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Research Article

A REVIEW PAPER ON ECO-FRIENDLY PRODUCTION AND USE OF ZINC OXIDE NANOPARTICLES

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Abstract

The development of sustainable and consistent methods for nanoparticle production is essential to the field of nanotechnology. Nanoparticles have been consistently evaluated and employed in various industrial applications during the past decade. Because of their many unique properties, such as UV filtering, photochemical activity, antifungal efficacy, catalytic capabilities, and antibacterial effects, zinc oxide nanoparticles (ZnO NPs) have attracted a lot of attention. Due to the elevated levels of harmful substances and the extreme conditions associated with chemical and physical techniques, eco-friendly approaches employing plants, fungi, bacteria, and algae have been implemented for nanoparticle synthesis. This study examines diverse sustainable production methods to demonstrate the importance of ZnO nanoparticles in numerous applications. Consequently, the study utilized multiple secondary sources to aggregate pertinent review papers. The findings show that compared to conventional physical and chemical synthesis methods, the green synthesis process is both much safer and more environmentally friendly. ZnO nanoparticles offer a viable substitute in water treatment technology and are efficient agents for wastewater treatment.

Keywords: Nanoparticle, ZnO.

INTRODUCTION

Nanotechnology is a swiftly advancing domain in science and technology, resulting in significant advancements in recent years [1]. The nanomaterial, defined by its unique physicochemical properties, has the ability to enhance many systems, structures, devices, and nanoplatforms across multiple domains [2]. Nanomaterials are nanoscale particles distinguished by their small size and remarkable thermal conductivity, catalytic reactivity, nonlinear optical characteristics, and chemical durability, due to their high surface area-to-volume ratio. This attribute has drawn numerous researchers to explore innovative synthesis techniques. Traditional methods (physical and chemical processes) produce significant quantities of nanoparticles rapidly; however, they necessitate hazardous materials, such as stabilizing agents, which contribute to environmental toxicity [3]. Consequently, green technology utilizing plants is emerging as an environmentally sustainable, non-toxic, and safe alternative, The creation of nanoparticles by extracts from plants is economically advantageous and offers natural binding substances in the type of proteins. The biological synthesis of diverse metal oxides and metal nanoparticles through plant extraction is utilized to mitigate environmental chemical toxicity. This approach is constrained in its capacity to manage chemical synthesis and facilitates precise control over nanoparticle morphology and dimensions through meticulous synthesis. ZnO-based nanoparticles are esteemed for several applications, including energy storage and wastewater treatment. The inherent properties of ZnO nanoparticles have attracted increased attention for biological uses [7]. The nanoparticles of zinc oxide dissolve in extracellular settings, hence increasing intracellular [Zn2+]. However, the breakdown process of nanoparticles composed of ZnO in the media and the mechanism responsible for the elevated intracellular [Zn2+] levels remain ambiguous [8].

