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Article

Synthesis and Characterization of Zinc Nanoparticles for Antibacterial Coating Applications in Laboratory Textiles

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Abstract: Zinc nanoparticles (Zn NPs) were successfully synthesized using a chemical precipitation technique to investigate their structural, morphological, and antibacterial characteristics. Sodium hydroxide was used as a catalyst to enhance solubility and control nanoparticle formation. The resulting Zn NPs were characterized by X-ray diffraction (XRD) and scanning electron microscopy (SEM). XRD analysis confirmed that the nanoparticles possess a polycrystalline structure composed mainly of hexagonal wurtzite and orthorhombic phases. SEM images revealed cylindrical and aggregated morphologies with particle sizes between 24 and 70 nm. The antibacterial performance of Zn NPs was tested against Escherichia coli (Gram- negative) and Staphylococcus aureus (Gram- positive), where significant inhibition zones were observed. These findings demonstrate the potential of Zn nanoparticles as an efficient, biocompatible, and low- cost antibacterial coating material suitable for laboratory textiles and biomedical applications.

Keywords: Zinc Nanoparticles, Antibacterial Coating, X-Ray Diffraction, SEM Analysis, Nanotechnology, Sol-Gel Synthesis, Biomedical Applications

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1. Introduction

Nanotechnology is an interdisciplinary science concerned with the design, synthesis, and manipulation of materials on the nanometer scale (1–100 nm). At these dimensions, materials exhibit unique optical, electrical, mechanical, and chemical behaviors that differ significantly from their bulk counterparts. The quantum confinement effect and large surface-to-volume ratio grant nanomaterials exceptional reactivity and tunable properties, making them highly valuable for applications in medicine, energy, electronics, and materials engineering [1], [2].

Among the different metal oxide nanomaterials, zinc oxide (ZnO) stands out for its high stability, low toxicity, chemical versatility, and biocompatibility. ZnO nanoparticles (ZnO NPs) have been used in catalysis, gas sensing, photocatalysis, and particularly in antibacterial coatings for medical and industrial uses. Their ability to generate reactive oxygen species (ROS), release zinc ions (Zn^{2+}), and disrupt microbial cell membranes gives them a remarkable antibacterial capacity even at low concentrations [3], [4], [5].

In the biomedical field, ZnO NPs have demonstrated activity against a wide range of microorganisms, including E. coli, S. aureus, Bacillus subtilis, and Candida albicans. The mechanism of antibacterial action involves ROS-mediated oxidative stress, membrane leakage, and interference with DNA replication. As a result, zinc oxide nanomaterials have gained attention as safe alternatives to conventional antibiotics and as additives in coatings for lab garments and medical fabrics to prevent microbial contamination.

Previous studies reported that ZnO NPs exhibit size-dependent antibacterial activity; smaller particles provide larger surface areas, enhancing the release of Zn^{2+} ions and ROS generation. However, optimizing synthesis parameters—such as precursor type, reaction temperature, and pH—remains a challenge for achieving consistent particle morphology and enhanced antibacterial effectiveness [6], [7], [8].

This study focuses on synthesizing Zn nanoparticles via a chemical precipitation approach, characterizing their structure and morphology using XRD and SEM techniques, and assessing their antibacterial efficiency against E. coli and S. aureus. The goal is to evaluate the potential of Zn nanoparticles as an antibacterial coating material for laboratory textiles, thereby improving hygiene and reducing infection risks in biomedical environments.

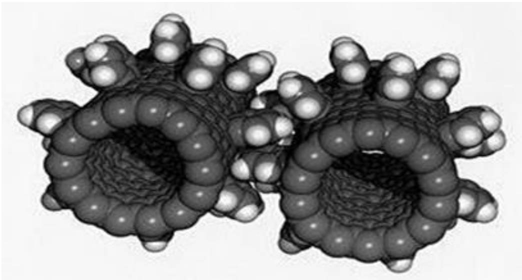

Figure 1. Fullerene Nanogears.

Literature Review

Zinc oxide nanoparticles (ZnO NPs) have gained significant attention in recent years due to their wide applications in biomedical, environmental, and industrial fields. Their unique physicochemical properties, including high surface-to-volume ratio, tunable band gap, and excellent biocompatibility, make them suitable candidates for antibacterial, anticancer, and photocatalytic applications. Numerous studies have investigated the synthesis methods, structural characteristics, and antimicrobial activities of ZnO nanoparticles using both chemical and biological routes.

