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Research Paper

Carbon Quantum Dot-Modified ZnO Nanomaterials for Photocatalytic and Antibacterial Applications

B. Maheshkumar*¹

¹Dept. of Humanities and Sciences, Siddhartha Institute of Technology & Sciences,
Hyderabad-500088, India.

Corresponding Author: maheshhiremath9@gmail.com

Abstract

The emerging pollutant discharge of organic contaminants, synthetic dyes, pharmaceutical remains, and pathogenic microorganisms in water bodies has raised a critical demand for multifunctional nanotechnology-based materials that can simultaneously degrade pollutants and inactivate microorganisms. Due to its various properties such as low-cost, environmental-friendly, chemical stability, photocatalytic and antibacterial activity, zinc oxide (ZnO) is one of the most widely studied semiconductor nanomaterials. The practical efficiency of pure ZnO is however limited by its wide band gap, its poor absorption in the visible light, its high rate of recombination of the electron-hole pairs generated by the light, and possible photo corrosion during prolonged irradiation. Carbon quantum dots (CQDs) are a novel type of 0D carbon nanomaterials with superior properties of photoluminescence, tuneable surface chemistry, water dispersibility, electron transferring capacity, low toxicity and visible light harvesting capacity, receiving significant attention. The modification of ZnO with CQDs is therefore expected to be an effective approach to improve photocatalytic and antibacterial activity. CQDs exhibit enhanced visible-light utilization, generation of reactive oxygen species, and act as photosensitizers, electron reservoirs, charge-transfer mediators and surface modifiers. CQD-modified ZnO can decompose organic pollutants like methylene blue, rhodamine B, methyl orange, phenolic compounds, pesticides, and pharmaceutical contaminants in photocatalytic systems. In the antibacterial application, the CQD-ZnO nanocomposites inhibit the bacterial growth by oxidative stress, cell membrane disruption, release of Zn²⁺ ions and intracellular damage. The properties, synthesis methods, characterization approaches, photocatalytic mechanism, antibacterial pathways, challenges and future prospects of CQD modified ZnO nanomaterials discussed. Their potential as sustainable multi-functional materials for wastewater treatment, environmental remediation and antimicrobial surface applications are highlighted.

Keywords: Carbon quantum dots, Zinc oxide, Photocatalysis, Antibacterial activity, Reactive oxygen species, Nanocomposites, Wastewater treatment.

1. Introduction

Environmental pollution and microbial contamination are two problems of global concern which impact public health, water quality, food safety and ecological balance. The introduction of a diverse spectrum of

persistent organic pollutants into natural waters has been caused by the rapid industrialization, processing of textiles, pharmaceutical production, agricultural operations and discharge of urban effluents. A significant number of synthetic dyes,

antibiotics, pesticides, phenolic compounds and endocrine-disrupting chemicals are chemically persistent and resistant to conventional treatment processes. Meanwhile, pathogenic microorganisms are spreading via water, food packaging, medical devices, and public surfaces, which increases the risk of infectious diseases. Traditional methods of disinfection like chlorination, ozonation and chemical disinfection can create secondary products or cost a lot of operating expenses (Rakshitha et al., 2024). Hence, the development of advanced materials that can effectively and simultaneously degrade pollutants and inactivate microbes is highly desirable. The small size of nanomaterials offers several advantages for use in the environment and for biomedical applications, including high surface area, tuneable surface chemistry, quantum confinement effects, and increased reactivity. TiO_2 , ZnO , Fe_2O_3 , CdS , WO_3 , $\text{g-C}_3\text{N}_4$, and Bi_2WO_6 are among the semiconductor nanomaterials that have been extensively explored for photocatalysis in light irradiation for their ability to generate electron-hole pairs. These charge carriers then combine with oxygen and water molecules to produce ROS (Reactive Oxygen Species) like hydroxyl radicals, superoxide radicals, and hydrogen peroxide. These species can oxidize organic contaminants and can damage microbial cells. ZnO is a semiconductor photocatalyst that has been given special attention because of its abundance, low cost, ease of synthesis and low toxicity at controlled concentrations and high oxidation ability (Bagheri et al., 2023). ZnO is also used in some commercial products including Sunscreen, Cosmetic products, Coating, Rubber, Ceramic material, Food packaging and

Biomedical materials. The photocatalytic and antibacterial dual-functionality of its interesting properties makes it attractive for integrated environmental and healthcare applications. The efficiency of ZnO under visible light is restricted as the band gap of ZnO is primarily absorbing in the ultraviolet region. This constraint is a limit on the amount of solar light that it can utilise because only a small fraction of the sun's light is in the UV range. For this reason, suitable modifications are necessary for ZnO to enhance its visible-light activity and charge-separation efficiency (Ghahfarokhi, 2023).

1.1. Importance of ZnO Nanomaterials

Zinc oxide is a direct band gap n-type semiconductor material with excitonic properties. The crystal structure of ZnO is normally hexagonal wurtzite, but sometimes zinc blende and rock salt structure are also found, depending on the conditions. It can be utilized in photocatalysis, antibacterial coatings, gas sensors, UV detectors, solar cells, piezoelectric devices, cosmetics and drug delivery. Photocatalysis involves the generation of electrons in the conduction band and holes in the valence band when photons are absorbed by ZnO and the energy of the photons is greater than or equal to the band gap of ZnO . The electrons convert dissolved oxygen to superoxide radicals and the holes oxidise water or hydroxide ions to hydroxyl radicals. These are reactive species that are involved in degradation reactions (Banumathi & Nirmala, 2021).

The ZnO nanomaterials can be prepared with various geometric shapes such as nanoparticles, nanorods, nanowires, nanosheets, nanoflowers, hollow spheres and hierarchical structure. Photocatalytic and antibacterial activity is highly

dependent on morphology. For instance, the smaller particles generally have larger surface area and more active sites, and one-dimensional nanorods and nanowires may enable the charge transport. Hierarchical structures can enhance light scattering, adsorption and surface reaction efficiency. In antibacterial applications, ZnO nanoparticles target the bacterial membranes, cause oxidative stress, release Zn^{2+} ions and disrupt the intracellular metabolic functions (Chang et al., 2021). The advantages of ZnO are that it is low cost, it is highly available, it is chemically stable, it is easy to prepare, it has high electron mobility and strong oxidation potential. ZnO is more environmentally acceptable than some NGB semiconductors which include cadmium or lead. However, there are some disadvantages of pure ZnO that limit its practical efficiency. They include short recombination time for the photogenerated charges, low response to visible light, aggregation of particles, and photo corrosion. Hence, various strategies including metal doping, non-metal doping, defect engineering, heterojunction formation, noble metal decoration, coupling with graphene-based materials and modification using carbon quantum dots have been investigated (Qi & Yu, 2020).

