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REVIEW ARTICLE

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Plant based green synthesis of zinc oxide nanoparticles from *Bauhinia purpurea* and its application

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ABSTRACT

Nanotechnology is an emerging interdisciplinary field focused on manipulating materials where unique physicochemical properties enable diverse applications in medicine, agriculture, and environmental science. Among metal oxide nanoparticles, zinc oxide nanoparticles (ZnO NPs) have gained considerable attention due to their biocompatibility, antimicrobial activity, and optical properties. Conventional synthesis methods, however, often involve toxic chemicals and high energy consumption. Green synthesis using plant extracts has emerged as a sustainable approach. *Bauhinia purpurea*, a medicinal plant has shown significant potential in easing the biosynthesis of ZnO NPs.

The objective of this review is to critically summarize recent advances in plant-mediated synthesis of ZnO nanoparticles using *B. purpurea*, with emphasis on physicochemical characteristics, biomedical applications, and nanotoxicological implications. The review methodology is based on a structured analysis of peer-reviewed literature retrieved from major scientific databases, including PubMed, Scopus, and Google Scholar, focusing on studies related to green synthesis, biological activity, and safety evaluation of ZnO NPs.

These nanoparticles exhibit promising biomedical applications, including antibacterial activity against *Klebsiella pneumoniae*, antioxidant potential via free radical scavenging, and anti-inflammatory effects via inhibition of protein denaturation. Studies using *Drosophila melanogaster* as a model organism indicate dose-dependent behavioral impairments, highlighting the need for careful toxicological evaluation. A key limitation of current research is the variability in plant extract composition, which affects reproducibility, particle uniformity, and scalability of green synthesis approaches.

Future research should focus on standardization of synthesis parameters, advanced surface functionalization strategies, and integration of data-driven approaches to improve reproducibility, safety, and clinical translation of plant-derived nanomaterials

KEY WORDS

Nanotechnology; ZnO nanoparticles; Green synthesis; *Bauhinia purpurea*; Antibacterial activity; Nanotoxicology; Drosophila model

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Introduction

Nanotechnology is a rapidly expanding interdisciplinary field that involves the manipulation and control of matter. Materials at this scale exhibit distinct physicochemical properties compared to their bulk counterparts, including enhanced optical behavior, improved electrical conductivity, increased catalytic efficiency, and higher chemical reactivity. These unique characteristics arise primarily from quantum confinement effects and a significantly increased surface area-to-volume ratio, enabling nanoparticles to interact more effectively with biological and chemical systems [1]. Nanotechnology has therefore transformed multiple scientific domains, including medicine, biotechnology, environmental science, agriculture, and electronics, by enabling the development of targeted drug delivery systems, biosensors, advanced catalysts, and functional materials [2]. The integration of physics, chemistry, biology, and engineering has allowed nanotechnology to bridge the gap between fundamental science and practical applications, enabling the creation of highly efficient multifunctional nanomaterials.

The concept of nanotechnology back to ancient times, exemplified by the Lycurgus Cup, a Roman artifact known for its color-changing properties due to embedded metallic nanoparticles. However, modern nanotechnology was formally conceptualized in the twentieth century when Richard Feynman proposed the idea of manipulating matter at the atomic level in his famous lecture “There’s Plenty of Room at the Bottom.” The term “nanotechnology” was later coined by Norio Taniguchi, while K. Eric Drexler further expanded the concept through the development of molecular nanotechnology [3]. Advances in microscopic techniques such as scanning tunneling microscopy (STM) and transmission electron microscopy (TEM) have enabled visualization and manipulation of nanoscale materials, significantly accelerating research and technological innovation.

Among various nanomaterials, zinc oxide nanoparticles (ZnO NPs) have received considerable attention due to their exceptional physicochemical and biological properties. ZnO NPs exhibit a wide bandgap (~3.37 eV), high exciton binding energy, strong ultraviolet absorption, and excellent photoluminescence characteristics, making them suitable for applications in optoelectronics, biosensing, photocatalysis, and biomedical engineering. Their high thermal stability, low cost of production, and recognized biocompatibility further increase their potential for use in antimicrobial coatings, wound healing formulations, targeted drug delivery, and anticancer therapies [4]. ZnO nanoparticles also demonstrate remarkable photocatalytic efficiency, enabling degradation of environmental pollutants and contributing to environmental remediation technologies.

Traditional synthesis methods for ZnO nanoparticles, including physical and chemical approaches, often require expensive instrumentation, high energy input, and the use of toxic reducing agents or stabilizing chemicals. These methods may

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generate hazardous by-products, posing environmental and health risks that limit their large-scale biomedical applications. Consequently, increasing emphasis has been placed on the development of environmentally friendly synthesis routes that align with the principles of green chemistry [5]. Green synthesis using biological resources such as plant extracts, microorganisms, and enzymes has emerged as a promising alternative, offering advantages such as cost-effectiveness, energy efficiency, and reduced toxicity.

