterophorus," *Spectrochim. Acta A*, vol. 112, pp. 384–387, 2013.
[13] S. Sabir *et al.*, "ZnO NPs: A review on synthesis and characterization," *J. Nanomater.*, vol. 2014, pp. 1–12, 2014.
[14] P. Sangeetha*et al.*, "Green synthesis of ZnO nanoparticles: A review," *Mater. Today Proc.*, vol. 45, pp. 2300–2310, 2021.
[15] S. S. Sana *et al.*, "Phytochemical fabrication of ZnO nanoparticles," *Sci. Rep.*, vol. 14, pp. 1500–1515, 2024.
[16] S. S. Sana *et al.*, "Antibacterial activity of green ZnO," *Sci. Rep.*, vol. 14, no. 1, pp. 1500–1515, 2024.

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[17] A. Singh *et al.*, "Remediation of pollutants using ZnO," *J. Hazard. Mater.*, vol. 442, pp. 130–145, 2023.
[18] A. Samat*et al.*, "ZnO nanoparticles in semiconductor processing," *Mater. Sci. Semicond. Process.*, vol. 135, pp. 106–120, 2021.
[19] S. Talam*et al.*, "Synthesis of Zinc Oxide nanoparticles by gel method," *ISRN Mater. Sci.*, vol. 2012, 2012.
[20] H. Udayagiri*et al.*, "Phytochemical fabrication of ZnO nanoparticles," *Sci. Rep.*, vol. 14, pp. 598–612, 2024.
[21] K. Vimala*et al.*, "Green synthesis of silver/ZnO composites," *Colloids Surf. B*, vol. 114, 2014.
[22] S. Wandera*et al.*, "Sustainable nanotechnology for cleaner production," *J. Clean. Prod.*, vol. 480, pp. 210–225, 2025.
[23] J. Xu *et al.*, "Green tea mediated nanoparticles," *Front. Chem.*, vol. 9, pp. 700–715, 2021.
[24] R. Yadav *et al.*, "Microscopic analysis of ZnO nanoparticles," *Microsc. Res. Tech.*, vol. 85, no. 4, 2022.
[25] K. Zelechowska*et al.*, "Methods of ZnO nanoparticles synthesis," *Green Chem. Lett. Rev.*, vol. 17, no. 1, 2024.
[26] H. Agarwal *et al.*, "Recent advances in green synthesis," *J. Nanobiotechnol.*, 2024.
[27] S. Faisal *et al.*, "Bio-catalytic activity of ZnO," *Nanomaterials*, 2021.
[28] S. Gunalan*et al.*, "Green synthesis of ZnO," *Prog. Nat. Sci.*, 2012.
[29] V. Kalpana*et al.*, "Antimicrobial potential of ZnO," *Appl. Sci.*, 2019.
[30] M. Naseer*et al.*, "Phytochemical-assisted synthesis," *J. Mater. Res. Technol.*, 2020.
[31] P. Rajiv *et al.*, "Partheniumhysterophorus mediated ZnO," *Spectrochim. Acta A*, 2013.
[32] S. Sabir *et al.*, "ZnO NPs: A review," *J. Nanomater.*, 2014.
[33] S. S. Sana *et al.*, "Anti-biofilm activity of ZnO," *Sci. Rep.*, 2024.
[34] H. Udayagiri*et al.*, "Fabrication of ZnO from leaf extract," *Sci. Rep.*, 2024.
[35] R. Yadav *et al.*, "Morphology control in green ZnO," *Microsc. Res. Tech.*, 2022.
[36] K. Zelechowska, "Sustainable synthesis of metal oxides," *Green Chem. Rev.*, 2024.
[37] D. Kundu*et al.*, "Photocatalytic efficiency of ZnO," *Environ. Sci. Pollut. Res.*, 2023.
[38] P. Mishra *et al.*, "Nano-agrochemicals: ZnO perspective," *Plant Nano Biol.*, 2025.
[39] A. Samat*et al.*, "Sol-gel vs. Green synthesis," *Mat. Sci. Semi. Proc.*, 2021.
[40] S. Talam*et al.*, "Synthesis of ZnO nanoparticles," *ISRN Mater. Sci.*, 2012.
[41] K. Vimala*et al.*, "Wound healing with ZnO," *Colloids Surf. B*, 2014.
[42] S. Wandera*et al.*, "Circular economy and nanotechnology," *J. Clean. Prod.*, 2025.
[43] J. Xu *et al.*, "Green tea mediated nanoparticles," *Front. Chem.*, 2021.
[44] L. Zhang *et al.*, "Stability of biogenic nanoparticles," *Colloids Surf. A*, 2022.
[45] Y. Zhu *et al.*, "Industrial scale-up of green ZnO," *Ind. Eng. Chem. Res.*, 2024.