1.2. Limitations of Pure ZnO

The photocatalytic efficiency of pure ZnO is mainly limited by four major limitations. The first is that the band gap of ZnO is large, typically 3.2 - 3.37 eV, meaning that it generally absorbs ultraviolet light. The visible light dominates the solar radiation, which restricts the use of ZnO with natural sunlight. Secondly, the electrons and holes generated by the photoexcitation of ZnO are short-lived, reaching the surface before they can recombine. Recombination lowers

the number of charge carriers available for redox reactions and decreases the amount of ROS. Third, third, third: In the presence of water, the nanoparticles of ZnO tend to cluster together because of their high surface energy. Agglomeration reduces the effective surface area which means that there is less interaction between the catalyst particles and the pollutants or microbes. Fourth, the long-term stability and reusability of ZnO could be influenced by photo corrosion during irradiation, particularly in aqueous solutions. Such constraints are particularly relevant in the real application of wastewater with ZnO because it contains complex organic matter, dissolved salts, turbidity and competing ions (Rajeswari & Venkatesh, 2021; Malhotra, 2020). Organic pollutants can be unevenly deposited on the catalysts' surface and natural organic matter can be able to trap in the catalytic reaction radicals. In the same way, the antibacterial activity can also differ with bacterial species, cell wall, pH, light intensity, exposure time, and concentration of nanoparticles. Gram-negative bacteria like *Escherichia coli* may have an outer membrane that can affect the interaction with nanoparticles, and Gram-positive bacteria like *Staphylococcus aureus* have a thicker peptidoglycan layer. Hence, modification of ZnO is necessary to enhance the light response, surface reactivity, charge transport and stability (Zyoud et al., 2021).

1.3. Role of Carbon Quantum Dots

Carbon quantum dots (CQDs) are sub-10 nm quasi-spherical carbon-based nanoparticles. Unique optical, electronic, and chemical properties include photoluminescence, quantum confinement, high water solubility, low cytotoxicity and good biocompatibility, surface functional groups and tuneable emission. CQDs can be

synthesized using different carbon sources such as citric acid, glucose, biomass waste, polymers, amino acids, plant extracts, and industrial wastes. They often have hydroxyl, carboxyl, carbonyl, amine and epoxy groups on their surface allowing strong interaction with the semiconductor surface. CQDs can enhance the photocatalytic performance when combined with ZnO in several ways. CQDs can work as photosensitizers to absorb visible light and transfer the excited electrons to ZnO. In addition, they can function as electron acceptors (reservoirs), thereby minimizing the rate of electron–hole recombination. They have surface functional groups that enhance dispersion and increase adsorption sites for pollutants (Mishra et al., 2024). Furthermore, CQDs can induce the generation of ROS through electron transfer across the interface. CQD's are also reported in some systems as having up conversion photoluminescence, whereby longer wavelength photons are converted to shorter wavelength photons that can excite ZnO. The mechanisms of up conversion will vary depending on the CQD structure and experimental conditions; but, by examining the available data, it is clear that CQDs enhance harvesting of visible light and charge dynamics in many semiconductor composites. CQDs could also be used to boost the activity of ZnO in antibacterial applications by increasing the contact with the bacterial cells, increasing the generation of ROS and surface charge modification. The antimicrobial property of CQDs can be showed depending on their size, surface functional group, doping atoms and charge. The ZnO nanocomposite when used in combination can exhibit simultaneous antibacterial activity mediated by oxidative stress, release of Zn^{2+} , interaction with the

membrane and photodynamic activity. Therefore, CQD modified ZnO is a multifunctional nanomaterial platform that can be used in both the degradation of pollutants and microbial inhibition (Singh et al., 2024).

The aim of this paper is to discuss the role of carbon quantum dot modification in improving the photocatalytic and antibacterial performance of ZnO nanomaterials. The paper highlights the properties of ZnO and CQDs along with the synthesis methods of CQD-ZnO nanocomposites, the characterization methods, degradation mechanism, antibacterial pathway, comparison with pure ZnO, challenges and future research directions. The scope of the paper is appropriate for a UGC or mini-review article and is focused on the environmental and biomedical relevance.

2. Carbon Quantum Dots: Properties and Significance

2.1. Structure and Optical Properties

Carbon quantum dots are nanoparticles of carbon, typically smaller than 10 nm in dimension. They can be composed of sp^2 -hybridized graphitic domains, sp^3 carbon regions, amorphous carbon and surface oxygen and nitrogen functionalities. Particle size, surface defects, functional groups, heteroatom doping, degree of graphitization, and method of synthesis all have a significant effect on the optical behaviour of CQDs. Photoluminescence is one of their foremost properties. CQDs are capable of absorbing light in the UV and visible spectrum and also emitting a fluorescent light at different wavelengths. Depending on their structure they can be excitation-dependent or excitation-independent emissions. Typically, quantum confinement, surface defect states, molecular fluorophores, and conjugated π -

domains are responsible for the photoluminescence of CQDs. They can emit blue to green, yellow, orange, or red. The introduction of heteroatoms (N, S, P, and B) and surface passivation can increase quantum yield and modify the optical properties. These optical properties are significant in photocatalytic systems as CQD can be able to absorb visible light and can be involved in charge transfer. The electron-rich structure makes them suitable for electron accepting, transporting or donating depending on the band alignment with the semiconductor. CQDs also have hydrophilic surface groups that allow for easy dispersion in water. Enviro-photocatalysis is of importance of this property as it will impact on the adsorption and reaction efficiency due to the dispersion of the catalyst. The high surface to volume ratio of their small size is advantageous for good interfacial contact with ZnO nanoparticles. Furthermore, the surface functional groups –OH, –COOH, and –NH₂ can interact with the surface of ZnO to enhance the stability of the composite material (Yao et al., 2022; You et al., 2024).

