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Nanostructured ZnO-CQD Hybrid Heterostructure Nanocomposites: Synergistic Engineering for Sustainable Design, Functional Properties, and High-Performance Applications

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Hybrid nanocomposites integrating nanostructured zinc oxide (ZnO) and carbon quantum dots (CQDs) with designed heterostructures possess exceptional optical and electronic properties. These properties hold immense potential for advancements across diverse scientific and technological fields. This review article investigates the synthesis, properties, and applications of ZnO-CQD heterostructure nanocomposites. Recent breakthroughs in fabrication methods are examined, including hydrothermal, microwave-assisted, and eco-friendly techniques. Key preparation methods such as sol-gel, co-precipitation, and electrochemical deposition are discussed, emphasizing their role in controlling heterostructure formation. This review analyses the impact of heterostructures on optical and electronic properties, such as fluorescence, photoluminescence, and photocatalytic activity. Synergistic interactions between ZnO and CQDs within heterostructures are highlighted, demonstrating how they lead to substantial performance improvements. Applications of ZnO-CQD heterostructures span solar cells, LEDs, photodetectors, water purification, antimicrobial treatments, gas sensing, catalysis, biomedical imaging, drug delivery, environmental sensing, and energy storage. Insights are provided into refining synthesis methods, enhancing characterisation techniques, and broadening the application landscape. Challenges like stability are addressed, along with strategies for optimised performance and practical implementation. This comprehensive review offers a thorough understanding of ZnO-CQD heterostructure nanocomposites, emphasising their significance within materials science and engineering. By addressing core concepts and future directions, it lays a foundation for continued innovation in this dynamic field.

1. Introduction

Quantum confinement effects give oxide quantum dots unique optical and electronic properties compared to their bulk forms.[1,2] This phenomenon arises from the restriction of electron and hole movement within the tiny dimensions of the quantum dot.[1] This ability to manipulate properties at the quantum level opens doors for designing highly efficient photocatalysts for various applications.[4,5] Furthermore, adjusting the size and shape of oxide quantum dots allows for further control over their optoelectronic properties, enabling the creation of materials with specific functionalities.[6] Oxide quantum dots offer several key advantages in various applications. These quantum dots exhibit high quantum efficiency, meaning that a larger proportion of generated electron-hole pairs participate in photocatalytic reactions. This increased efficiency enhances their effectiveness in catalysing reactions and driving various processes. The light absorption properties of oxide quantum dots are size-dependent, allowing for precise tuning to target specific wavelengths of light. This capability enables tailored absorption profiles, enhancing their suitability for diverse applications where specific wavelengths are desired or required. Oxide quantum dots offer tuneable luminescence, meaning that their emission properties can be customised or adjusted for specific applications. By controlling factors such as size, composition, and surface chemistry, researchers can fine-tune the emission characteristics to meet the requirements of various optical and electronic devices, including sensors, displays, and light-emitting diodes (LEDs). TiO_2 quantum dots excel as efficient photocatalysts for pollutant degradation and environmental remediation.[6] ZnO quantum dots are incorporated into UV protection films to shield against harmful ultraviolet radiation. SnO_2 quantum dots exhibit properties that

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make them valuable for detecting various gases. CuO quantum dots hold potential for advancements in high-temperature superconductivity research. Oxide quantum dots can initiate the photo polymerisation of acrylics, suggesting possibilities for other industrial processes.[7] Despite their potential, oxide quantum dots face challenges related to mechanical, thermal, and chemical instability, hindering their widespread commercialisation. Researchers are actively exploring solutions, such as embedding these quantum dots within protective matrices, to improve their stability and pave the way for broader adoption in various industries.[6] Beyond metal oxide quantum dots, carbon quantum dots (CQDs) and metal sulphide quantum dots (like CdS, SnS_2, and MoS_2) are emerging as exciting photocatalytic materials.[8] These nanostructures offer distinct advantages in various applications such as electron mediators, photosensitizers, or spectral converters, optoelectronic devices, sensor technology, and energy conversion.[9] CQDs exhibit low toxicity and good biocompatibility, making them attractive for biomedical applications and sustainable solutions.[10,11] Their efficient electron transfer properties contribute to their excellent photocatalytic activity.[10,11] CQDs have the capability to absorb light across a wide range of wavelengths, excellent electron transport ability, high crystallization, good dispersibility, and photoluminescence properties, making them suitable for light-based applications such as solar cells. CQDs can be easily modified through doping with heteroatoms, allowing for further customization to suit specific uses.[12,13] Metal sulphide quantum dots, such as CdS, demonstrate high activity under

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ultraviolet irradiation, making them suitable for applications involving dye degradation.[14] CQDs and metal sulphide quantum dots show great promise in degrading hazardous pollutants and reducing CO_2 emissions.[15] Their unique properties make them ideal platforms for various photocatalytic applications in environmental remediation, biomedicine, and more. Quantum dots (QDs) are inherently stable and possess favourable electronic properties, adding to their potential value.[16,17] Table 1 provides a comprehensive overview of quantum dots (QDs) and their nanocomposites, including insights into their electronic and optical behaviours across diverse applications.

Zinc oxide-carbon quantum dot (ZnO/CQD) nanocomposites, in particular, have garnered significant research interest due to their unique properties and potential across diverse technological fields.[23,24] The key lies in the interaction between ZnO and CQDs, which leads to hybrid nanocomposites with exceptional optical and electronic characteristics. This opens doors for exploration in diverse areas, such as photocatalysis, sensors, and energy devices.[25] Researchers have developed various methods to synthesise ZnO/CQD nanocomposites, offering control over their properties. For instance, a straightforward liquid-phase self-assembly method can create 0D/2D nanocomposites with ZnO quantum dots (ZnO QDs) and graphitic carbon nitride nanosheets.[26] This approach allows for simple and precise control over material properties. Additionally, a self-poring strategy allows for the synthesis of ZnO QDs embedded within highly porous carbon nanosheets, enabling further tailoring of functionalities.[27] ZnO QDs possess excellent inherent optical and electronic properties. When combined with CQDs, these properties can be synergistically enhanced, leading to improved functionalities in the resulting nanocomposite. Understanding the structural properties of ZnO/CQD nanocomposites is crucial for unlocking their potential in various technological applications. Various characterization techniques, such as microscopy and spectroscopy, can be employed to glean valuable insights into these nanocomposites' behavior. These techniques provide information about the specific structural features that influence their performance. ZnO/CQD nanocomposites offer several advantages that make them attractive for technological applications. They are often non-toxic, cost-effective, and can be synthesized using relatively simple methods.[26] A critical aspect governing their functionality is their electronic properties, particularly the bandgap – the energy difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). A smaller HOMO-LUMO gap typically translates to enhanced conductivity, a key parameter for optimizing electronic devices. Conversely, a larger bandgap can be advantageous for applications in optoelectronics, where light emission is desired. Fluorescence arising from transitions between LUMO and HOMO energy levels has found applications in biomolecular sensing. Spectroscopic techniques can further elucidate these electronic properties. Shifts in emission or absorption spectra, such as red or blue shifts, can provide valuable insights into the dynamics of charge carriers and structural changes within the material.[28] The combined optical and electronic properties of ZnO-CQD hybrid nanocomposites, as depicted in Figure 1, highlight the interplay between HOMO and LUMO and the significance of the energy gap.[28,29] These understanding drives research and development efforts towards exploring these nanocomposites for various groundbreaking applications across diverse fields.

Table 1. Quantum Dots (QDs) and Nanocomposites Overview.

Materials	Key Findings	References
Quantum Dots (QDs)	Quantum Dots (QDs) have applications in nanotechnology and electronics, including display technologies, biological imaging, and quantum computing	[18]
Quantum Dots (QDs)	Semiconductor nanocrystals (2–100 nm) with tuneable emission bands, high photostability, and unique optics	[18,19]
Core@Shell Quantum Dots (QDs)	Nanocomposites with distinct core and shell materials for enhanced properties	[19]
Core@Shell Quantum Dots (QDs)	Surface modifications for improved quantum yields, air stability, and functionalisation	[19,20]
$CuInS_2$/ZnS Quantum Dots (QDs)	Exceptional photoluminescence; promising for optoelectronic applications	[20]
$CuInS_2$/ZnS Quantum Dots (QDs)	Low cytotoxicity in vitro and in vivo, suitable for imaging and drug delivery	[20,21]
InP/ZnS Quantum Dots (QDs)	Excellent optical properties as an alternative to heavy metal containing QDs	[22]
$CuInS_2$/ZnS Quantum Dots (QDs)	Potential for inflammatory responses, requiring further investigation	[21,22]
Carbon Quantum Dots (CQDs)	Exceptional optical properties for imaging, drug delivery, and cancer treatment	[22]
Carbon Quantum Dots (CQDs)	Limited biosafety studies for comprehensive assessment	[21,22]
Challenges	Inorganic core exposure, waste management in large-scale production, and ensuring reproducibility	[20,21]
Prospects	Potential applications in theranostics, drug targeting, and diagnostics. Facing challenges such as in vivo toxicity and reproducibility	[20,21]

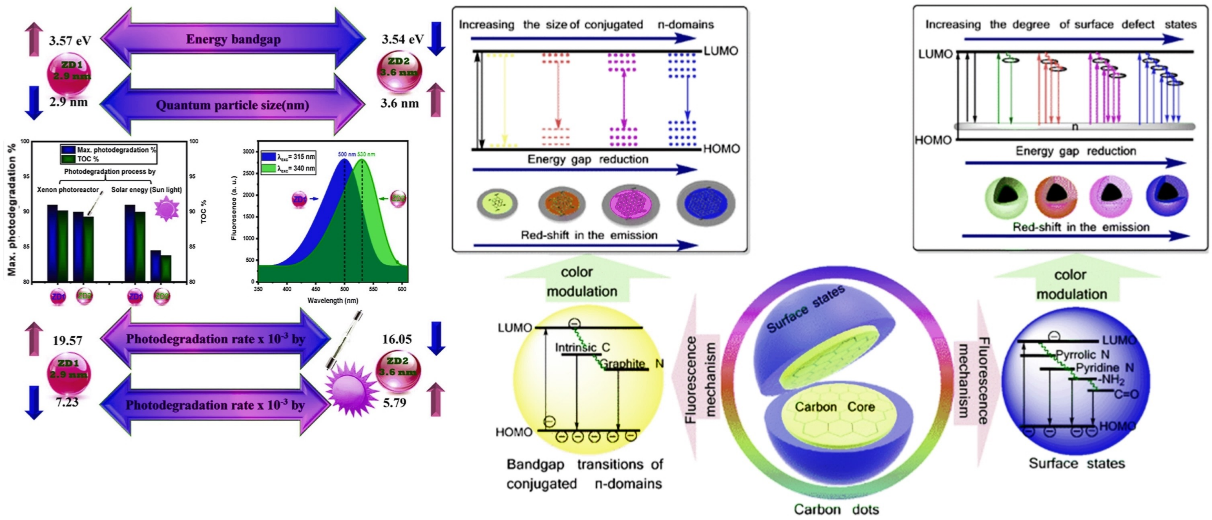


Figure 1. Optical and electronic behaviour of Zinc oxide (ZnO) (left side) and Carbon quantum dots (CQDs) (right side), Adopted with permission from.[28,29]

A key priority within ZnO/CQD research is the development of eco-friendly synthesis methods to address the environmental concerns associated with traditional processes.[30,31] Fruit and vegetable-based approaches align with green chemistry principles, making nanocomposite production more environmentally responsible. Additionally, techniques like hydrothermal synthesis and sol-gel offer precise control over the size, shape, and composition of ZnO/CQDs.[31] This precise control, coupled with green synthesis methods, significantly expands the versatility and potential applications of these nanocomposites. Physicochemical properties of ZnO/CQD nanocomposites are meticulously characterised using techniques like X-ray diffraction, transmission electron microscopy, and various forms of spectroscopy.[32] These insights are crucial for revealing the true potential of these materials. For example, ZnO/CQDs demonstrate exceptional promise as visible-light photocatalysts, facilitating the efficient degradation of organic pollutants like tetracycline hydrochloride.[33] Figure 2 illustrates the diverse range of applications for ZnO/CQD nanocomposites, highlighting their versatility. The ability to tailor the properties of ZnO/

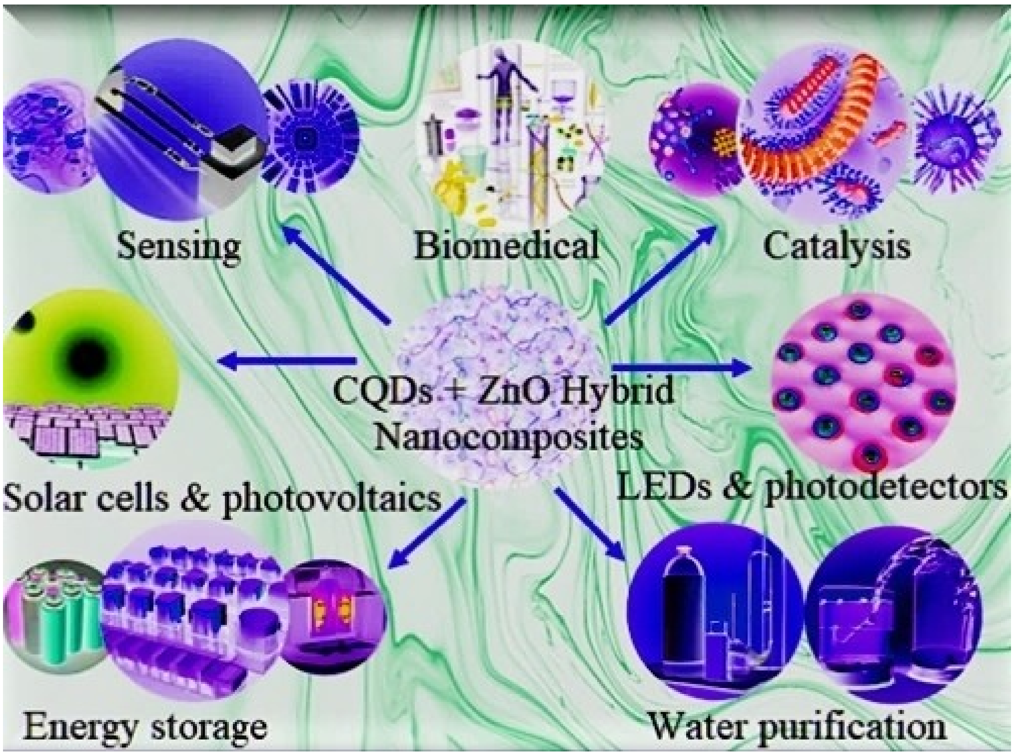


Figure 2. Applications of ZnO Quantum Dots- Carbon Quantum Dots (CQDs) Hybrid Nanocomposites in technological areas.

CQD nanocomposites paves the way for their application in numerous fields.[30,31] Their diverse functionality positions them as promising candidates for solar cells, LEDs, and energy storage devices. Additionally, they hold potential in water purification, environmental sensing, antimicrobial treatments, drug delivery, biomedical imaging, gas sensing, photodetectors, and electrochemical sensors. This broad applicability underscores the transformative potential of ZnO/CQD nanocomposites. By precisely controlling their properties through sustainable synthesis methods, researchers can unlock groundbreaking applications across a wide range of emerging technologies.

