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Eco-Friendly Approaches in the Synthesis of ZnO Nanoparticles using Plant Extract: A Review

Misbah Gul, Muhammad Kashif *, Kashif Shahid , Natasha

Department of Chemistry, Abdul Wali
Khan University Mardan, 23200, Pakistan

Correspondence
Muhammad Kashif
Email:mkashifsgr1@gmail.com

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Abstract

The synthesis of zinc oxide (ZnO) nanoparticles has garnered significant interest due to their extensive applications in various fields such as electronics, photonics, and biomedicine. Traditional synthesis methods, however, often involve toxic chemicals and harsh conditions that pose environmental and health risks. This review paper focuses on eco-friendly approaches to the synthesis of ZnO nanoparticles, emphasizing green chemistry principles. It explores the use of biological resources, including plant extracts, microorganisms, and biomolecules, as sustainable alternatives to conventional chemical methods. These green synthesis techniques not only reduce the reliance on hazardous substances but also offer advantages such as cost-effectiveness, biocompatibility, and the potential for large-scale production. The review highlights recent advancements, discusses the underlying mechanisms of green synthesis, and evaluates the physicochemical properties and applications of the resulting ZnO nanoparticles. By providing a comprehensive overview of eco-friendly synthesis strategies, this paper aims to underscore the importance of sustainable practices in nanotechnology and inspire further research in the development of safe and environmentally benign nanomaterials.

KEYWORDS

ZnO nanoparticles, Green Synthesis, Plant Mediated Synthesis

1.0 INTRODUCTION

Zinc oxide (ZnO) nanoparticles have emerged as a cornerstone in the field of nanotechnology due to their remarkable physicochemical properties and diverse applications across various industries [1]. These nanoparticles exhibit unique characteristics, including high surface area, tunable morphology, and exceptional optical, electronic, and antimicrobial properties [2]. Consequently, ZnO nanoparticles are extensively used in sectors such as electronics, optoelectronics, sensors[3], catalysts[4], and biomedical applications, including drug delivery, imaging, and antimicrobial treatment [5]. However, the traditional synthesis methods of ZnO nanoparticles, such as chemical vapor deposition, sol-gel processes, hydrothermal synthesis, and precipitation techniques, often involve the use of toxic chemicals, high temperatures, and energy-intensive procedures [6]. These methods pose significant environmental and health risks due to the generation of hazardous by-products, high energy consumption, and the use of non-renewable resources. The growing awareness of these issues has catalyzed a shift towards more sustainable and environmentally friendly synthesis methods [7].

Green synthesis, which adheres to the principles of green chemistry, offers a promising alternative to conventional methods[8]. Green chemistry emphasizes the reduction or elimination of hazardous substances in the design, manufacture, and application of chemical products. This approach seeks to utilize environmentally benign solvents, renewable resources, and energy-efficient processes, thereby minimizing the ecological footprint and enhancing the sustainability of nanoparticle synthesis[9]. One of the most innovative and effective strategies in green synthesis involves the use of biological entities as reducing and stabilizing agents[10]. Biological resources such as plant extracts, microorganisms, algae, and biopolymers are rich in natural compounds like proteins, polysaccharides, alkaloids, and flavonoids, which can facilitate the reduction of metal ions to nanoparticles [11-13]. These biological agents not only eliminate the need for toxic reagents but also operate under mild, ambient conditions, reducing energy consumption and enhancing the overall safety of the synthesis process[14]. Plant extracts, in particular, have shown great potential in the green synthesis of ZnO nanoparticles[15]. They are easily accessible, cost-effective, and contain a plethora of bioactive compounds that can act as natural reducing and capping agents[16]. Various parts of plants, including leaves, stems, roots, and flowers, have been utilized to synthesize ZnO nanoparticles with diverse morphologies and enhanced functional properties[17]. Similarly, microorganisms such as bacteria, fungi, and yeast have been employed in the biosynthesis of ZnO nanoparticles[18]. These microorganisms can secrete enzymes and other bioactive molecules that facilitate the reduction of metal ions, leading to the formation of nanoparticles [19]. In addition to plant extracts and microorganisms, biopolymers such as chitosan, starch, and cellulose have been explored for the green synthesis of ZnO nanoparticles[20]. These biopolymers offer the advantages of biocompatibility, biodegradability, and the ability to form stable and well-dispersed nanoparticles[21]. The use of biopolymers also provides additional functionalities to the nanoparticles, making them suitable for specific applications such as drug delivery and tissue engineering[22].

This review aims to provide a comprehensive overview of the eco-friendly approaches employed in the synthesis of ZnO nanoparticles. It will delve into the various biological resources utilized, elucidate the underlying mechanisms of nanoparticle formation, and highlight the advantages of green synthesis methods over conventional techniques. The review will also discuss the physicochemical properties, stability, and functional performance of ZnO nanoparticles synthesized through green methods, emphasizing their potential applications in various fields.

By collating and analyzing recent advancements in this burgeoning field, this paper seeks to underscore the significance of green synthesis as a viable and responsible alternative for nanoparticle production. It aims to inspire further research and development in the pursuit of safe, sustainable, and environmentally friendly nanomaterials. The adoption of green synthesis methods in the production of ZnO nanoparticles not only aligns with the global drive towards sustainability but also paves the way for the development of innovative and eco-friendly technologies that can address the pressing challenges of our time.

2.0 GREEN SYNTHESIS OF ZnO NPs

Green synthesis of ZnO nanoparticles using biological resources represents a sustainable and eco-friendly approach to nanoparticle production. This method leverages natural materials such as plant extracts, bacteria, fungi, and algae to act as reducing and stabilizing agents. The use of biological resources not only reduces the need for harmful chemicals but also enhances the biocompatibility and stability of the nanoparticles. This innovative approach is gaining attention for its potential applications in various fields, including medicine, environmental remediation, and materials science, due to its minimal environmental impact and cost-effectiveness.