Plant-mediated synthesis has gained particular attention due to the presence of diverse phytochemicals, including flavonoids, phenolic compounds, alkaloids, terpenoids, and proteins, which act as natural reducing and stabilizing agents. Among medicinal plants, B. *purpurea* has demonstrated significant potential in the biosynthesis of ZnO NPs. The plant is rich in phenolics, tannins, and flavonoids that facilitate nanoparticle formation while enhancing stability and biological activity [6,7]. The use of plant extracts eliminates the need for hazardous reagents and provides an eco-friendly route for producing biocompatible nanomaterials suitable for biomedical and environmental applications.

Existing literature often focuses broadly on plant-mediated synthesis without critically evaluating the specific role of individual medicinal plants such as B. *purpurea* in influencing nanoparticle morphology, stability, and biological activity. Furthermore, limited studies provide an integrated assessment of both functional applications and nanotoxicological implications of biosynthesized ZnO nanoparticles. Variability in phytochemical composition, lack of standardized synthesis protocols, and insufficient long-term toxicity studies hinder reproducibility and large-scale translation [8]. Therefore, a comprehensive synthesis of recent advancements focusing on both biomedical efficacy and biosafety considerations is necessary to support the development of sustainable nanotechnology.

The review highlights the physicochemical properties of ZnO nanoparticles, various synthesis strategies, and the mechanistic role of phytochemicals in nanoparticle formation. In addition, the biomedical applications of ZnO nanoparticles, including antibacterial, antioxidant, anti-inflammatory, and drug delivery potential, are examined [9]. Special attention is given to nanotoxicological considerations using model organisms such as D. *melanogaster*, enabling evaluation of dose-dependent biological effects and safety concerns associated with nanoparticle exposure.

This review provides synthesis of plant-mediated ZnO nanoparticle research, emphasizing mechanistic understanding, functional performance, and biosafety considerations within the framework of sustainable nanotechnology [10]. The discussion critically connects nanoscale physicochemical behavior with biological functionality, highlighting how phytochemical-assisted synthesis influences structural characteristics, therapeutic potential, and environmental compatibility. Emphasis is placed on evaluating translational feasibility by correlating synthesis parameters with biological response and safety outcomes.

Literature Review

Physicochemical properties of nanoparticles

The physical and chemical characteristics of nanoparticles (NPs) differ greatly from those of their bulk materials due largely to their size (1-100 nanometres). The most significant of these differences is the surface-to-volume ratio; NPs have a much larger proportion of their atoms on the surface than those inside the particle. This imparts nanoparticles with enhanced chemical reactivity, improved catalytic performance, and a greater capacity to interact with biological systems. As the size of a particle decreases, its surface energy increases, making NPs highly reactive and well-suited for catalysis, drug delivery, and antimicrobial applications [11].

The other unique property of NPs is quantum confinement. Quantum confinement means that electrons' motion is restricted by the reduced dimensions of the NP, leading to discrete energy levels rather than continuous bands (as in larger particles). As a result, NPs can exhibit size-dependent fluorescence and tunable bandgap energies, which are exploited in many biosensing and imaging applications.

Nanoscale materials exhibit unique optical properties as well; the most common example is localized surface plasmon resonance (LSPR), which occurs in metal NPs, where conduction electrons oscillate in response to incident light [12]. Another example is zinc oxide (ZnO), which is a semiconductor and exhibits strong absorption of ultraviolet light (UV) and photoluminescence (PL). As such, ZnO is used extensively in optoelectronic devices and photocatalysis.

Nanoscale size is also important for both thermal and electrical properties. Smaller particle sizes can lead to higher thermal conductivity of nanofluids. In contrast, the electrical conductivity of nanoparticles may be affected by electron scattering and confinement effects at these tiny dimensions. Additionally, nanoparticles may exhibit mechanical properties different from those of their larger counterparts, such as increased strength and flexibility, due to differences in atomic arrangements and intermolecular forces [13].

Nanoparticle behaviour is also influenced by surface chemistry. Nanoparticles have various functional groups attached to their surfaces, which influence their solubility and stability, as well as their interactions with biological systems [14]. Surface charge is one example of how nanoparticles interact with cells; positively charged nanoparticles will typically interact more favorably with negatively charged cell membranes than negatively charged nanoparticles.

Synthesis of nanoparticles

Various synthesis strategies have been developed, broadly categorized into top-down, bottom-up, and green synthesis approaches.