2. ZnO-CQDs Quantum Dots Hybrid Nanocomposites

Quantum dots (QDs), including zinc oxide quantum dots (ZnO QDs), have garnered significant interest due to their unique properties like biocompatibility and fluorescence, making them valuable for environmental applications. ZnO QDs, in particular, stand out for their ease of fabrication and versatility.[34] However, researchers are actively exploring composite structures, like MOF@QD composites, to overcome limitations and enhance functionalities of QDs.[35] Understanding carrier dynamics within QDs is crucial for optimising the efficiency of Quantum Dot Light-Emitting Diodes (QLEDs), as highlighted by Zheng et al..[36] Additionally, Zhou et al. provide a comprehensive overview of recent advancements in using QD photocatalysts for hydrogen production, CO_2 reduction, and pollutant degradation.[37] Researchers have demonstrated the ability to tailor QD properties for specific applications. For instance, Yang et al. modified semiconducting QDs with Zeolite imidazole frameworks (ZIF-8) to achieve desired functionalities.[38] Eco-friendly synthesis methods, such as the solvothermal approach used by Unnikrishnan et al. to create green, fluorescent carbon quantum dots (CQDs), contribute significantly to sustainable materials development.[39] Integrating QDs with other materials can further enhance their functionalities. Abraham et al. demonstrate this with $WO_3{\cdot}0.33H_2O$/casein derived CQD hybrid nanostructures for efficient hydrogen production.[40] Advancements in sensor technology are evident in the work of Li et al., Li et al. developed high quantum yield "on-off-on" CQD sensors with nitrogen-sulfur-sodium co-doping for environmental monitoring applications.[41] Saikia et al.'s work on the eco-friendly synthesis of CQDs from petroleum coke and kitchen tea residues highlights the potential for sustainable QD production, a crucial aspect for future advancements.[42] Quantum dots offer a platform with vast potential across various fields. Integrating waste-derived materials into quantum dot (QD) synthesis provides a sustainable approach to material development. Tyagi et al. exemplified this by creating nitrogen-doped carbon quantum dots (N-CQDs) incorporated into ZnO thin films for visible light photocatalysis.[43] This approach demonstrates the potential for waste-derived materials to enhance photocatalytic performance. Research efforts highlight the importance of material properties and composite structures in optimising QD performance for photocatalysis. Tran et al. studied visible light photocatalysis using oxygen defect-rich zinc oxide nanorods (ZnO NRs) decorated with carbon quantum dots (CQDs). Their work underscores the role of these defects in facilitating efficient electron transfer mechanisms essential for photocatalysis.[44] Xu et al. further emphasised the importance of nano structuring by exploring CQDs decorated ZnO heterostructure nanoflowers, achieving high efficiency photocatalysis.[45] The use of QDs extends beyond photocatalysis. Chen et al. investigated pollutant degradation using Fe3O4@CQDs composites for per-oxy-mono sulphate (PMS) activation under visible light, demonstrating their potential for environmental remediation applications.[46] Yashwanth et al. explored a different strategy, demonstrating enhanced hydrogen production using nitrogen and phosphorus co-doped carbon quantum dots (NPCQDs) anchored on ZnO nanorods.[47] This work highlights the potential of QDs for clean energy generation. Integrating QDs with other nanomaterials offers additional benefits. Serkjan et al. created a CQD-modified, organic-inorganic self-powered UV photodetector, showcasing the enhanced functionality achievable through QD integration for sustainable energy applications.[48] Choi et al. further emphasised the potential of QDs in energy-efficient devices by developing a stable hybrid ink using colloidal QDs and metal-oxide nanoparticles for efficient solar cells.[49] Doping QDs with specific elements can also improve their performance. Jinze Li et al. synthesised carbon-incorporated, burger-like ZnO nanoparticle clusters with improved photocatalytic activity, demonstrating the impact of carbon doping.[50] This approach opens doors for further exploration of dopant materials to optimise QD functionalities for various applications. High-Angle Annular Dark Field Scanning Transmission Electron Microscopy (HAADF-STEM) and Energy-Dispersive Spectroscopy (EDS) mapping form a powerful duo for unveiling the structural and compositional complexities of nanomaterials, particularly ZnO-Carbon Quantum Dot (CQD) hybrid nanocomposites.[51,52] HAADF-STEM excels at pinpointing interfaces within intricate structures like core/shell quantum dots, including ZnO-CQDs. This capability is crucial for understanding the interactions between ZnO and CQDs in the nanocomposite. HAADF-STEM generates high-resolution images where contrast directly correlates to the atomic number (Z) of the elements present. This allows researchers to visualise the detailed arrangement of atoms within the ZnO-CQD nanocomposite at the atomic level. Complementary to HAADF-STEM, EDS mapping identifies the specific elements present within a sample. For instance, researchers successfully utilised EDS to confirm the presence and verify the expected elemental composition (Zn, Mo, and O) in a ZnO@ZnMoO4 framework, revealing their homogeneous distribution throughout the structure.[53] The combined power of HAADF-STEM and EDS mapping has been instrumental in investigating ZnO/CQD heterostructures. Hydrothermal Synthesis approach utilises commercially available ZnO as a carrier for introducing CQDs. In Situ Synthesis, ZnO/CQD samples are directly created by adding zinc acetate to an existing aqueous suspension of CQDs.[33,53] HAADF-STEM has been used to visualise the spatial distribution of CQDs relative to the ZnO structure.

For example, one study revealed variations in CQD distribution, with CQDs either docking on the external surface of ZnO (ZnO©/CQD) or stacking between ZnO layers (ZnO (OP)/CQDs).[53] Combined with theoretical models and simulated HAADF-STEM images, researchers have developed methods for extracting information about the three-dimensional arrangement of atoms within complex nanostructures, like graphene sheets in amorphous carbon.[54] This approach highlights the power of HAADF-STEM to provide multi-dimensional insights. HAADF-STEM offers a high-resolution window into the intricate atomic structure of ZnO-CQD nanocomposites. This understanding is crucial as the arrangement of these components influences their properties and facilitates rational design for specific applications.[52] Together, HAADF-STEM and EDS mapping offer a comprehensive toolbox to analyse the intricate details of ZnO-CQD nanocomposites. These techniques provide essential information for understanding the structure-property relationships of these materials, paving the way for the development of novel functionalities. X-ray diffraction (XRD) patterns (Figure 3a) confirm the hexagonal wurtzite structure of ZnO in both ZnO and ZnO@CQD samples. There is minimal disruption observed in the peaks of the composite material, suggesting successful integration of CQDs without altering the fundamental crystal structure of ZnO. Scherrer formula calculations reveal a slight increase in crystallite size from 17 nm to 20 nm for ZnO@CQDs, which could be due to interactions between ZnO and CQDs. Fourier Transform Infrared Spectroscopy (FT-IR) analysis (Figure 3b) provides further evidence of interaction between ZnO and CQDs. The ZnO@CQDs spectrum reveals a new peak at 640 cm-1, which is absent in the pure

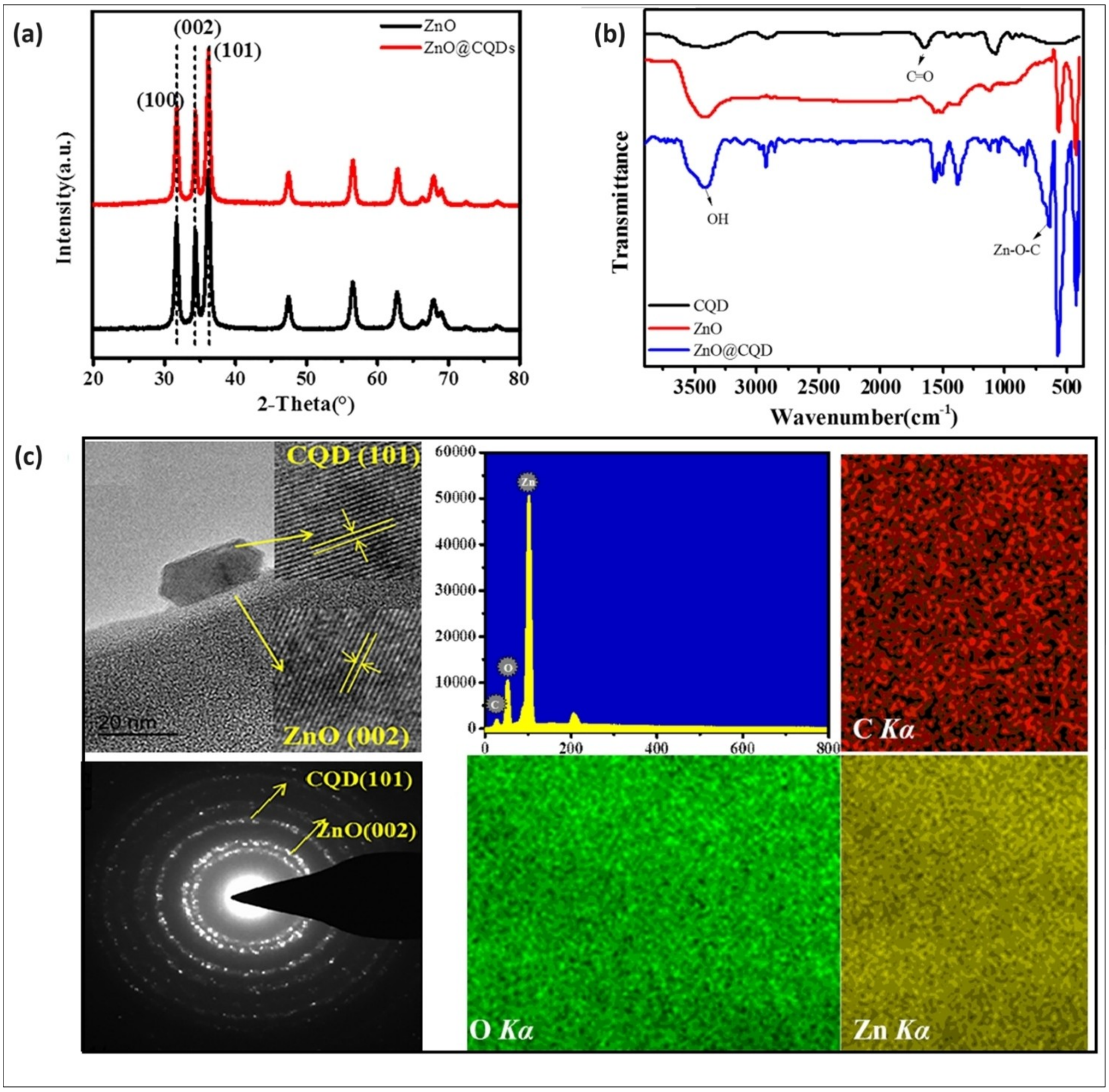


Figure 3. Characterisation of ZnO@CQD Nanocomposites, (a) X-ray Diffraction (XRD) Patterns, (b) Transmission Fourier-Transform Infrared Spectroscopy (FT-IR) Spectra, (c) High-Resolution Transmission Electron Microscopy (HRTEM) Images and Selected Area Electron Diffraction (SAED) Patterns and Energy-Dispersive X-ray Spectroscopy (EDX) Spectrum and Mapping, Adopted with permission from.[55]

ZnO spectrum. This peak is indicative of Zn-O–C bonding, suggesting the formation of chemical linkages at the interface between ZnO and CQDs. High-Resolution Transmission Electron Microscopy (HRTEM) (Figure 3c) offers high-resolution imaging that confirms the presence of both ZnO and CQDs within the nanocomposite. Lattice spacings observed in the HRTEM image correspond to the (101) planes of graphite for CQDs and the (002) planes of ZnO. Selected Area Electron Diffraction (SAED) analysis aligns with the HRTEM findings, further supporting the successful integration of ZnO and CQDs. Energy-Dispersive X-ray spectroscopy (EDX) analysis (Figure 3c) confirms the elemental composition of the ZnO@CQDs nanocomposite. The presence of Zn, O, and C peaks verifies the integration of all desired elements. Additionally, EDX mapping demonstrates a uniform distribution of these elements throughout the nanocomposite, suggesting successful co-deposition of ZnO and CQDs. The combination of XRD, FT-IR, HRTEM, SAED, and EDX techniques provides a comprehensive characterisation of the ZnO@CQD nanocomposite.[55]

Stability is a crucial factor for the practical implementation of photocatalysts. ZnO-CQD hybrid nanocomposites demonstrate enhanced stability compared to bare ZnO, making them exceptionally promising for various environmental remediation applications. Studies highlight the remarkable photocatalytic stability of these ZnO-CQD composites. For instance, a CQDs/ZnO composite maintained a consistent degradation rate of 99.58% for methylene blue over ten cycles, significantly outperforming bare ZnO.[56] This enhanced stability stems from two key mechanisms. ZnO-CQD composites exhibit superior resistance to photocorrosion, a common degradation process in bare ZnO exposed to light. This improved resistance ensures the longevity and reusability of the photocatalyst, allowing it to maintain its photocatalytic activity over extended periods.[57] The integration of CQDs with ZnO promotes efficient separation of electron-hole pairs generated by light irradiation. This reduces charge recombination, a major limitation in photocatalysis.[58] By facilitating efficient charge separation, CQDs contribute to the overall stability and improved performance of the nanocomposite. The superior stability of ZnO-CQD nanocomposites directly translates into their photocatalytic performance. Their ability to retain effectiveness over multiple cycles is crucial for practical applications. Studies with methylene blue (MB) degradation exemplify this link: composites featuring well-dispersed, narrow-sized CQDs on ZnO achieved a remarkable 97.6% degradation of MB after 180 minutes of visible light irradiation.[53] Several key mechanisms contribute to the superior stability and photocatalytic activity of ZnO-CQD nanocomposites. Electronic interactions at the interface between CQDs and ZnO promote efficient separation of photogenerated electron-hole pairs.[53,56] This reduces recombination, allowing for more efficient utilization of these charges in driving pollutant degradation reactions. CQDs act as a protective layer for ZnO, shielding it from photocorrosion under light irradiation and potential degradation in extreme pH environments.[59] Additionally, they can mitigate the formation of oxygen vacancies and surface defects on ZnO, which can hinder its photocatalytic activity.[60] The morphology and size of both CQDs and ZnO nanoparticles significantly influence their stability and photocatalytic performance. Smaller, well-dispersed CQDs enhance the transfer of light and reactive radicals throughout the composite, maximising its efficiency.[61] In contrast, larger, agglomerated CQDs can hinder these processes. Similarly, smaller, less-agglomerated ZnO crystallites provide a larger surface area and pore volume for improved reactant interaction.[53] Research on one-dimensional heterostructures, particularly ZnO nanorods decorated with nitrogen-doped carbon quantum dots (N-CQDs), offers exciting possibilities for advancements in photocatalysis, photovoltaics, and photodetection.[57] As illustrated in Figure 4, various configurations of quantum dot (QD)-nanorod heterostructures demonstrate promise for enhancing photocatalytic activity.[48,50,57] Figure 4a shows ZnO nanorods decorated with N-CQDs.[57] This configuration has been explored for its potential in visible-light photodegradation of organic pollutants, as shown in Figure 4b.[23] Figure 4c depicts stepwise synthesis of CQDs/ZnO@HNTs nanocomposites.[50] Figure 4d displays an organic-inorganic self-powered UV photodetector based on ZnO nanorods, further enhanced by carbon quantum dots.[48] The enhanced photocatalytic activity observed in these heterostructures stems from the role of QDs as electron acceptors. Light irradiation excites electrons within the ZnO nanorods. N-doped CQDs efficiently capture these excited electrons, promoting charge separation and minimising the recombination of electrons and holes within the ZnO nanorods. This minimises energy loss and facilitates the photocatalytic reactions responsible for pollutant degradation, as reported in studies on ZnO/CQD and ZnO NRs/CQDs.[38,44] By effectively separating charges, QD-nanorod heterostructures promote efficient photocatalysis, holding promise for various environmental applications such as water purification and pollutant degradation. One-dimensional ZnO-based heterostructures decorated with QDs offer a promising approach to enhance photocatalysis. The ability of QDs to act as electron acceptors and promote charge separation paves the way for developing efficient and sustainable solutions for environmental remediation.