2.1 Plant Extracts

Plant extracts have emerged as a highly effective and eco-friendly medium for the synthesis of ZnO nanoparticles[23]. These extracts contain a variety of bioactive compounds, such as alkaloids, flavonoids, tannins, and phenolics, which act as natural reducing and stabilizing agents[24]. The use of plant extracts not only simplifies the synthesis process but also eliminates the need for hazardous chemicals, making it a sustainable alternative to traditional methods[25]. Moreover, nanoparticles synthesized using plant extracts exhibit enhanced biocompatibility and stability, making them suitable for a wide range of applications, including biomedical, environmental, and industrial sectors[26]. The diversity of plant species and their unique phytochemical compositions offer a rich source for the tailored synthesis of ZnO nanoparticles with specific properties and functionalities[27].

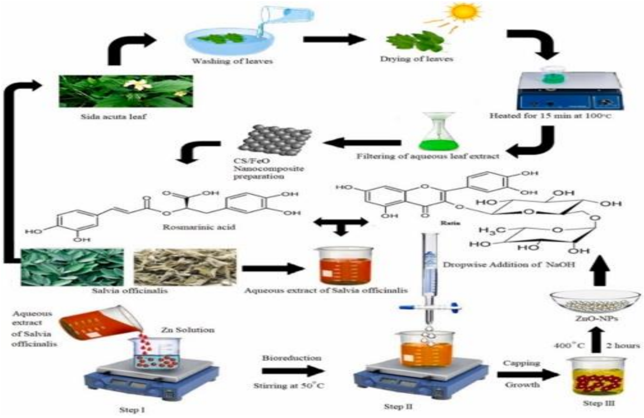

Figure 1. Shows the green synthesis of zinc oxide nanoparticles from Sida acuta leaf extract for antibacterial and antioxidant applications, and catalytic degradation of dye using a convolutional neural network[28]. Plants mediated green synthesis of ZnONPs, detailing the species, key reagents, nanoparticles morphology and size, and their various applications. Table 1 summarize the green synthesis of NPs using various plant extract and their applications

2.1.1 *Types of Plant Extracts Used*

Various types of plant extracts have been utilized in the green synthesis of ZnO nanoparticles, each offering distinct advantages based on their unique phytochemical profiles:

a).Leaf Extracts: Leaves from plants such as Aloe vera, Moringa oleifera, and Eucalyptus have been widely used due to their high content of antioxidants and polyphenols, which facilitate efficient reduction and stabilization of ZnO nanoparticles[29].

b).Fruit Extracts: Fruits like lemon, orange, and grape are rich in citric acid, flavonoids, and ascorbic acid, making their extracts excellent reducing agents for nanoparticle synthesis. These extracts often lead to nanoparticles with enhanced antibacterial and antioxidant properties[30].

c).Flower Extracts: Flowers such as Hibiscus rosa-sinensis and Bougainvillea are utilized for their diverse bioactive compounds, including flavonoids and anthocyanins, which aid in the formation and stabilization of ZnO nanoparticles[31].

d).Bark Extracts: The bark of trees like Cinnamon and Neem contains tannins and other phenolic compounds that effectively reduce zinc ions and stabilize the resulting nanoparticles, offering potential applications in antimicrobial and therapeutic fields[32].

e).Root Extracts: Roots of plants such as ginger and turmeric are known for their high concentrations of bioactive compounds like curcumin and gingerol, which contribute to the synthesis of ZnO nanoparticles with potent biological activities[33].

f).Seed Extracts: Seeds from plants like fenugreek and flaxseed are rich in proteins and essential oils that act as capping agents, promoting the formation of stable and uniform ZnO nanoparticles[34].

2.1.2 *Mechanisms of ZnO Nanoparticle Formation*

The synthesis of ZnO nanoparticles using plant extracts involves several key mechanisms facilitated by the bioactive compounds present in the extracts. Understanding these mechanisms is crucial for optimizing the synthesis process and tailoring the properties of the nanoparticles for specific applications.

i. **Reduction of Zinc Ions:** Plant extracts contain a variety of reducing agents, such as flavonoids, polyphenols, and alkaloids. These compounds reduce zinc ions (Zn^{2+}) to zinc atoms (Zn^0) through electron transfer reactions. For example, phenolic compounds donate electrons to zinc ions, leading to their reduction[35].

ii. **Nucleation:** Once zinc atoms are formed, they aggregate to form small clusters, initiating the nucleation process. The initial formation of these clusters is critical, as it determines the size and shape of the resulting nanoparticles. The high concentration of bioactive compounds in plant extracts provides a conducive environment for nucleation[36].

iii. **Growth of Nanoparticles:** Following nucleation, the growth phase involves the addition of more zinc atoms to the existing nuclei. The bioactive compounds in plant extracts play a dual role by stabilizing the growing nanoparticles and preventing excessive aggregation, which ensures the formation of well-defined nanoparticles.

iv. **Capping and Stabilization:** Plant extracts contain natural capping agents, such as proteins, polysaccharides, and organic acids, which adsorb onto the surface of the nanoparticles. These capping agents stabilize the nanoparticles by preventing agglomeration and controlling their size and morphology. For instance, proteins can form a protective layer around the nanoparticles, enhancing their stability in solution[8].

v. **Shape and Size Control:** The specific phytochemicals present in different plant extracts influence the shape and size of the ZnO nanoparticles. Factors such as the concentration of plant extract, pH, temperature, and reaction time can be adjusted to control the morphology of the nanoparticles. For example, certain flavonoids may promote the formation of spherical nanoparticles, while others might lead to rod-shaped or flower-like structures[37].

vi. **Formation of ZnO Crystalline Structure:** The final step in the synthesis process is the formation of the crystalline ZnO structure. This is typically achieved through annealing or calcination, where the nanoparticles are heated to a specific temperature to enhance crystallinity and remove any organic residues from the plant extracts[38].

