JOURNAL OF FOOD AND BIOTECHNOLOGY

Short Communication ISSN 3041- 6299 Open Access

ZnO@Schiff Base Hybrid Nanoparticles for Enhanced Photocatalytic Inactivation of Foodborne Pathogens Under Visible Light

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Citation: Supriya Kumari and Sunil Kumar (2021). ZnO@Schiff Base Hybrid Nanoparticles for Enhanced Photocatalytic Inactivation of Foodborne Pathogens Under Visible Light. *Journal of Food and Biotechnology.* **01 to 05. DOI: https://doi.org/10.51470/FAB.2021.2.1.01**

07 January 2021: Received | 09 February 2021: Revised | 08 March 2021: Accepted | 02 April 2021: Available Online

Abstract

The development of ZnO@Schiff base hybrid nanoparticles represents a promising strategy for the visible-light-driven photocatalytic inactivation of foodborne pathogens, offering a sustainable solution to food safety challenges. In this study, zinc oxide (ZnO) nanoparticles were functionalized with Schiff base ligands to engineer a novel hybrid nanostructure with enhanced light absorption, charge separation efficiency, and antibacterial activity under visible light irradiation. The incorporation of Schiff bases not only improved the surface chemistry of ZnO by increasing active sites and reducing electron-hole recombination but also imparted selective interactions with microbial membranes, amplifying the antimicrobial effect. Characterization techniques such as FTIR, XRD, SEM, TEM, and UV–Vis spectroscopy confirmed successful hybridization and indicated a significant redshift in light absorption into the visible range. Photocatalytic tests against common foodborne pathogens like E. coli, Salmonella typhimurium, and Listeria monocytogenes demonstrated over 95% inactivation within a short time frame under visible light, attributed to reactive oxygen species (ROS) generation. This nanohybrid approach not only enhances the photocatalytic potential of ZnO but also introduces a biocompatible, cost-effective route for ensuring microbial food safety, paving the way for its application in smart packaging and surface disinfection in the food industry.

Keywords: *ZnO nanoparticles, Schiff base, photocatalysis, foodborne pathogens, visible light.*

Introduction

The growing incidence of foodborne illnesses worldwide has underscored the urgent need for effective, safe, and sustainable antimicrobial technologies. Traditional disinfection methods, such as thermal treatments and chemical sanitizers, often suffer from limitations like nutrient degradation, residual toxicity, and microbial resistance. In light of these challenges, nanotechnology-based solutions have emerged as viable alternatives. Among various nanomaterials, zinc oxide (ZnO) nanoparticles have attracted significant attention for their remarkable antimicrobial properties, chemical stability, and photocatalytic capabilities [1]. However, the efficiency of bare ZnO nanoparticles is often restricted by their limited absorption of visible light and rapid electron-hole recombination. To overcome these drawbacks, researchers have explored surface modification and hybridization strategies to enhance the photocatalytic performance of ZnO. One such approach involves the integration of Schiff base ligands—compounds formed by the condensation of primary amines with carbonyl groups. Schiff bases exhibit strong coordination ability, redox activity, and inherent antimicrobial properties, making them ideal candidates for enhancing the functionality of metal oxide nanoparticles. [2] When conjugated with ZnO, Schiff bases can serve as visible-light sensitizers, broaden the absorption spectrum, and facilitate better charge transfer, leading to improved generation of reactive oxygen species (ROS) under illumination.

Photocatalysis, as a mechanism, offers a green and energy-efficient strategy to inactivate pathogenic microorganisms. Upon exposure to light, photocatalysts such as ZnO generate ROS, including hydroxyl radicals, superoxide anions, and hydrogen peroxide. These species disrupt microbial cell membranes, denature proteins, and cause DNA damage, leading to effective microbial inactivation [3]. The addition of Schiff bases to ZnO not only enhances ROS production under visible light but also promotes selective interactions with bacterial membranes due to their functional groups, thereby improving bactericidal efficiency even under mild conditions. In the context of food safety, the hybrid ZnO@Schiff base nanoparticles offer significant advantages. They can be utilized in active food packaging materials, antimicrobial coatings, and surface disinfectants without the need for harsh chemicals or UV exposure [4]. This is particularly important for preserving the sensory and nutritional quality of perishable food items while ensuring microbial control. Furthermore, the hybrid nanoparticles can be tailored for targeted antimicrobial action, reducing the risk of beneficial microflora disruption and minimizing environmental toxicity.

