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SYNTHESIS AND ENCAPSULATION OF BIOGENIC ZINC NANOPARTICLES: MECHANISMS, FUNCTIONALIZATION, AND DIVERSE APPLICATIONS IN MEDICINE, ENVIRONMENT, AGRICULTURE, AND NANOTECHNOLOGY

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ABSTRACT Crumb rubber is a term usually applied to recycled rubber from automotive and truck scrap tyres. During the recycling process steel and fluff is removed leaving Tyre rubber with a granular consistency. Continued processing with a granulator and/or cracker mill, possibly with the aid of cryogenics or mechanical means, reduces the size of the particles further. It is not possible to discharge the rubbers in the environment because they decompose very slowly and cause lots of pollution. So, it is necessary to have a relevant use of these wastages. These waste materials can be used to improve some mechanical properties of concrete. Addition of rubber to concrete results in the improvements of some mechanical and dynamical properties. Such as more energy absorption, better ductility and better crack resistance. By using the waste tyre (crumb rubber) one can reduce the harmful effect on environment and provide sustainable concrete.

KEYWORDS : Crumb Rubber, Utilization, Compressive Strength, Low Cost, Sustainable

INTRODUCTION

The rapid advancement of nanotechnology has significantly influenced various scientific domains, particularly in agriculture, biomedicine, and environmental sustainability. Among the wide range of nanomaterials, zinc oxide nanoparticles (ZnO NPs) have emerged as highly promising due to their unique physicochemical properties, including high surface area, enhanced reactivity, antimicrobial activity, and stability. These properties make ZnO nanoparticles suitable for diverse applications, especially in improving agricultural productivity and addressing micronutrient deficiencies (1,2).

In recent years, the focus has shifted toward biogenic or green synthesis approaches for the production of ZnO nanoparticles. Unlike conventional chemical and physical methods, green synthesis utilizes plant extracts, microorganisms, and biomolecules as reducing and stabilizing agents, thereby minimizing environmental toxicity and enhancing biocompatibility (3,4). This eco-friendly approach not only reduces hazardous byproducts but also imparts additional functional properties to the nanoparticles due to the presence of bioactive compounds.

Zinc is an essential micronutrient that plays a crucial role in plant growth, enzyme activation, and metabolic processes. However, zinc deficiency is a widespread problem affecting both crop productivity and human nutrition. The application of ZnO nanoparticles has been shown to improve zinc uptake, enhance crop yield, and increase nutritional quality, thereby contributing to biofortification strategies aimed at combating micronutrient malnutrition (5,6). For example, foliar application of biosynthesized zinc nanoparticles has been reported to significantly enhance yield and zinc content in crops such as amaranth, demonstrating improved zinc use efficiency (7).

Furthermore, ZnO nanoparticles have demonstrated the ability to enhance plant tolerance to abiotic stresses by modulating antioxidant defense systems and cellular redox balance. Studies have shown that these nanoparticles can improve plant resilience under stress conditions such as heavy metal toxicity and drought (8,9). In addition to agricultural applications, ZnO nanoparticles exhibit multifunctional roles in environmental remediation and biomedical applications, further expanding their significance.

An emerging area of interest is the encapsulation of biogenic Zn nanoparticles, which enhances their stability, controlled release, and targeted delivery. Encapsulation using biopolymers such as chitosan and other nanocarriers improves the efficiency and safety of nanoparticle applications in both agriculture and medicine. This approach also reduces nanoparticle aggregation and potential toxicity, thereby enabling more sustainable and controlled utilization (10).

Despite the promising potential of biogenic Zn nanoparticles, challenges such as scalability, standardization of synthesis methods, and environmental safety remain significant concerns. Therefore, a comprehensive understanding of synthesis strategies, encapsulation techniques, mechanisms, and applications is essential.

This review aims to provide an in-depth overview of the synthesis and encapsulation of biogenic zinc nanoparticles, focusing on their formation mechanisms, functionalization strategies, and diverse applications in agriculture, environmental remediation, and biomedicine. It also highlights current challenges and future perspectives for the development of sustainable nanotechnology-based solutions.

Biogenic Zinc Nanoparticles: Concept And Importance

Biogenic zinc nanoparticles, particularly zinc oxide nanoparticles (ZnO Nps), are synthesized using biological resources such as plant extracts, microorganisms, and biomolecules, offering an environmentally friendly alternative to conventional chemical and physical synthesis methods. These nanoparticles have gained considerable attention due to their sustainable production, reduced toxicity, and enhanced biocompatibility. The use of natural reducing and stabilizing agents in biogenic synthesis not only minimizes hazardous byproducts but also imparts unique surface functionalities that improve nanoparticle performance (1,3,4).

The concept of biogenic synthesis is rooted in green chemistry principles, where biological entities such as phytochemicals, enzymes, and microbial metabolites facilitate the reduction of zinc ions into nanoparticles. Plant-mediated synthesis is particularly advantageous due to its simplicity, cost-effectiveness, and scalability. Phytochemicals such as flavonoids, phenolics, alkaloids, and proteins play a crucial role in the reduction, capping, and stabilization of ZnO nanoparticles, thereby influencing their size, morphology, and functional properties (3,4).

