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Antibacterial Properties of Precious Metal-Modified Zinc Oxide Nanoparticles: A Review

Jiayi Feng[1], Yahan Wang[2], Shuqi Yu[3], Xinyan Zhao[4]

[1]Jinan Foreign Language School, Jinan, China
[2]Shandong Experimental High School, Jinan, China
[3]Wuhan-Britain China School, Wuhan, China
[4]New Channel Shanghai School, Shanghai, China
Email: 13910921634@139.com

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Abstract

In recent years, zinc oxide nanomaterials have emerged as highly promising new antibacterial materials. However, there is a lack of summary articles on the surface modification of their precious metals. This article summarizes the properties and applications of zinc oxide nanomaterials and their loading of precious metals, aiming to provide a reference for subsequent research on zinc oxide nanoparticles (ZnO NPs) with precious metal surface modification. This article summarizes the shortcomings of pure zinc oxide nanomaterials in terms of antibacterial properties, such as insufficient broad-spectrum antibacterial performance and excessive surface energy of the material. It also generalizes the action principles and application scenarios of ZnO NPs modified with different precious metals (Pt, Au, Pd, Ag). Although the antibacterial performance of surface-modified ZnO NPs has been comprehensively enhanced, there are still issues such as unknown safety and stability. However, concerns remain regarding potential ion leaching into biological systems, the unclear long-term environmental fate of these nanoparticles, and the possibility of chronic toxicity under prolonged exposure.

Keywords

Zinc Oxide Nanoparticles, Noble Metal (Pt/Au/Pd/Ag) Modification, Antibacterial Performance, Photocatalysis, Synergistic Effect

1. Introduction

As one of the latest antimicrobial materials, ZnO NPs have the potential to be-

come a promising antibacterial material to address the problem of antimicrobial resistance (AMR), which is a significant threat to global human health [1]. The antibacterial mechanism of ZnO NPs has three main aspects:

(1) The generation of reactive oxygen species (ROS), which are H_2O_2, OH^-, and O_2^{2-}, can drive interactions between ZnO NPs and bacteria.

(2) Zinc oxide particles can destroy the external structure of bacteria then exhibit the life activity of bacteria, ultimately achieving the purpose of sterilization.

(3) The nanoparticles can contact with bacterial cells to inhibit the life activity of bacteria [2].

There are outstanding advantages in the antibacterial mechanism of ZnO NPs. The large specific surface area due to the size of nanoparticles makes it easy to react with bacteria and the excellent biocompatibility is also a crucial characteristic for its application in antibacterial material. Additionally, the roughness of ZnO NPs can also improve the antibacterial effectiveness [3].

However, on the other hand, there are also non-negligible limitations on the antibacterial effectiveness of ZnO NPs. There are two main challenges:

(1) ZnO NPs exhibit non-specific toxicity.

(2) ZnO NPs undergo agglomeration easily over time, which affects the antibacterial effectiveness of ZnO NPs negatively [4].

To address these defects, surface modification of noble metals is a possible solution for two reasons:

(1) Research shows that surface modification of noble metals on ZnO NPs can improve its biocompatibility [4].

(2) Modification of noble metals on ZnO NPs can also enhance its stability in order to inhibit their agglomeration [2].

Based on the above content, the review explores modification of noble metals on ZnO NPs.

Enhanced Antibacterial Mechanisms of Precious Metal-Modified ZnO Nanoparticles.

Precious metal modification significantly strengthens the three major antibacterial mechanisms of ZnO NPs—ROS generation, membrane disruption, and metal ion release—through a series of electronic and structural effects. First, the incorporation of noble metals such as Pt, Au, Pd, and Ag creates Schottky barriers at the metal-semiconductor interface, which promote the rapid transfer of photogenerated electrons from ZnO to the metal surface. This electron-sink effect suppresses electron-hole recombination and effectively prolongs carrier lifetime, thereby markedly increasing the yield of reactive oxygen species (ROS), including ·OH, $O_2^-\cdot$, and H_2O_2. The enhanced ROS generation accelerates oxidative damage to bacterial membranes, proteins, and nucleic acids.