2.2. Advantages of CQDs in Nanocomposites

CQDs have several merits to serve as modifiers of semiconductor photocatalysts. They enhance the ability to absorb light in the visible range. The band gaps of many metal oxide semiconductors (ZnO and TiO₂) are primarily in the ultraviolet region. When solar-light is used, CQDs can be used to capture visible light and transfer electrons to the semiconductor, thereby improving the utilization of solar-light. Second, CQDs can inhibit charge recombination by trapping the photogenerated electrons. When transferring electrons from the CQDs to ZnO, and vice versa, separation of electrons

and holes is enhanced. This extends the duration of the charge carriers and enhances the surface redox reactions. Third, the presence of surface functional groups and the π – π interaction with pollutants offers more adsorption sites for pollutants. Organic dyes and aromatic contaminants may interact with CQD surfaces that leads to higher concentrations of pollutants near the active sites. Fourth, CQDs can enhance catalyst dispersion and decrease aggregation of nanoparticles. Fifth, CQDs are synthesized with biomass and waste materials and are relatively low cost, which is appropriate for the development of sustainable materials (M et al., 2022; Mozdbar et al., 2023).

In antibacterial systems, CQDs can be used to improve the generation of photo-induced ROS. The CQDs can produce singlet oxygen, superoxide radicals or undergo electron transfer with oxygen under light irradiation. The composite, when used in combination with ZnO, can yield several oxidative species which attack the membrane and other intracellular components of bacteria. The surface interaction of ZnO with bacterial cell may be further enhanced by the modification of the CQD, particularly if the CQD has functional groups that react with the components of the cell wall (Meziani et al., 2016).

3. ZnO Nanomaterials: Properties and Applications

3.1. Structural and Semiconductor Properties of ZnO

ZnO belongs to II-VI semiconductor material and it is chemically stable semiconductor with peculiar optical properties. It has the most stable structure at ambient conditions as the wurtzite structure. In this structure Zinc and Oxygen ions are arranged in hexagonal lattice. The

main point is that the n-type semiconductor is caused due to the native defects in ZnO namely oxygen vacancies and zinc interstitials. These are defects that affect the electrical conductivity, optical absorption and photocatalytic activity. The wide band gap of ZnO exhibits a strong UV absorption. When the UV lights are projected, the valence band electrons are excited to the conduction band, which results in the creation of holes in the valence band (Das, 2023). These photogenerated carriers go to the surface and start oxidation and reduction reactions. The conduction band electrons reduce oxygen molecules and the valence band holes oxidize water or hydroxyl ions. But due to the fast recombination of an electron and a hole, only a part of the carriers is involved in useful reactions. Modification with CQDs also overcomes this problem by enhancing charge separation. The synthesis methods for the preparation of ZnO nanostructures include precipitation, hydrothermal synthesis, sol-gel method, microwave-assisted synthesis, combustion method, green synthesis, electrochemical deposition, and vapor-phase techniques. The methods all have an impact on particle size, shape, crystallinity, defect density and surface area. Low-temperature wet chemical methods are economical and scalable processes and they are usually preferred for photocatalytic and antibacterial applications (Malhotra, 2020).

3.2. Photocatalytic and Antibacterial Potential of ZnO

ZnO is also a commonly used photocatalyst for degradation of organic dyes like methylene blue, rhodamine B, malachite green, Congo red, and methyl orange. It has also been used for the degradation of pharmaceuticals, pesticides, phenols and other emerging pollutants. In the

photocatalysis process, organic contaminants are converted to intermediate compounds and then to carbon dioxide, water and inorganic ions. The efficiency is affected by the amount of the catalyst, the concentration of the pollutants, the type of radiation, the pH, the temperature, dissolved oxygen and the shape of the catalyst (Rakshitha et al., 2024).

For the antibacterial applications, ZnO nanoparticles are effective against both Gram-positive and Gram-negative bacteria. The antibacterial activity takes place by several mechanisms. The ROS created at the surface of ZnO may be enough to oxidize lipids, proteins, and nucleic acids. Free Zn^{2+} ions from ZnO may disrupt the enzyme activity and cellular metabolism. Na^+ particles can directly interact with the bacterial membrane, disrupting its integrity and permeability, leading to leakage of intracellular contents. The smaller the particle size of the ZnO, the more potent the effect it has on the antibacterial activity of the cells, as a result of the larger surface area and increased contact between the ZnO particles and the bacterial cells. ZnO exhibits dual properties of photocatalytic and antibacterial action, which are suitable for water purification, self-cleaning surfaces, antimicrobial coatings, food packaging, wound dressings, and coatings of medical devices. But it does have the drawback of relatively low activity in the visible light range. Modifying CQD is thus an effective and eco-friendly approach for enhancing the performance of CQD (Ijaz et al., 2020).

4. CQD-Modified ZnO Nanocomposites

4.1. Synthesis Methods

There are various techniques for the synthesis of CQD-modified ZnO nanocomposites. The method of choice is determined by the size, shape, crystallinity,

surface properties and purpose of the particles. One of the most popular is the hydrothermal method. This process involves dissolving the zinc salts (usually zinc acetate, zinc nitrate or zinc chloride) in water or alcohol, and then adding a base (such as sodium hydroxide, ammonia or hexamethylenetetramine). The solution is to which CQDs are added and then heated in an autoclave. Hydrothermal conditions facilitate the growth of crystals and establish a high interaction between CQDs and ZnO. This technique gives well crystallized and well dispersed nanostructures. Sol-gel is a process that consists of hydrolysis and condensation of zinc precursors to obtain a gel, drying, and calcination. CQDs can be synthesized in the sol formation process or following the formation of ZnO. The composition and chemical homogeneity is good by this method. But, if the calcination temperature is too high, the structure of CQD can be changed (Toma et al., 2022).

Precipitation method is simple and economical. The ZnO nanoparticles are prepared by precipitation method from zinc salt solution by using alkaline agents. CQDs can be incorporated into the precipitation process. The method is suitable for large scale synthesis, but can give agglomerated particles if the reaction conditions are not controlled. The microwave-assisted synthesis offers uniform nucleation, short reaction time, and rapid heating. Can synthesize small size of ZnO nanoparticles and composites of CQD-ZnO with controlled morphology. Green synthesis involves the use of plant extracts; carbon sources derived from biomass or natural reducing/stabilizing agents. This is an appealing route as it minimizes the application of toxic chemicals and promotes sustainable production (Al-

Assaly et al., 2023). Post-synthesis modification is another way of doing it. This approach involves introducing pre-synthesized ZnO nanoparticles into the CQD solution under stirring or sonication or mild heating conditions. The CQDs can be bound to the surface of ZnO by electrostatic interaction, hydrogen bonding, or coordination. This technique is straightforward and enables control of the loading of the CQD. Weak interaction can however cause the CQD to detach with repeated use (Suzuki et al., 2021).