Amna Sirelkhatim reported that ZnO nanoparticles exhibit remarkable antibacterial properties attributed to their nanoscale size, which increases the surface area and enhances reactivity. The study emphasized that reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2), hydroxyl radicals (OH^-), and superoxide ions (O_2^{-2}), play a key role in bacterial inhibition by causing cell membrane damage, increased permeability, and cellular component leakage. The author also highlighted the use of ZnO-NPs as antibacterial agents in food packaging to prevent foodborne diseases [9], [10], [11], [12].

Similarly, Marina S. R. Barreto (2017) investigated ZnO nanoparticles synthesized and immobilized on a chitosan/alginate (CH/SA) matrix. The study demonstrated that ZnO nanocomposites possess strong antimicrobial activity and controlled release behavior of zinc ions (Zn^{2+}), which contributed to sustained antibacterial effects. Characterization techniques, including X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM), confirmed the structural stability and nanoscale morphology of the composites.

Khwaja Salahuddin Siddiqi highlighted that ZnO is an essential component in various biological and cosmetic formulations due to its UV absorption capability and biocompatibility. His research confirmed that ZnO nanoparticles exhibit strong antibacterial effects against several microbial species such as Staphylococcus aureus, Escherichia coli, and Candida albicans. The antibacterial mechanism was attributed to the penetration of nanoparticles through the bacterial cell wall, followed by intracellular interaction that leads to apoptosis and cell death [13], [14].

Ibrahim Khan reviewed the biosynthesis of ZnO nanoparticles using green chemistry approaches, emphasizing the use of plant extracts such as Carissa spinarum L. for environmentally friendly nanoparticle production. The study demonstrated that biologically synthesized ZnO nanoparticles display effective photocatalytic and antibacterial activities, comparable to chemically synthesized ones. The work also discussed that nanoparticle properties, including size and shape, significantly influence their optical absorption and biological activity [15], [16].

Furthermore, H. Ibrahim discussed the emerging role of nanotechnology in medicine, particularly in drug delivery and diagnostic applications. The review noted that nanostructures such as nanoparticles and nanofibers offer advantages due to their small size, high surface area, and biocompatibility. ZnO nanoparticles, in particular, have been identified as promising candidates for use in wound healing, antibacterial coatings, and drug encapsulation systems due to their unique electrical, optical, and antimicrobial properties [17].

Collectively, these studies underscore the growing interest in zinc oxide nanomaterials for medical and industrial applications. The literature reveals that the structural and functional properties of ZnO nanoparticles depend strongly on synthesis parameters such as precursor concentration, pH, temperature, and capping agents. Moreover, their antibacterial efficiency is governed by surface defects, particle size, and the generation of reactive oxygen species. The consistent findings across previous research provide a solid foundation for further exploration of ZnO nanoparticles in antibacterial coatings, biomedical devices, and nanomedicine.

2. Materials and Methods

Materials and Chemicals

All chemical reagents used in this study were of analytical grade and utilized without further purification. Zinc oxide (ZnO) nanopowder, sodium hydroxide (NaOH), ethanol, and acetone were obtained from reputable suppliers to ensure high purity and reliability of the experimental outcomes. Table (1) summarizes the chemical materials and their sources.

Table 1. Materials and chemicals used in this study.

No.	Chemical Material	Company / Country	Purity
1	Sodium hydroxide (NaOH)	Avoi Chem, UK	95%
2	Zinc oxide (ZnO)	BDH, UK	99.98%
3	Ethanol, Acetone	HAYMAN, UK	Analytical Grade

Apparatus and Instruments

The experimental procedures were performed using modern analytical instruments to ensure high accuracy in synthesis and characterization. Table (2) lists the main instruments and their manufacturers.

Table 2. Instruments and apparatus employed in the experimental work.

No.	Apparatus / Instrument	Manufacturer / Country
1	Cooling Centrifuge (CL008)	CYAN, Belgium
2	Hot Plate with Magnetic Stirrer	Thermo Scientific, USA
3	pH Meter	Martini Instruments, Italy
4	Sensitive Electronic Balance (ALJ220-4NM)	KERN, Germany

Synthesis of Zinc Oxide Nanoparticles

Zinc oxide nanoparticles (ZnO NPs) were synthesized via a chemical precipitation method, known for its simplicity, reproducibility, and cost-effectiveness. Initially, 3.0 g of ZnO powder was dissolved in 100 mL of deionized (DI) water under continuous stirring at room temperature. Subsequently, 5 mL of 1 M NaOH solution was added dropwise to the mixture under constant magnetic stirring at 250°C for 30 minutes. The reaction was maintained until a homogeneous white suspension appeared, indicating the formation of ZnO nanoparticles.