Second, noble metal nanoparticles deposited on ZnO induce local surface roughness, lattice defects, and enhanced electron mobility, all of which facilitate closer contact with bacterial cell walls. This promotes mechanical disruption of membrane integrity and increases permeability, making bacteria more susceptible to oxidative attack. In addition, Ag^+, Au^{3+}, Pd^{2+}, and Pt^{2+} ions released from the

modified surface interact with thiol-containing enzymes, respiratory proteins, and DNA, amplifying the damage initiated by Zn^{2+} released from ZnO. The coexistence of Zn^{2+} and noble metal ions produces a synergistic toxic effect, enabling multi-target interference with essential bacterial biological processes.

Lastly, precious metal modification stabilizes ZnO NPs against agglomeration and improves dispersion in aqueous environments, thereby increasing the effective surface area for antibacterial activity. The integration of electronic enhancement (via Schottky barrier formation), chemical enhancement (via multi-ion release), and structural enhancement (via improved contact and stability) enables precious metal-modified ZnO NPs to exhibit significantly stronger and more sustained antibacterial performance than pure ZnO.

2. The Characteristics of Four Kinds of Precious Materials (Pt, Au, Pd and Ag)

2.1. Pt-Modified ZnO NPs

Platinum is silver and solid at room temperature. There are platinum catalysts with various nanostructures such as spherical, sliced, and granular, which are used to increase the reaction rate [5].

2.1.1. Effect of Platinum-Modified ZnO NPs

(1) Improving photocatalytic performance, which can shift the absorption edge of zinc oxide from the ultraviolet region to the visible light region, and greatly improve the photocatalytic hydrogen production activity.

(2) Enhancing the stability of dehydrogenation during catalysis. In the propane dehydrogenation reaction, platinum acts as an "assistant" (*i.e.*, promoter) of the catalyst, which can convert zinc oxide into a stronger Lewis acid. At the same time, this catalyst uses less platinum than traditional platinum-based catalysts, and the reaction rate is also higher.

2.1.2. Application Fields of Platinum-Modified ZnO NPs

(1) Medical field; in the medical field, the catalytic synergistic effect of platinum and zinc oxide can be used to eliminate tumor cells with the assistance of ultrasound.

(2) Energy regeneration field; in the energy regeneration field, the photocatalytic property is used to increase the temperature to produce hydrogen, and solar energy can be converted into hydrogen energy to improve the stability and production efficiency of hydrogen.

2.1.3. Limitations of Platinum-Modified ZnO NPs

High cost; as a rare metal element, platinum is a non-renewable resource, so its price is high, leading to high preparation cost of platinum-modified ZnO NPs, which has great restrictions in industrial applications.

2.2. Au-Modified ZnO NPs

Au has many structures, such as porous and hollow structures, core-shell and het-

erostructures, etc. Among them, the most common is the spherical nanoparticle structure, which can be prepared by the citrate reduction method.

2.2.1. Effect of Au-Modified ZnO NPs

(1) Au nanoparticles can serve as catalytically active sites, which can reduce the adsorption capacity of gas molecules such as NO_2 and H_2S on the ZnO surface, thereby improving the gas sensitivity of ZnO, which can be used for gas detection. [6] At the same time, Au can accelerate the repair process of gas molecules on the ZnO surface and improve the yield [7].

(2) The modification of Au can reduce the release of zinc ions. Ming-Shui Yao *et al.* found through experiments that gold, as a physical barrier, effectively slows down the release of anions.

2.2.2. Application Fields of Au-Modified ZnO NPs

It can be used as an antibacterial material for making surface coatings of medical devices to protect them from bacterial contamination.

2.2.3. Limitations of Au-Modified ZnO NPs

To achieve uniform distribution of Au nanoparticles on the ZnO surface, very precise measuring instruments and processes are required, and the operation is extremely difficult.