Zinc is an essential micronutrient required for various physiological and biochemical processes in plants, animals, and humans. In agriculture, zinc plays a vital role in enzyme activation, protein synthesis, photosynthesis, and hormone regulation. However, zinc deficiency is a widespread global issue, particularly in developing countries, affecting both crop productivity and human nutrition (5,6). Biogenic Zn nanoparticles have emerged as an effective solution to address this problem by enhancing zinc bioavailability and uptake in plants, thereby improving crop yield and nutritional quality (7).

The importance of biogenic Zn nanoparticles extends beyond agriculture. Their unique physicochemical properties, including high surface area, antimicrobial activity, and photocatalytic efficiency, make them suitable for applications in environmental remediation, drug delivery, and antimicrobial treatments (2,8). In agricultural systems, these nanoparticles have been shown to enhance plant growth, improve stress tolerance, and modulate antioxidant defense mechanisms, thereby increasing resilience against abiotic stresses such as drought, salinity, and heavy metal toxicity (8,9).

Furthermore, the integration of biogenic Zn nanoparticles into sustainable agricultural practices supports the development of eco-friendly fertilizers, pesticides, and growth enhancers. Their controlled release and targeted delivery capabilities reduce excessive chemical inputs, thereby minimizing environmental pollution and promoting soil health. This aligns with global efforts to achieve sustainable agriculture and food security.

Despite these advantages, challenges such as variability in synthesis methods, lack of standardization, and potential environmental risks require further investigation. Nonetheless, biogenic zinc nanoparticles represent a promising and sustainable approach in nanotechnology, with significant potential to address current challenges in agriculture, environmental protection, and public health.

Sources For Biogenic Synthesis (Plants, Microorganisms, Biomolecules)

The biogenic synthesis of zinc nanoparticles relies on diverse biological sources, including plants, microorganisms, and biomolecules, which act as natural reducing and stabilizing agents. These sources provide an eco-friendly, cost-effective, and sustainable alternative to conventional synthesis methods, while also influencing the physicochemical properties of the resulting nanoparticles (3,4).

Plant-Mediated Synthesis

Plant extracts are the most widely used source for the green synthesis of zinc nanoparticles due to their availability, simplicity, and scalability. Various parts of plants, including leaves, stems, roots, flowers, and fruits, contain bioactive compounds such as flavonoids, phenolics, terpenoids, alkaloids, and proteins. These phytochemicals play a dual role by reducing zinc ions (Zn^{2+}) into nanoparticles and stabilizing them through capping mechanisms (3).

Plant-mediated synthesis offers several advantages, including rapid synthesis rates, low toxicity, and the elimination of the need for complex culturing conditions required in microbial methods. Additionally, the type and concentration of phytochemicals influence nanoparticle size, morphology, and stability, making this method highly tunable for specific applications (4). This approach has been widely explored for agricultural and biomedical applications due to its eco-friendly nature.

Microorganism-Mediated Synthesis

Microorganisms such as bacteria, fungi, algae, and yeast have also been extensively studied for the biosynthesis of zinc nanoparticles. These organisms possess inherent metabolic pathways and enzymatic systems capable of reducing metal ions into nanoparticles. The synthesis can occur either intracellularly or extracellularly, depending on the organism and conditions (4).

Bacterial synthesis is often rapid and can be easily controlled, while fungi are known for producing large quantities of nanoparticles due to their high tolerance to metal ions and secretion of extracellular enzymes. Algae-mediated synthesis is gaining attention due to its simplicity and the presence of natural biomolecules that facilitate nanoparticle formation. Microbial synthesis offers advantages such as uniform particle size and better control over morphology; however, it requires sterile conditions and careful handling, which may limit large-scale applications (3,4).

Biomolecule-Assisted Synthesis

Biomolecules such as proteins, enzymes, polysaccharides, amino acids, and vitamins can also be used independently for the synthesis of zinc nanoparticles. These molecules act as both reducing and capping agents, providing precise control over nanoparticle formation and stabilization. For instance, proteins and enzymes can facilitate controlled nucleation and growth of nanoparticles, resulting in uniform size distribution and enhanced functional properties.

Polysaccharides such as chitosan and starch are particularly important in this context, as they not only stabilize nanoparticles but also enhance their biocompatibility and applicability in drug delivery and environmental remediation (10). Biomolecule-assisted synthesis is advantageous due to its specificity, reproducibility, and ability to tailor nanoparticle properties for targeted applications.

Overall, the choice of biological source plays a critical role in determining the characteristics and performance of biogenic zinc nanoparticles. Plant-based methods are preferred for their simplicity and scalability, while microbial and biomolecule-assisted approaches offer better control and specificity. The integration of these biological sources into nanoparticle synthesis aligns with green chemistry principles and supports the development of sustainable nanotechnology solutions for diverse applications.

Green Synthesis Methods of Zn Nanoparticles

Green synthesis of zinc nanoparticles, particularly zinc oxide nanoparticles (ZnO Nps), has emerged as a sustainable and environmentally friendly alternative to conventional chemical and physical methods. This approach utilizes biological entities such as plant extracts, microorganisms, and biomolecules as reducing, stabilizing, and capping agents, thereby minimizing the use of toxic chemicals and energy-intensive processes (3,4). The green synthesis methods are simple, cost-effective, and align with the principles of green chemistry, making them highly suitable for large-scale production.

Plant Extract-Mediated Synthesis

Plant-mediated synthesis is one of the most widely adopted green methods for the production of Zn nanoparticles. In this approach, aqueous or solvent extracts of plant parts such as leaves, roots, stems, flowers, or fruits are mixed with zinc salt precursors (e.g., zinc nitrate, zinc acetate). The phytochemicals present in the extracts, including flavonoids, phenolics, terpenoids, and alkaloids, facilitate the reduction of Zn^{2+} ions and stabilize the formed nanoparticles (3).