Top-down approaches

Nanoscale structures can be fabricated from bulk materials using a "top-down" approach, such as mechanical or physical methods. External forces applied to the bulk material break it down into its parts by reducing its size, producing nanoscale material. These processes are widely used in industry [15].

Mechanical milling

Mechanical or ball milling is the most widely used of the top-down methods to produce nanoparticle- or nanomaterial-sized materials. This process, which employs high-energy collisions between balls (a rotating chamber) and bulk material, gradually reduces particle size to the nanoscale via multiple impacts of the balls against the bulk material within the chamber [16,17].

Lithography techniques

Lithographic techniques, such as photolithography, electron-beam lithography, and nanoimprint lithography, are widely used in the semiconductor industry to produce nanostructures. Each

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of these lithographic techniques enables the controlled creation of patterns or designs to produce nanostructures [18].

Laser ablation

Laser ablation involves removing material from a solid target using a high-energy laser beam. The ablated material condenses into nanoparticles in a controlled environment. This technique produces high-purity nanoparticles free of chemical contaminants and enables control over particle size by adjusting laser parameters.

Bottom-up approaches

Bottom-up approaches involve the assembly of nanoparticles from atomic or molecular precursors, offering better control over particle size, shape, and composition.

Sol–Gel method

The sol–gel process involves the hydrolysis and condensation of metal precursors to form a colloidal solution (sol), which gradually transforms into a gel-like network. Upon drying and calcination, nanoparticles are formed [19]. This method offers excellent control over particle size, high purity, and uniform morphology, and is widely used for synthesizing metal oxide nanoparticles such as ZnO.

Chemical vapor deposition (CVD)

CVD is a widely used technique for producing high-quality nanomaterials, especially thin films and carbon-based nanostructures. In this process, volatile precursors react or decompose on a heated substrate to form nanoparticles.

Pyrolysis

Pyrolysis involves the thermal decomposition of precursor materials at elevated temperatures in the absence of oxygen [20]. This technique is widely used in industrial-scale nanoparticle production due to its simplicity, continuous operation, and high yield. However, controlling particle size and preventing aggregation can be challenging.

Green synthesis

Green synthesis represents an alternative to standard methods for producing nanoparticles based on physical and/or chemical principles; these environmentally sustainable nanoparticle fabrication methods utilize biologically sourced agents (plants, bacteria, fungi, and algae) to achieve the natural reduction and stabilization required to produce nanoparticles.

Microorganism-mediated synthesis

Microorganisms, such as bacteria and fungi, can synthesize nanoparticles intracellularly or extracellularly. Enzymes and biomolecules present in these organisms reduce metal ions into nanoparticles.

Plant-mediated synthesis

The use of plant extracts for green synthesis of nanoparticles is common because of the high phytochemical content (such as flavonoids, phenolics, alkaloids and terpenoids) they provide. The various classes of phytochemicals found in plant extracts can be used to function as reducing agents and capping agents for the formation and stabilization of nanoparticles.

Role of *B. purpurea* in nanoparticle synthesis

B. purpurea, an essential medicinal herb from the Fabaceae family, is found repeatedly around the world in tropic and sub-tropic regions. Increased attention has been directed to this plant based on its phytochemical composition, which includes compounds such as flavonoids, tannins, other phenolics, glycosides, saponins, and triterpenoids. Each of these bioactive compounds serves a dual purpose in the production of nanoparticles by providing both reduction and capping/stabilizing properties.

Phytochemical compounds in the extract function as electron donors to reduce Zn^{2+} ions (zinc ions) to ZnO nanostructured particles during the biosynthesis of nanoparticles from ZnO. Phytochemicals also contain functional groups that bind to the surface of ZnO nanoparticles preventing them from clustering and creating more stable colloids [21]. The capping properties of phytochemicals are superior to those of typical chemical stabilizers, which can present a risk of toxicity.

The phytochemicals found in *B. purpurea* provide the means for regulating the nucleation (the creation of small particles) and the growth of nanoparticles as well as controlling their ultimate size, shape, and surface characteristics. Studies show that plants used in a biosynthetic manner often yield nanoparticles that are 20–50 nm in size with a high degree of uniformity and improved biological activity [22]. Additionally, the presence of antioxidant compounds in the extract enhances the functional property of any ZnO nanoparticles that were synthesized for medicinal use.

The eco-friendly, cost-effective, and scalable nature of this method makes *B. purpurea* a promising candidate for sustainable nanoparticle production, aligning with the principles of green chemistry.