4.2. Characterization Techniques

The successful formation of CQD-ZnO nanocomposites would need to be confirmed using characterization. Identification of crystalline phase of ZnO and crystallite size is carried out by x-ray diffraction. The strong diffraction peak is not guaranteed just because of the presence of CQDs because they might be small in particle size and low in loading. FTIR spectroscopy can be used to detect the presence of functional groups on the surface, like hydroxyl, carboxyl, carbonyl and Zn-O bonds. Raman spectroscopy can give information on the structure of carbon, such as D and G bands. The morphology, particle size and distribution of CQDs on the ZnO are observed by scanning electron microscopy and transmission electron microscopy. The lattice fringes of ZnO and the small carbon dots on the surface can be observed by TEM with high resolution. The composition of elements is confirmed by energy-dispersive X-ray spectroscopy. X-ray photoelectron spectroscopy (XPS) is used to obtain information on the surface chemical states, bonding interactions, presence of oxygen vacancies, and carbon functional groups (Thyda et al., 2025). Changes in band gaps and optical absorption are studied by UV-visible

diffuse reflectance spectroscopy. The modification of the CQD usually improves absorption in the region of visible light. The electron-hole recombination is evaluated by the use of photoluminescence spectroscopy. A decrease in PL intensity tends to correspond to decreased recombination and improved charge separation. Surface area and pore structure are obtained by Brunauer-Emmett-Teller analysis. The charge transfer efficiency can be further confirmed with electrochemical impedance spectroscopy and photocurrent response measurements (Cong & Zhao, 2018).

4.3. Effect of CQD Modification on ZnO

CQDs introduce several advantageous changes to the ZnO. CQDs have the ability to widen the optical absorption range of ZnO from the UV to the visible region. This makes the solar-light utilization better and photocatalytic efficiency higher under illumination by visible light. Second, CQDs suppress electron-hole recombination, as shown by a decrease in the PL intensity. Thirdly, CQDs can facilitate charge transfer processes at their interfaces. The transfer of electrons can occur between the conduction band of CQDs and the conduction band of ZnO or between the conduction band of ZnO and the conduction band of CQDs according to the band alignment. This increases separation of charges and generation of Reactive Oxygen Species. Third, CQDs have excellent adsorption ability because the functional groups and π -conjugated domains. Aromatic dye molecules can interact with CQDs via π - π interaction and polar pollutant molecules can interact with CQDs via hydrogen bond and electrostatic interactions. Fifth, the CQDs could also stabilize the surface of the ZnO aggregates. Fifth, CQDs could also act as surface stabilizers of ZnO aggregates. Sixth, the presence of CQDs can change the

defect structure and the presence of oxygen vacancies and may, in turn, influence the photocatalytic and antibacterial properties. But CQD loading needs to be optimized. Excessive CQD loading can prevent light from reaching the surface and even be recombination centers, however, too low of a CQD content may not significantly increase visible-light absorption and may cover the surface of the material, obscuring active sites. Hence, the optimum concentration of CQD is required for the best performance (Tran et al., 2023; Tegenaw et al., 2023).

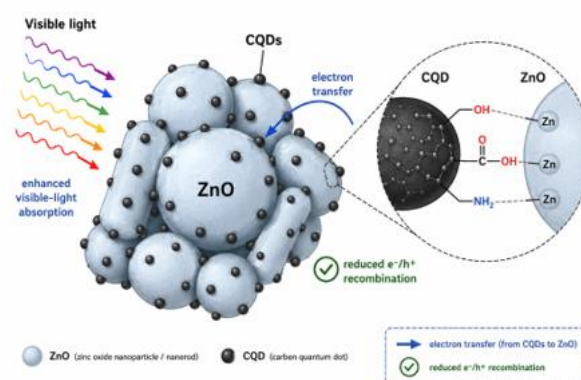


Figure 1. Schematic Representation of CQD-Modified ZnO Nanocomposite.

The various structural arrangement and functional role of carbon quantum dots (CQDs) on the surface of ZnO nanomaterials are shown in the figure 1. The ZnO nanoparticles/nanorods are displayed as larger light-coloured structures with CQDs appearing as a smaller dark dot uniformly distributed on the surface of the ZnO. The significance of this surface decoration is that CQDs can be used as visible light absorbers, electron mediators and surface modifiers. The visible light absorption by CQDs suggests that the light harvesting capability of Zinc Oxide, which is having a large band gap and could absorb only UV light, is improved by CQDs. The magnified inset illustrates how the CQDs

interact with the ZnO via surface functional groups like hydroxyl, carboxyl and amino groups. These functional groups will enhance the interfacial adhesion and facilitate charge transfer between CQD and ZnO. The electron-transfer pathway illustrated in the figure suggests that CQDs may help to shuttle the photogenerated electrons to minimize electron–hole

recombination. Consequently, increased number of charge carriers are available for photocatalytic reaction and generation of the reactive oxygen species. In general, this data indicates the enhanced photocatalytic and antibacterial properties of ZnO nanomaterials after modifications using CQDs.

Table 1. Properties of ZnO and Carbon Quantum Dots

Property	ZnO Nanomaterials	Carbon Quantum Dots	Relevance in CQD-ZnO Nanocomposites	Reference
Material type	Metal oxide semiconductor	Zero-dimensional carbon nanomaterial	Combination produces multifunctional semiconductor-carbon hybrid	(Jeon et al., 2026)
Typical size	10–100 nm depending on synthesis	Usually below 10 nm	Small CQDs decorate ZnO surface and improve interface contact	(Zhang et al., 2022)
Optical response	Mainly UV-active	UV-visible absorption and photoluminescence	CQDs improve visible-light harvesting	(Naik et al., 2025)
Band behavior	Wide band gap semiconductor	Tunable surface-state energy levels	Supports interfacial electron transfer	(de Andrade et al., 2022)
Surface chemistry	Zn–O surface, oxygen vacancies, hydroxyl groups	–OH, –COOH, C=O, –NH ₂ groups	Enhances adsorption and composite stability	(Nguyen & Ha, 2023)
Photocatalytic role	Generates electron–hole pairs	Photosensitizer and electron mediator	Improves ROS generation and degradation efficiency	(Jheeta, 2024)
Antibacterial role	ROS generation, Zn ²⁺ release,	Surface interaction and photodynamic contribution	Combined oxidative and contact-based	(Shitaw et al., 2025)

	membrane contact		antibacterial action	
Main limitation	Poor visible-light response and recombination	Possible instability depending on synthesis	Composite design reduces individual limitations	(Xu et al., 2023)

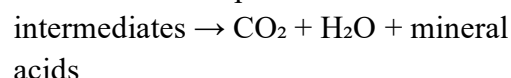
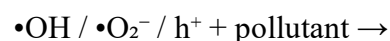
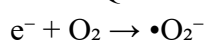
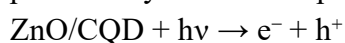
5. Photocatalytic Applications

5.1. Mechanism of Photocatalysis

Photocatalysis is the process of energy transfer that occurs when a semiconductor absorbs photons and creates electron-hole pairs. When UV light having energy equal to or greater than the band gap of ZnO strikes the surface, it will excite the electrons out of the valence band into the conduction band. This gives rise to gaps in the valence band. The photogenerated electrons convert the dissolved oxygen to superoxide radicals and the holes oxidize water or hydroxide ions to hydroxyl radicals. These radicals are highly reactive and can break down the organic pollutants (Molla et al., 2021).