2.3. Pd-Modified ZnO NPs

Pd is a silver metal with good plasticity and ductility because of its soft texture.

2.3.1. Effect of Pd-Modified ZnO NPs

(1) It can enhance the sensitivity of ZnO NPs to some gases [8].

(2) Increasing photocatalytic activity; Pd-modified ZnO NPs can accelerate the separation of photogenerated electrons (Pd can improve the diffusion rate of oxygen by controlling the interface electron transfer path), increase hydroxyl substances on the zinc oxide surface, thereby improving the photodegradation ability of ZnO NPs and reducing environmental pollution [8].

2.3.2. Functions of Pd-Modified ZnO NPs

The fields are mainly concentrated in environmental pollution monitoring and gas purification.

(1) Gas sensing for monitoring; it can identify ammonia, so in agricultural research, it can be used to monitor ammonia concentration to provide a reasonable growth environment for crops.

(2) Due to its good photocatalytic performance, it can be used to improve air quality in confined environments, such as shopping malls and large indoor amusement parks.

2.3.3. Limitations of Pd-Modified ZnO NPs

(1) Pd is a precious metal. Although it is a renewable resource, the regeneration cost is high and the price is expensive.

(2) The stability and environmental adaptability of Pd need to be improved. If Pd is used in environments with high temperature, high pressure, and high water content, it will undergo oxidation, corrosion, etc., leading to the reduction of material performance.

2.4. Ag-Modified ZnO NPs

Silver-based antibacterial materials are a highly efficient type of antibacterial agent, which is mainly reflected in their ability to exert antibacterial effects even at low concentrations (generally between 0.1 and 1 mg/ml). Their inhibitory effects on bacteria are multi-faceted, including disrupting the permeability of bacterial membranes, binding to various enzymes to inhibit their physiological activities, and damaging DNA/RNA. Bacteria find it difficult to develop drug resistance through a single mutation, so silver-based antibacterial agents have antibacterial properties against most bacteria. Moreover, studies have shown that trace amounts of Ag entering the human body are beneficial.

2.4.1. Functions of Ag-Modified ZnO NPs

In order to fully exert the efficacy of silver-based antibacterial agents, [9] found through research that after modifying Ag on the surface of ZnO NPs, the material had a core-shell hollow structure. This structure greatly increased the specific surface area of nanomaterials. Meanwhile, due to the characteristics of the ZIF-8 structure of ZnO NP itself, after loading Ag, the drug can more effectively contact microorganisms and exert antibacterial components [9].

(1) The photocatalytic property of the material has been significantly enhanced. Because surface ions such as silver nanoparticles resonate, they can enhance the absorption of visible light and thereby promote the excitation of ROS. The REDOX reaction of Ag enhances the efficiency of electron transfer, thereby promoting the extension of ROS lifetime. Moreover, as an electron capture agent, Ag can increase the yield of ROS by inhibiting the recombination of photogenerated carriers.

(2) The surface modification of the precious metal silver enables the zinc ions released by ZnO NPs, ROS and silver ions to work together to achieve a synergistic antibacterial mechanism by destroying bacterial membranes, interfering with enzyme activity, and destroying DNA and proteins, significantly enhancing the broad-spectrum antibacterial property of the material.

(3) Ag/ZnO NPs have relatively low environmental requirements. Its antibacterial efficiency under natural light can reach 99%. Research shows that after modifying zinc oxide with precious metal silver, the diameters of the inhibition zones of the material against Escherichia coli and Staphylococcus aureus under light are 18 ± 0.2 mm and 22 ± 0.3 mm, respectively. Even in the absence of light, it can achieve antibacterial effects through the slow release of silver ions. Although the diameter of its bacteriostatic zone is smaller than that under light, its antibacterial effect is still stronger than that of single Ag or pure zinc oxide.