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This review will thoroughly assess the present condition of nanoparticles of zinc oxide in biological applications, their environmentally sound production, and their uses. Nanoparticles are categorized into two types according to their composition refers to nanoparticles of organic matter and inorganic particles. Organic nanoparticles include carbon nanoparticles (fullerenes), whereas inorganic nanoparticles encompass magnetic nanoparticles, noble metal nanoparticles (gold and silver), and semiconductor nanoparticles like zinc oxide and titanium dioxide [9]. Nanoparticles can be classified according to their origin, size, and structural composition. Nanomaterials are classified into natural and artificial classifications derived from their source [10]. Nanomaterials are classified based on their dimensions into zero-dimensional, one-dimensional, two-dimensional, and three-dimensional categories. Zero-dimensional nanomaterials possess nano dimensions in all three spatial axes; one-dimensional nanomaterials exhibit a single nano dimension extending beyond the nanometre scale; The nanomaterials with possess two nanoscale dimensions. outside the nanometre range, while three-dimensional nanomaterials encompass all nano dimensions exceeding the nanometre scale. These consist of bulk materials composed of discontinuous blocks at the nanoscale (1–100 nm) [11]. Nanomaterials are categorized Composite elements and nano-dispersions according to their structural configuration and morphology; dendrimers are extensively branched macromolecules that are sized at a nanoscale level scale [12]. The primary constituent of metal-based materials is metal, which includes nanomaterials such as nanosilvernanogold, metal oxides such as titanium dioxide, and highly aggregated semiconductors, including quantum dots [13]. Carbon-based nanomaterials exist as tubes, cylindrical circles, or rectangles. Carbon nanoparticles that are spherical or ellipsoidal are referred to as fullerenes, whilst cylindrical forms are designated as nanotubes [14]. The two favored strategies for nanoparticle biogenesis are based on bottom- and upward techniques. The fundamental reaction in a bottom-up methodology is oxidation/reduction. The synthesis of nanoparticles has become a prominent research area focused on eco-friendly processes and sustainable materials for modern applications. The principal methods in nanoparticle creation, evaluated from the standpoint of green chemistry, include (i) the solvent medium used for synthesis, (ii) the use of environmentally benign reducing agents, and (iii) the use of non-toxic materials for nanoparticle stabilization [16]. The majority of the previously described chemical and physical processes primarily depend on organic solvents. This is mostly due to the hydrophobic characteristics of the utilized capping agents [17]. The synthesis including bio-organisms adheres to the principles of green chemistry: (i) ecologically sustainable approach, (ii) the employed reducing agent, and (iii) the applied capping agent in the reaction. The synthesis of inorganic metal oxide nanoparticles by biological resources has attracted considerable attention due to their remarkable properties (optical, electrical, chemical, etc.) [18]. Zinc Oxide Nanoparticles Metal oxides are essential in materials science, especially for the production of microelectronic circuits, sensors, piezoelectric devices, fuel cells, surface passivation coatings, and corrosion catalysts. Metal oxides have been employed as absorbers of environmental contaminants [19]. In nanotechnology, oxide nanoparticles exhibit unique chemical properties due to their small size and high edge density. ZnO is an n-type semiconductor metal oxide. In recent years, there has been heightened interest in zinc oxide nanoparticles owing to their varied applications, especially in biological systems, optics, and electronics [21]. ZnO nanoparticles attract considerable attention among metal oxides due to their exceptional properties, including a direct bandgap of 3.3 eV at room temperature, excitation energies of 60 meV, and notable optical characteristics, enhanced catalytic activity, anti-inflammatory effects, wound healing abilities, and UV filtration properties [22]. Zinc oxide, a cost-effective, safe, and readily available nonhygroscopic and nontoxic inorganic polar crystalline compound, has attracted considerable attention for its use in various organic transformations, sensors, transparent conductors, and surface acoustic wave devices [23, 24]. ZnO nanoparticles are distinctive materials that demonstrate semiconducting, piezoelectric, and pyroelectric properties, with many applications in transparent electronics, UV light emitters, chemical sensors, spin electronics, personal care products, catalysts, coatings, and paints [25, 26]. The biomolecules in the plant extract function as efficient capping agents, hence substantially improving nanoparticle synthesis [27]. Capping agents stabilize nanoparticles by many mechanisms, including electrostatic stability, steric stabilization, hydration force stabilization, and van der Waals force stabilization [28]. The utilization of ZnO nanoparticles (NPs) in food preservation and packaging, especially when combined with biodegradable polymeric matrices, has improved food quality and packaging via three main mechanisms: the liberation of antimicrobial ions, the disruption of bacterial cell integrity, and the production of light-induced reactive oxygen species (ROS) [29]. The environmentally sustainable production of ZnO nanoparticles has advanced, employing several processes that utilize a range of biological sources, such as bacteria, fungi, algae, and plants. A table was created to summarize the research undertaken in this field. Table 1.

Synthesis of Nanoparticles

Zinc oxide Nanoparticle: A The process of biosynthesis via Plant Interaction

An alternative to conventional physical and chemical ways of creating nanoparticles is the synthesis of biological nanoparticles. The majority of the research focused on producing metal and oxide nanoparticles through environmentally safe nanoparticle synthesis. [30]. The synthesis of nanoparticles from plants is a quick, affordable, environmentally benign, and human-safe process. Zinc nitrate hexahydrate was used as a precursor to create ZnO nanoparticles using Vitex negundo extract [31]. The green synthesized ZnO nanoparticles demonstrated antibacterial efficacy against Staphylococcus and Escherichia coli. [32]. These ZnO nanoparticles, which ranged in size from 60 to 70 nm, had a hexagonal shape [33]. The pulp extract of Lagenaria siceraria used to create zinc oxide nanoparticles, author also evaluated the antibacterial, antiarthritic, and antidandruff qualities of the biosynthesized ZnO nanoparticles [34]. Youssef et al. successfully produced ZnO nanoparticles using extract from green tea leaves in order to evaluate their capacitance properties for usage in supercapacitors [35].