The mechanism is more efficient in the case of CQDs in ZnO. Visible photons are absorbed by CQDs and cause the CQDs to become excited. Excited electrons may be transferred to various places, such as the conduction band of ZnO or to the oxygen molecules absorbed on the surface. CQDs can also be injected with an electron from ZnO, which decreases the recombination rate. Enhanced charge separation leads to enhanced production of reactive oxygen species. These ROS molecules attack pollutants through oxidation, bond cleavage, ring opening, dealkylation, hydroxylation and mineralization (Thyda et al., 2025).

The general reactions involved in photocatalysis can be represented as:



The predominant reactive species can also depend on the nature of the pollutant, the pH, the catalyst surface, the light source and the amount of oxygen present. The characterization of the primary species that can be determined by radical scavenging experiments. The hydroxyl radicals are trapped with isopropanol or tert-butanol, superoxide radicals with benzoquinone, and holes with EDTA or ammonium oxalate. The photocatalytic pathway can be confirmed with such experiments (Ding et al., 2023).

5.2. Degradation of Organic Pollutants

Many studies concerned with degradation of organic dyes have been conducted on CQD-ZnO nanocomposites. Textile dyes are widely used as model pollutants due to their colour, stability and UV-visible spectroscopy measurement capability. Commonly used dyes for testing photocatalytic performance include methylene blue, rhodamine B, methyl orange, malachite green and Congo red. The degradation process is usually followed by the accompanying decrease in the absorbance at the peak absorption wavelength of the dye. A typical photocatalytic reaction involves the addition of a certain amount of catalyst to a dye solution. The adsorption-desorption equilibrium is set by stirring the suspension in the dark. Afterward it is put under UV,

visible or "solar" light. Samples are taken at regular time intervals, centrifuged or filtered to separate out catalyst particles and analysed by UV–visible spectroscopy. The degradation efficiency is determined with the initial and final pollutant concentration (Mousavi et al., 2024).

In general, the degradation of CQD-ZnO is better than that of pure ZnO because of their better visible-light absorption and separation of charge. CQD-ZnO can also be used to degrade pharmaceutical contaminants like antibiotics, analgesics and hormones. These compounds are more environmentally relevant than dyes as they are present in wastewater and can increase resistance to antibiotics or endocrine disruption. But the intermediate products of the degradation of pharmaceuticals need careful investigation, since partial degradation can sometimes result in the formation of more toxic substances. Advanced evaluation requires use of techniques like high performance liquid chromatography, liquid chromatography–mass spectrometry, total organic carbon analysis, and toxicity tests. CQD-ZnO can also be used to degrade pesticides and phenolic compounds. Many of these pollutants are hard to break down by the biological treatment process and can survive in water and soil. Photocatalytic oxidation is a promising method to remove them. Not only degradation percentage but also mineralization, catalyst stability, reusability and performance in real water matrices are among the factors that influence the efficiency (Hsieh et al., 2022).

5.3. Factors Affecting Photocatalytic Performance

The photocatalytic activity of the CQD-ZnO nanocomposites is influenced by several factors.

Catalyst dosage: Typically, higher catalyst doses lead to higher degradation efficiency due to the availability of more active sites. Too much catalyst can lead to turbidity, light scattering and particle aggregation which will decrease light penetration (Liang et al., 2020).

Pollutant concentration: When the pollutant concentration is low, degradation is typically more rapid, as there are enough active sites and radicals. Pollutant molecules can be present in sufficient concentration to block light or be bound to the active sites, which would cause loss of efficiency (Do et al., 2024).

pH: The pH of solution affects the surface charge of the catalyst, pollutant ionization, the stability of the ZnO, and the radical formation. Alkaline conditions can enhance adsorption to a negatively charged surface for cationic dyes. Acidic conditions may be appropriate for anionic dyes. Very acidic or very alkaline conditions can influence the dissolution or stability of ZnO (Le et al., 2021).

Light source: UV light directly excites the ZnO, while visible light mostly excites CQDs or defect states. Solar light would be more useful in environmental applications. The intensity of light and the distribution of wavelengths have significant effects on photocatalytic activity (Hutsul et al., 2022).

CQD loading: It is one of the most important parameters and known as CQD concentration. Optimum loading results in better light absorption and charge separation. When the number of CQDs is too large, they can block active sites of ZnO, decrease surface area, or serve as recombination centers (Shalahuddin Al Ja'farawy et al., 2022).

Dissolved oxygen: Oxygen is an electron acceptor and required for the formation of superoxide radical. Photocatalytic

efficiency will decrease with low oxygen concentration (Yu et al., 2021).

Reusability: A photocatalyst with good activity should be reused multiple times. Reusability tests involve recovering the catalyst after each cycle, washing, drying, and reusing it. Catalyst loss, fouling of the surfaces, photo corrosion or changes in the structure can lead to loss of activity (Xiao et al., 2023).

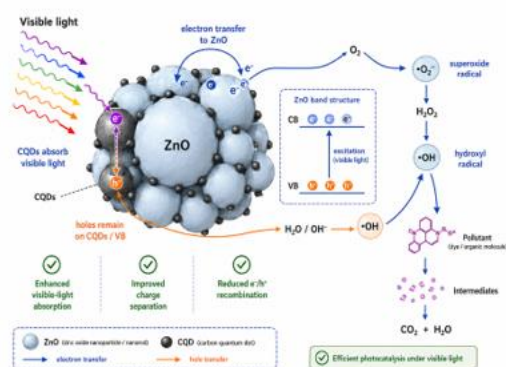


Figure 2. Photocatalytic Mechanism of CQD-ZnO Under Visible Light.