Addressing the need for efficient pollutant remediation, researchers have developed ZnO-based nanostructures decorated with carbon quantum dots (CQDs). This combination leverages the synergy between ZnO and CQDs to reduce recombination rates and enhance photocatalytic efficiency.[63] This not only expands the practical applications of ZnO in environmental remediation but also presents a novel strategy for pollutant removal. ZnO nanoflowers adorned with CQDs demonstrate enhanced efficiency in pollutant degradation.[45] Similarly, studies have explored the integration of QDs with hydrogels, highlighting their inherent flexibility and adaptability for environmental applications.[64] This combination creates a platform with enhanced photocatalytic capabilities. The mechanism behind the improved performance lies in the role of CQDs as electron acceptors. Upon light irradiation, electrons in the ZnO become excited.[44,45] The CQDs efficiently capture these excited electrons, minimising their recombination with holes in the ZnO. This separation of charges leads to enhanced photocatalytic activity, as demonstrated by the proficient removal of

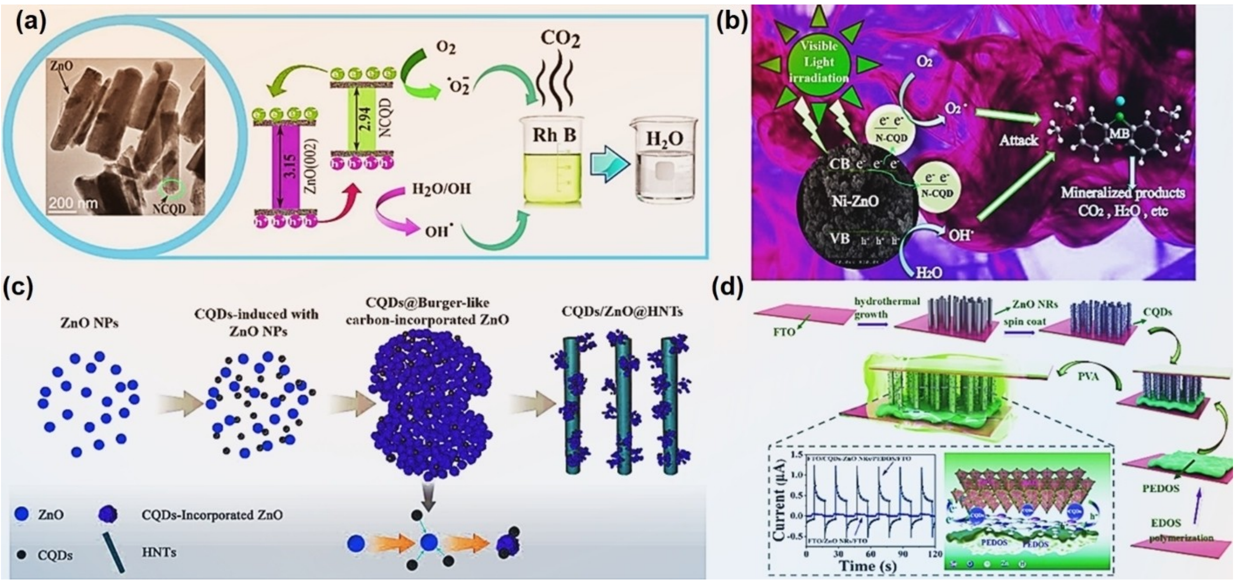


Figure 4. (a) Nitrogen-doped carbon quantum dot (N-CQD) decorated ZnO nanorods, Adopted with permission from,[57] (b) N-doped CQDs/Ni-doped ZnO nanocomposites for visible light photodegradation of organic pollutants, Adopted with permission from,[62] (c) Formation of CQDs/ZnO@HNTs in a stepwise synthetic process, Adopted with permission from,[50] and (d) Organic-inorganic face-to-face ZnO nanorod-based self-powered UV photodetector enhanced by carbon quantum dots, Adopted with permission from.[48]

nitrogen oxide (NO) under visible light using ZnO nanorods integrated with CQDs.[44] Furthermore, research has shown that nitrogen doped CQD/ZnO films exhibit improved efficiency under both visible and UV light conditions.[45] This suggests a synergistic effect within the hybrid structure, where nitrogen doped CQDs further enhance the photocatalytic activity of ZnO films. The adaptability of CQDs within hydrogels allows for tailoring photocatalytic properties for specific environmental challenges.[64] This versatility offers an effective solution for various environmental remediation applications. Integrating nitrogen-doped carbon quantum dots with zinc oxide holds significant promise for developing efficient photocatalysts for environmental remediation.[44,45,63,64] Figure 5 presents various nanomaterial configurations with promising applications in photocatalysis. Figure 5a depicts nitrogen-doped carbon quantum dots (N-CQDs) incorporated into ZnO thin films. This configuration exhibits visible emission from N-CQDs and enhanced UV band-edge emission from ZnO, suggesting efficient exciton generation (λex = 325 nm).[63] Figure 5b shows carbon quantum dots (CQDs) decorating ZnO nanoflowers grown on nanofiber membranes. This unique heterostructure demonstrates high photocatalytic efficiency.[45] Figure 5c highlights the growing interest in quantum dot-hydrogel composites, suggesting their potential for future advancements in photocatalysis.[64] Figure 4d illustrates the integration of CQDs with ZnO nanorods (NRs). This innovative combination effectively removes NO pollutants under visible light irradiation.[44] The diverse configurations highlighted in Figure 5 represent promising strategies for developing efficient photocatalysts for environmental remediation.

3. Synthesis Strategies for ZnO-CQDs Quantum Dots Nanocomposites

The environmental hazards posed by synthetic dye wastewater have spurred contemporary research efforts towards developing efficient treatment strategies. A promising frontier involves the creation and application of ZnO-CQD quantum dot nanocomposites.[28] ZnO, a popular photocatalyst, suffers from limitations due to its wide band gap (3.37 eV).[68] Strategies like metal ion doping and utilisation have been explored to enhance its photocatalytic activity.[25] A promising approach involves integrating ZnO with carbon quantum dots (CQDs), known for their water solubility and minimal toxicity.[69] These CQDs can be produced via various techniques, such as chemical oxidation and hydrothermal synthesis,[33] as shown in Figure 6. Studies have shown that ZnO/N, S-CQD hybrid nanoflowers exhibit superior photocatalytic performance in antibiotic degradation.[70] This highlights the effectiveness of ZnO functionalised with quantum dots. The synergistic effect of this hybridisation improves charge separation, light absorption, surface area, and photostability within the nanocomposite.[71] The practical viability of these nanocomposites is supported by rigorous analyses, including transient photocurrent response and Nyquist plots.[72] ZnO/CQD nanocomposites offer a promising strategy for degrading pollutants in wastewater treatment applications.

The field of integrating Zinc Oxide (ZnO) and Carbon Quantum Dots (CQDs) for photocatalysis[73–75] is propelled by the development of diverse methodologies. Approaches like the cost-effective ball mill-hydrothermal technique, used to create nitrogen-doped CQD-supported ZnO nanoflower photocatalysts, highlight this innovation.[76,77] Precise control over

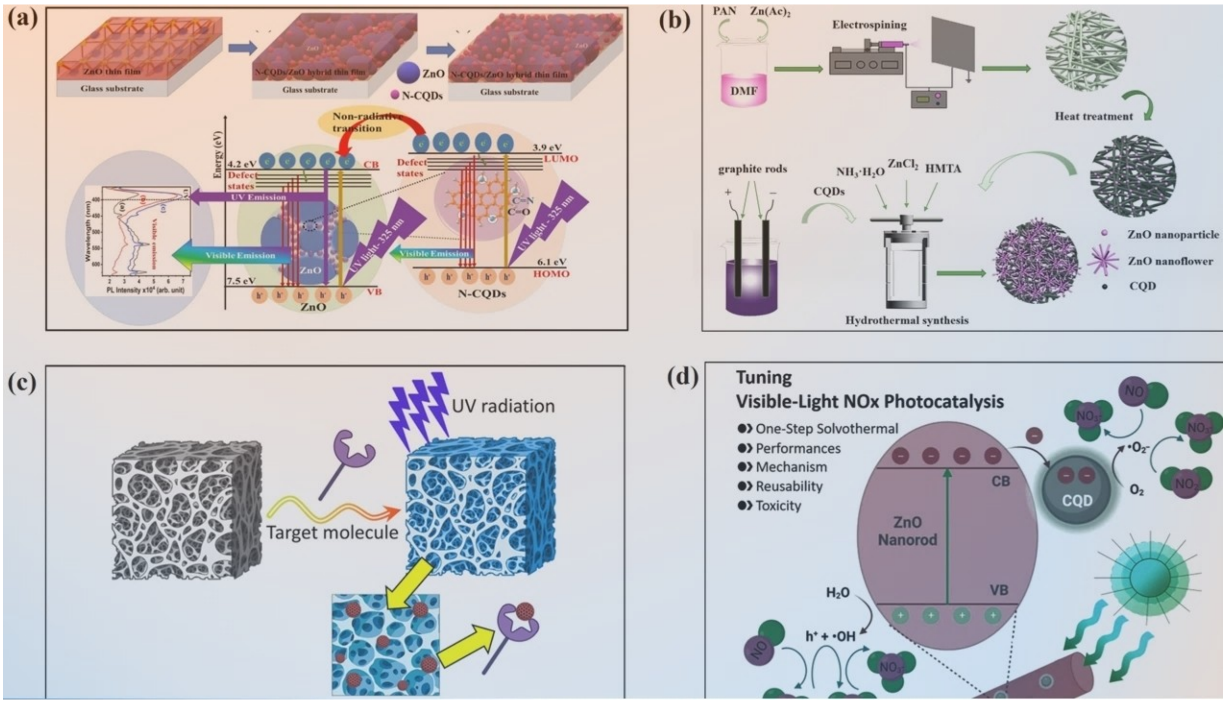


Figure 5. (a) N-CQDs/ZnO hybrid thin films, visible emission of N-CQDs, and enhanced UV band-edge emission of ZnO at λex = 325 nm, Adopted with permission from,[65] (b) Carbon quantum dots-decorated ZnO heterostructure nanoflowers on nanofiber membranes as high-efficiency photocatalysts, Adopted with permission from,[66] (c) Progress in quantum dots-hydrogel composites, Adopted with permission from,[64] (d) Integration of CQDs with ZnO NRs for efficient NO removal under visible light irradiation, Adopted with permission from.[67]

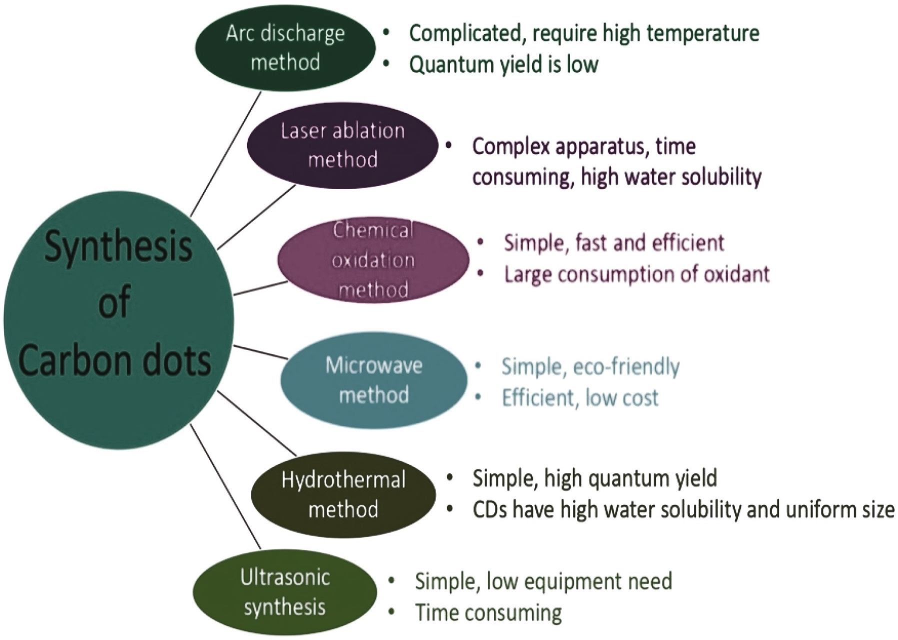


Figure 6. Various synthesis methods for CQDs and GQDs, Adopted with permission from.[33]

synthesis parameters is crucial for the formation of well-defined ZnO-CQD nanocomposites.[53] Structural characterisation techniques, like X-ray Diffraction (XRD), provide valuable insights into the composition and properties of these materials.[23,33,78,79] One of the key advantages of ZnO-CQD nanocomposites is their enhanced photocatalytic activity. This synergy is exemplified by the efficient visible light photodegradation of nitrobenzene achieved with these materials.[53] Their versatility is further demonstrated by the successful application of nitrogen-doped CQDs and nickel-doped ZnO nanocomposites for the visible light degradation of organic pollutants.[23] Sustainability is another important aspect of research in this field. The development of a ZnO/CQDs/AgNPs ternary heterostructure highlights efforts towards creating sustainable photocatalytic materials.[80] While the focus of this text is on ZnO-CQDs, it's important to note that research on Graphene Quantum Dots (GQDs) is also ongoing, with applications in electrochemical sensing being explored.[81,82] The integration of ZnO and CQDs offers significant advancements in photocatalysis. Controlled synthesis methods ensure precise material design, allowing for detailed structural characterisation and a thorough understanding of their properties. These multifunctional nanocomposites hold promise for various applications, including wastewater treatment and environmental remediation.