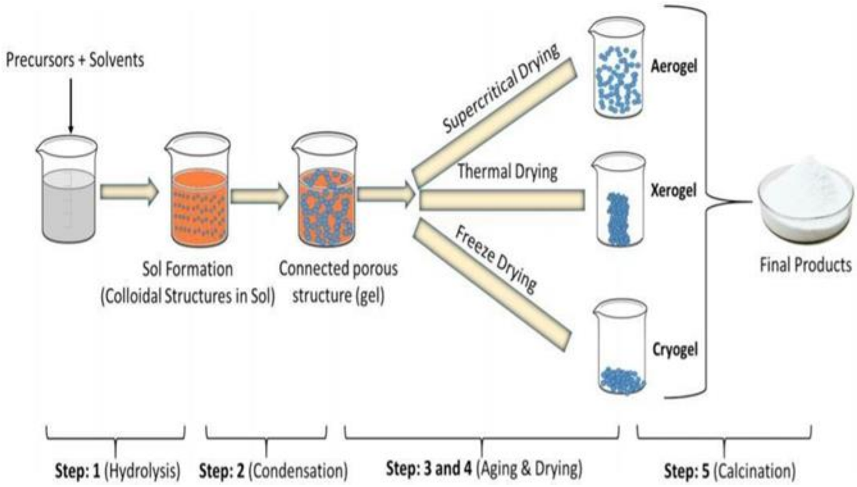

Figure 2. Mechanism sol-gel process to synthesize metal oxides nanoparticles.

After cooling to room temperature, 5 mL of triethylamine (TEA) was added as a stabilizing agent to prevent agglomeration. The resulting suspension was centrifuged and washed several times with DI water to remove residual ions and impurities. The purified nanoparticles were then dried and ground mechanically for 6 hours to achieve a fine and uniform nanopowder.

Structural and Morphological Characterization

X-Ray Diffraction (XRD) Analysis

The crystalline structure of the synthesized ZnO nanoparticles was examined using an X-ray diffractometer (XRD) equipped with Cu Kα radiation (λ = 1.5406 Å) operating at 40 kV and 30 mA. The diffraction patterns were recorded within a 2θ range of 20°–60° at a scanning rate of 4°/min. The obtained data were compared with standard ASTM cards to confirm the crystalline phase and lattice parameters of the nanoparticles.

Scanning Electron Microscopy (SEM)

The surface morphology and microstructure of ZnO nanoparticles were analyzed using a Scanning Electron Microscope (SEM). Samples were mounted on aluminum stubs using double-sided conductive carbon tape and coated with a thin layer of gold by sputtering (Polaron E6100, UK) to enhance surface conductivity. SEM images provided detailed information regarding particle size, shape, and distribution.

Preparation of Bacterial Cultures

Two bacterial strains were employed to evaluate the antibacterial activity of the prepared ZnO nanoparticles: Staphylococcus aureus (Gram-positive) and Escherichia coli (Gram-negative). Both strains were obtained from the Contamination Research Center, Ministry of Science and Technology (Baghdad, Iraq). Each bacterial culture was incubated at 37°C on nutrient agar for 24 hours. A single colony from each strain was transferred to 10 mL of nutrient broth and further incubated overnight at 37°C to ensure sufficient bacterial growth. The cultures were centrifuged at 6000 rpm for 5 minutes, and the supernatant was discarded. The bacterial pellets were washed three times with phosphate-buffered saline (PBS, pH 7.4) and finally re-suspended in 50 µL of PBS to obtain a homogeneous bacterial suspension with an optical density corresponding to approximately 10^8 CFU/mL.