The proposed photocatalytic mechanism of CQD- modified ZnO Nanomaterials under visible light irradiation is shown in figure 2. The photoexcited electrons in this system move from the CQD to the conduction band of ZnO; meanwhile, CQDs absorb visible

light. This process enhances charge separation and decreases the probability of charge recombination of photogenerated electrons and holes. The transferred electrons combine with dissolved oxygen molecules to create superoxide radicals and holes combine with water or hydroxide ions to create hydroxyl radicals. These ROS are very oxidative and are important for degradation of organic pollutants. The figure illustrates the gradual conversion of dyes, organic molecules, etc., into smaller intermediates and ultimately the mineralization products. The band structure representation also helps to elucidate the transport of electrons and holes during the photocatalysis process. The addition of CQDs to pure ZnO results in higher visible-light absorption, better electron transfer and higher radical formation. Thus, the photocatalytic degradation performance of CQD-ZnO nanocomposites can be better under visible light. This mechanism has been found to work well for their use in the removal of dyes, degradation of persistent organic contaminants and wastewater treatment.

Table 2. Suggested Experimental and Review Parameters for CQD-ZnO Photocatalytic and Antibacterial Studies

Application	Parameter to Report	Recommended Details
Photocatalysis	Pollutant type	Methylene blue, rhodamine B, methyl orange, phenol, tetracycline, ciprofloxacin, pesticides
Photocatalysis	Initial pollutant concentration	mg/L or ppm
Photocatalysis	Catalyst dosage	g/L or mg/100 mL
Photocatalysis	Light source	UV lamp, visible lamp, solar simulator, natural sunlight
Photocatalysis	Irradiation time	Time interval and total duration
Photocatalysis	Degradation efficiency	Percentage degradation and kinetic constant
Photocatalysis	Kinetic model	Pseudo-first-order model commonly used
Photocatalysis	Reusability	Minimum 3–5 cycles recommended
Photocatalysis	Radical scavenging	Identify $\cdot\text{OH}$, $\cdot\text{O}_2^-$, h^+ contribution
Antibacterial	Bacterial strain	<i>E. coli</i> , <i>S. aureus</i> , <i>P. aeruginosa</i> , <i>B. subtilis</i>

Antibacterial	Assay method	Zone of inhibition, colony count, MIC, MBC, live/dead staining
Antibacterial	Nanoparticle concentration	mg/mL or $\mu\text{g/mL}$
Antibacterial	Exposure condition	Dark, UV light, visible light, sunlight
Antibacterial	Mechanism analysis	ROS assay, membrane leakage, SEM/TEM, protein/DNA leakage
Safety	Toxicity evaluation	Cytotoxicity, environmental toxicity, Zn^{2+} release, reusability

6. Antibacterial Applications

6.1. Antibacterial Mechanism

The antibacterial activity of CQD-ZnO nanocomposites involves primarily oxidative stress, membrane disruption, ion release and intracellular damage. Under the illumination with light, the pairs of electrons-hole are created in ZnO. These charge carriers combine with oxygen and water molecules to create ROS. The important ROS are hydroxyl radicals, super oxide radicals, hydrogen peroxide and singlet oxygen. These species are known to cause damage to the membrane lipids, proteins, enzymes, and nucleic acids of bacterial cells. One of the first targets of the attack of nanoparticles is the bacterial membrane. Lipid peroxidation induced by ROS results in loss of integrity of membranes and enhances their permeability. With a damaged membrane, intracellular substances like proteins, sugars, electrolytes and DNA can escape. This causes the metabolism to become disrupted and the cells to die. Electrostatic interaction is also present between ZnO nanoparticles and the surfaces of bacteria. The surface of bacterial cells is typically negatively charged and the positive charges of the ZnO or Zn^{2+} species can bind to the bacterial surface. This communication impacts on the membrane potential and nutrient uptake (Kalra et al., 2022).

The other important mechanism is the release of Zn^{2+} . Zn^{2+} ions may be taken up by bacterial cells and disrupt the activity of enzymes, protein structure, and DNA replication. May disrupt electron transport chains and cellular respiration. But, under different conditions of pH, particle size, concentration and exposure, the relative contribution of Zn^{2+} release is different. A membrane interaction, ROS production and Zn^{2+} release are, in many cases, not single mechanisms for antibacterial action. To improve these mechanisms, CQDs are applied to the light absorption and charge separation. In the visible light, CQDs can produce or facilitate ROS production. They can also be responsible for enhanced dispersion of ZnO which enhances contact with the bacterial cells. Proteins and membrane components can interact with functional groups on CQDs. Thus, the antibacterial performance of the hybrid CQD-ZnO could be better than the pure ZnO (Jassim & Khayatian, 2022).

6.2. Activity Against Gram-Positive and Gram-Negative Bacteria

Although the two types of bacteria, Gram-positive and Gram-negative, have similar structures, their antibacterial performance will vary due to differences in their cell wall structure. *Staphylococcus aureus* and *Bacillus subtilis* are gram-positive bacteria that do not have an outer membrane and have a thick peptidoglycan layer. The

peptidoglycan layer is thinner in gram-negative bacteria (*Escherichia coli* and *Pseudomonas aeruginosa*) and they contain an outer membrane with lipopolysaccharides. These outer membranes can serve as protection from nanoparticles and antimicrobial agents (Bruna et al., 2021).

CQD-ZnO nanocomposites can be evaluated against *E. coli* and *S. aureus* using agar well diffusion, disk diffusion, the number of colony forming unit, minimum inhibitory concentration, minimum bactericidal concentration, the optical density and live/dead fluorescent staining. The zone of inhibition method is a simple method, which is appropriate for a preliminary screening. It is possible, however, that it is not a true reflection of the antibacterial activity, as the diffusion of nanoparticles in agar may be limited. More quantitative information is obtained from MIC and MBC tests (Jíra et al., 2021). There is the possibility of a direct measurement of viable bacteria reduction in colony counting. The antibacterial activity of CQD-ZnO can be stronger in the visible light than in dark condition in the tests of light assisted antibacterial activity, which is due to the higher production of ROS under illumination. This however, can also be observed in the dark with the effect of the release of the Zn^{2+} and direct interaction with the membrane. So, both light and dark experiments will be useful to understand the mechanism.

6.3. Factors that influence the effectiveness of antibacterials

The antibacterial effect of CQD-ZnO nanocomposites is affected by some factors.