4. Properties of Zinc Oxide (ZnO) and Carbon Quantum Dots (CQDs) Nanocomposites

The unique properties of ZnO-CQD nanocomposites have propelled their emergence as a material with applications in photocatalysis, sensors, and solar cells.[83,84] Researchers have explored various synthesis methods, including sol-gel, hydrothermal, and co-precipitation, to optimise the integration of ZnO and CQDs for specific functionalities.[85,86] Detailed characterisation techniques play a crucial role in understanding these materials. UV-Vis absorption and fluorescence spectroscopy provide valuable insights into the optical properties of ZnO-CQD nanocomposites.[87] The UV-Vis absorption spectrum helps determine the material's light absorption characteristics, which is crucial for photocatalytic activity. X-ray Photoelectron Spectroscopy (XPS) and impedance spectroscopy are employed to elucidate the electronic band structure and charge transfer mechanisms within the nanocomposite.[88,89] Time-resolved spectroscopy sheds light on the dynamic behaviour of these materials, revealing details about charge separation and recombination processes.[90,91] One of the most promising applications of ZnO-CQD nanocomposites lies in optoelectronic devices. Figure 7a shows N-CQDs/ZnO composites exhibit enhanced electrochemiluminescence via pyrolysis, presenting improved characteristics,[92] Figure 7(b) discuses carbon quantum dot/nitrogen-doped ZnO (CQD/N-ZnO) composites exhibiting exceptional photocatalytic performance under daylight irradiation.[93] This efficient degradation of dyes highlights their potential for environmental remediation applications. Beyond photocatalysis, ZnO-CQD nanocomposites demonstrate antimicrobial properties[94] and selective Hg^{2+} ion detection capabilities, expanding their application scope. Figure 7(c) depicts a colour-tuneable ZnO/CQDs nanocomposite serving as a fluorescence sensor for trace cadmium (Cd^{2+}) detection.[95] This research paves the way for environmentally friendly white LEDs and various sensing applications. The versatility of these nanocomposites is further emphasised by Figure 6(d), which pro-

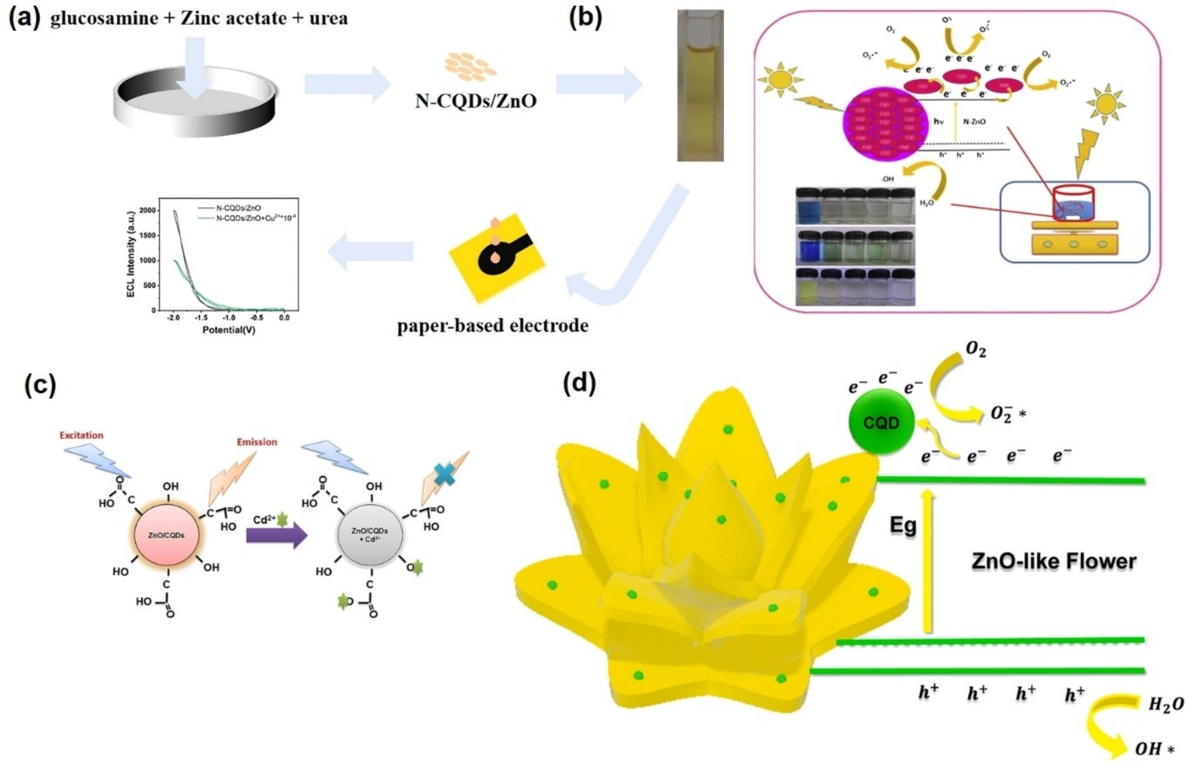


Figure 7. (a) N-CQDs/ZnO composites exhibit enhanced electrochemiluminescence via pyrolysis, presenting improved characteristics, Adopted with permission from,[92] (b) CQD/N-ZnO composites, synthesised through a one-step method, efficiently degrade dyes under natural daylight, Adopted with permission from,[93] (c) ZnO/CQDs nanocomposite serves as a colour-tuneable fluorescence sensor for trace Cd^{2+} detection with a low LOD of 0.14 μM, Adopted with permission from,[95] (d) Hydrothermally synthesised ZnO/NCQD nanoflowers show enhanced photocatalytic activity, achieving 80% degradation of methylene blue in 15 minutes, Adopted with permission from.[96]

vides nitrogen-doped carbon quantum dot-decorated zinc oxide (ZnO/NCQD) nanoflowers with enhanced photocatalytic activity.[96] Their diverse electronic characteristics make ZnO-CQD nanocomposites valuable for various technological advancements.[83]

Zinc oxide (ZnO) suffers from limitations like a wide bandgap and rapid charge carrier recombination, hindering its photocatalytic efficiency.[97] To address these challenges, researchers are exploring the integration of carbon quantum dots (CQDs) with ZnO. CQDs are attractive due to their simple synthesis and impressive photoluminescence properties. However, their role extends beyond just optical enhancements. Recent research suggests that CQDs play a crucial role in overcoming the limitations of ZnO.[98] Furthermore, synthesis methods for CQDs are being optimised to ensure biocompatibility and achieve smaller sizes for improved performance.[99] A key driver in this field is the development of ZnO-CQD nanocomposites with enhanced photocatalytic efficiency, particularly under visible light irradiation.[93] Researchers are actively exploring specific synthesis methods to bridge the gap in ZnO photocatalytic activity under visible light.[100,101] Figure 8 provides examples of ZnO-CQD nanocomposite applications. Figure 8(a) illustrates the templated synthesis of ZnO quantum dots using MOF-801, demonstrating its superior photocatalytic performance.[102] Figure 8(b) depicts the improved photovoltaic performance of organic solar cells (OSCs) incorporating CQDs with ZnO nanorod arrays.[103] While not directly related to photocatalysis, Figure 8(c) highlights the versatility of these materials by depicting a highly sensitive fluorescent probe for sparfloxacin determination. This probe integrates various components, including nitrogen-doped graphene quantum dots, zinc oxide-decorated carbon foam, and magnetite within a molecularly imprinted polymer matrix.[104] Integrating carbon quantum dots with ZnO offers a promising strategy for enhancing photocatalytic efficiency under visible light. This approach has the potential to improve ZnO's applicability in environmental remediation and other areas.

Photoluminescence (PL) plays a crucial role in materials science and optoelectronics due to its diverse applications.[102,106] Fluorescence, a key phenomenon in PL, involves the immediate emission of light upon photon absorption followed by a rapid return to the ground state.[107–109] Studying PL in ZnO thin films provides valuable insights into their optical properties. In ZnO, the emission of excitons (bound electron-hole pairs) near the band edge (NBE) in the ultraviolet region (around 380–390 nm) originates from the recombination of free excitons.[110] Doping ZnO thin films with transition metals (Co, Fe, Zr) has been shown to enhance structural stability and create unique granular arrangements.[87] Structural analyses employing X-ray diffraction (XRD) and atomic force microscopy (AFM) can validate metal doping in the ZnO lattice. Energy-dispersive X-ray spectroscopy (EDS) confirms the presence of the transition metals themselves. Fourier-transform infrared spectroscopy (FTIR) can reveal intricate chemical bonding patterns within the doped films.[111,112] A significant reduction in the bandgap is often observed in these doped films. This decrease in bandgap energy significantly influences their light absorption capabilities, affecting electronic transitions within the material.[110] Figure 9 illustrates the near-band-edge emission of ZnO in the UV region, highlighting its characteristic optical features. Studying photoluminescence helps elucidate the complex interplay between transition metal modification and the properties of ZnO thin films. Doping can enhance structural stability, create unique morphologies, and notably impact light absorption capabilities.

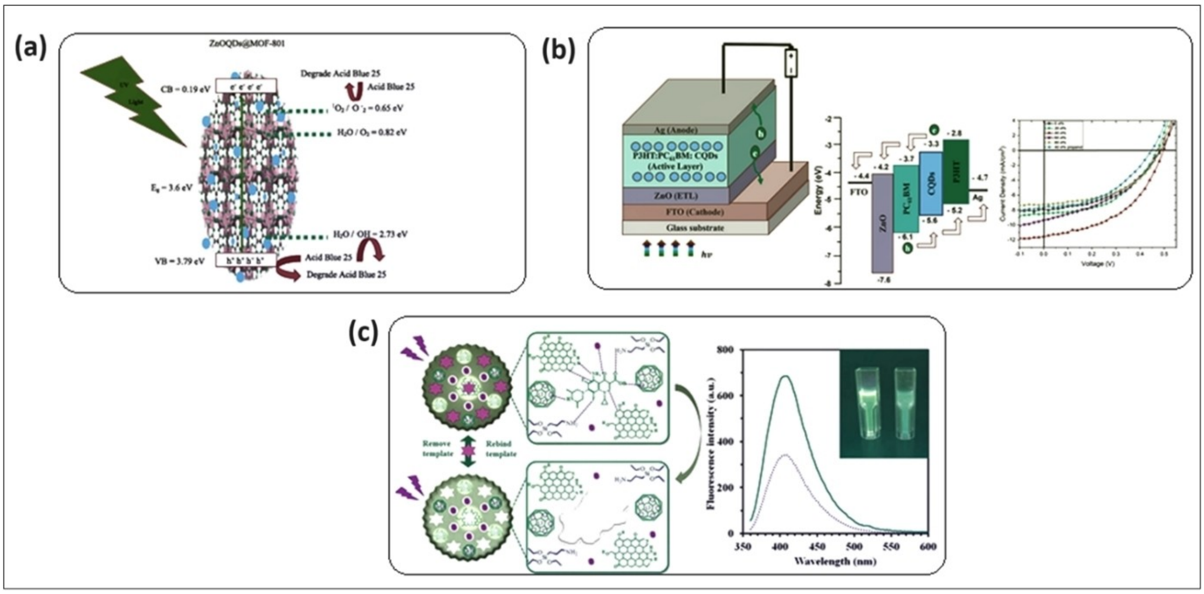


Figure 8. (a) Templated synthesis of ZnO QDs using MOF-801, demonstrating superior photocatalytic performance for Acid Blue 25 degradation under UV irradiation, Adopted with permission from,[105] (b) Improved photovoltaic performance in OSCs with CQDs and ZnO nanorod arrays as the electron transport layer, Adopted with permission from,[103] (c) A fluorescent nanocomposite probe for sparfloxacin determination, integrating nitrogen-doped graphene quantum dots, ZnO-decorated carbon foam, and magnetite within a molecularly imprinted polymer matrix, Adopted with permission from.[104]

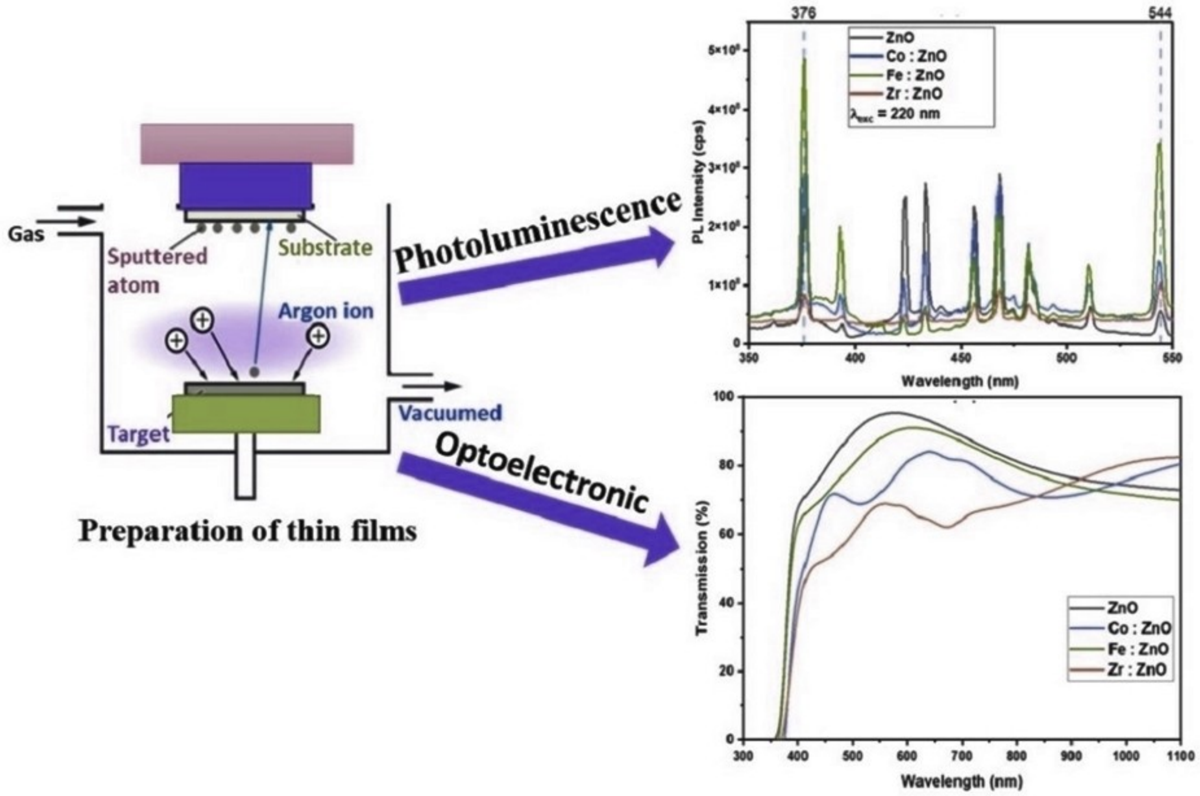


Figure 9. Investigates thin films of zinc oxide (ZnO) photoluminescence properties of the doped with the transition metals Co, Fe, and Zr ZnO thin films, Adopted with permission from.[110]

Doping ZnO thin films improves their electrical conductivity, making them suitable for applications in solar cells and light-emitting devices. Material properties are precisely controlled through techniques like RF and DC co-sputtering.[110] Studying photoluminescence (PL) in ZnO thin films provides valuable insights. Emissions in the green and yellow regions of the light spectrum arise from defects within the ZnO crystal lattice and offer information about these defects.[113] Temperature-dependent PL studies further elucidate ZnO's photoluminescence behaviour by shedding light on excitonic states.[114] Beyond thin films, ZnO's photoluminescence properties find applications in UV-emitting devices, lasers, sensors, and various optoelectronic devices.[115] Combining ZnO with carbon quantum dots (CQDs) offers significant promise for enhanced photocatalytic performance. The size-dependent emission of CQDs synergistically improves light absorption and promotes efficient charge separation through a direct Z-scheme mechanism.[116] This approach is exemplified by hybrid zinc oxide/graphene electrodes and nitrogen doped CQD/ZnO composites.[117] The quantum confinement effect in CQDs plays a crucial role in facilitating efficient photocatalytic degradation within hybrid composites.[116] Notably, the photocatalytic degradation efficiency is influenced by the solution's pH, with neutral and basic conditions leading to superior performance. This behaviour can be attributed to the impact of ZnO's point of zero charge (pHpzc) on adsorption capacity, which in turn affects the efficiency of the degradation process.[118] Experimental studies have shown that factors like pH variations and the presence of a Na_2CO_3/$NaHCO_3$ buffer significantly influence the degradation efficiency of pollutants like methylene blue. Importantly, CQDs act as protectors, preventing photo corrosion reactions and enhancing the structural stability of ZnO.[119] The decolouration process during methylene blue degradation can be monitored using UV-Vis spectra, which reveal a decrease in band intensity. Furthermore, the enhanced degradation kinetics observed with CQD/ZnO composites can be attributed to the unique properties of carbon quantum dots.[87] In one study, an impressive 98.2 % degradation of methylene blue (MB) was achieved after 180 minutes of UV irradiation at pH 6 using a CQD/ZnO composite. Interestingly, the presence of a Na_2CO_3/$NaHCO_3$ buffer during the same timeframe resulted in a lower degradation efficiency of 85 %. This decrease highlights the buffer's role as a hydroxyl radical (OH•) scavenger, similar to Na_2CO_3.[120] Figure 10a illustrates that the unique properties of carbon quantum dots contribute to optimising the photocatalytic performance of ZnO-based materials. Figure 10b shows the degradation kinetics of methylene blue (MB) for two different ZnO/CQD semiconductors, emphasising the efficacy of one specific composite.[53] The decay of the 665 nm band further underlines the role of this composite in facilitating MB degradation, providing valuable details about the photocatalytic process involving ZnO and CQD composites. Carbon quantum dots offer a promising strategy for enhancing the photocatalytic performance of ZnO. This approach has the