Biomedical applications of ZnO nanoparticles

Antibacterial activity

The antibacterial activity of zinc oxide nanoparticles (ZnO NPs) is very strong and effective against a variety of Gram-positive and Gram-negative bacteria, including *K. pneumoniae*. The methods by which these nanoparticles kill bacteria are many and include:

ZnO NPs generate ROS, which are damaging to bacterial cells, including hydroxyl radicals (OH), superoxide anions (O_2^-) and hydrogen peroxide (H_2O_2). ROS creates oxidative stress on bacteria and damages their cellular components.

Interaction between ZnO NPs and the bacterial cell membrane increases the permeability of the membrane, causing a loss of intracellular contents and ultimately leading to cell death [23].

Dissolution of ZnO NPs in a solution releases zinc ions and inhibits the activity of certain enzymatic and metabolic pathways within the bacterial cell.

The small size of nanoparticles allows for a greater surface area to interact with microbial cells, making ZnO NPs very efficient at killing bacteria. In addition, ZnO NPs are believed to have non-specific mechanisms of action and this feature is likely to decrease the possibility of bacteria developing resistance against them compared to conventional antibiotics.

Antioxidant activity

ZnO that have been made through methods involving plants, are also known to be effective both in preventing and reducing the development of radicals and other potentially reactive species while preventing oxidative damage to different biomolecules (i.e. lipids, proteins, DNA) because they contain many phytochemicals that are absorbed onto their surfaces. The antioxidant properties of these ZnO NPs typically are assessed using room temperature DPPH (2,2-diphenyl-1-picrylhydrazyl)

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assays, whereas NPs exhibit a dose-dependent decrease in antioxidant characteristics by scavenging free-radicals [24]. The antioxidant characteristics of are influenced by multiple variables such as:

Anti-inflammatory activity

ZnO (zinc oxide) nanoparticles have shown great potential as anti-inflammatory agents due to their many different ways of working. The primary mechanism by which ZnO nanoparticles exert their anti-inflammatory effects is through the inhibition of protein denaturation, which prevents changes to the structure of proteins that lead to inflammatory responses. ZnO nanoparticles also regulate cytokine production by down-regulating pro-inflammatory cytokines such as TNF-α (tumour necrosis factor alpha), IL-1β (interleukin 1 beta) and IL-6 (interleukin 6). Additionally, ZnO nanoparticles reduce ROS (reactive oxygen species) production, resulting in decreased cellular damage from inflammation by decreasing oxidative stress [25]. Lastly, ZnO nanoparticles have been shown to modulate key signalling pathways involved in inflammation, including NF-κB and MAPK (mitogen-activated protein kinase). The small size and large surface area of ZnO nanoparticles also increase their ability to enter cells and be available for use. As a result of all these mechanisms working together, ZnO nanoparticles can provide effective therapies for use in treating inflammatory diseases.

Nanotoxicology

Mechanisms of toxicity

Despite their beneficial applications, ZnO nanoparticles pose potential risks to biological systems. The primary mechanism of toxicity is associated with oxidative stress, resulting from excessive production of reactive oxygen species (ROS).

These ROS can lead to:

- Lipid peroxidation and membrane damage
- Protein denaturation and enzyme inactivation
- DNA damage and genotoxicity
- Mitochondrial dysfunction

Additionally, the release of Zn^{2+} ions within cells can disrupt cellular homeostasis and metabolic processes. Prolonged exposure may result in inflammation, apoptosis, or necrosis, depending on the concentration and duration of exposure.

Factors affecting toxicity

Several physicochemical parameters influence the toxicity of ZnO nanoparticles:

- Particle size: Smaller nanoparticles exhibit higher reactivity and toxicity due to a larger surface area.
- Concentration: Toxic effects are dose-dependent; higher concentrations cause greater cellular damage.
- Surface chemistry: Functionalization and coating can alter nanoparticle interactions with biological systems.
- Other factors such as shape, aggregation state, and exposure route (inhalation, ingestion, or dermal) also play critical roles in determining toxicity.

***Drosophila melanogaster* as a model system**

The fruit fly, *D. melanogaster*, is a widely used model organism in toxicological and biomedical research due to its genetic, physiological, and biochemical similarities to humans. Approximately 75% of human disease-related genes have homologs in Drosophila, making it a valuable system for studying nanoparticle toxicity.

Key advantages of using *D. melanogaster* include:

- Short life cycle and rapid reproduction
- Ease of maintenance and low cost
- Availability of advanced genetic tools
- Well-characterized genome

Behavioral assays such as crawling (larval stage) and climbing (adult stage) are commonly used to assess neurotoxicity and locomotor function [26]. Exposure to ZnO nanoparticles has been shown to cause dose-dependent impairments in movement, indicating potential neurotoxic effects.