2.1.3 *Advantages and Limitations of Using Plant Extracts in the Synthesis of ZnO Nanoparticles*

Some of the advantages and Disadvantages of ZnO nanoparticles are given below:

Advantages:

i. **Eco-Friendly Process:** Using plant extracts eliminates the need for toxic chemicals and solvents, reducing environmental pollution and health hazards. This green synthesis approach aligns with sustainable development goals and promotes cleaner production methods[39].

ii. **Cost-Effective:** Plant materials are often inexpensive and readily available, making the synthesis process more economical compared to conventional chemical methods that require costly reagents and sophisticated equipment[40].

iii. **Biocompatibility:** Nanoparticles synthesized using plant extracts tend to have higher biocompatibility due to the natural capping agents derived from the extracts. This makes them suitable for biomedical applications, such as drug delivery, imaging, and therapeutic agents[41].

iv. **Diverse Phytochemicals:** The wide range of bioactive compounds present in different plant extracts allows for the synthesis of ZnO nanoparticles with varied shapes, sizes, and properties. This diversity provides opportunities for tailoring nanoparticles for specific applications[42].

v. **Simplified Process:** The synthesis process using plant extracts is often straightforward, requiring fewer steps and less stringent conditions (e.g., lower temperatures and ambient pressure) compared to traditional chemical methods[43].

vi. **Enhanced Stability:** Natural capping agents from plant extracts can enhance the stability of ZnO nanoparticles, preventing aggregation and prolonging their shelf life[44].

Limitations:

i. **Variability in Plant Extracts:** The composition of plant extracts can vary significantly depending on factors such as plant species, growth conditions, and extraction methods. This variability can lead to inconsistencies in the properties of the synthesized nanoparticles[45].

ii. **Scalability Issues:** While plant extract-mediated synthesis is effective at the laboratory scale, scaling up the process for industrial production can be challenging. Maintaining uniformity and consistency in large-scale batches can be difficult[46].

iii. **Purity Concerns:** Plant extracts may contain impurities or other organic compounds that can interfere with the synthesis process or remain on the surface of the nanoparticles, affecting their performance in certain applications[47].

iv. **Characterization Challenges:** The presence of complex phytochemicals in plant extracts can complicate the characterization and analysis of the synthesized nanoparticles. Advanced techniques are often required to understand the exact role of each bioactive compound in the synthesis process[48].

v. **Limited Control over Particle Size and Shape:** Although plant extracts can influence the size and shape of ZnO nanoparticles, achieving precise control over these parameters can be more challenging compared to conventional chemical synthesis methods that allow for fine-tuning of reaction conditions[49].

vi. **Reproducibility Issues:** Due to the natural variability of plant materials, reproducibility can be a significant concern. Consistently obtaining nanoparticles with the same properties across different batches may require careful standardization of extraction and synthesis protocols[50].

2.1.4 *Microorganisms in the Green Synthesis of ZnO Nanoparticles*

Microorganisms such as bacteria, fungi, and algae have gained significant attention in the green synthesis of ZnO nanoparticles due to their inherent biological processes and ability to mediate nanoparticle formation. These organisms offer a sustainable and environmentally friendly alternative to traditional chemical synthesis methods[51].

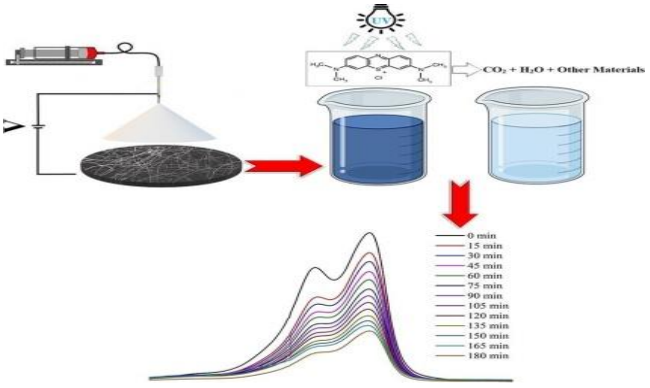

Figure 2. Illustrates the supercritical CO_2 directional-assisted green synthesis of ZnO nanoparticles obtained from *Euphorbia stricta* L. for functional applications[52].

Types of Microorganisms Used:

I. Bacteria: Various bacterial species, including *Bacillus subtilis*, *Escherichia coli*, and *Pseudomonas aeruginosa*, have been utilized for ZnO nanoparticle synthesis. Bacteria secrete enzymes and metabolites that can reduce metal ions to nanoparticles and stabilize them[53].

II. Fungi: Fungi such as *Aspergillus niger*, *Fusarium oxysporum*, and *Penicillium sp.* are effective in synthesizing ZnO nanoparticles due to their ability to produce large amounts of extracellular enzymes. Fungi-mediated synthesis often results in nanoparticles with unique morphologies and enhanced stability.

III. Algae: Algal species, including *Chlorella vulgaris* and *Sargassum muticum*, are used for their rich content of polysaccharides, proteins, and other bioactive compounds that facilitate nanoparticle synthesis. Algae offer the additional advantage of being photosynthetic, which can be harnessed for sustainable production. Table 2 summarize Fungal, Algal and Microbial-mediated green synthesis of ZnONPs, detailing the species, key reagents, nanoparticles morphology and size, and their various applications.

Advantages:

I. Eco-Friendly Process: The use of microorganisms avoids harmful chemicals and reduces environmental impact, making the synthesis process safer and more sustainable.

