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Recent Advances In The Applications Of Zinc Oxide Nanomaterials

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Abstract:

Zinc oxide (ZnO) nanomaterials have emerged as versatile candidates in various fields due to their unique properties and wide-ranging applications. This review article provides a comprehensive overview of recent advances in the utilization of ZnO nanomaterials across diverse domains. It has garnered significant attention in biomedical applications, particularly in drug delivery systems, tissue engineering, antibacterial agents, and bioimaging. Their biocompatibility, tunable surface chemistry, and photocatalytic properties make them promising candidates for addressing various challenges in healthcare, such as wound healing cancer therapy and antimicrobial treatments. Moreover, ZnO nanomaterials exhibit excellent catalytic activity and photocatalytic efficiency, making them valuable assets in environmental remediation strategies. From wastewater treatment to air purification, ZnO-based photocatalysts demonstrate remarkable efficacy in degrading organic pollutants and detoxifying environmental contaminants, thereby contributing to sustainable and eco-friendly solutions.

Keywords: zinc oxide nanomaterials, biomedicine, cancer treatment, cosmetic, antimicrobial

1. Zinc Oxide Nanoparticles

Recent advancements in nanotechnology have opened up enormous possibilities in diverse sectors such as industries, agriculture, environmental remediation, electronics, medicine and varied industries. Among metal oxide nanoparticles, zinc oxide nanoparticles have gained considerable attention due to their fascinating physiochemical properties (1). Zinc oxide nanoparticles have many applications, including agriculture, industry and biomedicine (2) (3). They have special properties such as temperature, structure and electronics that make them valuable in various fields (3). In the field of biomedicine, they have been shown to reduce the growth of biofilms, exhibit antibacterial and antimicrobial properties, and effectively deliver drug molecules to target sites (4). The production of these nanoparticles was also employed using green synthesis and their properties and applications in medicine, including antibacterial, antifungal, anticancer, anti-inflammatory, and wound healing, have also been investigated (2). Additionally, its UV filtering, photochemical antifungal, high catalytic and antibacterial properties make it suitable for use in electronics, photonics, acoustics and sensing fields (5).

In this review, we aim to provide a comprehensive overview of recent advances in the applications of ZnO nanomaterials across various disciplines. Furthermore, we will discuss the challenges associated with the utilization of ZnO nanomaterials and outline future research directions in this rapidly evolving field. Through this review, we hope to shed light on the immense potential of ZnO nanomaterials and inspire further research endeavors aimed at harnessing their capabilities for addressing global challenges and improving quality of life.

2. Biomedical Application:

Till date, different types of conventional drugs have been used to fight tumors. However, they have significant flaws, including their usage being constrained because of their low bioavailability, poor supply, and serious side effects. The modern combination therapy has been viewed as a potent strategy for treating serious illnesses, including cancer-type feared diseases. The nanoparticles are a promising choice for cancer therapeutic and diagnostic applications because of their fascinating optoelectronic and physicochemical features. Among the metallic nanoparticles, Zinc oxide nanoparticles possess interesting physicochemical and anti-cancer characteristics, such as ROS generation, high retention, enhanced permeability etc., making them attractive candidates for the treatment and diagnosis of cancer (Figure 1). Singh et al. synthesized organic/inorganic hybrid nanosystems containing chymotrypsin (Chymo) protein and AzureC (AzC) conjugated to zinc oxide nanoparticles (ZnONPs). In vitro cytotoxicity of AzC-ZnONPs was demonstrated in the A-549 adenocarcinoma cell line. The results of physicochemical studies showed that chymotrypsin bound to AzC-conjugated ZnONPs could be used as novel nanoconjugates in various cancer phototherapies (6). ZnO NPs are also considered as anti-inflammatory molecules or drug delivery vectors due to their stable nature and selective targeting (7). Sarkar and colleagues investigated the importance of these properties for triggering cytotoxicity upon exposure to ZnO nanoparticles. They showed that in vitro cytotoxicity is closely related to the dose of nanoparticles, followed by the exposure time, the type of the cell line, and the size of these nanoparticles, among other things (8).