(4) The research by Yunyan Wu *et al.* pointed out that silver modification ac-

celerated the separation of photogenerated electrons and holes, which not only enabled zinc oxide to produce more reactive oxygen species with antibacterial activity, but also avoided oxidative stress damage caused by excessive photogenerated carriers. In addition, the release of silver ions from silver nanoparticles is continuous and slow, rather than in large quantities. This significantly reduces its non-specific toxicity to normal organisms.

2.4.2. Limitations of Ag-Modified ZnO NPs

Compared with other precious metals, the synthesis method of Ag-modified ZnO NPs is relatively simple, and its antibacterial effect is more significant. However, at present, there are relatively few studies on Ag/ZnO, and its stability and safety remain questionable.

2.4.3. Application Fields of Ag-Modified ZnO NPs

Apart from the application of Ag/ZnO in antibacterial aspects, it also has practical value in fields such as antioxidation and ethanol concentration detection.

(1) Antioxidant application: The antioxidant activity of Ag/ZnO synthesized by the sol-gel method was verified through free radical scavenging experiments such as DPPH and ABTS, making it more widely used in the fields of biomedicine and environmental remediation [10].

(2) Gas-sensitive applications: Ag/ZnO prepared by the calcination method of electrospinning precursors responds optimally to ethanol and hydrosulfuric acid, mainly due to the spillover effect and electron sensitization of Ag [11].

To provide a clearer comparison of the four noble metals used to modify ZnO NPs, it is important to evaluate their antibacterial enhancement mechanisms alongside practical considerations such as cost and synthetic feasibility. Pt and Pd generally exhibit strong carrier-separation capabilities due to their high work functions, resulting in significantly improved photocatalytic and ROS-mediated antibacterial performance; however, both metals are expensive and require complex synthesis routes, limiting large-scale applications. Au-modified ZnO offers excellent biocompatibility and effectively regulates Zn^{2+} release, but the uniform deposition of Au nanoparticles demands precise instrumentation, increasing preparation difficulty. In contrast, Ag-modified ZnO provides the most pronounced antibacterial enhancement through synergistic Ag^{+} and Zn^{2+} ion release, shows strong ROS generation under visible light, and remains relatively low in cost. Nevertheless, its long-term stability and safety still require further investigation. A concise comparison of the advantages and limitations of Pt, Au, Pd, and Ag as ZnO modifiers is summarized in **Table 1**.

2.5. The Mechanism of Action of the Schottky Barrier

Under light exposure, the light-absorbing function of zinc oxide generates highly active photogenerated electrons and holes. The built-in electric field of the Schottky barrier can drive electrons to cross the barrier, flow from the semiconductor to the metal, and be captured and enriched by metal nanoparticles. At the same time,

positively charged holes are retained on one side of the semiconductor. This process greatly suppresses the probability of electron and hole recombination. It provided sufficient time for the subsequent chemical reactions.

Table 1. The characteristics of four kinds of precious material used to modify ZnO NPs (Pt, Au, Pd and Ag).

Precious metal	Relative cost	Synthesis difficulty	Photocatalytic property	Antibacterial property	Gas sensitivity	Key application areas
Pt	High	High	Improved	Improved greatly	/	Medical field: eliminate tumor cells; Energy regeneration field: increase the temperature to produce hydrogen
Au		High	/	Improved	Improved	Medical field: Antibacterial material for making surface coatings of medical devices; Gas detection field
Pd	High	High	Improved	/	Improved	Gas sensing for monitoring; improve air quality in confined environments
Ag		Relatively low	Improved greatly	Improved	/	Antioxidant application; Gas-sensitive application

3. Application of ZnO NPs

3.1. Antibacterial Uses of Plant Based ZnO NPs

Plant-derived zinc oxide nanomaterials exhibit three major advantages in antibacterial applications—high efficiency, strong synergism, and low risk of resistance—each corresponding to multiple mechanisms of action.

The high efficiency arises from the nanoscale effect, which brings small particle size, large specific surface area, high surface reactivity, and excellent biocompatibility, enabling significant broad-spectrum antibacterial activity at relatively low doses. This is achieved through multiple pathways, including enhanced bacterial contact, photocatalytic/surface reactions generating reactive oxygen species (ROS), sustained Zn^{2+} release, direct disruption of cell membrane structure, and inhibition of biofilm formation.