The process typically involves mixing the extract with the precursor solution under controlled conditions of pH, temperature, and reaction time, followed by calcination to obtain ZnO nanoparticles. This method is advantageous due to its simplicity, rapid synthesis, and ability to produce nanoparticles with diverse morphologies and sizes. Additionally, the presence of natural capping agents enhances the stability and functional properties of the nanoparticles (4).

Microbial-Mediated Synthesis

Microbial synthesis involves the use of bacteria, fungi, algae, or yeast to produce Zn nanoparticles through biological processes. Microorganisms possess enzymes and metabolic pathways capable of reducing metal ions into nanoparticles either intracellularly or extracellularly. Enzymes such as reductases play a key role in the conversion of Zn^{2+} ions into ZnO nanoparticles (4).

Fungi are particularly efficient in nanoparticle synthesis due to their high metal tolerance and secretion of extracellular enzymes, while bacteria offer faster synthesis rates and ease of genetic manipulation. Although microbial methods provide better control over particle size and morphology, they require sterile conditions and careful optimization of growth parameters, which can limit scalability (3,4).

Biomolecule-Assisted Synthesis

Biomolecule-assisted synthesis utilizes isolated biological compounds such as proteins, enzymes, polysaccharides, amino acids, and vitamins for nanoparticle production. These biomolecules act as both reducing and stabilizing agents, enabling controlled nucleation and growth of nanoparticles. For example, polysaccharides like chitosan and starch can stabilize Zn nanoparticles and improve their biocompatibility and dispersion (10).

This method offers advantages such as reproducibility, specificity, and the ability to tailor nanoparticle properties for targeted applications. It is particularly useful in biomedical and environmental applications where precise control over nanoparticle characteristics is required.

Green Sol Gel and Precipitation Methods

Green adaptations of conventional sol gel and precipitation methods have also been developed, where biological extracts or biomolecules are incorporated into the synthesis process. In these methods, zinc precursors undergo hydrolysis and condensation reactions in the presence of green stabilizing agents, resulting in the formation of ZnO nanoparticles (1).

These approaches allow better control over particle size, crystallinity, and morphology while maintaining environmental sustainability. The use of eco-friendly solvents and mild reaction conditions further enhances the green nature of these methods.

Overall, green synthesis methods offer a versatile and sustainable route for the production of Zn nanoparticles with enhanced functional properties. The choice of method depends on factors such as desired nanoparticle characteristics, scalability, and application requirements. Continued advancements in green synthesis are expected to play a crucial role in the development of next-generation nanomaterials for agriculture, environmental remediation, and biomedical applications.

Encapsulation Techniques (Polymeric, Liposomal, Nano-carriers)

Encapsulation of biogenic zinc nanoparticles (Zn Nps), particularly

ZnO nanoparticles, is a crucial strategy to enhance their stability, bioavailability, controlled release, and targeted delivery. Encapsulation also minimizes nanoparticle aggregation and potential toxicity, thereby improving their efficiency and safety in agricultural, environmental, and biomedical applications. Various encapsulation techniques have been developed, including polymeric systems, liposomal carriers, and other nanocarrier-based approaches (10).

Polymeric Encapsulation

Polymeric encapsulation is one of the most widely used techniques for stabilizing zinc nanoparticles. Natural and synthetic polymers such as chitosan, alginate, starch, poly(lactic acid) (PLA), and polyethylene glycol (PEG) are commonly employed as encapsulating agents. Among these, chitosan is particularly advantageous due to its biodegradability, biocompatibility, and presence of functional groups that facilitate strong interactions with nanoparticles (10).

In polymeric encapsulation, Zn nanoparticles are either embedded within the polymer matrix or coated with a polymeric layer, forming nanocapsules or nanospheres. This approach enhances dispersion, prevents agglomeration, and allows controlled release of zinc ions. In agricultural applications, polymer-encapsulated Zn nanoparticles can provide sustained nutrient delivery, improving zinc uptake efficiency and reducing leaching losses (5). Additionally, polymer coatings can improve the stability of nanoparticles under varying environmental conditions.

Liposomal Encapsulation

Liposomal encapsulation involves the incorporation of Zn nanoparticles within lipid bilayer vesicles known as liposomes. These vesicles are composed of phospholipids and cholesterol, which form a biocompatible and biodegradable structure capable of encapsulating both hydrophilic and hydrophobic substances.

Liposomes offer several advantages, including enhanced stability, protection of nanoparticles from degradation, and targeted delivery. In biomedical applications, liposomal Zn nanoparticles have been explored for drug delivery, antimicrobial treatments, and wound healing due to their ability to interact effectively with biological membranes (10). Moreover, liposomal systems can improve the controlled release of zinc, thereby reducing toxicity and enhancing therapeutic efficacy.

Nano-carrier-Based Encapsulation

Nano-carriers represent a broad class of delivery systems that include dendrimers, nanoemulsions, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs), and inorganic carriers such as silica and clay. These systems are designed to improve the delivery, stability, and functionality of Zn nanoparticles.

Nano-carrier-based encapsulation enables precise control over particle size, surface properties, and release kinetics. For instance, silica-based carriers provide high surface area and porosity, facilitating efficient loading and release of Zn nanoparticles. Similarly, lipid-based carriers such as SLNs and NLCs enhance bioavailability and reduce toxicity, making them suitable for both agricultural and biomedical applications (2).