Treatment for burn wounds is still a major concern in the management of wound care, particularly in cases of multidrug-resistant bacterial infection and buildup. The main cause of delayed wound healing is the inefficiency of commercially available wound dressings, which shield the wound but are less effective at healing. Therefore, many researchers are currently focusing on nano-based wound dressings, which may offer an effective way to regulate wound healing. In their study, Sajjad and colleagues reported that they modified and evaluated zinc oxide (ZnO) or silver nanoparticles (Ag NPs) embedded with vitamin A or E nanocomposite embedded in gluten (WG) films. The presence of ZnO and Ag NPs and vitamins (A and E) in WG films make them effective against Gram-positive and Gram-negative bacteria and have antioxidant properties. Their research showed that ZnO or Ag NPs doped with vitamin A or E conjugated to WG could be effectively used in the treatment of inflammation, depending on their physical and biological properties (9). Similarly, another study showed that keratin (K) and sodium alginate (A) wound dressings loaded with green zinc oxide nanoparticles (ZnO NPs) using herbs from C. roseus (leaves) and M. recutita (part of the Daisy flower) which could be used as a bioactive, dual antibacterial wound dressing (10).

3. Cosmetic Products:

The development of nanotechnology has promoted the use of nanoparticles (NPs) in various fields, including industry, agriculture, construction, cosmetics and medicine. The use of nanoparticles in cosmetics and skin products is increasing due to their large surface area and unique physicochemical properties (11). Nanoparticles such as (ZnO) NPs are included in various skin care products due to their ability to protect against ultraviolet (UV) protection, which has led to their widespread use in cosmetics, skin cosmetics, and dermatology. A study by Lee et al showed that NP penetration is negligible in healthy skin but may increase with skin damage. Therefore, the ability of to stimulate the skin may differ between mixtures and nanoparticles (12). Due to their potential for skin sensitization, Gautam et al. also advised against using skincare or dermal products based on ZnO NPs. Their study's conclusions recommend using ZnO NPs in dermal cosmetics sparingly to prevent potential skin irritation. Furthermore, applying NPs-based products to skin that is broken or injured may increase the number of NPs that penetrate the skin, increasing the chance of skin sensitization (11).

4. Antimicrobial Activity:

The rapid development of antibiotic resistance is considered a major public health problem [13] [14]. Nanomaterials have emerged as a potent tool to address this issue by means of several antibacterial processes. The enhanced bactericidal activities of metal oxide structures are attributed to the optimized and customized physiochemical features of secondary nanoarchitectures. But building secondary structures with moderately green manufacturing techniques is still difficult. A study by Yang et al reported an antibacterial ZnO nanocrystal cluster produced by the green synthesis process, in which elementary ZnO nanoparticles <10 nm in size were assembled into different clusters depending on the zinc concentration and temperature. ZnO clusters with a rougher surface and a stable loose-assembly structure demonstrated superior bactericidal activity. The fundamental process involves increasing bacterial contact, releasing tiny ZnO nanoparticles, and producing more reactive oxygen species, all of which have the potential to worsen bacterial cell membrane damage and ultimately cause bacterial death. Because of their excellent performance and environmentally friendly fabrication process, the developed ZnO clusters have a good prospect in antibacterial applications. With their work, they proposed a feasible and clean strategy to improve the bioactivity of ZnO by positively controlling its growth, and the developed ZnO complexes have good antibacterial activity prospects due to their good performance and green synthesis [13]. Another study described the simplest and most economical co-precipitation method for producing pure and Na-doped ZnO nanopowders. The zone of inhibition increases with increasing Na concentration, according to the antibacterial activity of pure and Na-doped zinc oxide nanoparticles against both Gram-positive and Gram-negative pathogens, including Staphylococcus aureus and Escherichia coli, Pseudomonas aeruginosa, and Klebsiella pneumoniae. Antifungal activity against Aspergillus and Candida was investigated. These findings showed that in the presence of visible light, pure and Na-doped ZnO samples show increased antibacterial and antifungal activity with increasing particle size, suggesting that they could be effective antifungal and antibacterial agents (15). Additionally, a simple approach of synthesizing ZnO NP utilizing powdered SA (Scadoxus multiflorus leaf) was used, and it demonstrated encouraging results in treating dengue fever by inhibiting A. ageypti. According to the study, S. multiflorus-mediated ZnO NPs have potential uses in the pharmaceutical and biological fields and can be employed as efficient instruments for controlling mosquito larval populations (16).

