Pro Index | Journal of Science in Medicine and Life
Volume: 3 Issue: 3 Year: 2025
ISSN: 2992-9202 | http://journals.proindex.uz

Characterization and Application of Zinc Oxide Nanoparticles

Nidaa Yousif Amrullah, Rand Sabry Abdullah
Division of Continuing Education, College of science, Diyala University, Diyala, Iraq
nedaayousef95@gmail.com

Abdullah Muhsin Hazbar
Department of Chemistry, College of science, Diyala University

Abstract: Zinc oxide nanoparticles (ZnO-NPs) have garnered significant interest in the food and agricultural sectors for their potential to eliminate or reduce microbial activity. The antibacterial properties of ZnO nanoparticles may improve food quality, hence directly impacting human health.

ZnO-NPs, among the most extensively studied inorganic nanoparticles, have been used across several domains and has the potential to rapidly garner attention in the food and agricultural sectors. This study covers the synthesis of ZnO nanoparticles, their characterisation, modifications, uses, antimicrobial efficacy, testing methodologies, and effects, covering both bactericidal and bacteriostatic processes.

This study aims to enhance understanding of the preparation and use of ZnO nanoparticles in the food and agricultural sectors, while also promoting their advancement in these domains.

Keywords: ZnO nanoparticles, structure, antibacterial properties, food.

1-Introduction

While "nanotechnology" was first conceptualized in 1974 by Japanese scientist Norio Taniguchi, its roots may extend before 1959. This field has become the most current, innovative, and prominent topic of research in modern science owing to its unique characteristics and the significant relevance of nanoparticles. Nanoparticles are extensively used in the fields of electronics, optics, biology, and materials research. Their inventive solutions across several scientific fields have resulted in their unexpected ascent in popularity in recent years.[1]

They display size-dependent properties that significantly diverge from bulk materials and possess distinct attributes relative to their macroscale equivalents due to their elevated surface area-to-volume ratio and unique physicochemical characteristics, including color, dispersion, and thermodynamics.[2]

In the field of food science, nanotechnology is used in more advanced manners and has become an essential element of food production, processing, storage, and quality assurance.

Zinc oxide nanoparticles (ZnO-NPs) are categorized as metal oxide nanomaterials and constitute an important and versatile inorganic compound due to their unique physical and chemical characteristics. These nanoparticles have exceptional chemical stability, a broad radiation absorption spectrum, a high electrochemical coupling coefficient, and outstanding photostability, represented by the molecular formula ZnO .[4]

ZnO nanoparticles have been extensively manufactured and utilized in a diverse array of commercial and additive products, including ceramics, cement, plastics, glass, ointments, lubricants, adhesives, sealants, pigments, batteries, ferrites, fire retardants, cosmetics, and sunscreens, and are also employed in food products as a source of zinc nutrients.[5]

Nanosized ZnO particles have significant antibacterial characteristics due to their small size, which may trigger many bactericidal pathways upon penetrating the bacterial cell. These processes may include interactions with the bacterial surface or core, the production of reactive oxygen species (ROS), the liberation of Zn2+, and the possibility of endocytosis by cells. (Figure 1) [6]

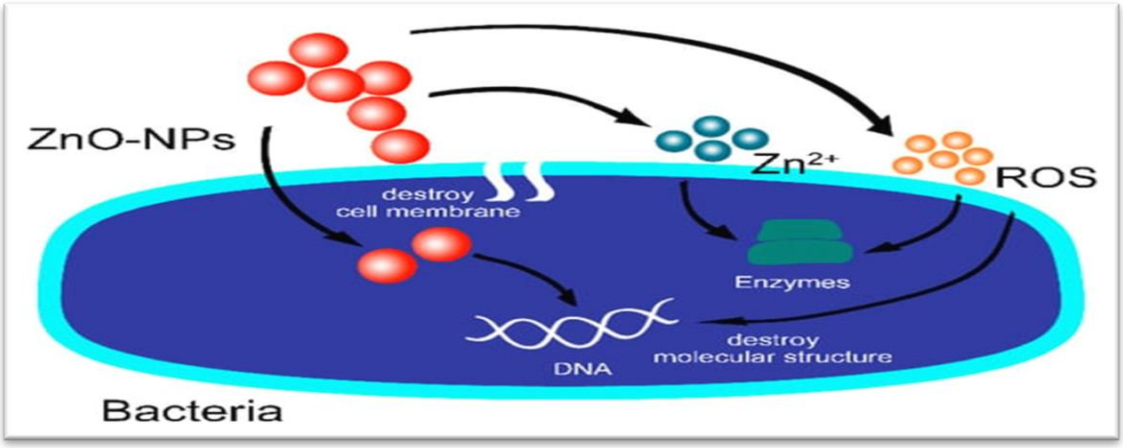

Figure 1. Antibacterial mechanism of ZnO-NPs. (ROS formation, Zn2+ release, internalized ZnO-NPs, and electrostatic interactions.).