Particle size: Smaller particles tend to have larger surface area and increased interaction with bacterial cells. They may also generate

more ROS as a result of higher activity sites (Ragupathi et al., 2021).

Surface charge: Positively charged particles can have a stronger affinity for the negatively charged bacterial membranes. But the accumulated positive charge may also make it more toxic to mammalian cells (Tsikourkitoudi et al., 2022).

CQD loading: Optimum CQD loading improves ROS production and bacterial contact. Too many CQDs could lead to less exposure to the ZnO or to an unfavourable surface charge (Ye et al., 2022).

Light condition: the activation and ROS production are increased in the presence of visible-light irradiation. Dark activity is more contact damage and release of Zn^{2+} (J. Zhang & Liu, 2020).

Concentration of nanoparticles: As the concentration of nanoparticles increases, so does their antibacterial activity, but the higher the concentration, the more likely they are to aggregate and pose safety concerns (Jasmine et al., 2025).

Exposure time: The longer the exposure time the more ROS is accumulated and the more damage is done to the membrane (Bour et al., 2019).

Bacterial strain: resistance mechanisms, membrane structure, efflux system and antioxidant defenses vary among different bacteria (Lam et al., 2020).

Medium composition: The stability of the nanoparticles and the release of ions can be affected by proteins, salts, organic matter and pH (Mulenos et al., 2020).

To be practical, it is necessary that the antibacterial is biocompatible. The antimicrobial material that kills bacteria well may not be good for biomedical or environmental applications if it is toxic to human cells or aquatic organisms. Thus, assessment of toxicity is critical.

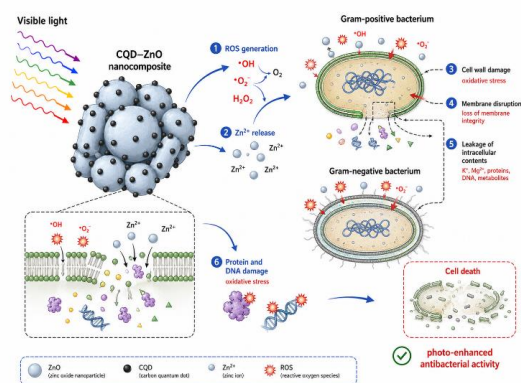


Figure 3. Antibacterial Mechanism of CQD-ZnO Nanomaterials.

The mechanism of action of CQD-ZnO nanocomposites against the Gram-positive and Gram-negative bacteria is described in figure 3. The CQD-ZnO system generates reactive oxygen species like hydroxyl radicals, super oxide radicals and hydrogen peroxide under visible light irradiation. They are found to induce oxidative stress in bacterial cells and damage important cellular components. Apart from the generation of ROS, ZnO also produces Zn^{2+} ions that can interact with the bacterial membranes and affect the normal cellular metabolism of bacteria. As can be seen in the figure, CQD-ZnO particles target the bacterial cell walls and bacterial membranes, causing the loss of integrity of the membranes. When the membrane is damaged, the cell releases intracellular substances like proteins, DNA, ions, and metabolites. This leakage has implications for key biological functions and causes cell death. The figure also indicates that protein and DNA damage are proteins that are involved in further contributing to the bacterial inactivation. The nanocomposite appears to have bactericidal activity against both Gram-positive and Gram-negative bacteria. The visible-light activation and ROS generation were optimized with CQDs, resulting in enhanced antibacterial activity. In overall, it has been illustrated

that the CQD-ZnO nanomaterials exhibit photo-enhanced antibacterial activity due to mixture of oxidative stress, release of Zn^{2+} ions, membrane disruption, leakage of biomolecules, and damage to biomolecules.

7. Comparative Discussion

7.1. Pure ZnO vs CQD-Modified ZnO

Pure ZnO shows activity in UV light and low activity in visible light. Due to the photosensitizing effect of CQDs, the ZnO is activated to absorb visible light, therefore the visible-light absorption of CQD modified ZnO is improved. Though pure ZnO has fast electron-hole recombination, CQDs can separate the electron-hole pairs acting as an electron acceptor or transport mediator. ZnO might exhibit particle aggregation in its pure form, whereas CQDs can enhance the dispersion by means of surface functional groups. The degradation efficiency and the reaction kinetics in photocatalysis are in general higher for CQD-ZnO. Under visible light, CQD-ZnO can generate more ROS in antibacterial applications, and enhance the contact of bacteria. But CQD-ZnO is not necessarily better in all circumstances. The performances are influenced by the synthesis method, the quality of the CQDs, the number of CQDs, the morphology of ZnO, the type of pollutant, the pH and the light source. Too high a CQD loading may decrease activity due to blocking of the active sites of ZnO or increase recombination. Thus, optimization is needed (Toma et al., 2022).

7.2. Photocatalytic Advantages

The photocatalytic properties of CQD-ZnO are increased solar-light utilization, increased degradation rate, increased ROS production, and increased charge-separation. The absorption edge of ZnO can be moved towards the visible region by CQDs. They can also enhance the

adsorption of organics via surface functional groups. The dual adsorption/reaction effect is significant because the degradation by photocatalysis takes place predominantly at or near the photocatalyst surface. CQD-ZnO is particularly effective for the degradation of dyes as many dyes are sensitive to visible light, and also can sensitize the degradation. But the degradation of the dye must not be interpreted as being adequate for treatment of wastewater. Colorless pollutants, pharmaceutical residue, a combination of pollutants, removal of TOC, and toxicity of the degradation products should be studied in the future (Widiyandari et al., 2023).

7.3. Antibacterial Advantages

CQD-ZnO possesses multiple synergistic antibacterial effects. Pure ZnO can cause the damage of bacteria by ROS, Zn^{2+} ions and interaction with membrane. The modification of CQD results in better dispersion and better ROS generation under visible light. The composite can be applied in antimicrobial coatings, water disinfection, food packaging, wound dressing materials, surfaces that are able to clean themselves. The material should be tried in realistic conditions for practical implications. For instance, in the context of antibacterial coatings, considerations include adhesion, durability, repeated use, and safety. All water disinfection materials should be tested in natural water with organic matter and salts present in the water. Cytotoxicity testing of mammalian cells should be implemented for biomedical applications (Satinder Pal Kaur Malhotra, 2021).