In agriculture, nano-carriers can be used for the controlled release of zinc fertilizers and pesticides, improving nutrient use efficiency and reducing environmental impact. In environmental applications, these systems enhance the dispersion and reactivity of Zn nanoparticles, improving their performance in pollutant removal.

Overall, encapsulation techniques play a vital role in optimizing the performance of biogenic zinc nanoparticles. By improving stability, reducing toxicity, and enabling controlled release, these approaches significantly enhance the applicability of Zn nanoparticles across diverse fields. Continued research in advanced encapsulation strategies is expected to further expand the potential of these nanomaterials in sustainable agriculture, environmental remediation, and biomedicine.

Characterization Techniques

Characterization of biogenic zinc nanoparticles (Zn Nps), particularly zinc oxide nanoparticles (ZnO NPs), is essential to determine their structural, morphological, optical, and chemical properties. These characteristics significantly influence their performance in various applications, including agriculture, environmental remediation, and biomedicine. A combination of analytical techniques is typically employed to obtain comprehensive information about nanoparticle size, shape, crystallinity, surface chemistry, and stability (1,3).

UV Visible Spectroscopy (UV Vis)

UV Visible spectroscopy is a widely used technique for the preliminary confirmation of nanoparticle formation. ZnO nanoparticles exhibit a characteristic absorption peak in the UV region (typically around 300 380 nm), corresponding to their band-gap energy. This technique is useful for monitoring nanoparticle synthesis, stability, and optical properties (3).

X-ray Diffraction (XRD)

X-ray diffraction analysis is employed to determine the crystalline structure, phase purity, and average crystallite size of ZnO nanoparticles. The characteristic diffraction peaks correspond to the hexagonal wurtzite structure of ZnO. The crystallite size can be estimated using the Debye Scherrer equation, providing insights into nanoparticle formation and growth (1).

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis is used to identify functional groups present on the surface of nanoparticles and to confirm the involvement of biomolecules in reduction and stabilization. Peaks corresponding to OH, NH, C=O, and other functional groups indicate the presence of phytochemicals or biomolecules acting as capping agents (4). This technique is particularly important in biogenic synthesis to understand nanoparticle biomolecule interactions.

Scanning Electron Microscopy (SEM)

SEM provides detailed information about the surface morphology, shape, and size distribution of Zn nanoparticles. It allows visualization of particle aggregation, surface texture, and structural uniformity. SEM images are essential for understanding the physical characteristics of nanoparticles synthesized through different methods (1).

Transmission Electron Microscopy (TEM)

TEM is a powerful technique for analyzing nanoparticle size, shape, and internal structure at the nanoscale. It provides high-resolution images that reveal particle morphology, crystallinity, and dispersion. TEM is often used in conjunction with selected area electron diffraction (SAED) to confirm crystalline structure (3).

Dynamic Light Scattering (DLS) and Zeta Potential Analysis

DLS is used to measure the hydrodynamic size distribution of nanoparticles in suspension, while zeta potential analysis provides information about surface charge and stability. High zeta potential values indicate good colloidal stability, which is crucial for preventing aggregation and ensuring effective application (4).

Energy Dispersive X-ray Spectroscopy (EDX/EDS)

EDX analysis is used to determine the elemental composition and purity of Zn nanoparticles. It confirms the presence of zinc and oxygen in ZnO nanoparticles and detects any impurities or additional elements introduced during synthesis (1).

Overall, the characterization of Zn nanoparticles using these techniques provides critical insights into their physicochemical properties, which directly influence their functionality and application performance. A comprehensive characterization approach is essential for optimizing synthesis methods and ensuring reproducibility and reliability in practical applications.

Mechanisms of Formation and Stabilization

The formation and stabilization of biogenic zinc nanoparticles (Zn Nps), particularly zinc oxide nanoparticles (ZnO NPs), involve complex physicochemical and biological processes. These mechanisms are primarily governed by reduction, nucleation, growth, and stabilization stages, which are facilitated by biomolecules present in plant extracts, microorganisms, or isolated biological compounds (3,4).

Reduction and Nucleation

The initial step in the formation of Zn nanoparticles is the reduction of zinc ions (Zn^{2+}) into zinc or zinc oxide nuclei. In biogenic synthesis, this reduction is mediated by phytochemicals such as flavonoids, phenolics, terpenoids, and proteins, or by microbial enzymes such as reductases. These biomolecules donate electrons to zinc ions, leading to the formation of neutral atoms that subsequently aggregate to form nuclei (3).

Once the concentration of reduced atoms reaches a critical supersaturation level, nucleation occurs, resulting in the formation of small, stable clusters. This stage is crucial as it determines the number of nanoparticles formed and influences their final size distribution.

Growth and Aggregation

Following nucleation, nanoparticles undergo a growth phase, where additional zinc atoms or ions are deposited onto the existing nuclei. This process can occur through mechanisms such as Ostwald ripening, where smaller particles dissolve and redeposit onto larger ones, leading to an increase in particle size.

Without proper stabilization, nanoparticles tend to aggregate due to high surface energy. Therefore, controlling the growth phase is essential to achieve uniform particle size and desired morphology. Factors such as pH, temperature, precursor concentration, and reaction time significantly influence the growth process (1).