This study aims to provide an overview of the use of ZnO nanotechnology in the food business and agriculture, while also providing food and agricultural experts with a thorough viewpoint on ZnO nanotechnology. This technique enables rapid, precise, and efficient identification of microbiological contamination, hazardous substances, and pesticides in food and agricultural processes.

2-Framework

Zinc and oxygen are members of the second and sixth groups of the periodic table, respectively; hence, ZnO is categorized as a known II-VI semiconductor in materials science. The ZnO semiconductor exhibits numerous exceptional and beneficial attributes, such as excellent transparency, antimicrobial properties, elevated electron mobility, a broad bandgap, and substantial thermal and mechanical stability at ambient temperature, in addition to pronounced luminescence at room temperature. The substantial bandgap of 3.37 eV is located at the threshold between ionic and covalent semiconductors.[7]

The crystal structure of ZnO has a wurtzite (B4) configuration, characterized by a hexagonal unit cell with lattice parameters a = 0.325 nm and c = 0.521 nm. In this hexagonal wurtzite structure, each anion is coordinated by four cations located at the vertices of a tetrahedron, illustrating tetrahedral coordination and displaying sp3 covalent bonding. The tetrahedral configuration of ZnO produces a non-centrosymmetric structure (Figure 2).[8]

Figure 2. Crystal structure models of ZnO: (a) zinc blende, (b) wurtzite, and (c) rock salt.[9]

Ultraviolet-Visible Absorption Spectrum

The dimensions of nanoparticles significantly influence the overall characteristics of materials. Consequently, the size development of semiconducting nanoparticles is crucial for investigating the characteristics of the materials. UV-visible absorption spectroscopy is a frequently used method for analyzing the optical characteristics of nanosized particles. It displays a pronounced absorption band at around 355 nm [9]. An excitonic absorption peak occurs at around 258 nm, attributed to the ZnO nanoparticles, which are significantly below the band gap wavelength of 358 nm (Eg = 3.46 eV). The very acute absorption of ZnO clearly reveals the monodispersed character of the nanoparticle dispersion.[10]

The mean particle size in a nanocolloid may be determined from the absorption beginning in UV-vis absorption spectra using the effective mass model (Figure 3), where the band gap E* can be estimated by

$$E^{*} = E_g^{\text{bulk}} + \frac{\hbar^2\pi^2}{2er^2}\left(\frac{1}{m_e^{*}m_0} + \frac{1}{m_h^{*}m_0}\right) - \frac{1.8e}{4\pi\varepsilon\varepsilon_0 r} - \frac{0.124e^3}{\hbar^2(4\pi\varepsilon\varepsilon_0)^2}\left(\frac{1}{m_e^{*}m_0} + \frac{1}{m_h^{*}m_0}\right)^{-1},$$

The mathematical equation delineates the bulk band gap in electronvolts (eV), where $\hbar$ represents Planck’s constant, r denotes the particle radius, me signifies the effective mass of the electron, mh indicates the effective mass of the hole, m0 refers to the mass of a free electron, e is the charge of the electron, ε symbolizes the relative permittivity, and ε0 stands for the permittivity of free space. [11]

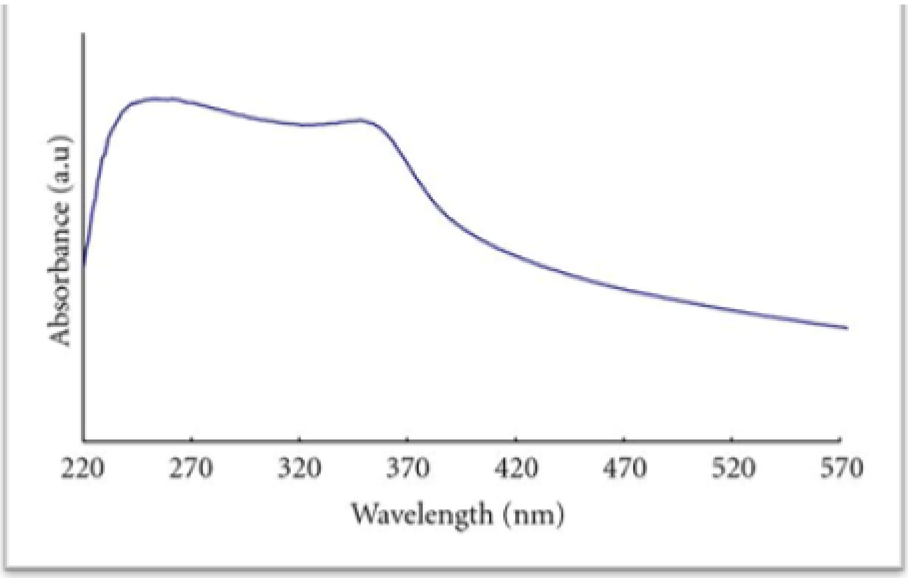

Figure 3: UV-vis absorption spectrum of ZnO nanoparticles.