Strong synergism is reflected in its combination with other antibacterial agents (e.g., chitosan), whereby the physical disruption of chitosan (destabilizing cell membranes) is combined with the chemical bactericidal effects of ZnO quantum dots (Zn^{2+} release and ROS generation), along with biofilm removal and immune modulation functions. This forms a multi-target, multi-mechanism synergistic bactericidal mode, thereby markedly enhancing antibacterial efficacy and reducing recurrence risk.

The low resistance risk stems from the fact that its bactericidal mechanisms do not rely on a single molecular target but rather rapidly kill bacteria through multiple pathways—mechanical damage, chemical reactions (ROS generation and metal ion release), photothermal effects, and photocatalysis—making it nearly impossible for bacteria to develop complete resistance via single-gene mutation or horizontal gene transfer. Furthermore, the instability of nanoparticle size, mor-

phology, and surface active sites in the environment further impedes the development of stable resistance.

3.2. ZnO NPs as Potent Antioxidant Agents

Zinc oxide nanoparticles (ZnO NPs) can act as potent antioxidants, functioning through multiple mechanisms to cooperatively reduce oxidative damage and enhance the body's antioxidant defense capacity.

First, they can bind with various ROS via electron transfer reactions, converting them into stable molecules, thereby interrupting free radical chain reactions and reducing oxidative damage to cells. Simultaneously, ZnO NPs significantly enhance the activities of endogenous antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT), promoting the decomposition of superoxide anion ($O_2^- \cdot$) and hydrogen peroxide (H_2O_2) and inhibiting their conversion into more destructive hydroxyl radicals (·OH).

In addition, ZnO NP treatment reduces the level of malondialdehyde (MDA), a lipid peroxidation biomarker, thereby mitigating oxidative damage to membrane lipids and maintaining the integrity and fluidity of the cell membrane. Animal experiments further confirm their in vivo antioxidant effects; in a chicken pullorum model, individuals ingesting ZnO quantum dots exhibited significantly increased SOD and CAT activities and markedly decreased MDA content, demonstrating their ability to enhance systemic antioxidant capacity and alleviate oxidative stress.

3.3. Anti-Cancerous Application of ZnO NPs

ZnO NPs possess anticancer activity characterized by selective cytotoxicity, which arises from the increased negative charge on cancer cell membranes due to the externalization of negatively charged phospholipids. This leads to strong electrostatic attraction with positively charged or surface-modified positively charged ZnO NPs, enhancing their binding and endocytosis at the cancer cell membrane, thus achieving preferential accumulation in cancer cells while maintaining lower uptake in normal cells, conferring a degree of targeting ability.

Once inside the cell, ZnO NPs can induce cell death via multiple pathways:

(1) Excessive ROS generation within cancer cells, disrupting redox homeostasis and activating multiple cell death signaling pathways;

(2) Disruption of mitochondrial membrane structure, leading to loss of membrane potential, release of cytochrome c, and activation of the apoptotic cascade;

(3) Induction of endoplasmic reticulum (ER) stress and the unfolded protein response (UPR);

(4) DNA double-strand breaks and other genetic material damage, further promoting apoptosis;

(5) Membrane damage accompanied by significant lactate dehydrogenase (LDH) leakage, a key biochemical indicator of cytotoxicity.

Overall, the anticancer mechanism of ZnO NPs is a multistage process—from selective accumulation, oxidative stress, and organelle damage to the final induc-

tion of apoptosis or necrosis—combining both physicochemical destruction and molecular signaling regulation.