Stabilization and Capping

Stabilization is a critical step that prevents nanoparticle aggregation and ensures long-term stability. In biogenic synthesis, biomolecules act as capping agents, binding to the surface of nanoparticles through functional groups such as –OH, $–NH_2$, and –COOH. These interactions create a protective layer around the nanoparticles, reducing surface energy and preventing agglomeration (4).

Plant-derived compounds such as polyphenols and proteins not only stabilize nanoparticles but also influence their size, shape, and surface charge. Similarly, in microbial synthesis, extracellular proteins and enzymes contribute to nanoparticle stabilization. This natural capping enhances the biocompatibility and functional properties of Zn nanoparticles.

Role of Environmental Parameters

The formation and stabilization mechanisms are strongly influenced by reaction conditions. Parameters such as pH, temperature, precursor concentration, and reaction time play a significant role in determining nanoparticle characteristics. For example, alkaline pH conditions generally favor the formation of ZnO nanoparticles, while higher temperatures can accelerate reaction kinetics and influence crystallinity (1,3).

Mechanism of ZnO Formation

In most green synthesis routes, zinc salts undergo hydrolysis and condensation reactions, leading to the formation of $Zn(OH)_2$ intermediates, which are subsequently converted into ZnO nanoparticles upon dehydration or calcination. Biomolecules present in the system facilitate these transformations and stabilize the resulting nanoparticles (1).

Overall, the formation and stabilization of biogenic Zn nanoparticles are governed by a combination of chemical and biological interactions. The involvement of natural reducing and capping agents not only ensures environmentally friendly synthesis but also enhances the functional properties of nanoparticles. A thorough understanding of these mechanisms is essential for controlling nanoparticle characteristics and optimizing their performance for specific applications.

Surface Functionalization Strategies

Surface functionalization of biogenic zinc nanoparticles (Zn Nps), particularly ZnO nanoparticles, is a critical step to enhance their stability, dispersibility, selectivity, and overall performance in various applications. Functionalization involves the modification of nanoparticle surfaces with specific chemical groups, polymers, or biomolecules to tailor their physicochemical properties and improve their interaction with target systems (4,10).

Chemical Functionalization

Chemical functionalization involves the introduction of functional groups such as hydroxyl (–OH), carboxyl (–COOH), amino ($–NH_2$), and thiol (–SH) onto the surface of Zn nanoparticles. These groups enhance the binding affinity of nanoparticles toward specific molecules or ions through mechanisms such as coordination, hydrogen bonding, and electrostatic interactions.

For example, the incorporation of carboxyl or amine groups improves the adsorption of heavy metals and organic pollutants, making functionalized Zn nanoparticles highly effective in environmental remediation. Chemical modification also enhances colloidal stability by preventing aggregation and improving dispersion in aqueous media (1).

Polymer Coating

Polymer-based functionalization is widely used to improve the stability and biocompatibility of Zn nanoparticles. Polymers such as chitosan, polyethylene glycol (PEG), polyvinyl alcohol (PVA), and alginate are commonly used as coating agents. These polymers form a protective layer around the nanoparticles, reducing agglomeration and enhancing resistance to environmental conditions (10).

Chitosan-coated Zn nanoparticles, for instance, exhibit improved antimicrobial activity and controlled release properties, making them suitable for applications in agriculture and biomedicine. Polymer coatings also enable sustained release of zinc ions, which is beneficial for nutrient delivery in plants (5).

Biomolecule Functionalization

Biomolecule-based functionalization utilizes proteins, enzymes, polysaccharides, and other biological compounds to modify nanoparticle surfaces. These biomolecules not only stabilize the nanoparticles but also introduce functional groups that enhance specificity and biocompatibility.

For example, proteins can facilitate targeted interactions with biological systems, while polysaccharides such as starch and chitosan improve dispersion and reduce toxicity. This approach is particularly useful in biomedical applications, where biocompatibility and targeted delivery are essential (4).

Ligand and Surfactant Modification

Surface modification using ligands and surfactants is another effective strategy to control nanoparticle size, morphology, and surface charge. Ligands such as citrate, oleic acid, and ethylenediamine can bind to nanoparticle surfaces, altering their chemical reactivity and interaction with surrounding media.

Surfactants help reduce surface tension and prevent aggregation during synthesis, resulting in well-dispersed nanoparticles with uniform size distribution. These modifications are particularly important in applications requiring high stability and reproducibility (1).

Functionalization for Targeted Applications

Advanced functionalization strategies focus on tailoring Zn nanoparticles for specific applications. For instance, in agriculture, functionalized nanoparticles can be designed for controlled nutrient release and enhanced uptake efficiency. In environmental applications, surface-modified Zn nanoparticles can selectively adsorb pollutants or degrade contaminants through photocatalytic activity. In biomedical fields, functionalization enables targeted drug delivery, antimicrobial activity, and reduced cytotoxicity (2,8).

Overall, surface functionalization plays a pivotal role in enhancing the performance and applicability of biogenic zinc nanoparticles. By modifying surface properties, it is possible to improve stability, selectivity, and efficiency across diverse applications. Continued advancements in functionalization techniques are expected to further expand the potential of Zn nanoparticles in sustainable and high-performance nanotechnology applications.

Biomedical Applications

Biogenic zinc nanoparticles (Zn Nps), particularly zinc oxide nanoparticles (ZnO NPs), have gained significant attention in the biomedical field due to their unique physicochemical properties, biocompatibility, antimicrobial activity, and ability to interact with biological systems. Their nanoscale size, high surface area, and reactive surface functionalities enable them to be effectively utilized in various biomedical applications, including antimicrobial therapy, drug delivery, wound healing, and anticancer treatment (2,10).