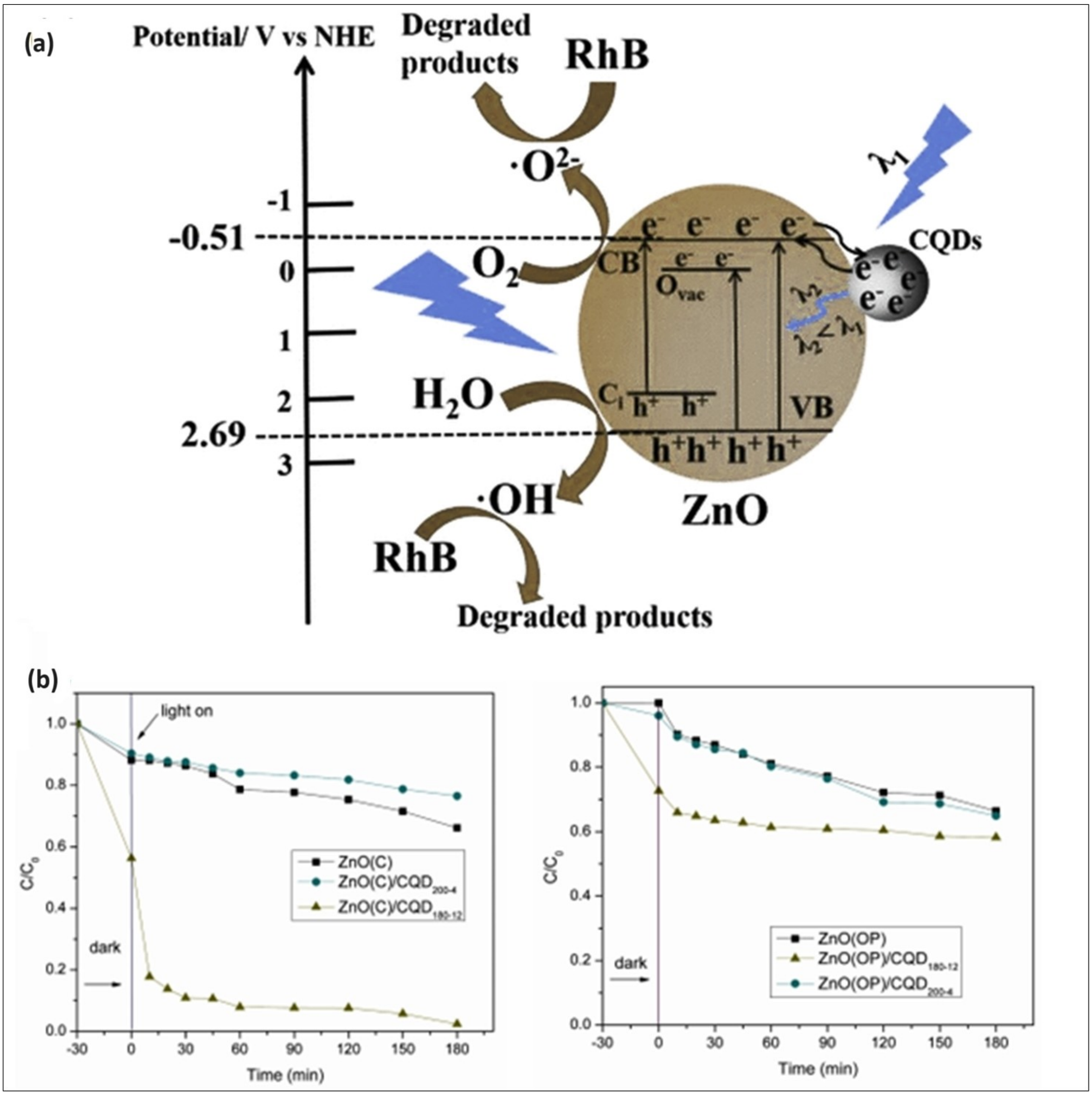


Figure 10. a) Visible-light degradation of Rhodamine B (RhB) using ZnO nanoparticles and CQDs/ZnO composites, Adopted with permission from,[87] b) Temporal evolution of MB degradation (665 nm band) under UV irradiation for (a) ZnO(C)/CQD, ZnO (OP)/CQD semiconductors, Adopted with permission from.[53]

potential to improve ZnO's applicability in environmental remediation and other areas.

Research explores integrating CQDs with zinc oxide (ZnO) and hydroxyapatite (HA) to achieve tuneable fluorescence characteristics. Figure 11(a) depicts a typical CQD structure. Figure 11(b) shows an EDA-carbon dot with a unique "core-shell" nanostructure. Researchers have developed a one-pot synthesis and purification route for CQDs, offering insights into how this approach influences their fluorescence properties (Figure 11(c)(1)). Notably, Figure 11(c)(2) presents the fluorescence intensities of eight different CQD samples synthesised using this method. The corresponding Photoluminescence (PL) emission spectra are shown in Figure 11(c)(3).[121,122] Surface passivation and the presence of functional groups significantly affect the fluorescence efficiency of CQDs. By controlling synthesis parameters, such as the ZnO to CQD ratio and surface modifications, researchers can tailor the fluorescence properties of these materials.[123] This research demonstrates the potential for tuning the fluorescence behaviour of CQDs within ZnO-HA composites. This ability to control fluorescence properties opens doors for various applications in sensing and bioimaging.

Hydroxyapatite (HA) is a well-established biomaterial with applications in bone regeneration and drug delivery. Recent research explores integrating HA with carbon allotropes, such as nanotubes and graphene, to create composites with enhanced mechanical properties. These composites hold promise for applications in orthopaedic implants, osteoporosis treatment, and regenerative medicine.[124] Zinc oxide (ZnO), a wide-

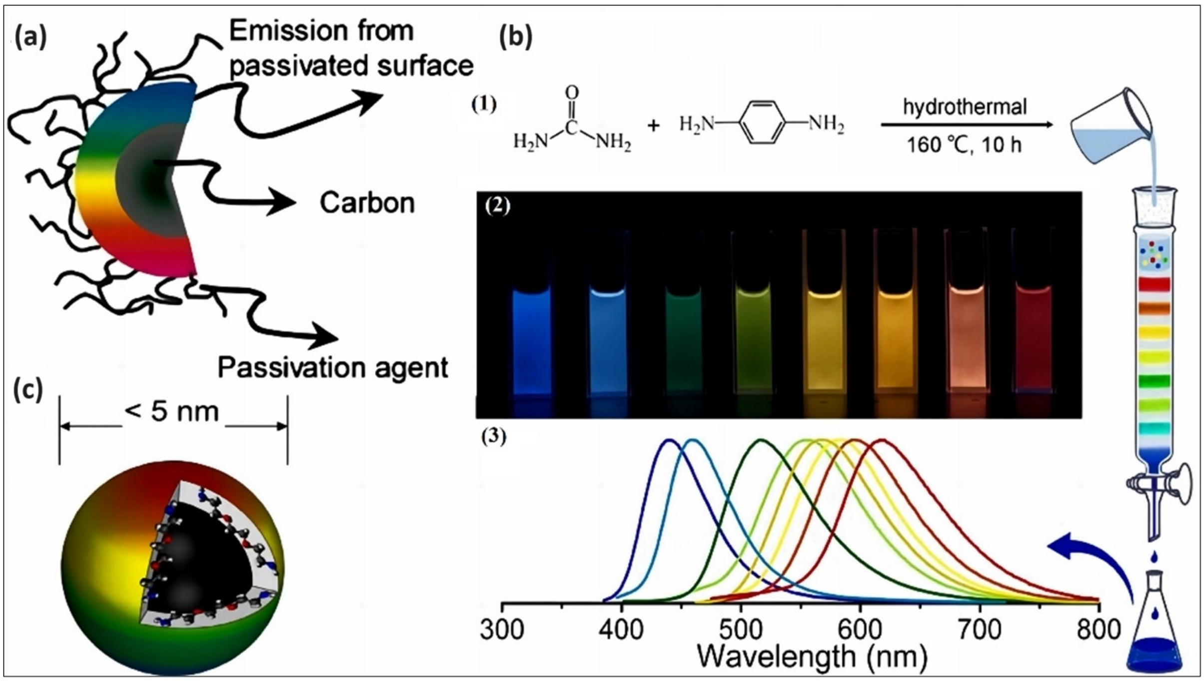


Figure 11. (a) The C–Dot (CQD) structure, (b) illustration of an EDA-carbon dot, essentially a special "core-shell" nanostructure with a small carbon nanoparticle as the core and a soft shell of tethered EDA molecules, (c) (1) one-pot synthesis and purification route for CQDs with distinct fluorescence characteristics, (c) (2) eight CQD samples under 365 nm UV light, (c) (3) corresponding PL emission spectra of the eight samples, with maxima at 440, 458, 517, 553, 566, 580, 594, and 625 nm, Adopted with permission from.[121,122]

bandgap semiconductor, is recognised for its remarkable photocatalytic properties.[125,126] However, ZnO suffers from limitations, such as low visible light responsiveness. Strategies to address this challenge include metal doping and the design of semiconductor heterojunctions.[127,128] One promising approach involves integrating ZnO with carbon quantum dots (CQDs). ZnO-CQD nanocomposites exhibit enhanced photocatalytic performance due to improved light absorption and reduced charge carrier recombination.[119] Figures 12 and 13 illustrate various ZnO-CQD nanocomposite structures. While Figure 12 focuses on the role of ZnO-CQD nanocomposites in degrading pollutants, the synergy between these materials extends beyond photocatalysis.[93,129] The potential for combining ZnO-CQD nanocomposites with HA opens doors for exciting new applications that leverage the unique properties of each material. For instance, ZnO-CQD nanocomposites could enhance the mechanical properties of HA, while HA could improve the biocompatibility of ZnO-CQD nanocomposites. The combination of ZnO-CQD nanocomposites and hydroxyapatite offers a promising avenue for advancements in bone regeneration, drug delivery, and other biomedical applications.

Figure 13 exemplifies the benefits of carbon quantum dots (CQDs) in ZnO-based photocatalysts. This figure depicts the improved charge separation observed in ZnO/NiO and ZnO/NiO/Cdots (Cdot refers to carbon quantum dot) nanocomposites. The p-n heterojunction formed between ZnO and NiO facilitates charge separation, but the introduction of CQDs further enhances this process by minimising electron recombination. Research on these nanocomposites revealed significant performance improvements. The p-n heterojunction promotes efficient separation of photogenerated electron-hole pairs, reducing their recombination. Carbon quantum dots play a crucial role in this process by effectively converting photons into charges and minimising energy barriers at material interfaces.[131] Zinc oxide (ZnO) is a popular choice for photocatalytic applications due to its non-toxicity and unique electronic properties.[132,133] Morphology optimisation techniques, such as using metal-organic frameworks (MOFs) as precursors, can further enhance the photocatalytic efficiency of ZnO nanomaterials.[134,135] Integrating carbon quantum dots with ZnO offers a promising strategy for overcoming limitations associated with charge recombination. This approach also extends the light absorption range of ZnO to include visible light, making it more efficient for solar-driven applications. While the focus here is on photocatalysis, the combination of CQDs with ZnO and hydroxyapatite (HA) holds promise for advancements in other areas, potentially improving both fluorescence properties and photocatalytic efficiency.

5. Applications of Carbon-ZnO Quantum dots Hybrid Nanocomposites

Carbon-ZnO quantum dot hybrid nanocomposites offer distinct advantages over traditional quantum dots due to their enhanced biocompatibility, reduced toxicity, and lack of heavy metals. These favourable properties have sparked considerable research interest in their potential applications.[136] The optical properties of CQDs and GQDs make them ideal candidates for

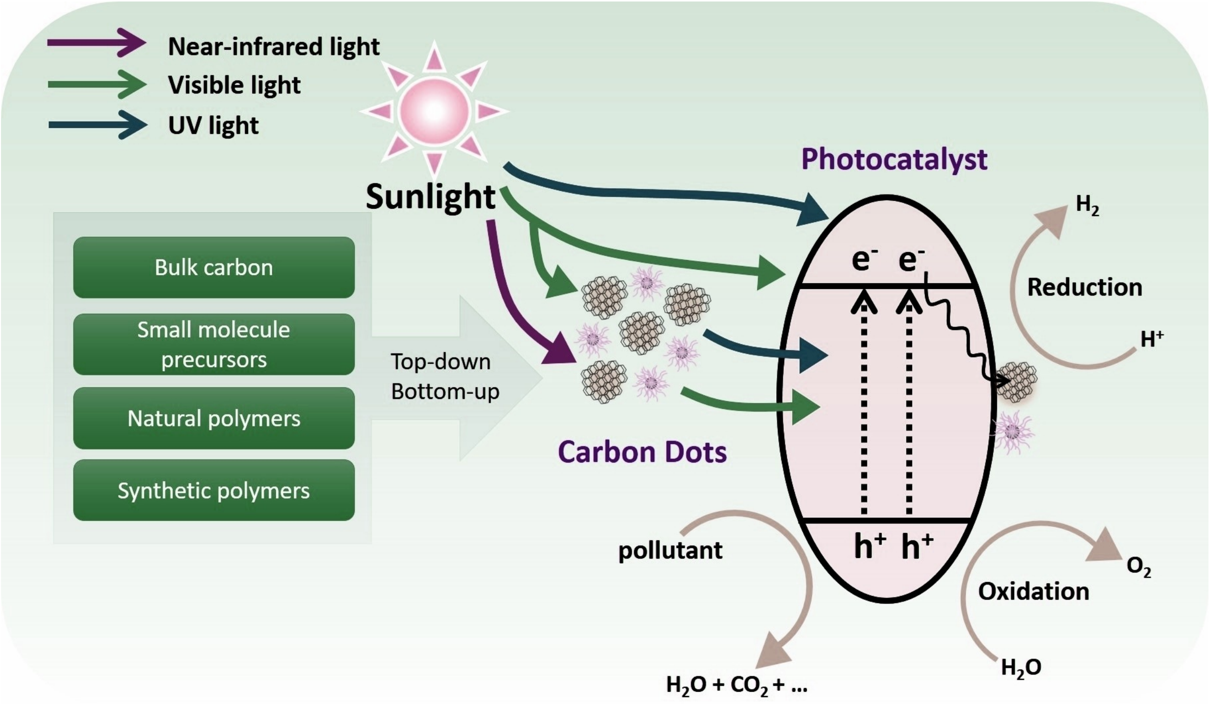


Figure 12. Combination of CDs and ZnO in nanocomposites for photocatalytic activity, particularly in the degradation of dyes and gas-phase pollutants, Adopted with permission from.[130]