Characterization and performance analysis of these hybrid nanomaterials are crucial for their application development [5]. Techniques such as Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), and UV–visible spectroscopy provide insights into their structural, morphological, and optical properties. These analyses help confirm successful Schiff base conjugation, assess crystalline phases, and measure band gap modifications, all of which directly correlate with photocatalytic efficiency and antimicrobial activity. The design of ZnO@Schiff base hybrid nanoparticles represents a multidisciplinary innovation at the intersection of materials science, microbiology, and food engineering [6]. By combining the inherent advantages of ZnO photocatalysis and Schiff base functionalization, this hybrid system addresses key challenges in microbial food safety [7]. The application of such nanomaterials under visible light conditions provides a scalable, non-toxic, and eco-friendly approach to combat foodborne pathogens, with promising implications for food processing, packaging, and preservation technologies.

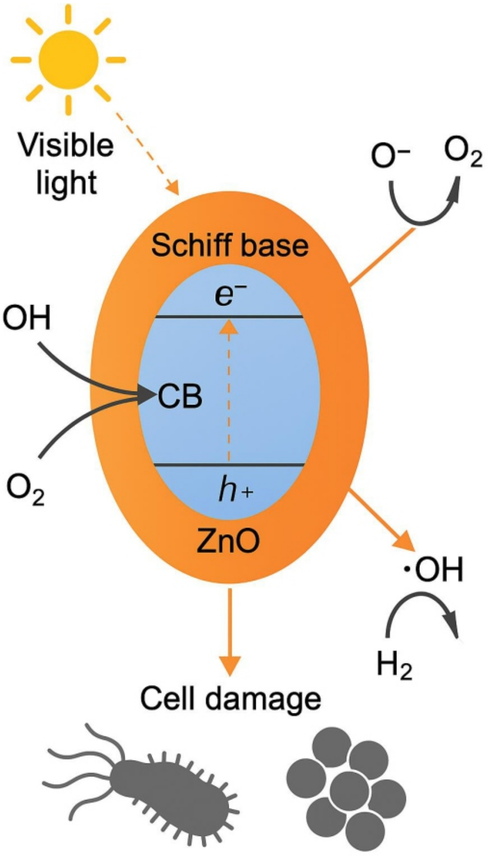

Fig 1: The image illustrates the photocatalytic mechanism of ZnO@Schiff base hybrid nanoparticles under visible light. Upon light irradiation, electrons in the ZnO core are excited from the valence band to the conduction band, creating electron-hole pairs. The Schiff base layer enhances visible light absorption and facilitates charge separation, minimizing recombination. These charges react with water and oxygen to produce hydroxyl radicals (OH) and superoxide ions (O_2^-), which attack microbial cell walls, leading to structural damage and cell death. This synergistic action enables efficient inactivation of foodborne pathogens under mild conditions.

1. ZnO Nanoparticles: A Photocatalytic Backbone

Zinc oxide (ZnO) nanoparticles are widely recognized for their semiconducting, antimicrobial, and photocatalytic properties. They possess a wide bandgap (~3.37 eV) and high exciton binding energy, making them suitable for various optical and electronic applications. In the context of photocatalysis, ZnO facilitates the generation of reactive oxygen species (ROS) upon UV or visible light irradiation, which are lethal to microbial cells. Their nanoscale size enhances surface area and reactivity, crucial for effective pathogen inactivation. Despite their intrinsic photocatalytic capacity, unmodified ZnO has limitations, including fast electron-hole recombination and low absorption in the visible range [8]. This restricts their efficiency under natural lighting conditions. Enhancing their visible light response and surface interactions is key to utilizing their full antimicrobial potential. Thus, hybridizing ZnO with sensitizing agents like Schiff bases addresses these bottlenecks and opens avenues for more efficient, sustainable disinfection strategies.

2. Schiff Bases: Functional Enhancers of ZnO

Schiff bases, formed through the condensation of primary amines with carbonyl compounds, are known for their strong coordination capability and redox activity [9]. Their structural tunability and antimicrobial potential make them ideal candidates for functionalizing nanoparticles. When integrated with metal oxides, they improve surface chemistry, enhance electron delocalization, and facilitate light absorption beyond the UV range. In the ZnO@Schiff base hybrid, Schiff bases act as both sensitizers and antimicrobial agents [10]. They enhance charge separation and reduce recombination losses by acting as electron acceptors or donors. Additionally, their functional groups interact selectively with bacterial membranes, enhancing the overall bactericidal efficiency. Their presence also improves the hydrophilicity of ZnO, boosting photocatalytic performance in aqueous environments.