Antimicrobial Activity

One of the most prominent biomedical applications of ZnO nanoparticles is their broad-spectrum antimicrobial activity against bacteria, fungi, and viruses. The antimicrobial mechanism is primarily attributed to the generation of reactive oxygen species (ROS), release of Zn^{2+} ions, and disruption of microbial cell membranes. These processes lead to oxidative stress, protein denaturation, and eventual cell death (2).

Biogenic Zn nanoparticles often exhibit enhanced antimicrobial activity due to the presence of bioactive compounds on their surface, which act synergistically with ZnO to inhibit microbial growth. This makes them suitable for applications in coatings, disinfectants, and antimicrobial formulations (4).

Drug Delivery Systems

Zn nanoparticles are increasingly being explored as drug delivery carriers due to their ability to encapsulate and release therapeutic agents in a controlled manner. Surface functionalization and encapsulation techniques, such as polymeric or liposomal systems, improve the stability and targeting efficiency of Zn nanoparticles.

Their pH-responsive behavior allows for targeted drug release in specific environments, such as tumor tissues or infected sites. Additionally, their biocompatibility and biodegradability reduce the risk of adverse side effects, making them suitable for advanced drug delivery applications (10).

Wound Healing Applications

ZnO nanoparticles play a crucial role in wound healing due to their antimicrobial, anti-inflammatory, and tissue regeneration properties. They promote faster wound closure by enhancing cell proliferation, collagen synthesis, and angiogenesis.

Zn nanoparticles are often incorporated into wound dressings, hydrogels, and nanofibrous scaffolds to provide sustained antimicrobial protection and accelerate the healing process. Their ability to prevent infection while supporting tissue repair makes them highly effective in clinical applications (2).

Anticancer Activity

Recent studies have demonstrated the potential of ZnO nanoparticles in cancer therapy. Zn nanoparticles can selectively induce cytotoxic effects in cancer cells through mechanisms such as ROS generation, apoptosis induction, and DNA damage. Their ability to preferentially target cancer cells while minimizing effects on normal cells makes them promising candidates for anticancer applications (8).

Furthermore, functionalized Zn nanoparticles can be used for targeted drug delivery in cancer treatment, improving therapeutic efficacy and reducing systemic toxicity.

Biosensing and Diagnostic Applications

Zn nanoparticles are also used in biosensing and diagnostic systems due to their optical, electrical, and catalytic properties. They can be employed in the detection of biomolecules, pathogens, and disease markers with high sensitivity and specificity.

The integration of Zn nanoparticles into biosensors enhances signal transduction and detection accuracy, making them valuable tools in medical diagnostics and monitoring (1).

Overall, the biomedical applications of biogenic zinc nanoparticles are extensive and continue to expand with advancements in nano-technology. Their multifunctional properties, combined with eco-friendly synthesis and enhanced biocompatibility, make them highly promising for next-generation medical applications. However, further studies on toxicity, long-term effects, and clinical validation are essential to ensure their safe and effective use in healthcare.

Environmental Applications

Biogenic zinc nanoparticles (Zn Nps), particularly zinc oxide nanoparticles (ZnO NPs), have emerged as highly effective materials for environmental remediation due to their unique physicochemical properties, including high surface area, photocatalytic activity, and strong adsorption क्षमता. These properties enable Zn nanoparticles to efficiently remove a wide range of environmental pollutants, making them valuable in water treatment, air purification, and soil remediation (1,2).

Water and Wastewater Treatment

One of the most significant environmental applications of Zn nanoparticles is in water and wastewater treatment. ZnO nanoparticles exhibit strong adsorption and catalytic properties, allowing them to remove contaminants such as heavy metals (e.g., Pb^{2+}, Cd^{2+}, Cr^{6+}), dyes, and organic pollutants from water.

Additionally, ZnO nanoparticles act as effective photocatalysts, generating reactive oxygen species (ROS) under light irradiation, which degrade complex organic compounds into less harmful substances. This makes them highly suitable for the treatment of industrial wastewater containing dyes and toxic chemicals (1). Their incorporation into membranes and nanocomposite systems further enhances filtration efficiency and fouling resistance.

Degradation of Organic Pollutants

Zn nanoparticles play a crucial role in the photocatalytic degradation of organic pollutants, including pesticides, pharmaceuticals, and endocrine-disrupting compounds. Under UV or visible light, ZnO nanoparticles generate electron hole pairs that lead to the formation of reactive radicals such as hydroxyl (OH) and superoxide (O_2^-), which break down organic pollutants into simpler, non-toxic molecules (2).

Biogenic Zn nanoparticles often exhibit enhanced photocatalytic efficiency due to the presence of surface-bound biomolecules that improve light absorption and charge separation.

Air Purification

ZnO nanoparticles are also utilized in air purification systems due to their ability to degrade airborne pollutants and microorganisms. Their antimicrobial and photocatalytic properties enable them to eliminate harmful gases, volatile organic compounds (VOCs), and airborne pathogens.

Zn nanoparticle-based coatings and filters are increasingly being used in air purification devices to improve indoor air quality and reduce environmental pollution (2).

Soil Remediation

In soil remediation, Zn nanoparticles are used to remove or neutralize contaminants such as heavy metals and organic pollutants. Their high reactivity allows them to interact with toxic substances, reducing their mobility and bioavailability in soil.