II. **Biocompatibility:** Nanoparticles synthesized by microorganisms are often capped with biocompatible molecules, making them suitable for biomedical applications.

III. Cost-Effective: Microbial synthesis is generally cost-effective, as it utilizes inexpensive and readily available biological resources.

IV. Scalability: Microorganisms can be easily cultured and scaled up for large-scale production of ZnO nanoparticles[54].

Limitations:

I. Complexity of Culture Conditions: Maintaining optimal conditions for microbial growth and nanoparticle synthesis can be complex and may require precise control over factors such as pH, temperature, and nutrient supply[55].

II. Variability in Nanoparticle Properties: The properties of the synthesized nanoparticles can vary depending on the microorganism and culture conditions, leading to challenges in achieving consistent results.

III. Purification Challenges: The presence of residual biological materials in the nanoparticle suspension can complicate purification processes and may affect the final application of the nanoparticles.

IV. Reproducibility Issues: Ensuring reproducibility across different batches can be challenging due to the natural variability in microbial cultures and their metabolic activities.

2.1.5 *Mechanisms of Green Synthesis in ZnO Nanoparticles*

Role of Biomolecules in Reduction and Stabilization

Green synthesis of ZnO nanoparticles harnesses biomolecules from various natural sources, including plants, fungi, bacteria, and algae. These biomolecules—proteins, polysaccharides, vitamins, and phenolic compounds—serve as reducing and stabilizing agents due to their unique chemical structures[56].

I. Reduction Process

Plant Extracts: Phytochemicals like flavonoids, alkaloids, and terpenoids found in plant extracts play a pivotal role in reducing zinc ions (Zn^{2+}) to zinc oxide (ZnO). For instance, the hydroxyl and carboxyl groups in these compounds donate electrons, facilitating the reduction process.

Microbial Synthesis: In bacteria and fungi, enzymes and other metabolites act as reducing agents. For example, bacteria secrete enzymes that can interact with metal ions, leading to their reduction.

II. Stabilization Process

Capping Agents: Once the zinc ions are reduced to ZnO, biomolecules act as capping agents, stabilizing the nanoparticles. This prevents aggregation and controls particle growth. For instance, proteins can form a protective layer around the nanoparticles, ensuring uniform size distribution[57].

Understanding the Formation Pathways

The synthesis of ZnO nanoparticles via green methods involves several distinct stages:

1. Nucleation:

Initial Formation: Zinc ions in the solution are reduced to form small ZnO clusters. This stage is crucial as it determines the number and size of nanoparticles that will be formed.

II. Growth:

Controlled Expansion: These clusters grow into larger nanoparticles. The biomolecules present in the solution play a significant role in directing this growth. They attach to the surface of the nanoparticles, guiding their shape and size. For example, polysaccharides from plant extracts can promote the formation of rod-shaped nanoparticles.

III. Maturation:

Final Stabilization: In this stage, the nanoparticles achieve their stable form. The capping biomolecules ensure that the nanoparticles do not aggregate, thus maintaining their shape and size. For example, aloe vera extract, rich in polysaccharides and glycoproteins, can direct the formation of specific nanoparticle morphologies, such as spheres or rods.

Factors Influencing Nanoparticle Size and Morphology

The size and morphology of ZnO nanoparticles synthesized via green methods are influenced by several factors:

Type of Biomolecule:

Diverse Influences: Different biomolecules have varying abilities to reduce and stabilize nanoparticles. Proteins typically produce larger nanoparticles due to their bulk and structure, whereas smaller molecules like phenolics tend to result in smaller particles.

Concentration of Biomolecules:

Stabilization and Size: Higher concentrations of biomolecules enhance stabilization but can also lead to larger particle sizes due to increased aggregation.

pH of the Solution:

Charge Interactions: The pH affects the charge on both biomolecules and zinc ions, impacting the reduction process and the final nanoparticle size. Optimal pH levels, often neutral or slightly alkaline, facilitate the formation of uniformly sized nanoparticles.

Reaction Time and Temperature:

Growth Conditions: Longer reaction times and higher temperatures generally lead to larger particles. However, green synthesis methods are advantageous as they often proceed efficiently at room temperature, making them more environmentally friendly and cost-effective.

Applications and Future Directions

Green synthesis of ZnO nanoparticles holds significant promise for various applications due to its eco-friendly nature. These nanoparticles are used in:

Photocatalysis:

Environmental Cleanup: ZnO nanoparticles are effective in degrading organic pollutants under UV light, making them useful for water purification and air cleaning.

Sensors:

Sensitive Detection: Their high surface area and reactivity make ZnO nanoparticles ideal for use in gas sensors and biosensors.

Drug Delivery:

Targeted Therapy: ZnO nanoparticles can be functionalized with drugs for targeted delivery in cancer therapy, reducing side effects and improving efficacy.

2.1.6 *Advantages of Green Synthesis Over Conventional Methods*

Reduced Toxicity

Chemical Reagents: Conventional synthesis often uses hazardous chemicals like metal salts, strong acids, or bases. In contrast, green synthesis employs non-toxic, eco-friendly reagents, such as plant extracts, biopolymers, or natural compounds.

By-products: Green methods usually generate fewer toxic by-products, which simplifies waste management and reduces environmental harm.

Energy Efficiency

Process Conditions: Traditional methods often require high temperatures or pressures, consuming significant energy. Green synthesis can occur under ambient conditions or milder conditions, thus reducing energy requirements.

Reaction Time: Some green synthesis methods can be more time-efficient, further contributing to energy savings.

Waste Reduction

Minimal Waste: Green synthesis typically produces fewer waste products or uses waste materials in the synthesis process, contributing to a reduction in overall waste.

Resource Efficiency: Techniques like using natural plant materials often integrate multiple stages of synthesis or recycling, reducing the overall resource consumption[58].