3.4. Antidiabetic Activities of ZnO NPs

ZnO NPs also exhibit multifaceted and synergistic mechanisms in antidiabetic applications. The released Zn^{2+} can directly participate in the stabilization and storage regulation of insulin crystals, protect the structure and function of pancreatic β-cells, alleviate oxidative stress, enhance the activities of antioxidant enzymes (SOD, CAT, glutathione peroxidase [GPx]), and improve insulin synthesis and secretion capacity. Simultaneously, they can upregulate insulin signaling pathways (e.g., PI3K/Akt) and promote GLUT4 expression and membrane translocation, thereby enhancing glucose uptake and utilization in peripheral tissues and improving insulin sensitivity. Additionally, by reducing oxidative damage products such as MDA, they lower systemic oxidative stress levels, regulate lipid metabolism (reducing TC, TG, and LDL-C while increasing HDL-C), and indirectly decrease insulin resistance.

Their advantages lie in the nanoscale properties that provide a high specific surface area and high bioavailability, enabling Zn^{2+} release efficiency and target engagement superior to conventional zinc supplements, thus achieving significant hypoglycemic and insulinotropic effects at low doses. The multi-target synergistic regulation of pancreatic secretion, tissue sensitivity, antioxidant systems, and lipid metabolism matches the multi-stage pathological features of type 2 diabetes.

Green-synthesized ZnO NPs not only maintain high activity but may also incorporate plant polyphenols and other natural antioxidants, enhancing hypoglycemic and antioxidant synergy and improving biocompatibility. Animal experiments suggest that they can not only improve blood glucose in the short term but may also delay β-cell functional decline, indicating long-term protective potential.

3.5. A New Prospective of ZnO NPs as an Antiviral

Drug for SARS-CoV-2.

ZnO NPs also show multiple mechanisms of action against SARS-CoV-2.

First, they can bind to ACE2 receptors on the host cell surface and interfere with TMPRSS2-mediated activation of the viral spike protein, thereby blocking viral entry.

Second, they can inhibit RNA-dependent RNA polymerase (RdRp) activity, disrupting viral genome replication and transcription, weakening viral structural integrity, and suppressing its amplification within host cells.

Third, the released Zn^{2+} can enhance host antiviral immune responses while downregulating pro-inflammatory cytokines such as IL-6 and TNF-α, thereby suppressing excessive inflammatory responses and reducing COVID-19-related inflammatory damage.

Their advantages include low cytotoxicity to host cells, good biocompatibility, multi-target synergy in blocking viral entry, inhibiting replication, and modulat-

ing immunity, as well as ease of formulation into sprays, oral preparations, and other dosage forms to meet different clinical needs.

4. Conclusions

Zinc oxide nanomaterials, as emerging antibacterial materials, are applied in various fields including but not limited to antibacterial, anti-cancer, and the treatment of some diseases. It is a breakthrough for people to combat bacterial resistance. Its surface modification not only makes up for the defect of certain bacterial species' resistance to pure zinc oxide nanoparticles, but also enhances its antibacterial performance in multiple aspects (such as increasing the photocatalytic rate and generating a synergistic antibacterial mechanism, etc.), and enables it to be applied in more other fields such as: Fields such as energy regeneration, medical devices, environmental pollution monitoring and gas purification. However, although the performance of zinc oxide nanomaterials modified with different precious metals has been improved in all aspects, there are still obvious deficiencies in some aspects such as preparation conditions, synthesis efficiency and economy. Although the zinc oxide nanomaterials composed of precious metal silver have fewer similar problems compared to other precious metals, due to the current limited research, their stability and safety remain issues worthy of study.

Specifically, noble metal-modified ZnO NPs may undergo ion leaching, which can introduce excessive metal ions into biological systems and potentially trigger cytotoxic or inflammatory responses. In addition, the long-term environmental fate of these nanomaterials remains unclear, as their persistence, transformation, and ecological impact under natural conditions have not been fully evaluated. Structural instability caused by fluctuations in light exposure, pH, or temperature may further alter their physicochemical behavior over time. Moreover, the chronic toxicity associated with long-term or repeated exposure to these nanoparticles has not been systematically assessed, raising important questions about their biocompatibility and long-term safety.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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