Additionally, Zn nanoparticles can enhance soil health by improving nutrient availability and microbial activity, making them beneficial for sustainable agriculture and environmental restoration (5).

Antimicrobial Environmental Applications

The antimicrobial properties of Zn nanoparticles are also valuable in environmental contexts, particularly for controlling microbial contamination in water and soil. They can inhibit the growth of harmful bacteria, fungi, and algae, thereby improving environmental hygiene and safety (2).

Overall, the environmental applications of biogenic zinc nanoparticles are diverse and highly impactful. Their ability to simultaneously adsorb, degrade, and neutralize pollutants makes them versatile tools for environmental remediation. However, concerns regarding nanoparticle accumulation, potential toxicity, and long-term environmental effects must be carefully addressed. Future research should focus on developing safe, sustainable, and scalable approaches for the practical implementation of Zn nanoparticles in environmental applications.

Agricultural Applications

Biogenic zinc nanoparticles (Zn Nps), particularly zinc oxide nanoparticles (ZnO NPs), have gained considerable attention in agriculture due to their ability to enhance crop productivity, improve nutrient use efficiency, and increase plant resistance to environmental stresses. Their nanoscale size, high surface area, and controlled release properties make them highly effective as nano-fertilizers, growth promoters, and plant protection agents (2,5).

Nano-fertilizers and Nutrient Delivery

One of the primary applications of Zn nanoparticles in agriculture is as nano-fertilizers. Zinc is an essential micronutrient involved in enzyme activation, photosynthesis, and protein synthesis in plants. However, conventional zinc fertilizers often suffer from low bioavailability and high losses due to leaching and fixation in soil.

Zn nanoparticles provide a more efficient alternative by enabling controlled and sustained release of zinc ions, thereby improving nutrient uptake and utilization efficiency. Studies have shown that the application of ZnO nanoparticles significantly enhances crop yield and zinc content in edible plant parts, contributing to biofortification and improved nutritional quality (5,7).

Plant Growth Promotion

Zn nanoparticles play a vital role in stimulating plant growth and development. They enhance seed germination, root elongation, chlorophyll synthesis, and overall biomass production. These effects are attributed to improved nutrient availability and activation of key metabolic pathways in plants (8).

Additionally, Zn nanoparticles influence hormonal regulation and enzyme activity, leading to improved physiological performance and crop productivity.

Stress Tolerance and Antioxidant Activity

Zn nanoparticles are known to enhance plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity. They help regulate the cellular redox balance by activating antioxidant defence systems, including enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) (8,9).

This improved stress tolerance enables plants to maintain growth and productivity under adverse environmental conditions, which is critical for sustainable agriculture in the context of climate change.

Pest and Disease Management

Biogenic Zn nanoparticles exhibit strong antimicrobial and antifungal properties, making them effective in controlling plant pathogens. They can inhibit the growth of bacteria, fungi, and other harmful microorganisms that affect crop health.

Zn nanoparticles are also being explored as nano-pesticides, offering targeted action with reduced environmental impact compared to conventional chemical pesticides. Their use can help minimize chemical residues and promote eco-friendly pest management practices (2).

Soil Health and Nutrient Management

Zn nanoparticles contribute to improved soil fertility and nutrient cycling by enhancing microbial activity and nutrient availability. Their application can help correct zinc deficiency in soils, which is a major constraint in agricultural productivity in many regions (5,6).

Furthermore, the integration of Zn nanoparticles with organic amendments and sustainable farming practices supports long-term soil health and agricultural sustainability.

Overall, the application of biogenic zinc nanoparticles in agriculture represents a significant advancement toward sustainable and efficient farming systems. Their ability to improve crop yield, nutritional quality, and stress resilience highlights their potential as a key component of next-generation agricultural technologies. However, careful evaluation of dosage, environmental impact, and long-term effects is necessary to ensure their safe and effective use.

Industrial Applications

Biogenic zinc nanoparticles (Zn Nps), particularly zinc oxide nanoparticles (ZnO NPs), have found extensive applications across various industrial sectors due to their unique physicochemical properties, including high surface area, catalytic activity, antimicrobial behavior, and UV-blocking capability. These properties make Zn nanoparticles valuable in industries such as textiles, cosmetics, electronics, food packaging, and environmental engineering (1,2).

Textile Industry

In the textile sector, ZnO nanoparticles are widely used for imparting antimicrobial, UV-protective, and self-cleaning properties to fabrics. Coating textiles with Zn nanoparticles enhances resistance to bacterial growth and odor formation, improving hygiene and durability. Additionally, ZnO nanoparticles provide protection against harmful ultraviolet (UV) radiation, making them suitable for protective clothing and outdoor textiles (2).

Cosmetics and Personal Care Products

ZnO nanoparticles are extensively used in the cosmetic industry, particularly in sunscreens, lotions, and skin-care products. Due to their strong UV-absorbing and scattering properties, they act as effective physical sunscreens, protecting the skin from both UVA and UVB radiation. Their biocompatibility and low toxicity make them suitable for topical applications (1).

Moreover, their antimicrobial properties contribute to their use in formulations aimed at preventing skin infections and promoting skin health.

Electronics and Optoelectronics

ZnO nanoparticles possess unique semiconducting and optical properties, making them useful in electronic and optoelectronic applications. They are employed in devices such as sensors, light-emitting diodes (LEDs), solar cells, and photodetectors.