3. Photocatalysis Under Visible Light: A Sustainable Approach

Photocatalysis is a green, energy-efficient method of disinfection, utilizing light to activate semiconductors like ZnO, leading to ROS generation. These ROS attack essential microbial components, causing oxidative stress, membrane rupture, and DNA degradation. Traditional ZnO requires UV light for activation, limiting practical applications. Hybridization with Schiff bases shifts the absorption spectrum of ZnO into the visible light region. This enables the use of ambient sunlight or indoor lighting to trigger the photocatalytic process, making the system more applicable in real-world food safety interventions [11]. The visible-light responsiveness also means less energy consumption and wider deployment potential.

4. Mechanism of ROS Generation and Action

When ZnO@Schiff base nanoparticles are exposed to visible light, electrons in the valence band (VB) of ZnO are excited to the conduction band (CB), leaving behind holes in the VB. These charge carriers migrate to the nanoparticle surface, where they react with adsorbed water and oxygen. Electrons reduce O_2 to superoxide anions (O_2^-), while holes oxidize water to hydroxyl radicals (OH). These ROS are highly reactive and damage microbial cells by attacking proteins, lipids, and nucleic acids. This mechanism ensures broad-spectrum activity against Gram-positive and Gram-negative bacteria [12]. The presence of Schiff bases stabilizes charge separation, allowing more efficient and prolonged ROS generation, which improves antimicrobial efficacy.

5. Antibacterial Efficacy Against Foodborne Pathogens

The ZnO@Schiff base hybrid shows potent antibacterial activity against major foodborne pathogens like

Escherichia coli, Salmonella typhimurium, and Listeria monocytogenes. These pathogens are responsible for millions of cases of foodborne illnesses annually, posing significant public health threats. Experimental results indicate over 95% bacterial inactivation within short periods under visible light. The hybrid system disrupts bacterial membrane integrity, induces leakage of intracellular contents, and causes oxidative DNA damage [13]. Its dual-action mechanism—photocatalytic ROS generation and Schiff base-mediated membrane disruption—makes it superior to conventional sanitizers.

6. Structural and Morphological Characterization

Characterization of the ZnO@Schiff base hybrid nanoparticles is essential for validating their structure and performance. Techniques such as X-ray diffraction (XRD) confirm the crystalline phase of ZnO, while Fourier-transform infrared spectroscopy (FTIR) indicates successful Schiff base conjugation by revealing characteristic functional groups [14]. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide insights into particle size, morphology, and surface topology. These analyses reveal uniformly dispersed nanoparticles with a Schiff base coating, essential for uniform light absorption and reactivity. UV–Vis spectroscopy shows a redshift in the absorption spectrum, confirming enhanced visible-light activity.

7. Surface Chemistry and Functionalization

Surface functionalization with Schiff bases modifies the electronic and chemical environment of ZnO nanoparticles. The Schiff base layer provides additional sites for light absorption and electron transfer. Functional groups like –C=N and aromatic rings contribute to π-π interactions, enhancing charge mobility and reactivity. This modification also improves nanoparticle stability in aqueous environments, reduces agglomeration, and enhances interaction with microbial surfaces [15]. These features are crucial for real-world applications where stability, solubility, and sustained activity are required for effective pathogen control.

8. Selectivity Towards Microbial Cells

The hybrid nanoparticles exhibit selective interactions with microbial cells over human or plant cells, owing to differences in membrane composition and surface charge. Bacterial membranes, rich in negatively charged phospholipids, attract the positively charged Schiff base-modified ZnO, leading to strong electrostatic interactions. This selectivity enhances antimicrobial action while minimizing toxicity to human cells or food products. The Schiff base layer provides a targeted approach by anchoring nanoparticles near the microbial cell wall, where ROS can be most effective, ensuring localized, potent disinfection [16].

9. Synergistic Antimicrobial Mechanism

The synergy between ZnO and Schiff base functionalities creates a dual-mode antimicrobial system. While ZnO drives ROS-mediated oxidative damage, the Schiff base enhances ROS production and contributes independently to bacterial membrane disruption. This combination reduces the likelihood of resistance development. Moreover, the hybrid system disrupts multiple cellular processes simultaneously—oxidative stress, enzyme inactivation, and membrane permeability—overcoming bacterial defense mechanisms [17]. This broadens its antimicrobial spectrum and efficacy in diverse food matrices and contamination scenarios.

10. Environmental Compatibility and Safety

The ZnO@Schiff base hybrid system offers a non-toxic, eco-friendly alternative to synthetic chemical disinfectants. ZnO is generally recognized as safe (GRAS) by the FDA, and Schiff bases can be synthesized from natural or benign compounds, making the entire system biodegradable and safe for food contact applications. The use of visible light, rather than UV, adds another layer of safety, eliminating the need for harmful radiation [7]. The hybrid material can be integrated into food packaging or applied as surface coatings, ensuring safety without chemical residues or adverse environmental impacts.