5. Biofilm:

Biofilms are microbial colonies confined to biotic and abiotic factors within a polymeric matrix, allowing them to settle on medical devices and contribute to many life-related disease-causing factors. There is an urgent need to discover new biological agents for prevention and treatment due to antimicrobial resistance. ZnO NPs were synthesized using the cyanobacterium Gleocapsa gelatinosa, which extracts cells in a green and inexpensive manner. ZnO NPs showed high antibiofilm activity against B. cereus and E. coli interacting with cell components, leading to biofilm destruction [17]. The antibacterial activity of bare ZnO and tin (Sn)-coated ZnO nanostructures synthesized by simple, versatile and wet chemical techniques was examined against Escherichia coli, methicillin-resistant Staphylococcus aureus and Pseudomonas aeruginosa. It was clearly observed that Sn addition increased the inhibitory activity of ZnO against S. aureus better than the other two microorganisms. The distinct behaviour of Sn-doped ZnO nanostructures provides a new way to prevent infections caused by S. aureus bacteria, especially on the skin, when these nanostructures are used in oils or cosmetics in addition to sunscreen as ultraviolet filters [18]. A study by Ali et al demonstrated the synthesis of various ZnO nanostructures with various sizes and geometries, such as nanoparticles, nanorods, and nanosheets, in organic solvents by coprecipitation using zinc acetate as a precursor. ZnO nanostructures exhibit different sizes and shapes with different combinations of functional groups emitted from the electrode. Moreover, the nanostructure synthesis method showed significant effects on biological and microbial properties as well as cytotoxic potential [19]. Additionally, a nanocomposite (NC) was prepared using the combination of zinc oxide, silver, and chitosan with lemon seed as a binder, and its antimicrobial activity against Enterococcus faecalis (E. faecalis) was evaluated. This use of NC based on lemon extracts, silver, zinc and chitosan has been proven to be antibacterial ant faecalis [20]. Another study demonstrated cost-effective, bacteria-based "green" synthesis of ZnO nanoparticles using the zinc-tolerant bacterium Serratia nematodiphila. Antimicrobial and antifungal studies are carried out in various ways using the agar diffusion method, in which the microbial concentration decreases with the increase of nanoparticles. Additionally, photocatalytic experiments were carried out using methyl orange (MO) as the indicator dye [21].

6. Agriculture:

Recent developments have attracted interest in using metal-based biometals to obtain better biometals and exploit their advantages in various fields. Endophytically mediated by zinc oxide nanoparticles (ZnO NPs), it is an economical and environmentally friendly method for agriculture to prevent Zn deficiency in rice plants and achieve high yields. Here, we synthesized ZnO NPs using the endophytic bacterium Enterobacter hormaechei (E. hormaechei). The results showed that the prepared NPs had antifungal, antibacterial and antioxidant properties. The prepared ZnO NPs were used as biofertilizers in various forms such as foliar spray, which showed improvement in rice plant growth, chlorophyll, protein and carotenoid content [22]. The development of useful crops is an important topic that has attracted the attention of researchers for years. Beheiry and colleagues developed environmentally friendly nano-coated components prepared using a green method for the treatment of citrus fruits (Citrus aurantifolia swingle). Here, biosynthesis of ZnONPs was carried out through the extraction of lime wastes. They reported that these nanoparticles produced better sperm production [23].