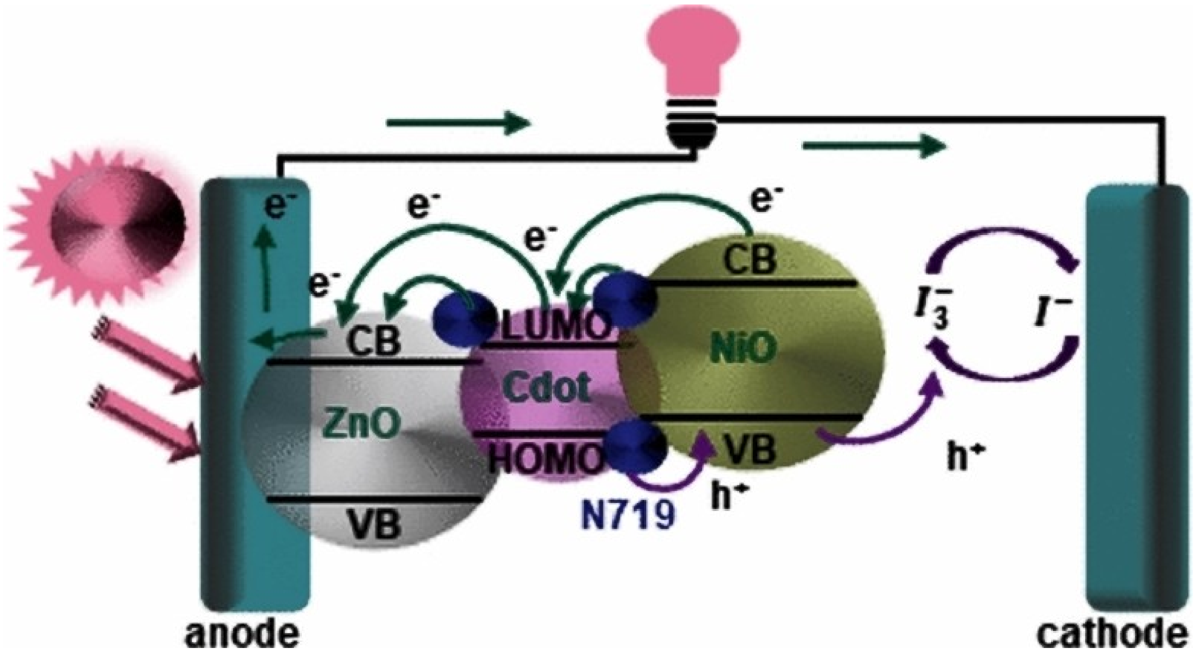


Figure 13. the nanocomposite structures of ZnO/NiO and ZnO/NiO/Cdots depicting the enhanced charge separation facilitated by the p–n heterojunction and the influence of carbon quantum dots on charge carrier transport, Adopted with permission from.[131]

developing photoluminescence-based sensors.[137] These sensors are particularly valuable in analytical chemistry because of their strong selectivity, allowing for the detection of specific ions or molecules even within complex mixtures.[138] Their impressive low limits of detection, reaching nanomolar, picomolar, or even femtomolar levels, underscore their ability for precise analyte identification.[139] In the realm of biosensing, CQDs′ biocompatibility and non-toxic nature make them effective carriers for drugs and genes. For instance, researchers have successfully loaded the antitumor drug doxorubicin onto arginine-glycine-aspartic acid-functionalised GQDs, demonstrating their potential for drug delivery applications.[140] Figure 14a illustrates the

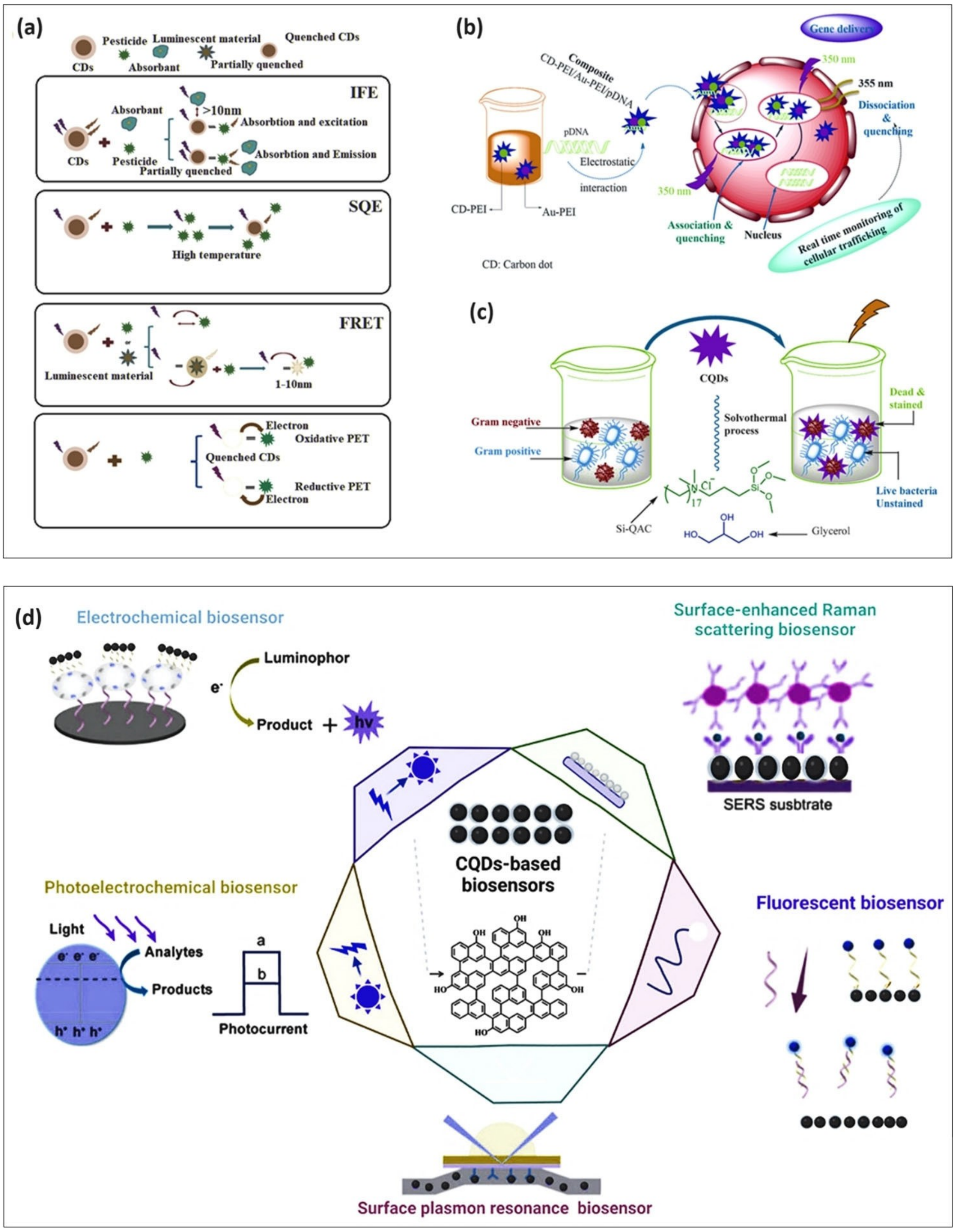


Figure 14. (a) Sensing mechanisms of fluorescent carbon dots (CDs): Inner Filter Effect (IFE), Static Quenching Effect (SQE), Forster Resonance Energy Transfer (FRET), Photoinduced Electron Transfer (PET), Adopted with permission from,[33] (b) Assembly penetrated cells with CQDs situated in the cell cytoplasm, facilitating the release of pDNA into the cell nuclei, Adopted with permission from,[141] (c) Schematic of carbon dots preparation for selectively imaging and killing Gram-positive bacteria, Adopted with permission from,[141] (d) CQDs′ properties and their role in biosensors and disease detection, Adopted with permission from.[142]

quenching effects observed in fluorescent carbon dots, which are crucial for understanding their sensing mechanisms.[33] Figures 14b and 14c show the use of CQDs for imaging and eliminating Gram-positive bacteria, highlighting their potential in selective targeting.[141] Several factors contribute to the attractiveness of CQDs for biosensing. Their zero-dimensional structure facilitates easy interaction with biological targets. Excellent solubility in water allows for efficient dispersion within biological environments. Low toxicity minimises potential risks associated with their use in biological applications. Simple synthesis procedures make them a cost-effective option for developing biosensors. Compared to traditional quantum dots, CQDs offer superior solubility, lower toxicity, and simpler synthesis methods, making them especially promising for biosensing applications.[142] The quantum confinement effect in CQDs and GQDs tailors their optoelectronic properties, enabling them to serve diverse functions in various applications.[143,144] Figure 14d highlights some of the key optical features that make CQDs valuable for disease detection biosensors.[142]

Recent research has focused on the distinct properties of carbon quantum dots (CQDs) and zinc oxide quantum dots (ZnO QDs). CQDs offer significant potential for advancements in biosensing and drug delivery due to their biocompatibility, unique optical properties, and ease of use. Their unique combination of features has sparked considerable interest in the field.[140] Their zero-dimensional structure facilitates interaction with biological targets, while excellent water solubility ensures efficient dispersion within biological environments. Furthermore, CQDs exhibit low toxicity compared to traditional quantum dots, making them a safer choice for biological applications. Simple synthesis procedures further enhance their appeal for developing cost-effective biosensors.[142] The quantum confinement effect in CQDs allows for fine-tuning of their optoelectronic properties, enabling them to serve diverse functions.[143,144] ZnO QDs, on the other hand, excel in nanocomposites for optoelectronic devices, energy storage, flame retardancy, and sensing applications.[145–147] Researchers can precisely tailor the properties of ZnO QDs through controlled synthesis techniques, such as sol-gel and APTES surface modification. High-resolution X-ray photoelectron spectroscopy (XPS) provides valuable insights into these customised interactions at the atomic level.[148–150] ZnO-CQD nanocomposites have garnered attention in environmental remediation due to their enhanced lithium storage capabilities and visible light catalytic properties.[151,152] Figure 15 illustrates the effect of synthesis temperature on quantum confinement in ZnO QDs, revealing how it influences particle size and optoelectronic behaviour.[153] Notably, ZnO-CQD nanoflowers exhibit promising visible light catalytic properties, while the incorporation of carbon quantum dots enhances the photocatalytic degradation of toxic gases.[129,154] ZnO QDs, with their 3.37 eV band gap, find applications across diverse fields, including material engineering, health sciences, drug delivery, photocatalysis, gas sensing, cancer therapy, LEDs, solar cells, and photodetectors.[155,156] Tailored synthesis techniques using sol-gel and APTES surface modification enable precise control over their properties,

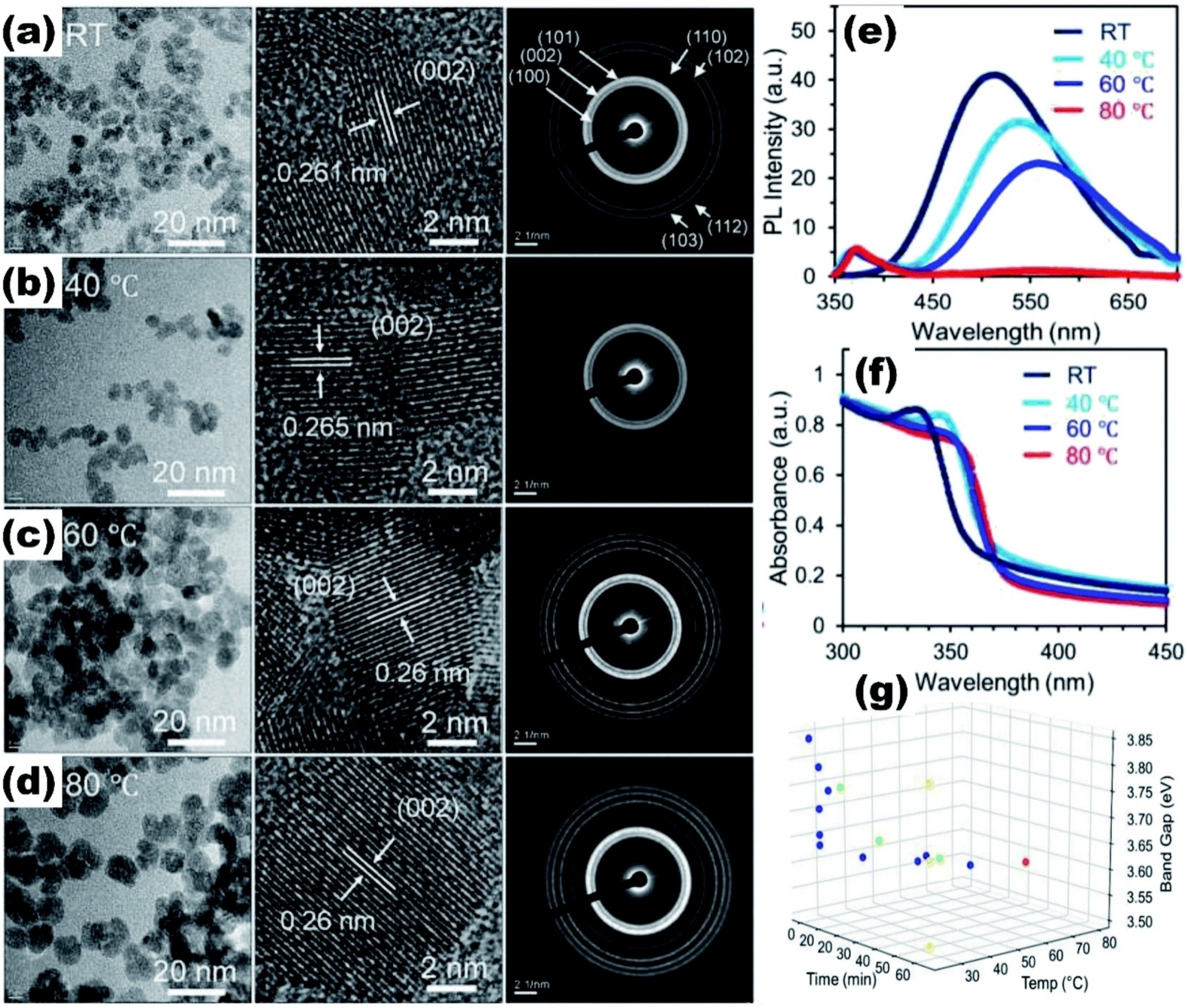


Figure 15. TEM images decreasing particle size; spectra demonstrate quantum confinement for ZnO QDs,, Adopted with permission from.[153]

making them suitable for anti-counterfeiting packaging and personalised printing.[97] Studies exploring the impact of ZnO QD size on their optoelectronic properties reveal a wide range of potential applications.[24] Figure 15 (a-d) depict TEM images illustrating the decrease in particle size with increasing synthesis temperature for ZnO QDs (quantum confinement effect). Figure 15 (e) and (f) present the corresponding photoluminescence and absorbance spectra. Figure 15 (g) highlights the training and testing datasets used for ZnO QD characterisation.[37]

By understanding these unique properties, scientists can optimize ZnO-CQDs for specific needs in fields ranging from biosensing and drug delivery to optoelectronics and environmental remediation.[157,158] Researchers have explored strategies to tailor the properties of ZnO-CQD thin films by controlling the deposition temperature of carbon quantum dots.[159] High-resolution X-ray photoelectron spectroscopy (XPS) provides valuable insights into the complex interactions between ZnO, CQDs, and other components within these films.[148–150] Studies on ZnO-nano-carbon composites reveal promising potential for stable lithium storage applications.[150] ZnO/S and N-doped graphene quantum dots/polyaniline binary nanohybrids demonstrate advancements in sensor technology.[149] Hybrid nanocomposites, such as NiO-decorated CNT/ZnO core-shell hybrids, exhibit enhanced electrode performance.[160] Investigations into the optoelectronic properties of ZnO quantum dots combined with carbon and ZnO nanotubes contribute to the development of reliable power sources.[150] ZnO-CQD nanoflowers demonstrate remarkable photocatalytic properties under visible light, making them suitable for environmental remediation.[129] The incorporation of carbon quantum dots further enhances the photocatalytic degradation of toxic gases in ZnO/CQD nanocomposites.[154] Carbon quantum dot-ZnO nanorods exhibit antimicrobial properties, suggesting their potential for use in antimicrobial coatings.[161] Injectable folic acid-conjugated polydopamine hydrogels decorated with CQDs and ZnO show promise for biomedical applications due to their superior bacteria-killing capabilities.[162] Colloidal carbon quantum dots, explored as light absorbers, demonstrate efficiency and stability for eco-friendly photoelectrochemical hydrogen generation.[163] Metal and carbon quantum dot photocatalysts offer possibilities for sustainable water treatment through photocatalytic degradation and antimicrobial approaches.[164] ZnO nanoparticles modified by carbon quantum dots have also shown effectiveness in removing synthetic pollutants, highlighting their potential for environmental remediation.[87] The extensive research on ZnO-based nanocomposites across various domains underscores their versatility and potential to address critical challenges in energy storage, environmental remediation, biomedicine, and beyond.