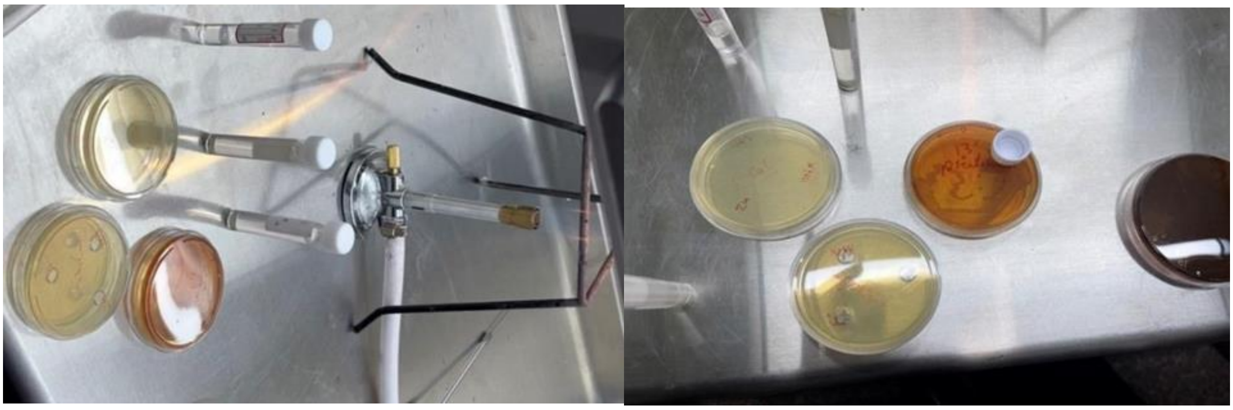

Figure 3. The figure shows how to prepare the bacteria.

Antibacterial Testing Procedure

The antibacterial activity of ZnO nanoparticles was evaluated using the agar diffusion method. Nutrient agar plates were inoculated with the prepared bacterial suspensions, and ZnO nanoparticle solutions of known concentrations were introduced into wells on the agar surface. The plates were incubated at 37°C for 24 hours. The inhibition zones around each well were measured using a digital caliper to determine the antibacterial effectiveness of the ZnO nanoparticles against Escherichia coli and Staphylococcus aureus.

3. Results and Discussion

X-ray diffraction

We note that from the figure the crystalline structure of Zn nano particles have both orthomobic and hexagonal structure

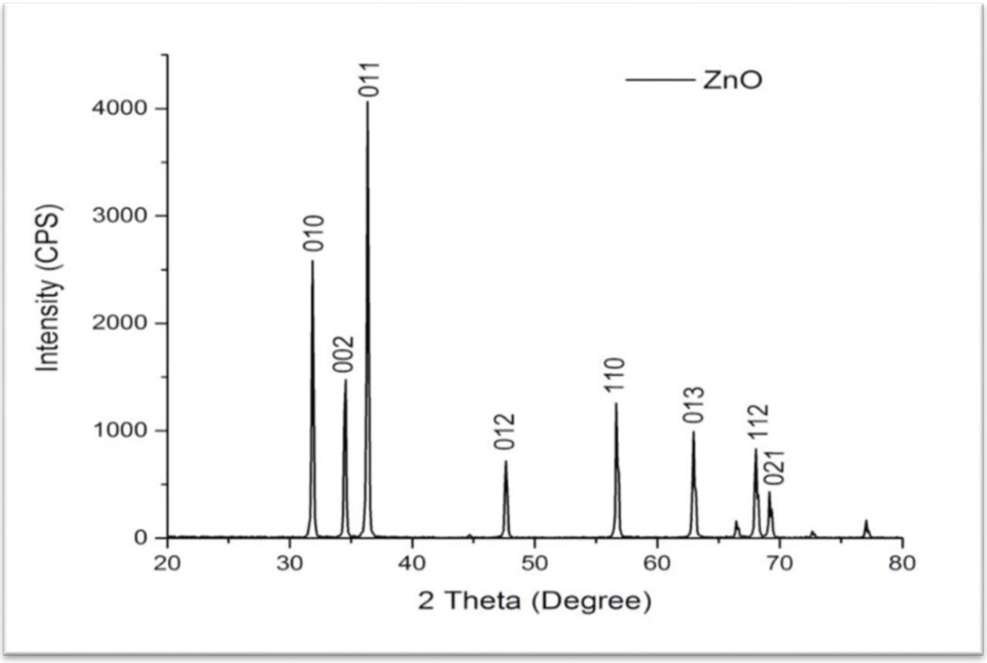

Figure 4. The figure shows the X-ray diffraction of Zn.