7. Dye Removal:

The textile industry is one of the largest users of water, using approximately 230-270 tonnes of water per tonne of fabric produced and producing 20% of the world's water supply [24]. The main pollutants found in wastewater are dyes [25]. Artificial dyes are considered toxic substances and therefore cannot be easily removed by conventional water purification methods. Sachin and his colleagues demonstrated the synthesis of pure and manganese (Mn), silver (Ag) and iron (Fe) doped zinc oxide (ZnO) nanoparticles for the removal of synthetic dyes such as Congo Red from dirty dyes and found that Mn doped. ZnO can be used as an adsorbent to clean dirty water [26]. In another study, the surface of zinc oxide nanoparticles (ZnO NPs) was coated with a surfactant molecule (CTAB) and an ionic liquid (BMTF) to efficiently remove Eriochrome Black T (EBT) from aqueous media. Toxicity estimation of treated dye solutions was performed using the activity of flowers and fungi to determine their nontoxic properties before release into the environment. These results supported the unique potential of ZnO NPs to eliminate EBT in a cost-effective manner [27]. Furthermore, CuO-ZnO-Carbon (CZC) nanocomposites (NCs) were synthesized using a green method at 300 and 400 °C by Prajapati et al., and the temperatures were calculated using marigold flower litter from leaves as the reduced carbon source. These newly functionalized CZC NCs showed better adsorption of toxic Cr (VI) and Congo red (CR) compared to unsupported carbon NCs [28].

8. Food Technology:

Nanotechnology is an innovative food packaging technology that utilizes and utilizes nanomaterials with new physiochemical and microbiological properties. It may use preservatives and microbes to extend the shelf life of food in packaging. The use of microbial nanomaterials in food packaging materials typically involves the incorporation of inorganic nanoparticles such as metals [Silver (Ag), Copper (Cu), Gold (Au)] and metal oxides [Titanium dioxide (TiO2), Silicon oxide (SiO2). , Zinc oxide (ZnO)] [29]. Incorporating large nanoparticles into biopolymer packaging material can reduce material waste during packaging [30]. Therefore, nanomaterials used in the field of food packaging technology have potential applications as antimicrobial, antioxidant and functional materials in food packaging [31].

Disadvantages of ZnO Nanoparticles:

The rapid incorporation of zinc oxide nanoparticles (ZnO NPs) into nanotechnology-based products in the last decade has posed a new threat to the environment. Excessive use of nano-sized zinc products will definitely be excreted and released, eventually released into the environment and causing a lot of damage. Seo et al investigated the effects of the test environment on the changes related to the physicochemical properties of Ag, CuO, and ZnO NPs and the toxicity of the NPs towards freshwater Daphnia magna. By comparing EC50 values based on the sum of NPs and the solubilization of NPs with iron salt solutions, we found that both dissolved and dissolved fractions are likely responsible for the toxicity of Ag NPs, while the dissolved fraction mainly plays a role. CuO and ZnO in the toxicity of NPs [32]. Another study investigated the in vivo cytotoxicity of industrially synthesized ZnO nanoparticles in zebrafish. Studies have shown that cytotoxicity in zebrafish embryos is the result of accumulation and internalization of hypoxic cells and interference with normal adaptive responses leading to apoptosis. Studies have demonstrated the quantification and hidden costs of in vivo cytotoxicity of ZnO nanoparticles in zebrafish embryos [33].