8. Challenges and Future Perspectives

A number of laboratory-scale methods have been reported, but large-scale synthesis of the CQD-ZnO is still challenging. Autoclave and long reaction time are

sometimes necessary for hydrothermal synthesis. Sol-gel and precipitation methods are more scalable but can result in agglomerated particles. Biomass-based synthesis of CQDs is desirable, but batch-to-batch fluctuations are possible with natural sources. In industrial applications, the process of synthesis is requested to be simple, inexpensive, repeatable, and eco-friendly. The ability of a photocatalyst to be stable in repeated cycles is a key feature of a good photocatalyst. If the interaction between the CQDs and ZnO is weak, the CQDs may be separated from the ZnO during washing or irradiation. Photo corrosion of ZnO is also possible within an aqueous environment. Thus, good interfacial bonding and stable composite formation is significant. Structural characterization following repeated cycles should be included in reusability studies to verify the stability of the structure. A significant drawback of the use of a nanoparticle photocatalyst is its recovery following treatment. The nanoparticles may produce secondary pollution if they are not filtered out of treated water. The recovery can be enhanced by immobilization of the CQD-ZnO on substrates like glass, ceramic membranes, polymer films, cotton fabrics, activated carbon, or magnetic supports. The separation of the magnetic CQD-ZnO composites might also be simple with the help of an external magnet. The model dyes used in most studies are done in distilled water. There are a number of pollutants in real wastewater; not only that, but the wastewater itself has varying levels of dissolved organic matter, inorganic ions, suspended solids, and pH. These components may interfere with photocatalytic reactions in a variety of ways, including blocking the light, competing with the reaction for active sites,

and scavenging the radicals. Thus, in the future, studies of CQD-ZnO should be carried out with actual textile wastewater, pharmaceutical wastewater, hospital wastewater and municipal effluents. While ZnO and CQDs are regarded as safer as compared to other toxic semiconductor materials, their safety needs to be thoroughly assessed. Aquatic organisms can be impacted at high concentrations of Zn^{2+} release.

The nanoparticles can interact with biological membranes, leading to an oxidative stress. CQD toxicity is dependent on precursor and synthesis method, surface groups, and doping elements. Hence, studies of cytotoxicity, ecotoxicity and environmental fate should be carried out prior to any large-scale application. More detailed mechanistic studies are needed to understand charge-transfer pathways in CQD-ZnO. Advanced techniques like time-resolved photoluminescence, electron spin resonance, transient photocurrent response, electrochemical impedance spectroscopy, Mott-Schottky analysis, and density functional theory (DFT) calculations can yield more detailed understanding. Radical trapping and isotope studies can help to elucidate the role of ROS. Improved mechanistic understanding can be gained from live/dead staining, SEM/TEM imaging, detection of intracellular ROS, analysis of membrane potential, protein leakage, DNA damage assays, and transcriptomic studies for antibacterial applications. Designing CQD-ZnO composites with controllable morphology, optimized CQD loading, good bonding between CQD and ZnO, low toxicity, and high visible-light activity is suggested for future research. Nitrogen-doped and S-doped CQDs can additionally boost charge transfer and antibacterial activity. Possible

better photocatalytic activity could be achieved by ternary composites like CQD-ZnO/g- C_3N_4 , CQD-ZnO/ Bi_2WO_6 , CQD-ZnO/Ag and CQD-ZnO/graphene. But there should be a compromise between the complexity of the material and the cost, stability, and safety of the environment.

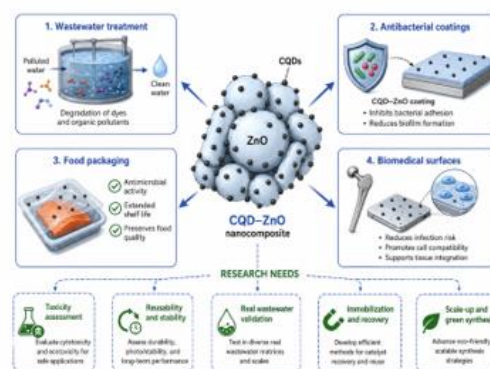


Figure 4. Future Application Pathways of CQD-ZnO Nanocomposites.

The potential application pathways and future research needs of CQD-ZnO nanocomposites are summarized in Fig. 4. The multifunctional property of this material is presented by the central CQD-ZnO structure, which offer photocatalytic and antibacterial activity, in addition to enhancing the material's ability to absorb the visible light spectrum, and its charge-transfer efficiency. Four main application areas are illustrated: Waste water treatment, Antibacterial coatings, Food packaging, Biomedical surfaces. CQD-ZnO can break down dyes and organic pollutants to generate clean water in wastewater treatment. For antibacterial coatings, the coating material may inhibit bacterial adhesion and biofilm growth on surfaces. In food packaging, CQD-ZnO can be used to enhance the antimicrobial properties, promote shelf stability, and ensure food quality. In biomedical surfaces, it could lower the risk of infection and facilitate safer implant and/or device applications. The lower part of the figure underlines the

main research needs such as the toxicity assessment, the reusability, real wastewater validation, immobilization and recovery, and the scale-up via green synthesis. These are key factors to consider prior to implementation. This highlights the potential of CQD-ZnO nanocomposites, but their long-term stability, environmental safety, recovery, and performance need to be properly evaluated for sustainable applications.

9. Conclusion

The carbon quantum dot modified ZnO nanomaterials are one of interesting class of multifunctional nanocomposites which can be used in photocatalytic and antibacterial applications. Although pure ZnO has the characteristics of low cost, chemical stability, photocatalytic effect and antibacterial properties, its wide band gap and low absorption of visible light, fast electron-hole recombination, aggregation and photo corrosion limit its practical application. The modification of CQD is an effective solution that can be achieved by increasing the efficiency of harvesting visible-light, improving charge separation, increasing surface adsorption, and promoting the generation of reactive oxygen species. CQD-ZnO can be used to photocatalysis the degradation of various organic pollutants such as dyes and emerging contaminants using ROS-mediated oxidation in photocatalytic applications. For antibacterial applications, the composite exhibits antibacterial activity through oxidative stress, release of Zn^{2+} ions, disruption of cell membranes, leakage of cellular components, and damage to DNA/protein. The material is especially appealing because of its ability to combine the environmental remediation and microbial control within one platform. But the work remains to be done in order to

meet the requirements of large-scale synthesis, stability over time, catalyst recovery, real wastewater performance, toxicity, and mechanism. Further studies should go beyond using model pollutants and laboratory strains to environmental and biomedical conditions. Optimized and safety assessed, CQD-ZnO nanocomposites could be useful for sustainable water treatment, antimicrobial coatings, food packaging, and for disinfection technologies related to healthcare.

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