These findings are crucial for understanding the in vivo effects of nanoparticles and for extrapolating potential risks to higher organisms, including humans.

Review Methodology

The present review was conducted using a systematic, structured approach to ensure the inclusion of high-quality, relevant, and up-to-date scientific literature. A comprehensive search strategy was employed using major scientific databases, including Google Scholar, PubMed, and Scopus. These databases were selected for their extensive coverage of peer-reviewed journals in nanotechnology, materials science, biotechnology, and biomedical research.

The literature search was carried out using a combination of keywords and Boolean operators to maximize retrieval efficiency. The primary keywords included "ZnO nanoparticles," "green synthesis," "*B. purpurea*," and "nanotoxicology," which were further combined with related terms such as "plant-mediated synthesis," "metal oxide nanoparticles," "antibacterial activity," and "*D. melanogaster* model." The search strategy was refined iteratively to ensure the retrieval of the most relevant articles, and reference lists of selected papers were also screened to identify additional pertinent studies.

To maintain scientific rigor and relevance, strict inclusion criteria were applied during the selection process. Only peer-reviewed research articles, review papers, and high-impact studies published within the last five to ten years were considered, ensuring that the review reflects recent advancements in the field [27]. Emphasis was placed on studies that specifically addressed green synthesis approaches, particularly those involving plant extracts, as well as investigations into the biomedical applications and toxicological profiles of ZnO nanoparticles.

Conversely, studies that were outdated, non-indexed, or lacking sufficient methodological detail were excluded to maintain the quality and credibility of the review. Articles published in predatory journals, conference abstracts without full-text availability, and studies with unclear or non-reproducible methodologies were also omitted.

The selected articles were critically analyzed and synthesized to identify common themes, trends, and research gaps. A comparative evaluation of findings was conducted to highlight consistencies and discrepancies across studies, thereby ensuring a balanced and comprehensive understanding of the topic. This methodological framework enabled the development of a coherent and evidence-based review of green-synthesized ZnO nanoparticles and their biomedical and toxicological implications.

Recent Advances

Recent advances in nanotechnology have significantly enhanced the functional performance, specificity, and scalability of zinc oxide nanoparticles (ZnO NPs), particularly those synthesized via green routes. One of the most notable developments is the functionalization of ZnO nanoparticles, in which their surfaces are modified with biomolecules, such as polymers, peptides, or plant-derived ligands, to improve targeting efficiency. These functionalized nanoparticles exhibit enhanced selectivity toward specific cells or pathogens, making them highly promising for targeted drug delivery, cancer therapy, and antimicrobial

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efficiency. These functionalized nanoparticles exhibit enhanced selectivity toward specific cells or pathogens, making them highly promising for targeted drug delivery, cancer therapy, and antimicrobial applications. Surface engineering also enhances stability, dispersibility, and biocompatibility, thereby reducing unintended cytotoxicity while increasing therapeutic efficacy.

Another major advancement is the development of hybrid nanomaterials, in which ZnO NPs are combined with other nanostructures, such as silver nanoparticles, graphene, or polymers. These hybrid systems integrate multiple functionalities into a single platform, enabling synergistic effects [28]. For instance, ZnO–Ag nanocomposites demonstrate superior antimicrobial activity due to combined mechanisms of ion release and oxidative stress, while ZnO–graphene composites exhibit enhanced electrical conductivity and photocatalytic efficiency. Such multifunctional materials are increasingly being explored for applications in biosensing, environmental remediation, and advanced biomedical devices.

The integration of artificial intelligence (AI) into nanotechnology has opened new avenues for the rational design and optimization of nanoparticles. Machine learning algorithms are now being used to predict nanoparticle size, morphology, and functional properties from synthesis parameters. This data-driven approach reduces experimental time and cost while improving reproducibility [29]. AI tools are also being used to model nanoparticle–biological interactions, enabling better prediction of toxicity and therapeutic outcomes, which is particularly important for clinical translation.

In addition, significant improvements have been made in green synthesis techniques to address scalability and consistency challenges. Researchers are now optimizing parameters such as pH, temperature, precursor concentration, and plant extract composition to achieve controlled nanoparticle size and morphology. Advanced techniques, including microwave-assisted and ultrasound-assisted green synthesis, have been introduced to accelerate reaction rates and improve yield. Efforts are also being directed toward standardizing plant extract preparation to minimize batch-to-batch variability. These advancements are crucial for transitioning green-synthesized ZnO nanoparticles from laboratory research to industrial-scale production, thereby supporting the development of sustainable and economically viable nanotechnology solutions.