Their wide band gap and high exciton binding energy enable efficient performance in electronic devices, while their nanoscale size allows for improved sensitivity and miniaturization of components (1).

Food Packaging Industry

In the food industry, Zn nanoparticles are used in active and smart packaging systems. Their antimicrobial activity helps inhibit the growth of foodborne pathogens, thereby extending the shelf life of food products. ZnO nanoparticles can be incorporated into packaging materials to provide protective barriers against microbial contamination and oxidation (2).

Additionally, their ability to interact with environmental stimuli makes them suitable for developing intelligent packaging systems that monitor food quality.

Catalysis and Environmental Engineering

Zn nanoparticles are widely used as catalysts and photocatalysts in industrial processes. They facilitate chemical reactions, including oxidation, reduction, and degradation of pollutants, with high efficiency. Their photocatalytic properties are particularly useful in wastewater treatment and environmental remediation (1).

In industrial wastewater management, ZnO nanoparticles are employed to degrade toxic organic compounds and dyes, contributing to cleaner production processes.

Overall, the industrial applications of biogenic zinc nanoparticles are diverse and continue to expand with advancements in nanotechnology. Their multifunctional properties, combined with eco-friendly synthesis methods, make them highly attractive for sustainable industrial development. However, issues related to large-scale production, cost, and environmental safety must be carefully addressed to ensure their widespread adoption.

Toxicity, Safety, and Biocompatibility

Despite the promising applications of biogenic zinc nanoparticles (Zn Nps), concerns regarding their toxicity, safety, and long-term effects on biological systems and the environment remain critical. The toxicity of Zn nanoparticles is primarily influenced by factors such as particle size, concentration, surface charge, and exposure duration (1,2).

ZnO nanoparticles can generate reactive oxygen species (ROS), leading to oxidative stress, cellular damage, and inflammation in living systems. At higher concentrations, they may induce cytotoxic and genotoxic effects, affecting cell viability and DNA integrity (2). However, biogenic Zn nanoparticles generally exhibit lower toxicity compared to chemically synthesized counterparts due to the presence of natural capping agents, which enhance their biocompatibility (4).

In biomedical applications, Zn nanoparticles are considered relatively safe at controlled doses, as zinc is an essential trace element required for physiological functions. Their biodegradability and ability to release Zn^{2+} ions in a controlled manner further contribute to their safety profile (10). In agricultural applications, excessive accumulation of Zn nanoparticles in soil may affect microbial communities and soil health, necessitating careful dosage optimization (5).

Therefore, comprehensive toxicological studies, including in vitro and in vivo evaluations, are essential to ensure the safe application of Zn nanoparticles. Regulatory frameworks and standardized assessment protocols are also needed to address potential risks associated with their widespread use.

Challenges and Limitations

Despite significant advancements, several challenges hinder the large-scale application of biogenic zinc nanoparticles. One of the major limitations is the lack of standardization in synthesis methods, leading to variability in nanoparticle size, morphology, and properties (3).

Another key challenge is scalability, as most green synthesis approaches are developed at the laboratory scale and may face difficulties in industrial-scale production. Additionally, controlling the uniformity and reproducibility of nanoparticles remains a concern (1).

The potential environmental risks, including nanoparticle accumulation and unintended ecological impacts, also pose significant challenges. The release of Zn nanoparticles into soil and water systems may affect non-target organisms and disrupt ecological balance (2).

Furthermore, issues related to stability, aggregation, and limited shelf life can affect the performance of Zn nanoparticles in practical applications. The high cost of advanced characterization techniques and encapsulation processes also limits their commercial viability.

Future Perspectives

The future of biogenic zinc nanoparticles lies in the development of advanced, sustainable, and application-specific nanomaterials. Emerging research is focused on smart and functionalized nanoparticles that can respond to environmental stimuli such as pH, temperature, and light, enabling targeted and efficient applications (1).

Advancements in encapsulation and surface functionalization techniques are expected to improve stability, reduce toxicity, and enable controlled release systems for agricultural and biomedical applications. The integration of Zn nanoparticles with other nanomaterials may lead to the development of hybrid systems with enhanced multifunctional properties.

Furthermore, the adoption of green and scalable synthesis methods using renewable resources will play a crucial role in promoting sustainable nanotechnology. Interdisciplinary research combining nanotechnology, biotechnology, and environmental science is essential for addressing current limitations.

Future studies should also focus on long-term safety assessments, regulatory guidelines, and real-world applications to bridge the gap between laboratory research and industrial implementation.

CONCLUSION

Biogenic zinc nanoparticles represent a promising and sustainable advancement in nanotechnology, offering diverse applications in agriculture, environmental remediation, and biomedicine. Their eco-friendly synthesis, enhanced biocompatibility, and multifunctional properties make them highly attractive alternatives to conventional materials.

This review highlights the key aspects of synthesis, encapsulation, characterization, mechanisms, and applications of Zn nanoparticles, emphasizing their potential to improve crop productivity, environmental sustainability, and healthcare outcomes. Despite existing challenges related to scalability, stability, and safety, ongoing research and technological advancements are expected to overcome these limitations.

In conclusion, the integration of biogenic zinc nanoparticles into modern scientific and industrial practices holds significant potential for addressing global challenges related to food security, environmental protection, and public health. Continued innovation, coupled with responsible application and regulation, will be essential for realizing the full potential of these nanomaterials.

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