Polycrystalline structure observed of Rutile phase of Polycrystalline structure observed peaks located at 32^o, 34^o, 36^o, 47^o,57^o, , 64^o ,67^o and 69^o corresponding to the crystalline plains (010), (002), (011), (012), (110), (013),(112) and (021) respectively, identical the peaks width (FWHM) increasing indicate on increasing crystalline size. identical with standard card No. 043-002 from Joint Committee on Powder Diffraction Standards(JCPDS).

Rutile is a major stage compared to the other structure, because it needs a high temperature to form in a crystalline form. The interatomic layer spacing dhkl for diffraction peaks war calculated using Bragg's law.

$n\lambda = 2d \cdot \sin\theta$ where

•n is an integer determined by the order given.

•λ is the wavelength of x-rays, and moving electrons, protons and neutrons.

•d is the spacing between the planes in the atomic lattice.

• θ is the angle between the incident ray and the scattering planes.

The crystalline sizes (C.S) for the deposited samples were calculated using Sherrer's formula as shown in equ

$D=0.9\lambda/\beta \cos \theta$

• where D is the crystal size

• λ is the wavelength of X-ray

• β is the line broadening at half the maximum intensity (FWHM)

• θ is the Bragg angle

Figure 5. The figure shows device X-ray diffraction (XRD).

Scanning Electron Microscopy (SEM)

The topography of the surface studied using the scanning electron microscopic of Zn nano particles . We found from figure (7- a) that the nanoparticles has cylindrical shape this indicate to quantum wire in this type the quantum qunfinment in two dimension and number of free dimension equal to one .

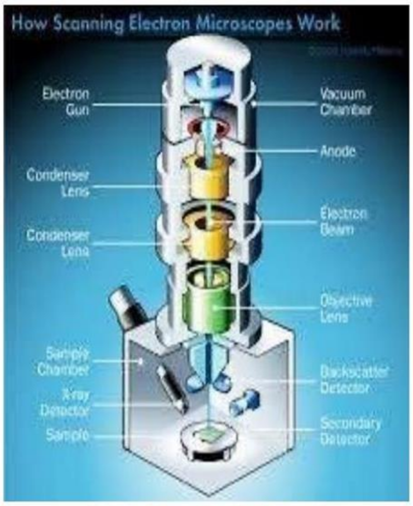

Figure 6. The figure shows device Scanning Electron Microscopes (SEM).

From figure (7-b) show the show there are cluster structures ranging in size from 24 to 70 nm, and the higher the proportions, the greater the grain size.The percentage of benefit from this heterogeneous composition, the process will be ineffective when sunlight falls due to the inhomogeneity

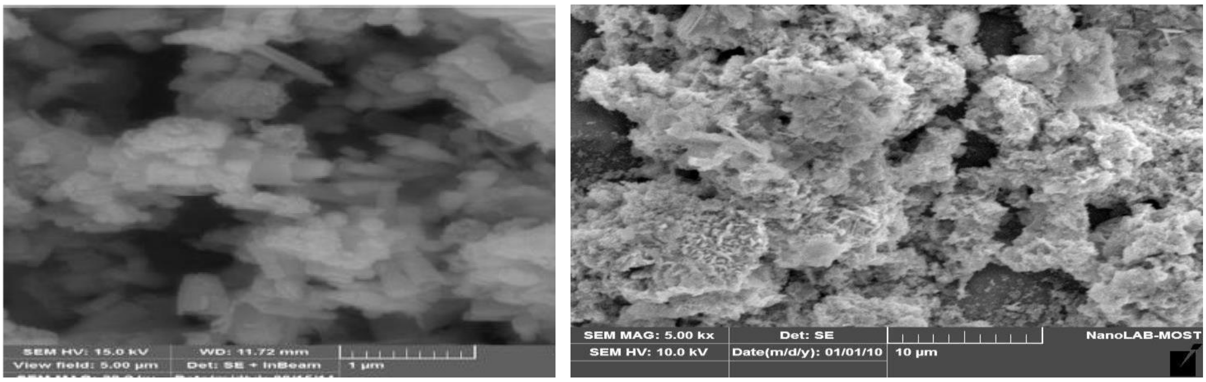

Figure 7. The figure shows the SEM image of Zn

Application (Test of bacteria)

Bacteria Escherichia (E-coli) .