FTIR Analysis

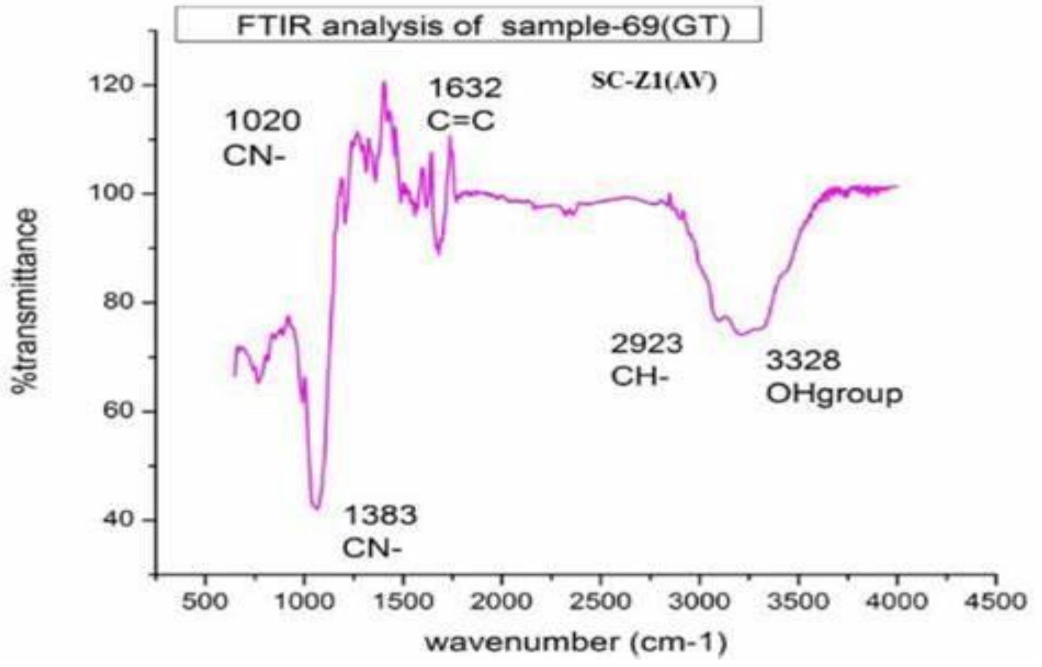

Figure 4: FTIR spectrum of ZnO nanoparticles

The FTIR spectrum of zinc oxide nanoparticles synthesized through a chemical route exhibited a significant absorption peak at 546 cm^{-1} [12]. According to the data shown in the picture, the following is a comprehensive examination of the FTIR spectrum for the zinc nanoparticle sample (sample-69(GT)):

1. Principal Absorption Peaks and Their Chemical Significance:

- Peak at 3328 cm^{-1} (OH group): Signifies the existence of hydroxyl groups (O-H), presumably resulting from moisture adsorption on the nanoparticle surface or leftover watery solvents from the production procedure.
- Peak at 2923 cm^{-1} (C-H): Ascribed to C-H stretching vibrations in alkyl moieties (e.g., CH_2 or CH_3). This indicates the existence of organic contaminants, including residual solvents or stabilizers used during synthesis.
- The peak at 1622 cm^{-1} (SC-Z1(AV)) is characterized by unclear tagging. Nonetheless, peaks within this range (1600–1650 cm^{-1}) may relate to :
- C=C stretching vibrations in aromatic compounds or alkenes.
- H-O-H bending (water absorption) occurs in the presence of moisture.
- Interfacial chemical interactions between nanoparticles and adjacent agents.
- Peaks at 1383 cm^{-1} and 100 cm^{-1} (CN_): Probably linked to C≡N bonds (cyanide) or other indeterminate groups. These may signify contamination or byproducts during synthesis.
- The peak at 1383 cm^{-1} may possibly originate from NO_3^- bonds, contingent upon the use of nitrates in the process.
- Peak at 1020 cm^{-1} (C=C): Indicates the presence of carbon-carbon double bonds, perhaps originating from leftover organic molecules or reducing agents used in the synthesis process.

2. **Unaccounted Peaks (e.g., 500, 1000, 1500 cm^{-1}) :**

- These values may signify reference markers on the wavenumber axis instead of genuine absorption peaks .
- If they are genuine peaks, potential explanations encompass :

600–500 - cm^{-1}: Zn-O vibrational modes (not specifically identified, creating concerns over sample cleanliness) .