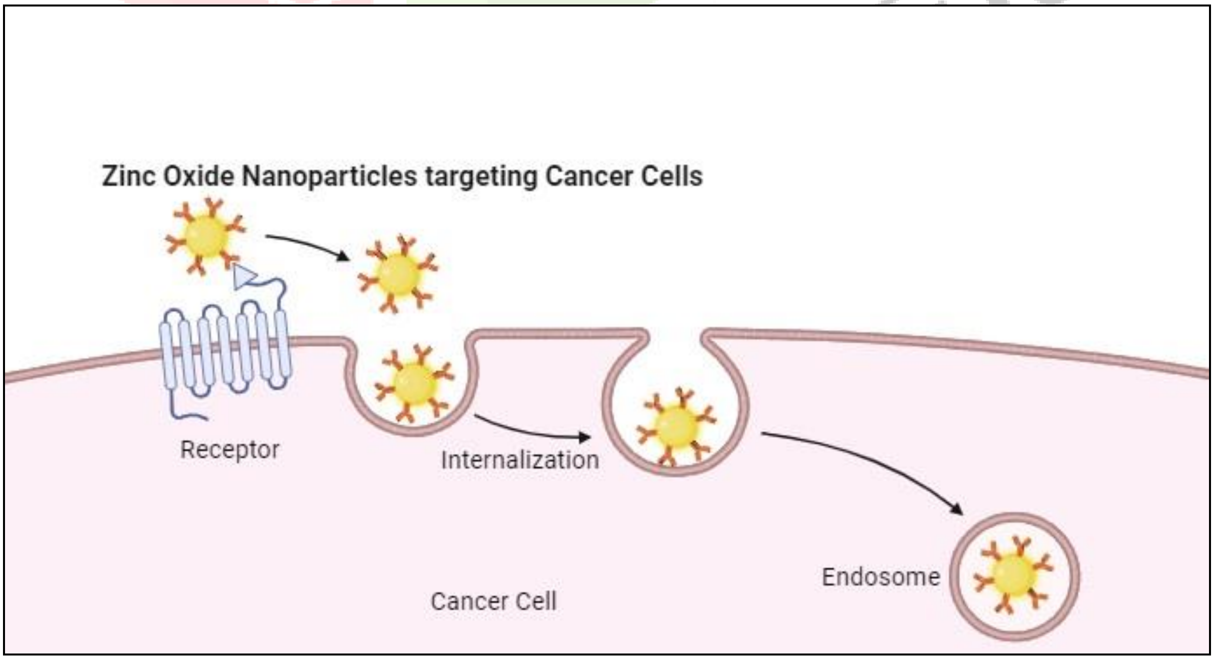
The physiological properties of pokeweed, soil bacteria, and physiochemical and enzyme activities of soil in Zno-contaminated samples were determined by Shi et al. Pokeweed growth was slightly inhibited and acid-base homeostasis was affected by contaminated ZnONPs [34}. Meanwhile, the activity of soil C-related enzymes was increased and the population structure of bacteria at the phylum and species level was changed. Particularly for ZnONPs, the abundance of degradable hydrocarbon taxa decreased significantly. Additionally, Acidobacteria in Group 10 were identified as indicators of soil contaminated with ZnONPs. Our study showed changes in plant growth, soil ecology, and soil microbial communities in solid waste soils treated with ZnONPs. The results of this study provide evidence of the toxicity of ZnONPs to the urban environment. The rapid incorporation of zinc oxide nanoparticles (ZnO NPs) into nanotechnology-based products in the last decade has posed a new threat to the environment. Excessive use of nano-zinc products will definitely be excreted and released, eventually released into the environment and causing a lot of damage.

I also coated ZnO particles because of their large surface area, which shows the different interactions of aquatic organisms. They can be modified in various ways due to their unique physicochemical properties and drug acceptance properties. Therefore, evaluating its effects is important not only for solving existing problems, but also for preventing undesirable environmental effects. Since algae are the primary production of aquatic organisms, the impact of the use of large NPs on environmental health can be evaluated. Because of their nutritional needs and their position at the bottom of the aquatic food web, measurements of algae provide unique information about their environment. Moreover, algae is now an important part of the circular economy. Therefore, it is important to understand the physical, metabolic, and morphological changes caused by ZnO NPs in algal cells and to develop methods that provide a mechanism for their toxicity [35]. Rehman and colleagues investigated the effect of ZnO NPs on the growth and antioxidant activity of Brassica nigra. The results showed that the presence of ZnO NPs in soil had a negative effect on germination. However, it was observed that ZnO NPs had a significant effect on plant growth and other physiological parameters, that is, with increasing NP concentration, stem length increased and root length decreased. Phytochemical analysis of apical, central and basal leaves showed high phenolic and flavonoid content [36].

Summary:

In conclusion, this review overview the recent advancements and emerging trends in the applications of ZnO nanomaterials, underscoring their significance in addressing critical challenges across multiple disciplines.

Figure 1: Role of Zinc Oxide Nanoparticles in the Treatment of Cancer



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