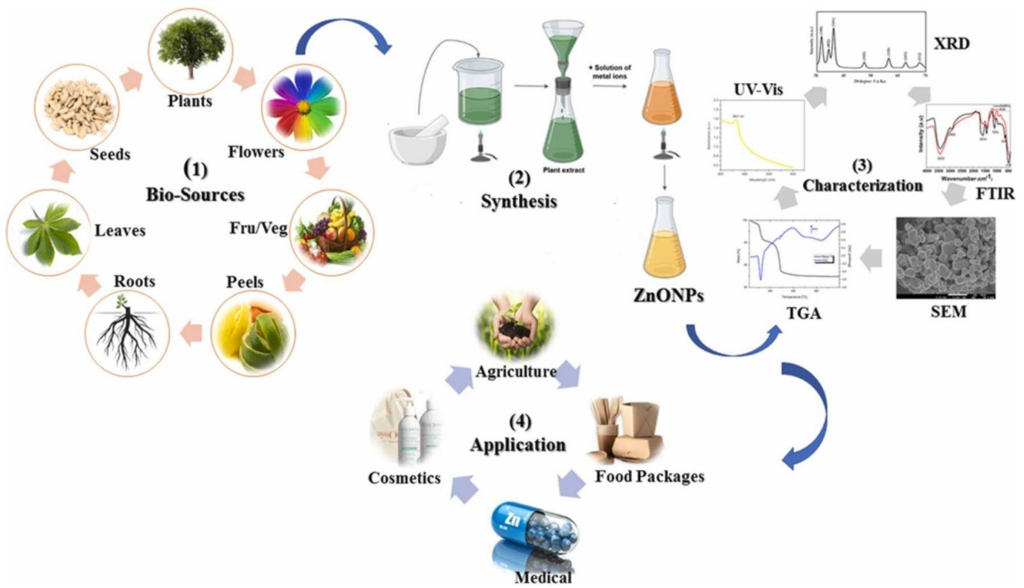

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Figure 1. Biological sources, production, characterization, and applications of zinc oxide nanoparticles

Table 1. Green synthesis of ZnO NPs using various sources:

Used material / Organism	Nanoparticle size (nm)	Shape of nanoparticles	Activity	References
Limoniaacidissima(leaf)	12–53	Spherical	Antibacterial activity against Mycobacterium-tuberculosis	[47]
EuphorbiaJatropha(stem)	15	Hexagonal	Used as semiconductors Antibacterial potential against	[48]
Ceropegia candelabrum(leaf)	12 -35	Hexagonal	Staphylococcus aureus, Bacillus subtilis, Escherichia coli, Salmonella typhi	[49]
Celosia argentea(leaves)	25	Spherical	Anti-bacterial potential against Escherichia coli, Salmonella, Acetobacter; drug delivery	[50]
Couroupita guianensis (leaves)	57	Hexagonal unit cell	pneumonia, Escherichia coli, Mycobacterium luteus, V. cholerae	[51]
Solanum nigrum (leaves)	29	Quasispherical	Staphylococcus aureus Salmonella para typhi, Vibrio cholerae	[52]

The primary application for zinc oxide nanoparticles, which are known to be versatile inorganic materials, is the treatment of urinary tract infections [36]. Chandra, Harish et al. synthesized ZnO nanoparticles using Passiflora caerulea extract of the leaves and assessed their effectiveness against pathogenic cultures taken from a patient's urine who had a UTI [37]. The antioxidant potential of ZnO nanoparticles and looked into its efficacy as a photocatalyst for the degradation of various organic dyes, such as methylene blue and methyl orange, using the DPPH method in combination with Eucalyptus globulus [38]. Aloe vera leaf extract and zinc nitrate combined to form stable, spherical ZnO nanoparticles. ZnO nanoparticles' varied properties were examined using FTIR, photoluminescence, XRD, SEM, TEM, and UV-Vis spectrophotometry [39].