Environmental and Health Benefits

Lower Environmental Impact

Pollution Reduction: By avoiding hazardous chemicals and reducing waste, green synthesis minimizes environmental pollution.

Sustainable Materials: Utilizing renewable resources (e.g., plant extracts, agricultural by-products) ensures that the materials used are sustainable and have a lower environmental footprint.

Reduced Health Risks

Worker Safety: Using non-toxic reagents and safer processes reduces the risk of exposure to harmful substances for workers in laboratories and industrial settings[58].

Community Impact: Reduced emissions and less hazardous waste contribute to better air and water quality for surrounding communities.

Sustainable Practices

Renewable Resources: Emphasize the use of biodegradable or renewable resources, such as natural polymers or extracts, which are more sustainable compared to synthetic chemicals.

Circular Economy: Some green methods incorporate principles of circular economy, such as recycling waste products or using by-products from other processes.

Cost-Effectiveness and Scalability

Economic Viability

Reagent Costs: Green synthesis often utilizes inexpensive and readily available natural materials instead of costly synthetic reagents.

Operational Costs: Lower energy requirements and reduced need for complex equipment can result in lower operational costs[59].

Scalability

Laboratory to Industrial Scale: Discuss whether the green synthesis methods are easily scalable. Some methods that work well in the lab might be challenging to scale up due to process complexity or material availability.

Manufacturing Feasibility: Evaluate if the methods can be integrated into existing industrial processes or if they require significant modifications.

Raw Material Costs

Availability and Cost: Consider the availability and cost of raw materials used in green synthesis. For example, using agricultural waste as a raw material might be cost-effective but requires a reliable supply chain.

Biocompatibility and Biomedical Applications

Safe for Biological Systems

Toxicity Testing: Review studies on the biocompatibility of green-synthesized ZnO nanoparticles, including their interaction with cells and tissues. Green methods might result in nanoparticles with fewer toxic effects.

Regulatory Compliance: Green-synthesized nanoparticles might more easily meet regulatory standards for safety in biomedical applications.

Biomedical Uses

Drug Delivery: Explore how green-synthesized ZnO nanoparticles can be used as carriers for targeted drug delivery, improving the efficacy and reducing side effects.

Imaging and Diagnostics: Discuss their role in imaging techniques, such as fluorescence or MRI, and their potential for enhancing diagnostic capabilities[60].

Antimicrobial Agents: Green-synthesized ZnO nanoparticles are often evaluated for their antimicrobial properties, making them useful in coatings, wound dressings, and other medical devices.

Toxicity Assessments

Comparative Studies: Review comparative studies that analyze the toxicity of green-synthesized versus conventionally synthesized nanoparticles in medical applications.

Long-Term Effects: Consider the long-term effects and stability of these nanoparticles in biological systems, ensuring their safety for prolonged use.

2.1.6.A *Biomedical Applications of Green-Synthesized ZnO Nanoparticles*

Antimicrobial Activity

Generation of Reactive Oxygen Species (ROS): ZnO nanoparticles can generate ROS, such as hydroxyl radicals and superoxide anions, which damage microbial cell membranes, proteins, and DNA, leading to cell death.

Surface Interaction: The high surface area-to-volume ratio of nanoparticles allows for better interaction with microbial cell walls and membranes, enhancing their antimicrobial effectiveness.

Release of Zinc Ions: ZnO nanoparticles can release Zn^{2+} ions, which interfere with microbial enzyme systems and metabolic processes, contributing to their antimicrobial action.

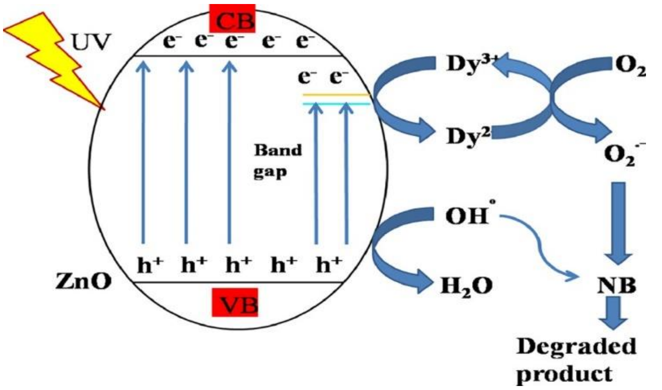

Figure 3. Demonstrates the Photocatalytic and antimicrobial studies of green synthesized Dy^{3+}doped ZnO nanoparticles prepared from *Rhododendron arboreum* petal extract [61].

Applications:

Wound Dressings: ZnO nanoparticles are incorporated into wound dressings to prevent infections and promote healing. Their antimicrobial properties help reduce the risk of bacterial contamination in wounds[62].

Coatings: ZnO nanoparticles are used to coat surfaces and textiles to provide antimicrobial properties. This is beneficial for medical devices, hospital furnishings, and protective clothing[63].

Water Purification: Green-synthesized ZnO nanoparticles are employed in water treatment systems to eliminate pathogenic microorganisms, improving water quality.

Advantages:

Eco-Friendly: Green synthesis methods often use natural substances that are less toxic and environmentally benign compared to conventional methods[64].

Enhanced Efficacy: The nanoparticles synthesized through green methods may exhibit improved antimicrobial activity due to their unique size and shape characteristics.

Drug Delivery Systems

Mechanism of Action:

Targeted Delivery: ZnO nanoparticles can be engineered to deliver drugs specifically to target cells or tissues, reducing side effects and enhancing therapeutic efficacy. This is achieved through surface modifications or conjugation with targeting ligands.

Controlled Release: ZnO nanoparticles can be designed to release drugs in a controlled manner, ensuring a sustained release over time. This can be particularly useful for chronic conditions requiring long-term treatment.