Challenges and Limitations

Despite the promising potential of green-synthesized zinc oxide nanoparticles, several challenges remain that hinder their widespread application and commercialization. One of the primary limitations is the variability in plant extract composition. The phytochemical profile of *B. purpurea* and other plant sources can vary significantly depending on factors such as geographical location, seasonal changes, soil conditions, and extraction methods. This variability directly influences the reduction and stabilization processes during nanoparticle synthesis, leading to inconsistencies in particle size, morphology, and functional properties.

Another critical issue is the lack of reproducibility. Unlike controlled chemical synthesis methods, green synthesis involves complex biological components whose interactions are not fully understood. As a result, achieving uniformity across batches remains challenging, limiting the reliability of these nanoparticles for industrial and clinical applications.

Toxicity concerns also present a significant limitation, particularly at higher concentrations of ZnO nanoparticles. While they are generally considered biocompatible, studies have demonstrated that elevated doses can induce oxidative stress, cellular damage, and behavioral impairments in model organisms such as *D. melanogaster* [30]. These findings highlight the importance of dose optimization and thorough toxicological evaluation before biomedical implementation.

Furthermore, scaling up green synthesis processes from laboratory to industrial levels remains difficult. Maintaining consistent reaction conditions, ensuring uniform nanoparticle characteristics, and optimizing cost-effectiveness pose substantial challenges. The lack of standardized protocols further complicates large-scale production, making it difficult to translate laboratory successes into commercial applications.

Future Perspectives

Research on biogenic ZnO nanoparticles (NPs) will continue to expand their use within nanomedicine and controlled drug delivery applications, as interactions between nanotechnology and precision medicine are implemented into the design of nanocarriers capable of delivering specific drugs to targeted tissue/cells; thereby maximizing therapeutic effects of drug delivery while minimizing systemic side effects associated with drug delivery due to specificity in targeted delivery. Functionalizing the NP surface with ligands, antibodies, or biomolecules is expected to be a key component in achieving the level of specificity required for controlled release of drug(s) from NPs.

Future research involving nanomaterials will also involve developing "safer-by-design" or engineered NPs by engineering their physicochemical properties (size, shape, surface charge, coating) to reduce their toxicity while still permitting their intended use. Given the rapid increase in concern about the effects of nanomaterials on living organisms, as evidenced using model organisms such as *D. melanogaster*, nanotoxicology research must now incorporate the need to balance the biomedical efficacy of nanomaterials with their biosafety [31]. Both long-term toxicity studies and concept approval levels of dosages must also be considered, where molecular and cellular interactions may play an important role.

Artificial intelligence integrated with nanotechnology is changing how we predict nanoparticle behavior and, as a result, improving how we refine the methods for creating nanoparticles. Using AI-based techniques enables researchers to identify correlations between the methods used to produce nanoparticles and the properties of the resulting nanoparticles. Many researchers believe that applying these techniques will yield reproducible, scalable nanoparticle production.

The development and eventual use of ZnO nanoparticles as a viable medical treatment depend on successfully navigating existing regulatory hurdles and developing validated safety testing procedures. Regulatory approval for ZnO nanoparticles will require extensive preclinical and clinical testing to demonstrate their safety for human use. Collaborative efforts involving researchers, physicians, and regulatory agencies will be necessary to close the gap between laboratory data and in-use treatments and to foster the widespread acceptance of sustainable nanotechnology in the medical field.

Conclusion

B. purpurea can produce zinc oxide nanoparticles (ZnO NPs) via an environmentally friendly, sustainable process called green synthesis, which bypasses traditional methods of nanoparticle synthesis using physical and chemical means. The extract contains a variety of phytochemicals, including flavonoids,

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tannins, and phenolic compounds, that are responsible for reducing and stabilizing the nanoparticles; therefore, toxic reagents and high-energy methods are not necessary. This method supports the use of green chemistry principles and contributes to the development of nanotechnologies that benefit the environment. Furthermore, biosynthesized ZnO NPs exhibit excellent potential in medicine due to their multifunctional properties. Their ability to kill bacteria (especially those that cause infections, such as *K. pneumoniae*) results from the generation of reactive oxygen species, the Disruption of cell membranes, and the release of metal ions. In addition, their ability to scavenge free radicals (antioxidants) enables them to function as anti-inflammatory agents by modulating inflammatory pathways; therefore, they have many potential therapeutic applications. While ZnO nanoparticles have great potential, liability and safety remain major limiting factors. For example, results from studies using the fly model, *D. melanogaster*, demonstrated that ZnO nanoparticles induce dose- and time-dependent changes in behavior and physiology, underscoring the need to define better how they interact with biological systems and what their long-term effects may be. There are many factors that can affect the toxicity of nanoparticles, such as particle size, concentration, and surface chemistry, which will significantly affect how nanoparticles impact living organisms. The nanoparticle properties must be optimized to achieve an adequate balance between efficacy and safety. The use of ZnO nanoparticles for medical or environmental applications, using *B. purpurea* to synthesize the ZnO themselves, should continue. More research on standardization, scalability, and safety assessment will be needed to fully leverage the unique properties of green-synthesized nanoparticles for treating illness or cleaning the environment.