5.1. ZnO/Carbon Quantum Dots Nanocomposites for Solar Cells and Photovoltaics

The drive towards renewable energy has fueled research into integrating carbon quantum dots (CQDs), graphene quantum dots (GQDs), and other QDs with ZnO nanostructures to optimize solar cell performance. Diverse techniques have been developed for this integration, leading to significant efficiency improvements in ZnO-based solar cells.[43,165] Using ZnO nanorod arrays in the electron transport layer and incorporating a P3HT:PC61BM system, researchers have achieved substantial efficiency gains with CQD integration.[103] QDSSCs based on ZnO, and other materials have broadly demonstrated efficiency improvements ranging from 0.12% to an impressive 18.1%.[166,167] Investigations into the use of CQDs for TiO_2 and various metal oxide sensitisers in DSSCs have revealed significant enhancements.[166] One notable study achieved a high 8.6% power conversion efficiency with PbS/CdS QDs sensitising ZnO nanorod array solar cells.[168] Research efforts have yielded promising results with other solar cell architectures. For example, a commendable 5.27% power conversion efficiency was achieved in a ZnO nanosheets/GQDs composite,[169] while ZnO-based DSSCs with Cdots exhibited a noteworthy 5.9% efficiency.[170] Inverted polymer solar cells with ZnO@graphene core–shell quantum dots reached a substantial 10.3% conversion efficiency.[170] Meticulous studies have shown that tailoring the ZnO nanostructure can further improve solar cell performance. For example, researchers discovered that ZnO nanotapers offer superior photoconversion efficiency, short-circuit current, and minimal charge transfer resistance compared to nanorods. Sensitising ZnO nanotapers with NGQDs resulted in a peak photoconversion efficiency of approximately 1.15%.[171] Figure 16a Illustrates an architecture capable of achieving an 8.6% power conversion efficiency.[168] Figure 16b shows the microstructural evolution from ZnO nanorods to nanotapers and the resulting performance enhancements with NGQDs sensitisation.[171] Optimisation techniques include the use of down-converting glass to broaden the absorption spectrum. SEM analysis confirms the formation of desired ZnO nanostructures, while UV-Vis spectroscopy validates the efficacy of down-converting glass.[168,171] Tailoring of nanostructures frequently involves the hydrothermal growth of ZnO nanorod arrays on FTO-coated glass substrates.[171]

Dye-sensitised solar cells (DSSCs) with ZnO-based photoanodes can benefit from the integration of quantum dots (QDs) like graphene quantum dots (GQDs) and nitrogen-doped carbon quantum dots (NCQDs). These materials improve cell performance by increasing surface area and facilitating charge transport. Figures 17a illustrates the enhanced performance of DSSCs incorporating ZnS/GQDs composites.[169] The increased surface area and superior charge mobility offered by ZnS/GQDs contribute to this improvement. Figure 17b illustrates the impact of CQDs on ZnO-based DSSCs, specifically emphasising the heightened efficiency achieved with a 10 wt.% CQD concentration.[170] Figure 17c shows NCQDs synthesised through a hydrothermal method.[153] These NCQDs led to a remarkable 75% increase in the photoconversion efficiency of ZnO-based solar cells.

Table 2 summarises the integration of various QDs with ZnO across different solar cell architectures. This table highlights the general trend of improved efficiency and charge transfer properties achieved through QD incorporation.

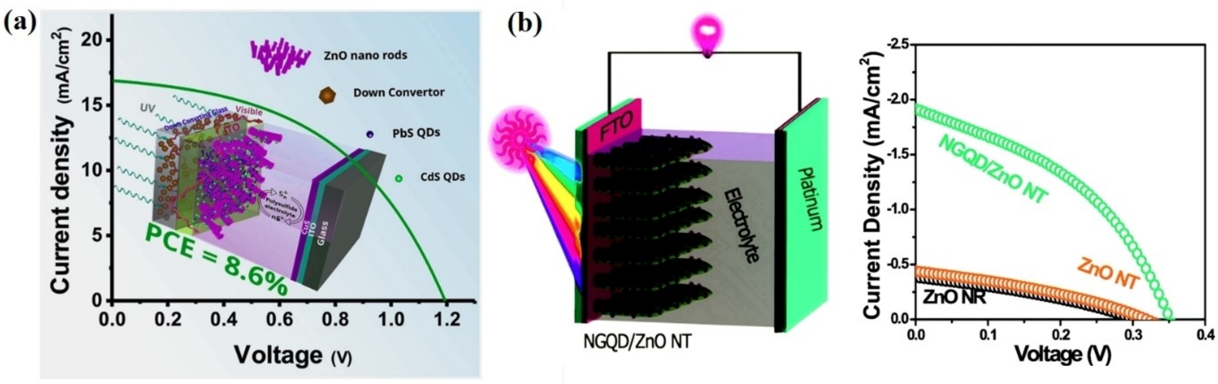


Figure 16. (a) Cost-effective architecture for PbS/CdS quantum dots sensitised ZnO nanorods array solar cells by using down-converting glass as a substrate, enhancing the absorption spectrum, Adopted with permission from,[168] (b) ZnO nanotapers arrays grown on FTO-coated glass substrates using the hydrothermal method with nitrogen-doped graphene quantum dots (NGQDs NGQDs-sensitised nanotaper photoanodes in quantum dot-sensitised solar cells, Adopted with permission from.[171]

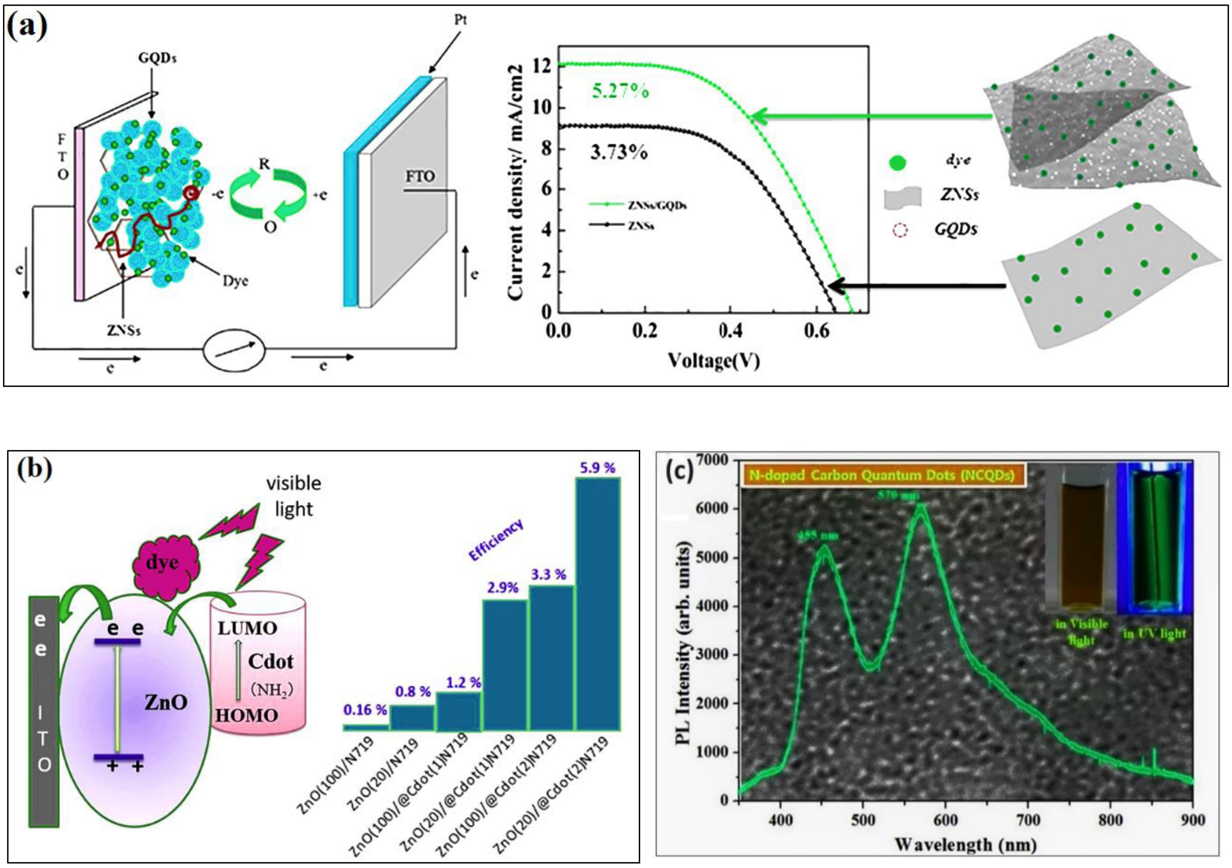


Figure 17. (a) Enhanced performance of ZnO nanosheets (ZNSs)/graphene quantum dots (GQDs) composite in dye-sensitised solar cells (DSSCs) due to increased surface area and superior charge mobility, Adopted with permission from,[169] (b) Evaluation of the impact of carbon dots (Cdots) on ZnO-based dye-sensitised solar cells (DSSCs), Adopted with permission from,[170] (c) Structure and characteristics of the synthesised NCQDs-sensitised ZnO photoanodes, Adopted with permission from.[152]

5.2. ZnO/Carbon Quantum Dots for Light-Emitting Diodes (LEDs) and Photodetectors

The unique optical properties of carbon-based and zinc oxide quantum dots (QDs) make them highly promising for optoelectronic devices. Their ability to tailor light absorption and emission characteristics has spurred considerable research into their applications. In particular, GQDs and CQDs can enhance the performance of photodetectors by acting as efficient photosensitizers. Studies by Yue et al. explored various device configurations, responsivity, detectivity, response times, and recovery times.[189] Researchers have also introduced a ZnO/

Table 2. Materials, Key Findings, and References of carbon quantum dots with ZnO in solar cell architectures.

Materials	Key Findings	References
ZnO nanorods + biomass derived CQDs	New hybrid materials for solid-state nanostructured solar cells. Device performance dependent on CQD functional groups. Highest efficiency with layer-by-layer coating of two types of CQDs.	[172]
$CH_3NH_3PbI_3$ perovskite solar cells + GQD and CQD	Supramolecules of GQD and CQD in perovskite solar cells. Best results with wrapped PBDT-TIPS-DTNT-DT/GQD and wrapped PBDT-TIPS-DTNT-DT/CQD devices.	[173]
ZnO/C core-shell nanorods + nitrogen-doped graphene QDs	Carbon-functionalised, carbon-doped ZnO/C nanorods exhibit superior photoconversion efficiency. NGQDs as photosensitiser show higher power conversion efficiency.	[174]
Polymer homo-tandem solar cells + CQD-doped tunnel junction	CQD-doped PEI in tunnel junction improves electron extraction and overall efficiency. Highest PCE achieved: 12.13 %.	[175]
ZnO nanorod-array-based QD-sensitised solar cells	Metal-sulphide spheres as counter-electrode catalysts. NiS demonstrates highest catalytic activity, leading to significantly higher power conversion efficiencies compared to Pt CE-based counterparts.	[176]
GQDs impact solar cell efficiency	GQDs synthesised via bottom-up approach. Excitation wavelength dependence observed. Morphological changes from spherical to sheet-like with increased reaction time.	[177]
Zinc Oxide (ZnO) in solar cells	Coupling synthesised GQDs with ZnO to form ZnO:GQDs nanocomposites. Effective interfacial charge transfer observed, enhancing photo absorption of ZnO in UV to visible region. Catalytic applicability demonstrated in synthesising tetrasubstituted propargylamines.	[177]
Graphene Counter Electrode + CdSe QDs, TiO_2, ZnO	Dye-sensitised solar cells with various counter electrodes. Improved performance observed in cells with graphene counter electrodes.	[178]
ZnO Quantum Dots (ZnO QDs) in solar cells	Low temperature processed pure ZnO ETLs for perovskite solar cells. ZnO QDs stabilised by DMSO used as ETLs. Champion PSC reaches max PCE of 20.05 %. Improved stability observed in ambient conditions and elevated temperature.	[179]
Ag-doped ZnO nanocomposite + Graphene Oxide	GO incorporated in Ag-doped ZnO enhances electron extraction for planar perovskite solar cells. Improved photovoltaic performance observed.	[180]
ZnO nanostructured film + Graphene Oxide	ZnO nanostructured film supported by GO provides enhanced mechanical strength and electrical conductivity. Synergistic effects with lower c-axis strain and higher oxygen vacancies improve adsorption, photocatalysis, and stability.	[181]
ZnO:C nanocomposites for solar applications	Hydrothermally synthesised ZnO:C nanocomposites enhance light absorption and charge transport. Varying carbon concentrations cause lattice compression, resulting in improved photo responses and photoelectrochemical efficiency.	[182]
Bilayer ZnO/C-QDs electron extraction layer	Bilayer ZnO/C-QDs enhances electron extraction efficiency in solar cells. High power conversion efficiency achieved through improved exciton dissociation and reduced charge recombination.	[183]
ZnO/GO and ZnO/CQDs hybrid solar cells	Hybrid solar cells combining ZnO with GO or CQDs. Improved charge transport and light absorption. Addition of CQDs significantly enhances overall cell efficiency.	[43]
C QDs/p-type $CuAlO_2$/n-type ZnO bilayer films	Bilayer films show promise for solar cells and sensors. Enhanced photovoltage and photocurrent attributed to unique C QDs′ photoluminescence behaviour.	[184]
Carbon dots impact ZnO nanoparticle based DSSCs	Cdots impact ZnO nanoparticle-based dye-sensitised solar cells, improving light absorption, charge separation, and overall efficiency.	[170]
ZnO/CQDs heterostructure for sensors and optoelectronic devices	Integration of ZnO with CQDs exhibits potential in sensors and optoelectronic devices. Enhanced charge separation, reduced recombination, and improved photocatalytic properties make it promising for solar applications.	[185]
ZnO QDs/Carbon Nanodots hybrid films for UV photodetectors	Hybrid films enable highly sensitive UV photodetectors with improved performance, high detectivity, and low noise equivalent power.	[186]
ZnO nanorods in CNT-GO nanocomposites for DSSCs	ZnO/CNT-GO nanocomposite shows superior performance in DSSCs, attributed to enhanced charge collection efficiency.	[187]
Porous ZnO/Carbon nanocomposites from metal-organic frameworks	Porous ZnO/Carbon nanocomposites enhance light absorption and electron transport. Achieve high-power conversion efficiency in DSSCs, surpassing other composites.	[188]