Applications:

Cancer Therapy: ZnO nanoparticles are used to deliver anticancer drugs directly to tumor cells, minimizing damage to healthy cells and enhancing the drug's effectiveness. They can also be functionalized to target specific cancer markers.

Antibiotic Delivery: These nanoparticles can deliver antibiotics directly to infection sites, increasing the concentration of the drug where it's needed most and reducing systemic side effects.

Gene Delivery: ZnO nanoparticles have potential for delivering genetic material (e.g., DNA, RNA) into cells for gene therapy applications, offering a non-viral method for genetic modification.

Advantages:

Biocompatibility: Green-synthesized ZnO nanoparticles are often more biocompatible and less toxic, which is crucial for safe drug delivery.

Versatility: The ability to modify the surface of ZnO nanoparticles allows for a wide range of applications in drug delivery systems[65].

Bioimaging

Mechanism of Action:

Fluorescence Imaging: ZnO nanoparticles can be engineered to emit fluorescence upon excitation, allowing for imaging of biological tissues and cells. Their size and surface properties can be tailored to enhance imaging contrast.

X-ray Imaging: ZnO nanoparticles have high atomic numbers, making them suitable for enhancing contrast in X-ray imaging. This helps in visualizing tissues and detecting abnormalities with higher clarity.

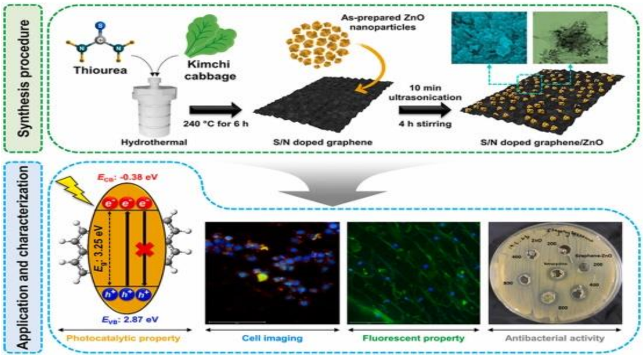

Figure 4. Explains Green approach for the fabrication of dual-functional S/N doped graphene tagged ZnO nanograins for *in vitro* bioimaging and water pollutant remediation[66].

Applications:

Cell Imaging: ZnO nanoparticles are used to label and track cells in vivo or in vitro, providing insights into cellular processes and interactions. They can be used in studying cell dynamics, migration, and localization.

Tumor Imaging: In cancer research, ZnO nanoparticles are utilized to enhance the imaging of tumors, allowing for better detection and monitoring of cancer progression and treatment efficacy.

Diagnostic Imaging: These nanoparticles can improve the sensitivity and specificity of diagnostic imaging techniques, providing more accurate and detailed images for medical diagnosis.

Advantages:

High Resolution: ZnO nanoparticles offer high resolution and contrast in imaging, aiding in the detection of subtle changes at the cellular and molecular levels.

Versatility in Imaging Techniques: Their ability to be used in various imaging modalities (e.g., fluorescence, X-ray) makes them versatile tools for different types of biomedical imaging.

Photocatalysis for Water Treatment

Mechanism: ZnO nanoparticles act as photocatalysts under UV light, generating reactive oxygen species (ROS) that break down organic pollutants, dyes, and other contaminants in water. The nanoparticles enhance the degradation of hazardous substances and contribute to cleaner water.

Applications: Used in wastewater treatment plants, water purification systems, and for cleaning contaminated water sources.

Benefits: Effective in degrading a wide range of pollutants, can be used in both small-scale and large-scale water treatment systems, and offers an environmentally friendly approach to addressing water pollution.

E. Sensing and Detection

Mechanism: ZnO nanoparticles are employed in sensors due to their high surface area and sensitivity to various gases and chemical species. They exhibit changes in electrical or optical properties in the presence of target substances, making them effective for detecting environmental contaminants.

Applications: Used in gas sensors for detecting pollutants like nitrogen dioxide (NO_2) and carbon monoxide (CO), and in biosensors for detecting pathogens or chemical residues.

Benefits: High sensitivity and selectivity, potential for real-time monitoring, and capability to detect trace levels of contaminants.

2.1.6.B *Industrial Applications of Green-Synthesized ZnO Nanoparticles*

Electronics and Optoelectronics

Mechanism: ZnO nanoparticles are used in electronic devices and optoelectronic applications due to their semiconducting properties. They can be integrated into various electronic components, such as transistors, diodes, and light-emitting devices.

Applications: Employed in photovoltaic cells, LED technology, and transparent conductive films. They are also used in touch screens and sensors.

Benefits: Enhances the performance of electronic devices, contributes to energy-efficient technologies, and supports the development of flexible and transparent electronics.

Coatings and Pigments

Mechanism: ZnO nanoparticles are utilized as pigments and in coatings due to their UV-blocking and antimicrobial properties. They improve the durability and functionality of coatings and provide color and protection in various applications.

Applications: Used in protective coatings for paints, automotive finishes, and textiles. Also employed as pigments in cosmetics, paints, and plastics.

Benefits: Provides UV protection, enhances the longevity of coatings, and imparts antimicrobial properties to prevent microbial growth on surfaces.

3.0 Future Perspective and Challenges

The future of green-synthesized ZnO nanoparticles is filled with potential advancements and opportunities. Continued development of synthesis techniques promises enhanced control over the size, shape, and properties of these nanoparticles. Innovations in synthesis methods, including the use of novel biological sources or hybrid approaches, could lead to more efficient and scalable production processes. Integrating green synthesis with advances in nanotechnology may result in multifunctional ZnO nanoparticles with tailored properties, opening new possibilities in fields such as drug delivery and electronics.