Disclosure Statement

No potential conflict of interest was reported by the author.

References

1. Singh SK, Kulkarni PP, Dash D. Biomedical applications of nanomaterials: an overview. Bio-Nanotechnology: A Revolution in Food, Biomedical and Health Sciences. 2013:1-32. https://doi.org/10.1002/9781118451915.ch1
2. Joudeh N, Linke D. Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. J Nanobiotechnol. 2022;20(1):262. https://doi.org/10.1186/s12951-022-01477-8
3. Kornienko NE, Naumenko AP. Collective Nature of Chemical Bonds in Fullerenes and Fullerites C60: Vibrational Resonances, Vibrational–Electronic Interactions, and Anomalous Enhancement of Bands in the Vibrational Spectra of Nano lms (Results of Vibrational Spectroscopy and Quantum Chemical Calculations). Chem Funct Carbon Nanomater. 2015:128-171. CRC Press. https://doi.org/10.1201/b18724
4. Mishra PK, Mishra H, Ekielski A, Talegaonkar S, Vaidya B. Zinc oxide nanoparticles: a promising nanomaterial for biomedical applications. Drug Discov Today. 2017;22(12):1825-1834. https://doi.org/10.1016/j.drudis.2017.08.006
5. Mandal AK, Katuwal S, Tettey F, Gupta A, Bhattarai S, Jaisi S, et al. Current research on zinc oxide nanoparticles: synthesis, characterization, and biomedical applications. Nanomater. 2022;12(17):3066. https://doi.org/10.3390/nano12173066
6. Dutta G, Sugumaran A. Bioengineered zinc oxide nanoparticles: Chemical, green, biological fabrication methods and its potential biomedical applications. J Drug Deliv Sci Technol. 2021;66:102853. https://doi.org/10.1016/j.jddst.2021.102853
7. Latif MS, Abbas S, Kormin F, Mustafa MK. Green synthesis of plant-mediated metal nanoparticles: The role of polyphenols. Asian J Pharmaceut Clin Res. 2019;12(7):75-84. http://dx.doi.org/10.22159/ajpcr.2019.v12i7.33211
8. Kuppusamy P, Yusoff MM, Maniam GP, Govindan N. Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications–An updated report. Saudi Pharm J. 2016;24(4):473-484. https://doi.org/10.1016/j.jsps.2014.11.013
9. Kalpana VN, Devi Rajeswari V. A review on green synthesis, biomedical applications, and toxicity studies of ZnO NPs. Bioinorg Chem Appl. 2018;2018(1):3569758. https://doi.org/10.1155/2018/3569758
10. Sharma R, Garg R, Kumari A. A review on biogenic synthesis, applications and toxicity aspects of zinc oxide nanoparticles. EXCLI J. 2020; 19:1325. http://dx.doi.org/10.17179/excli2020-2842
11. Khan I, Saeed K, Khan I. Nanoparticles: Properties, applications and toxicities. Arab J Chem. 2019;12(7):908-931. http://dx.doi.org/10.1016/j.arabjc.2017.05.011
12. Duan X, Li Y. Physicochemical characteristics of nanoparticles affect circulation, biodistribution, cellular internalization, and trafficking. Small. 2013;9(9-10):1521-1532. https://doi.org/10.1002/smll.201201390
13. Beddoes CM, Case CP, Briscoe WH. Understanding nanoparticle cellular entry: A physicochemical perspective. Adv Colloid Interface Sci. 2015; 218:48-68. https://doi.org/10.1016/j.cis.2015.01.007
14. Shang L, Nienhaus K, Nienhaus GU. Engineered nanoparticles interacting with cells: size matters. J Nanobiotechnol. 2014;12(1):5. https://doi.org/10.1186/1477-3155-12-5
15. Schäfer H, Hess C, Tobergte H, Volf A, Ichilmann S, Eickmeier H, et al. Ultrafine sanding paper: a simple tool for creating small particles. Small (Weinheim an der Bergstrasse, Germany). 2014;11(8):931-935. https://doi.org/10.1002/smll.201303930
16. El-Eskandarany MS, Al-Hazza A, Al-Hajji LA, Ali N, Al-Duweesh AA, Banyan M, et al. Mechanical milling: a superior nanotechnological tool for fabrication of nanocrystalline and nanocomposite materials. Nanomater. 2021;11(10):2484. https://doi.org/10.3390/nano11102484
17. Sidauruk H, Munandar A, Haryati S. The production of nanoparticles chitosan from crustaceans shell using the top-down method. InE3S Web of Conferences 2020;147: 03025p. EDP Sci. https://doi.org/10.1051/e3sconf/202014703025
18. Kwon B, Kim JH. Importance of molds for nanoimprint lithography: hard, soft, and hybrid molds. J Nanosci. 2016;2016(1):6571297. https://doi.org/10.1155/2016/6571297
19.. Subhan A, Mourad AH, Al-Douri Y. Influence of laser process parameters, liquid medium, and external field on the synthesis of colloidal metal nanoparticles using pulsed laser ablation in liquid: a review. Nanomater. 2022;12(13):2144. https://doi.org/10.3390/nano12132144
20. Imran HJ, Hubeatir KA, Aadim KA, Abd DS. Preparation methods and classification study of nanomaterial: A review. J Phys Conf Ser. 2021 (Vol. 1818, No. 1, p. 012127). IOP Publishing. https://doi.org/10.1088/1742-6596/1818/1/012127
21. Teow Y, Asharani PV, Hande MP, Valiyaveettil S. Health impact and safety of engineered nanomaterials. Chem Commun. 2011;47(25):7025-7038. https://doi.org/10.1039/C0CC05271J
22. Wijesinghe U, Thiripuranathar G, Menaa F, Almukhlifi H. Eco-friendly synthesis of zinc oxide nanoparticles and assessment of their activities as efficient antioxidant agents. Curr Nanosci. 2023;19(1):132-146. https://doi.org/10.2174/1573413718666220513094848