ZnO Nanoparticle synthesis Initiated by Microorganisms:

Examples of how microbes create nanoparticles include basic cellular biochemistry, or ionic the metal transport across membranes within cells, bacterial defense strategies to toxins, activated metal-binding sites, intracellular ion accumulation, and metal oxide creation [40]. Rhodococcuspyridinivorans NT2 rapid production of ZnO nanoparticles demonstrated notable stability and a spherical shape, with an average particle size of 100–120 nm [41]. Selvarajan and Mohanasrinivasan described a new method for utilizing the probiotic bacteria Lactobacillus plantarum VITES07 to create ZnO nanoparticles [42]. ZnO nanoparticles from a zinc sulfate solution using the actinobacterium Rhodococcuspyridinivorans NT2. Synthesized ZnO nanoparticles were used to study multifunctional textile finishing and in vitro anticancer drug delivery in the HT-29 colon carcinoma cell line [43]. Bacillus cereus as a biotemplate to create ZnO nanoparticles with raspberry and plate-like morphologies through a simple thermal breakdown of zinc acetate while maintaining the initial pH of the reaction mixtures [44]. The synthesis of extracellular fungal nanoparticles is especially beneficial due to its low cost, simplicity of downstream processing, and potential for large-scale manufacturing [45]. Fungi are preferable to bacterial strains due to their enhanced metal bioaccumulation and tolerance characteristics [46].

1. Characterization of ZnO NPs:

A range of methodologies is employed to investigate and compare size distributions. TEM, XRD, and FE-SEM (illustrated in figures 2-4) yielded comparable measurements, while SEM and EDAX produced results divergent from those of XRD Coarse [53]. The Debye-Scherrer equation corroborated that the nanoparticles derived from the flowers and leaves of Vitex negundo exhibited a uniform size of 38.17 nm [54]. TEM and XRD analyses identified nanobuds, hexagonal discs, and spherical forms, affirming the consistent size range of nanoparticles observed across experiments [55].

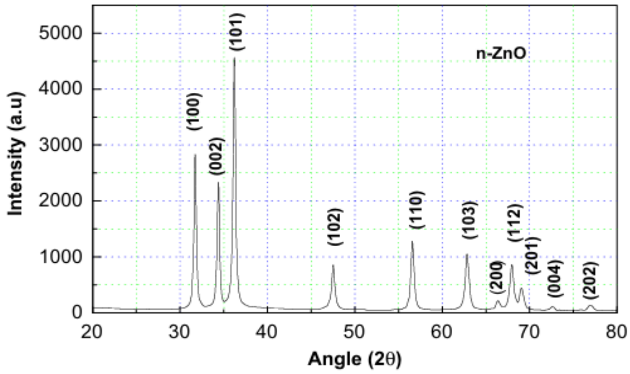

Figure 2. XRD pattern of Zinc oxide nanoparticle

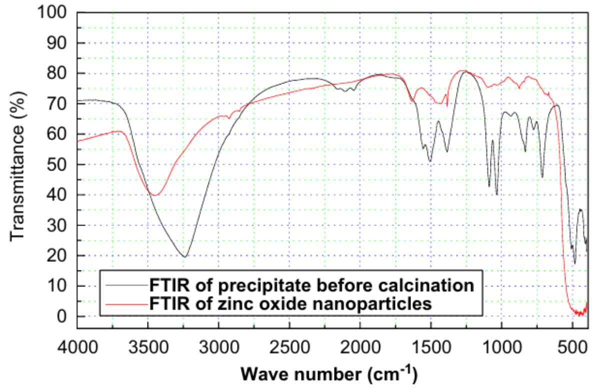

Figure 3. FTIR of ZnO nanoparticles

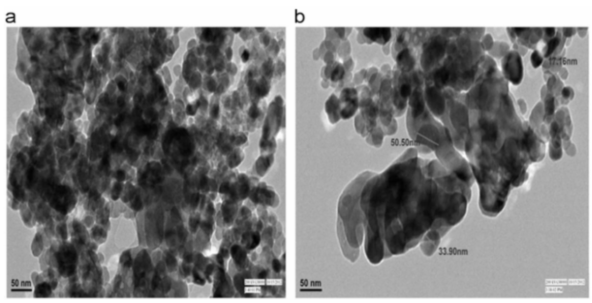

Figure 4. (a & b) TEM structure of ZnO

Applications of ZnO NPs:

The application of zinc oxide nanoparticles showing in the given figures (Figure 5 &6). Zinc oxide used in photocatalytic degradation,which are generally non-toxiccan effectively remove pollutants from the environment. The following lists a variety of uses for ZnO nanoparticles:

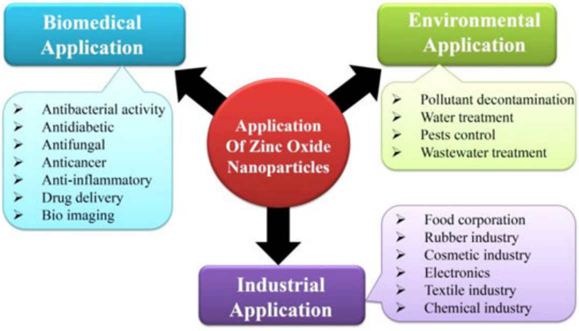

Figure 5. Major application of ZnO nanoparticles

Source: https://www.researchgate.net/publication/361579243_Zinc_Oxide_Nanoparticles_Different_synthesis_approaches_and_applications/figures?lo=1

Figure 6. Described application of ZnO nanoparticles

Drug Delivery

Two primary arguments underscore the advantages of utilizing ZnO nanoparticles for drug delivery [56]. Due to their diminutive size, nanoparticles can penetrate narrower capillaries and be assimilated by cells, hence promoting targeted drug accumulation at specific sites, and synthesis of nanoparticles from biodegradable substances facilitates the prolonged release of pharmaceuticals at the targeted site over several days or even weeks [57]. The analysis of metronidazole benzoate diffusion through an egg membrane enabled researchers to investigate the role of synthesized ZnO nanoparticles in drug release. The findings indicated that the incorporation of ZnO nanoparticles with the drug substantially modifies the biological membrane [58].

Bioimaging of ZnO Particles

Fluorescence imaging is extensively utilized in preclinical research because to its cost efficiency and adaptability [59]. ZnO nanoparticles demonstrate robust excitonic blue and near-UV emissions, along with green fluorescence due to O_2 vacancies [60]. Multiple prior studies highlight the application of ZnO nanostructures in cellular imaging. Transferrin-conjugated green fluorescent ZnO nanoparticles exhibited no damage during cancer cell imaging. [61].

Cosmetic Application of ZnO Nanoparticles

ZnO nanoparticles demonstrate exceptional UV-blocking capabilities alongside its previously mentioned applications, which encompass gas sensors, chemical and biosensors, light-emitting diodes, photodetectors, and photocatalytic functions [62]. Cosmetic formulations typically incorporate UV-filtering agents to safeguard the skin. ZnO nanoparticles are superior to TiO2 as a UV-blocking agent for safeguarding skin against UV-A rays [63]. The photocatalytic activity of ZnO limits its potential use in cosmetic formulations, despite its superior absorption of UV-A radiation compared to TiO2 [64]. Furthermore, the elevated photocatalytic activity of ZnO generates reactive oxygen species capable of oxidizing components within the cosmetic composition.

Conclusions and Future prospective

The feasibility of synthesizing ZnO nanoparticles by eco-friendly methods employing diverse biological materials has been investigated. The comprehensive data obtained from this analysis demonstrates that the green synthesis of zinc oxide nanoparticles is markedly safer and more ecologically sustainable than conventional physical and chemical manufacturing techniques. Biological entities serve as reducing and capping agents to control the synthesis of zinc nanoparticles with specific size and shape. The generation of reactive oxygen species and the ease of ZnO nanoparticles' penetration across cell membranes make it a prospective therapeutic agent for cancer and microbial diseases. ZnO nanoparticles serve as nanofertilizers that improve plant productivity and growth while mitigating abiotic stresses. It functions as an efficient element for sustainable agriculture. The future prospects of biogenic synthesis of zinc oxide nanoparticles include extensive laboratory research for large-scale production commercialization, evaluation of toxicity and environmental safety for diverse applications, and genome analysis coupled with gene expression studies to clarify the mechanisms governing plant growth, development, and abiotic stress management.

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