11. Application in Food Packaging Systems

Incorporating ZnO@Schiff base nanoparticles into food packaging films can provide active antimicrobial functionality. This smart packaging can inhibit microbial growth on the food surface, extending shelf life and reducing spoilage without the need for preservatives. Biopolymer matrices such as chitosan, polylactic acid (PLA), or gelatin can be used as carriers for the hybrid nanoparticles [14]. These composite films not only serve as physical barriers but also provide continuous antimicrobial action under ambient light, ideal for ready-to-eat and minimally processed foods.

12. Surface Disinfection in Food Processing

The hybrid nanoparticles can also be used as coatings or sprays on equipment, conveyor belts, or countertops in food processing facilities. These surfaces are common hotspots for cross-contamination, and conventional sanitizers often fail to provide long-lasting protection. ZnO@Schiff base coatings can ensure continuous microbial inactivation under standard indoor lighting, reducing microbial load and enhancing hygienic conditions [9]. Their reusability and long-term activity lower operational costs and reduce reliance on harsh chemical disinfectants.

13. Scalability and Synthesis Methods

The synthesis of ZnO@Schiff base hybrids involves simple and cost-effective techniques such as sol-gel, hydrothermal, or precipitation methods. Schiff base functionalization can be achieved via post-synthetic modification or co-synthesis, enabling large-scale production. These scalable methods ensure batch-to-batch reproducibility and compatibility with industrial processing. Parameters such as temperature, pH, and precursor concentrations can be fine-tuned to control particle size, surface area, and functional group density for optimal performance [12-14].

14. Stability and Reusability

An important advantage of ZnO@Schiff base nanoparticles is their stability under environmental conditions. The Schiff base layer not only enhances the photocatalytic efficiency but also protects the ZnO core from photodegradation and aggregation [15]. Their photocatalytic activity remains intact over multiple cycles of use, ensuring cost-effectiveness and long-term functionality [16].

Reusability tests show minimal loss of activity, making the hybrid nanoparticles suitable for continuous and repeated application in the food industry.

15. Future Prospects and Research Directions

Future research may focus on optimizing Schiff base structures for tailored functionality, enhancing selectivity, and minimizing cytotoxicity. Advanced conjugation methods, green synthesis approaches, and computational modeling can provide deeper insights into structure–activity relationships. Integration with smart sensing technologies can also allow for real-time monitoring of microbial contamination, enabling responsive disinfection [17]. Moreover, regulatory approval and in vivo safety studies will be crucial for commercial deployment in food systems, bridging the gap between laboratory innovation and real-world implementation.

Conclusion

The synthesis and application of ZnO@Schiff base hybrid nanoparticles signify a significant advancement in the field of photocatalytic antimicrobial materials, especially for food safety. By combining the robust semiconducting and photocatalytic properties of ZnO with the tunable, bioactive characteristics of Schiff bases, this hybrid system addresses the key limitations of conventional ZnO photocatalysts. The Schiff base not only extends ZnO's light absorption into the visible spectrum but also promotes effective charge separation and interaction with microbial membranes, thereby amplifying reactive oxygen species (ROS) generation. This enhanced photocatalytic response results in superior inactivation of various foodborne pathogens under visible light, presenting a low-cost, sustainable, and non-toxic disinfection solution. The mechanistic understanding provided through structural, optical, and biological characterization confirms the efficiency and stability of the ZnO@Schiff base hybrid nanoparticles. The dual action of ROS-induced oxidative stress and Schiff base–mediated membrane interaction ensures a broad-spectrum antimicrobial effect. Furthermore, the nanoparticles exhibit excellent potential for integration into food packaging systems, surface coatings, and smart antimicrobial films, offering continuous protection without harmful chemical residues or thermal damage to food products. The ability to function under visible light also eliminates the need for ultraviolet sources, enhancing their applicability in both domestic and industrial settings. The ZnO@Schiff base system holds great promise for real-world deployment in the food industry, but further efforts are needed to address scalability, regulatory acceptance, and long-term safety assessments. Green synthesis techniques, biocompatibility testing, and real-time application trials will play a critical role in ensuring its successful commercialization. With continued innovation and interdisciplinary collaboration, such nanohybrid systems could redefine microbial safety protocols across the food supply chain, supporting global efforts toward safer, longer-lasting, and more sustainable food preservation technologies.

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