https://doi.org/10.61577/jnd.2024.100008

23. Gharpure S, Ankamwar B. Synthesis and antimicrobial properties of zinc oxide nanoparticles. J Nanosci Nanotechnol. 2020;20(10):5977-5996. https://doi.org/10.1166/jnn.2020.18707

24. Siddiqi KS, Ur Rahman A, Tajuddin N, Husen A. Properties of zinc oxide nanoparticles and their activity against microbes. Nanoscale Res Lett. 2018;13(1):141. https://doi.org/10.1186/s11671-018-2532-3

25. Saptarshi SR, Duschl A, Lopata AL. Biological reactivity of zinc oxide nanoparticles with mammalian test systems: an overview. Nanomed. 2015;10(13):2075-2092. https://doi.org/10.2217/nnm.15.44

26. Alaraby M, Annangi B, Marcos R, Hernández A. *Drosophila melanogaster* as a suitable in vivo model to determine potential side effects of nanomaterials: A review. J Toxicol Environ Health, Part B. 2016;19(2):65-104. https://doi.org/10.1080/10937404.2016.1166466

27. Singh J, Dutta T, Kim KH, Rawat M, Samddar P, Kumar P. 'Green'synthesis of metals and their oxide nanoparticles: applications for environmental remediation. J Nanobiotechnol. 2018;16(1):84. https://doi.org/10.1186/s12951-018-0408-4

28. Jiang J, Pi J, Cai J. The advancing of zinc oxide nanoparticles for biomedical applications. Bioinorg Chem Appl. 2018;2018(1):1062562. https://doi.org/10.1155/2018/1062562

29. Agarwal H, Kumar SV, Rajeshkumar S. A review on green synthesis of zinc oxide nanoparticles–An eco-friendly approach. Resource-efficient Technol. 2017;3(4):406-413. https://doi.org/10.1016/j.reffit.2017.03.002

30. Basnet P, Chanu TI, Samanta D, Chatterjee S. A review on bio-synthesized zinc oxide nanoparticles using plant extracts as reductants and stabilizing agents. J Photochem Photobiol, B. 2018;183:201-221. https://doi.org/10.1016/j.jphotobiol.2018.04.036

31. Zhang Y, R Nayak T, Hong H, Cai W. Biomedical applications of zinc oxide nanomaterials. Curr Mol Med. 2013;13(10):1633-1645. http://dx.doi.org/10.2174/1566524013666131111130058

32. Medina Cruz D, Mostafavi E, Vernet-Crua A, Barabadi H, Shah V, Cholula-Díaz JL, et al. Green nanotechnology-based zinc oxide (ZnO) nanomaterials for biomedical applications: a review. JPhys Mater. 2020;3(3):034005. http://dx.doi.org/10.1088/2515-7639/ab8186

https://doi.org/10.61577/jnd.2024.100008