Expanding research into biomedical applications holds promise for new therapies and diagnostic tools, including personalized medicine and advanced imaging techniques. Similarly, there is potential for broader environmental applications, such as addressing emerging pollutants and contributing to climate change solutions. Establishing comprehensive regulatory frameworks and standardized protocols will be crucial for the safe and effective use of these nanoparticles across various applications. Ensuring that they meet necessary safety and efficacy standards will facilitate their adoption and integration into industry.

Sustainability remains a key focus, with future research likely to emphasize resource efficiency and the principles of a circular economy. Enhancing the sustainability of synthesis processes and conducting lifecycle assessments will be vital to minimize waste and evaluate the environmental impact of ZnO nanoparticles throughout their lifecycle.

However, several challenges must be addressed. Scaling up from laboratory to industrial production involves maintaining consistent quality and managing costs. The economic viability of green synthesis methods compared to traditional approaches needs ongoing evaluation as market demands and technological requirements evolve. Standardized methods for characterizing nanoparticles are essential to ensure accuracy and reproducibility, given their diverse properties influenced by synthesis methods.

Long-term environmental impacts of ZnO nanoparticles need thorough investigation to avoid unintended consequences. Effective waste management and recycling strategies are also crucial. Additionally, raising public awareness and education about the benefits and safety of green-synthesized nanoparticles will foster acceptance and promote their adoption. Navigating regulatory requirements and gaining approval for new applications can be complex, requiring collaboration between researchers, industry, and regulatory bodies.

4.0 CONCLUSION

The review of eco-friendly approaches in the synthesis of ZnO nanoparticles underscores the transformative potential of green synthesis methods in advancing both environmental and industrial applications. Green synthesis techniques, which leverage natural, non-toxic materials and milder conditions, offer several key advantages over conventional methods. These include reduced environmental impact, minimized health risks, and enhanced cost-effectiveness, making them an attractive alternative for large-scale production. The environmental benefits of green-synthesized ZnO nanoparticles are significant. Their application in photocatalysis for water treatment demonstrates their capability to degrade pollutants and purify water efficiently, contributing to cleaner water resources. Furthermore, their role in sensing and detection provides a means for monitoring and mitigating environmental contaminants with high sensitivity and selectivity.

In industrial contexts, the versatility of green-synthesized ZnO nanoparticles is equally impressive. Their integration into electronics and optoelectronics enhances the performance and efficiency of various devices, from photovoltaic cells to LED technology. Additionally, their use in coatings and pigments not only improves product durability and functionality but also supports the development of eco-friendly materials.

Overall, the adoption of green synthesis methods for ZnO nanoparticles represents a significant step toward more sustainable practices in material science. By continuing to explore and refine these eco-friendly approaches, researchers and industries can further harness the potential of ZnO nanoparticles to address environmental challenges and drive innovation in diverse applications. The positive impact on both ecological health and technological advancement highlights the importance of pursuing and supporting green synthesis techniques in future research and development efforts. This section is mandatory. The conclusion section in a research paper serves to summarize key findings, their significance in the research context, and whether hypotheses were supported. It discusses practical implications, acknowledges study limitations, suggests future research directions, and concludes with a concise statement emphasizing the research's significance without introducing new information.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

Table 1. Plants mediated green synthesis of ZnONPs, detailing the species, key reagents, nanoparticles morphology and size, and their various applications

S.No	Specie used	Key reagents	Morphology and size	Applications	References
1	Rhamnus virgata	Aqueous solution of Rhamnus virgata	Crystalline and of about 20nm	Potential Antioxidant, Enzyme inhibition and biological applications	[67]
2	Salvia officinalis	Zinc oxide and Salvia officinalis leaf extract	Not specified	Photocatalytic degradation of methyl orange, antifungal activity against Candida albicans, and probable development of novel antifungal agents.	[68]

3	Scoparia dulcis	Zinc oxide + Scoparia dulcis extract	Pebble-like morphology with size of approximately 20 nm	Antimicrobial activity and antioxidant properties for biomedical uses.	[69]
4	Leaves of Syzygium cumini	Zinc salt and the plant extract	Hexagonal and spherical with no specific size	Enhancing seed germination, degrading Rhodamine B dye, and purifying dye-polluted water.	[70]
5	Pomegranate peel aqueous extract	Zinc salt + plant extract	Hexagonal, with varying sizes of 18.53, 29.88, and 30.34 nm	Antibacterial activity against Gram-positive and Gram-negative bacteria	[71]
6	Swertia chirayita leaf extract	Plant extract with Zinc salt	Not-specified	Antibacterial activity against Gram-positive Staphylococcus aureus and Gram-negative Escherichia coli and Salmonella enterica	[72]
7	Citrus jambhiri leaf extract	Zinc salt and the plant extract	No specific morphology and particle sizes ranging from 10 to 35 nm	Effective photodegradation of methylene blue dye	[73]
8	Onion Peel (Allium cepa)	Aqueous extract of onion peel	Spherical shape with20–80 nm (FESEM), 500 nm hydrodynamic size (DLS)	Nutrient source for agricultural purposes, enhancing growth in Vigna radiate (mung bean) and Triticum aestivum (wheat seeds).	[74]
9	Heritiera fomes, Sonneratia apetala	Aqueous extracts of Heritiera fomes and Sonneratia apetala	Monodispersed nanoparticles with narrow particle size distribution	Antioxidant, anti-inflammatory, antidiabetic, and antibacterial properties for use in the cosmetic, food, and biomedical industries	[75]
10	Cinnamomum verum	Cinnamomum verum plant extract	Agglomerated particles	Effective against Escherichia coli and Staphylococcus aureus	[76]