1500–1000 - cm^{-1}: C-O or C-N bonds in organic molecules .

3. **General Observations Regarding the Sample :**

- Organic Impurities: Absorption peaks at 2923 cm^{-1} (C-H), 1020 cm^{-1} (C=C), and 3328 cm^{-1} (O-H) indicate the presence of residual organic substances or solvents, potentially impacting nanoparticle efficacy .
- Low Purity: The lack of a distinct Zn-O peak (anticipated at 400–600 cm^{-1}) casts doubt on the synthesis of pure ZnO nanoparticles. Additional purification may be necessary .
- Surface Interactions: The peak at 1622 cm^{-1} may signify chemical interactions occurring on the nanoparticle surface with the ambient environment .

The spectrum indicates the existence of nanoparticles with notable organic impurities; nevertheless, it does not definitively verify the creation of zinc oxide (ZnO) nanoparticles, since the distinctive Zn-O peak is absent. Additional detailed studies (e.g., XRD, SEM) and thorough documenting of synthesis and measurement circumstances are highly advisable to corroborate the findings. [13,14].

Utilization as an Antimicrobial Agent against Foodborne Pathogens

ZnO nanoparticles significantly impacted the management of foodborne illnesses. Foodborne illnesses are endangering the whole globe. Each year in the United Kingdom, 20,000 individuals are hospitalized due to foodborne diseases, with 56 fatalities reported, as per the UK Food Standards Agency (FSA). Foodborne infections provide several hurdles, including health issues, poverty, and economic difficulties [15]. ZnO nanoparticles are increasingly useful in battling harmful bacteria and avoiding food contamination via adsorption-induced membrane damage and reactive oxygen species-mediated cellular toxicity. ZnO nanoparticles have shown efficacy as an antibacterial agent against pathogenic microorganisms present in food, including Staphylococcus aureus, Escherichia coli, Bacillus subtilis, Pseudomonas vulgaris, Bacillus megaterium, Candida albicans, Klebsiella pneumoniae, and Aspergillus niger, among others .[16]

Research has been conducted on metal oxide particles to produce active oxygen species, which may serve as the primary mechanism for their antibacterial efficacy .[17]

Firouzabadi et al. investigated the practical use of a ZnO solution with 0.3% citric acid at several doses (0, 1, 3, 5, 8 mM) against Listeria monocytogenes, Escherichia coli, Staphylococcus aureus, and Bacillus cereus. The development of all strains was markedly suppressed over 12 hours of culture, with the ZnO solution containing 5 mM and 8 mM citric acid demonstrating the highest efficacy across all strains. Consequently, 5 mM and 8 mM ZnO were chosen for future investigation in mango juice. The ZnO-NPs were capable of diminishing the initial growth count of all aforementioned strains in the mango solution. Reference[18]

ZnO nanoparticles (ZnO-NPs) directly interact with cell membranes, allowing their entry into microbial cells and inducing oxidative stress, which leads to inhibited growth and cell death. This study advocates for the use of ZnO-NPs as an effective antimicrobial agent in food preservation. ZnO nanoparticles are often used as disinfectants and sterilizers for equipment and containers used in the food sector to combat contamination by foodborne pathogenic microorganisms.[19]

Final Assessment

This study emphasizes the considerable potential of zinc oxide nanoparticles (ZnO-NPs) in mitigating microbial contamination within the food and agricultural sectors. ZnO nanoparticles have remarkable antibacterial characteristics via processes including the formation of reactive oxygen species (ROS), the release of Zn^{2+} ions, and direct interactions with microbial cell membranes. These methods result in the efficient inhibition of diverse foodborne pathogens, becoming ZnO-NPs a significant asset for improving food safety and quality.

Applications include food preservation, equipment sterilization, and packaging, whereby ZnO-NPs have shown efficacy in diminishing microbial contamination and extending shelf life. Research has shown their efficacy against many infections, including Staphylococcus aureus, Escherichia coli, and Listeria monocytogenes. These results highlight their capacity to alleviate foodborne infections, which continue to pose a worldwide health and economic challenge.

Improvements in synthesis processes and characterization technologies, including FTIR and UV-Vis spectroscopy, allow the optimization of ZnO nanoparticles for diverse applications. Their adaptability in antimicrobial applications and their function in safeguarding crops underscore their significant influence on agricultural sustainability.

In summary, ZnO-NPs provide a viable answer to microbial issues in food and agriculture. Ongoing research and development are essential to improve their efficacy, guarantee safety, and mitigate any environmental issues. By surmounting these obstacles, ZnO-NPs may significantly enhance global food security and public health.

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