E-coli bacteria.The main part of the intestinal family that invades the intestines after birth and coexists . naturally, while some of its strains have an opportunistic tendency to infect the host with diseases after the availability of . for optimal growth conditions Urinary tract infections are one of the most common diseases, and this bacteria is the main culprit About 90% of cases of urinary tract infections for age groups between (69- 60) years and between (39-30) years, in addition to the fact that the rate of infection in females is greater than in males for the age groups between (09-00) years, and it is considered one of the main problems in hospital injuries due to infection People in convalescent homes .

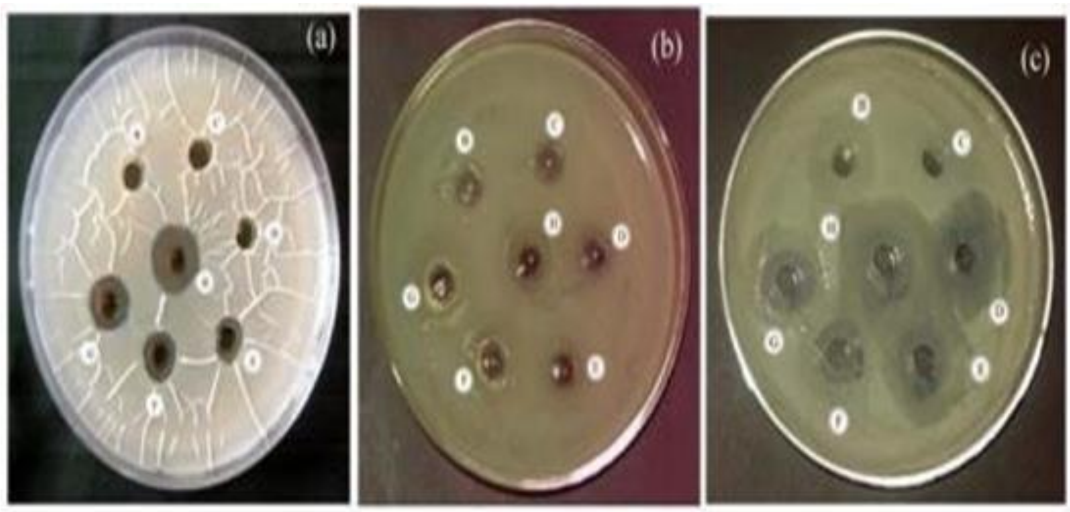

Figure 8. The figure shows bacteria Escherichia

4. Conclusion

Based on the obtained findings, the structural properties of the TiO_2 nanocrystal alloy can be concluded as follows:

a. Scanning Electron Microscopy (SEM) analysis revealed that the nanoparticles exhibit a cylindrical morphology, indicating the formation of quantum wires. In this configuration, quantum confinement occurs in two dimensions, leaving one free dimension.

b. X-Ray Diffraction (XRD) analysis demonstrated that the Zn possesses a polycrystalline nature characterized by both hexagonal and orthorhombic structures.
c. The antibacterial test against E. coli showed that the nanoparticle solution inhibited bacterial growth, as evidenced by the appearance of a clear (white) inhibition zone surrounding the bacterial colonies.

Future Work

1. Preparation of Zn Nanoparticles Using Pulsed Laser Deposition (PLD):

Future studies should focus on synthesizing zinc nanoparticles through the pulsed laser deposition technique. This method offers precise control over particle size, morphology, and crystallinity, allowing for the optimization of nanostructural characteristics suitable for biomedical and electronic applications.

2. Investigation of Laser Parameter Effects on Structural Properties:

It is recommended to systematically study the influence of various laser parameters—such as pulse energy, wavelength, deposition time, and substrate temperature—on the structural, optical, and electrical properties of the prepared nanoparticles. Understanding these relationships will help in tailoring material properties for specific functional uses.

3. Development of Antibacterial Coatings Using ZnO Nanoparticle Sprays:

Future work should include preparing and testing spray coatings composed of ZnO nanoparticle suspensions. These coatings can serve as antibacterial layers for medical instruments, implants, and surfaces, offering an effective means of protection against bacterial infections such as E. coli and Staphylococcus aureus.

4. Exploration of TiO_2–ZnO Composite Nanostructures:

Further research can also investigate the fabrication of TiO_2–ZnO hybrid nanostructures to enhance photocatalytic efficiency and antibacterial performance. Such composites could provide improved charge separation, optical activity, and long-term stability.

5. In-vitro Biocompatibility and Toxicity Assessment:

Before large-scale application, biocompatibility tests should be performed to ensure that the synthesized nanoparticles and coatings are safe for human use and do not induce cytotoxic effects.

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