	(cinnamon plant extract)				
11	Laurus nobilis	Zinc oxide and aqueous leaf extract	Flower-like with a hexagonal wurtzite structure and size is 47.27 nm	antibacterial activity and cancer cell inhibition.	[77]
12	Pomegranate	zinc oxide and pomegranate peel extract,	Spherical and hexagonal, size ranges from 20 to 40 nm	Antimicrobial activity, antioxidant activity, and promoting seed germination, root length, and shoot height in barley.	[78]
13	Mentha spicata	Zinc oxide with Mentha spicata leaf extract	Spherical form with size 74.68 nm	Systemic acquired resistance, reducing disease severity, and antiviral activity in tomato plants.	[79]
14	Southern African native medicinal plants	Zinc oxide and medicinal plant extracts	Not specified	Antibacterial, anticancer properties, varistor applications, and photodegradation of organic dyes.	[80]
15	Acorus calamus	Zinc oxide + Acorus calamus aqueous extract,	Spherical and hexagonal wurtzite with no exact size ranges	Antioxidant activity and potential use as an antioxidant supplement against oxidative stress and infections.	[81]
16	Caesalpinia crista	Zinc oxide with Caesalpinia crista seed extract	Irregular morphology, size ranges from 20-44 nm to 34.67 nm	Antimicrobial, antioxidant, and cytotoxic effects.	[82]
17	Artemisia absinthium	zinc oxide and Artemisia absinthium leaf extract	Spherical and elliptical with size ranges from 18.77 to 24.39 nm	Enhanced surface area and band-gap energies for potential use in various applications.	[83]
18	Cow (Bos taurus)	Zinc oxide and cow dung extract,	Morphology and size are not specific	Increasing seed germination, root length, and shoot length	[84]

				with lower antimicrobial potential for sustainable agriculture.	
19	Citrus reticulata	Citrus reticulata peel extract + Zinc oxide	Morphology is spherical, size ranges from 23-90 nm with a crystallite size of 8.62-8.89 nm	Enhancing seed germination and seedling vigor of Brassica nigra as eco-friendly nano-fertilizers.	[85]
20	Garcinia gummi-gutta	Zinc nitrate with Garcinia gummi-gutta seed extract	Not specified	Photoluminescence, antioxidant properties, and catalysis for formylation of aromatic amines and biodiesel production.	[86]

Table 2. A summary of Fungal, Algal and Microbial-mediated green synthesis of ZnONPs, detailing the species, key reagents, nanoparticles morphology and size, and their various applications

S.No	**Specie used**	**Key reagents**	**Morphology and size**	**Applications**	**References**
1	Cochliobolus geniculatus	Zinc metal and the fungus’s mycelial filtrate	squasi-spherical, size is not specified	biosynthesis of ZnO nanoparticles	[87]
2	Xylaria acuta,	Zinc oxide + fungal extract	Not specified	Antimicrobial and anticancer activities, specifically against human MDA-MB 134 mammary gland carcinoma cells.	[88]
3	Cladosporium tenuissimum FCBGr	Zinc oxide and the fungal extract	No specific size and morphology	Antimicrobial treatments for textiles, functionalized paints, dye degradation, and anticancer activity against HeLa cell lines.	[89]

4	Aspergillus sp isolated from Dictyota dichotoma,	Zinc oxide and the fungal extracellular product	Spherical, with a size of ∼80–100 µm	Dye degradation and antibacterial effects against pathogenic bacteria.	[90]
5	Phanerochaete chrysosporium	P. chrysosporium with glycerol as a stabilizer	Shape from hexagonal (83.9 nm) to spherical (59.5 nm),	Antibacterial activity against Staphylococcus aureus and Escherichia coli.	[91]
6	Aspergillus niger, Aspergillus tubulin, Aspergillus fumigatus, Penicillium citrinum, and Fusarium oxysporum	Fungal isolates with Zinc sulfate	Hexagonal wurtzite structure with sizes between 30–100 nm	Excellent antibacterial activity against both Gram-positive and Gram-negative bacteria.	[92]
7	Acremonium potronii	Fungal strains	Spherical with sizes ranging from 13 to 15 nm	Demonstrated 93% catalytic activity in the degradation of methylene blue dye.	[93]
8	Aspergillus niger	Zinc salts	Spherical and sizes 80–130 nm	Antioxidant, antimicrobial, and anticancer activity.	[94]
9	Ulva fasciata;	Aqueous extract of marine green macroalgae;	Spherical and crystalline ZnO-NPs, 3–33 nm	Antibacterial activity, methylene blue dye degradation, and decolorizing tanning wastewater.	[95]
10	Sargassum wightii;	Ethanol extract of Sargassum wightii;	Spherical, hexagonal, anisotropic, and triangular ZnO-NPs with sizes ranging from 20.51 to 31.75 nm;	Antibacterial activity against various pathogens and anticancer activity with an IC50 value of 78.33 µg/mL against MCF-7 cells.	[96]

11	Microalgae strains ZAA1 (MF140241), ZAA2 (MF114592), and ZAA3 (MF114594)	zinc nitrate solution	No specific morphology and size	Antibacterial activity against E. coli, S. aureus, M. luteus, K. pneumoniae, and C. freundii.	[97]
12	Various microbes (bacteria, actinomycetes, fungi, yeast)	Biotic sources (plants, microbes) as bio-reductants and stabilizers	Not-specified	Medicine, agriculture, environmental remediation (e.g., drug delivery, antibacterial agents, bioimaging, biosensors, nano-fertilizers).	[98]
13	Streptomyces plicatus;	Marine S. plicatus;	Hexagonal morphology, average grain size of 41.76 nm	Antibacterial and antibiofilm activity against Streptococcus mutans, cytotoxicity against oral KB cancer cells, hemolysis, and artemia toxicity.	[99]
14	Lactobacillus spp	Lactobacillus spp extract	Not-specified	Antimicrobial and biocompatibility analysis, demonstrating effectiveness against various pathogens and HT-29 cancer cells.	[100]

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