GQDs/ZnO (ZGZ) sandwich structure for photodetectors, demonstrating improved detectivity. Another study provides a multidimensional graphene and ZnO-based heterostructure for flexible transparent UV photodetectors, exhibiting enhanced photocurrent. Notably, Si photodiode detection capabilities were expanded down to 300 nm using GQDs.[190] Figures 18a and 17b illustrate these photodetector architectures. Zinc oxide offers promise for LEDs. Chakraborty et al. investigated LEDs using ZnO phosphors co-doped with gadolinium and ytterbium ions, achieving successful doping and evaluating crystalline defects.[191] Zhou et al. synthesised multi-coloured ZnO nanoparticles for UV-pumped white light-emitting diodes (WLEDs), demonstrating tuneable emission colours.[192] Yun et al. improved QLED performance through solvent-mediated surface ligand exchange, enhancing charge transport.[193] Hierarchical ZnO/Si nanowire arrays sensitised with In_2S_3 nanosheets and Ag_2S quantum dots exhibit enhanced photocatalytic performance.[194] Colloidal quantum dots offer versatility beyond

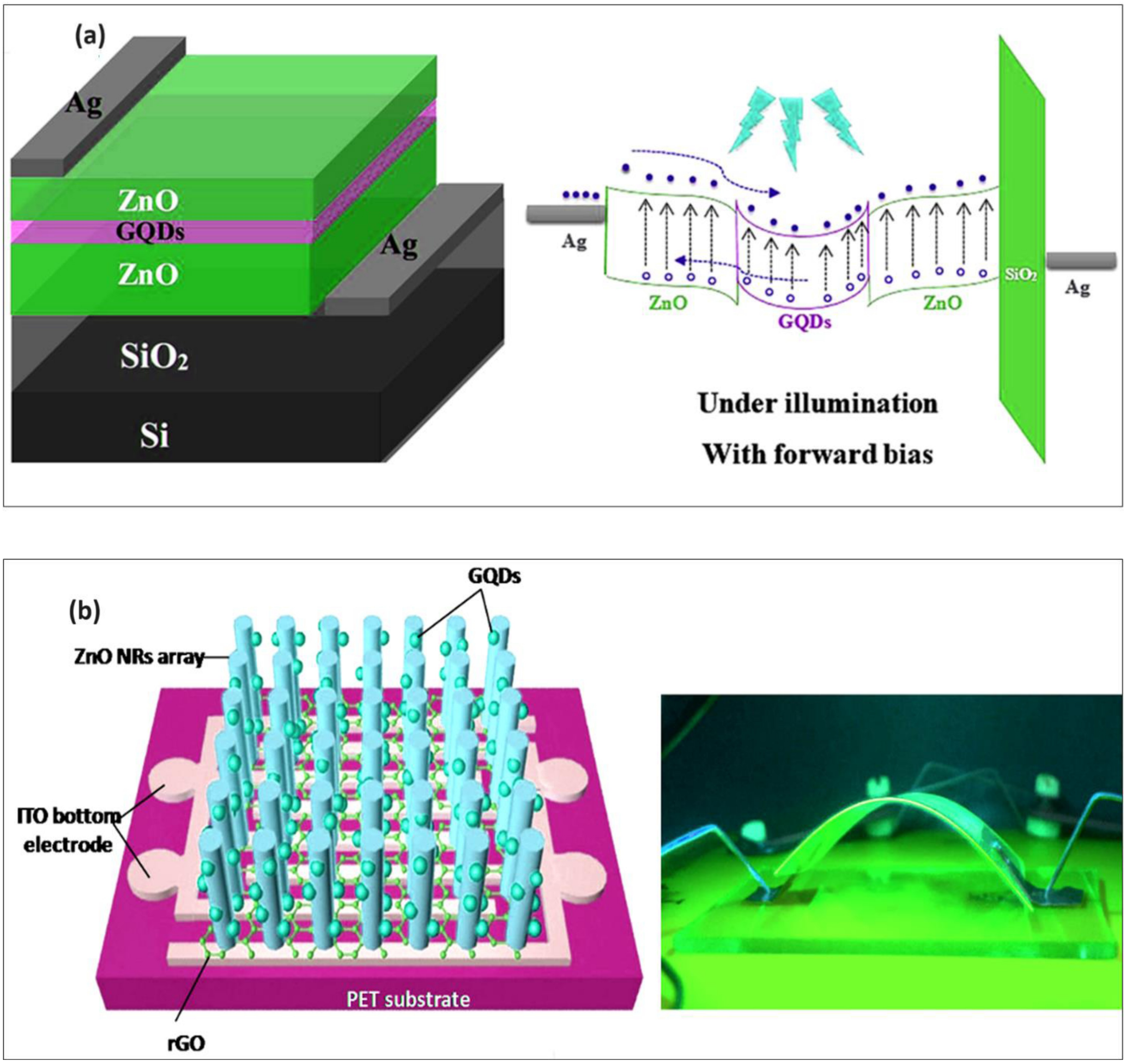


Figure 18. (a) Schematic representation of the sandwich structure with graphene quantum dots (GQDs) as an interlayer between two zinc oxide (ZnO) thin films (ZGZ), (b) a schematic representation of the flexible transparent ultraviolet photodetector (UV-PD) based on a multidimensional graphene and ZnO-based heterostructure, grown on an indium tin oxide-coated polyethylene terephthalate substrate (ITO-coated PET), Adopted with permission from.[198]

optoelectronics. Mallick et al. explored their use in down-conversion technology, biological imaging, and photovoltaic devices.[195] Ma et al. provided a comprehensive review on metal oxide-based photodetectors for various applications, including medical, military, and civilian functionalities.[196] Bera et al. investigated the synthesis and optical properties of sol-gel derived zinc oxide quantum dots.[197] CQDS /ZnO heterostructure ability to tailor light interaction makes them valuable for photodetectors, LEDs, QLEDs, and photocatalysis.

Researchers have successfully integrated ZnO@GQDs with poly (vinyl alcohol) matrix to create polymer-based photodetectors, demonstrating enhanced performance.[199] Figure 19a illustrates this type of photodetector. Furthermore, the use of GQDs with Si photodiodes has extended detection capabilities down to 300 nm, showcasing their potential in improving UV detection technologies.[200] Figure 19b highlights this advancement.

Quantum dots (QDs) offer unique functionalities for innovative photodetector design. Figure 20a depicts a self-powered photodetector incorporating TeO_2-doped ZnO composite nanorods integrated into a silicon (Si) heterojunction .[201] This design allows for distinct responses to both ultraviolet (UV) and near-infrared (NIR) light. Figure 20b shows a transparent and flexible UV photodetector fabricated using ZnO@GQDs on an eco-friendly keratin textile.[202] This design offers advantages such as enhanced photocurrent, photosensitivity, and responsivity.

Quantum dots (QDs) push the boundaries of optoelectronic devices. By incorporating QDs into materials, researchers can significantly enhance performance across various applications. For example, Figure 21a demonstrates that incorporating car-

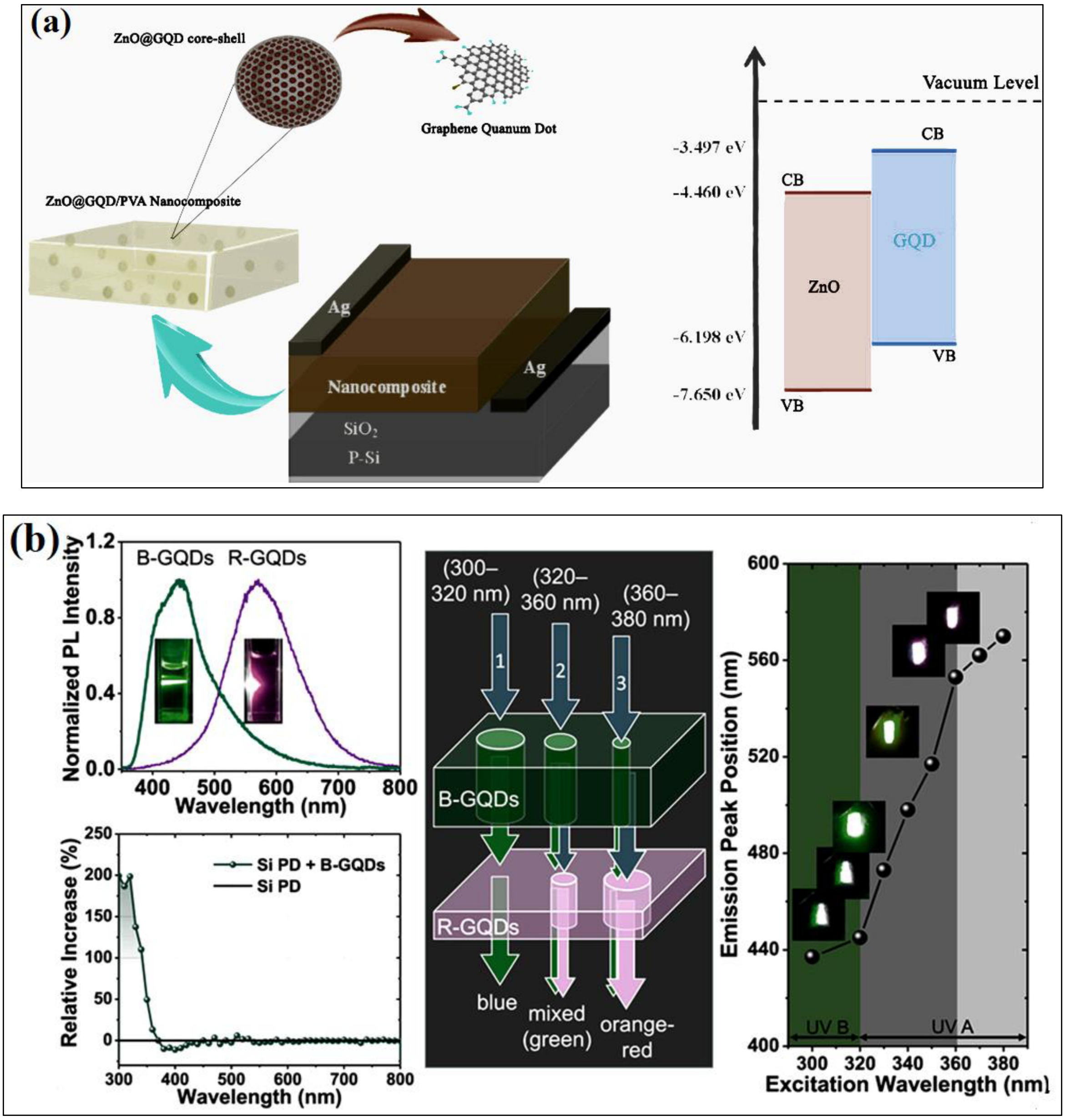


Figure 19. (a)Schematic representation of the polymer-based photodetector utilising ZnO@graphene quantum dots (GQDs) in a Poly (vinyl alcohol) matrix, Adopted with permission from,[199] (b) UV detection with graphene quantum dots (GQDs): Solution-processed GQDs sensitise Si photodiodes, extending responsiveness down to 300 nm, and facilitating visible responses to UV excitation, Adopted with permission from.[200]

bon quantum dots (CDs) into a ZnO photodetector extends its photo response from the UV to the visible range, achieving broadband detection capabilities.[204] This advancement expands the range of light the photodetector can sense. Figure 21b offers the impact of nitrogen-doped carbon dots (N-CDs) in OLEDs. These N-CDs exhibit anisotropic behavior within the composite film structure, ultimately contributing to improved OLED performance.[205] These examples highlight the versatility of QDs, applicable not only in photodetectors but also in LEDs and photocatalysts. Their remarkable properties hold significant promise for advancements across various technological domains.

5.3. ZnO/Carbon Quantum Dots for Catalysis and Water Purification

Zinc oxide (ZnO) nano-semiconductors show great promise for sewage treatment and environmental remediation due to their efficient pollutant degradation capabilities under different light sources. Incorporating quantum dots (QDs) into ZnO further enhances these properties, making ZnO/QD hybrids powerful photocatalysts for water purification. Studies by Liang et al. and Xu et al. show improved photocatalytic performance for ZnO composites incorporating carbon quantum dots (CQDs).[45,72] These composites achieve efficient degradation of pollutants like methylene blue and phenol under visible light, surpassing

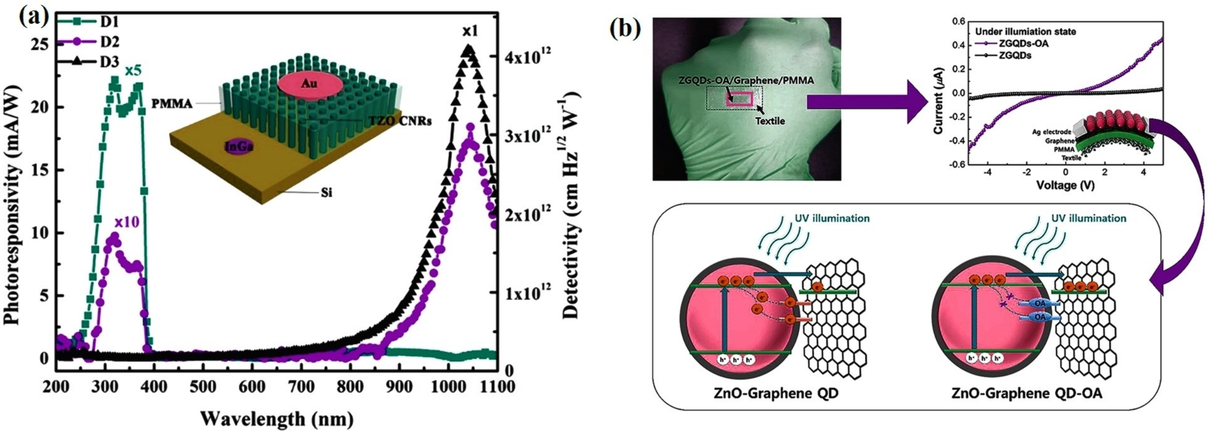


Figure 20. (a) Self-powered TeO_2-doped ZnO composite nanorods/Si heterojunction photodetectors with distinct responses to UV and NIR lights, Adopted with permission from,[203] (b) Transparent and flexible UV photodetector with ZnO@graphene quantum dots (ZGQDs) on eco-friendly keratin textile, Adopted with permission from.[201,202]

the capabilities of pure ZnO. Enhanced carrier separation is a key factor contributing to this improvement.[72] Liu et al. investigated ZnO nanoflake arrays for photoelectrochemical water oxidation. Their findings demonstrate that incorporating carbon quantum dots improves the photo response of these materials.[206] Integration of graphene quantum dots (GQDs) with ZnO nanorods has led to remarkable photostability and recyclability for environmental remediation applications. Kumar et al. achieved this through a three-step hydrothermal synthesis process, resulting in ZnO/N-CQD nanocomposites with superior photocatalytic efficiency.[207] It was observed similar improvements using N-CQDs, demonstrating superior performance compared to commercial ZnO photocatalysts .[92,207] Studies by Li et al. explored the role of CQDs in ZnO photocatalysis. They found that CQDs accept electrons from ZnO, preventing rapid recombination and enhancing photocatalytic activity.[92] Decorating ZnO nanoflowers with CQDs on nanofiber membranes improves light absorption and promotes effective degradation of pollutants under natural sunlight, as demonstrated by Chen et al..[46] Figure 22a Illustrates the processing and structure of a carboxymethylcellulose (CMC) and ZnO quantum dot (QD) coating.[208] Figure 22b shows the structural and compositional analysis of l-proline-assisted CuO/ZnO@N-GQDs hexagonal nanocomposites designed for robust multicomponent reactions.[209] Figure 22c presents a schematic diagram of the ultraviolet (UV) light detection mechanism in a surface acoustic wave (SAW) sensor setup, employing a GQD@ZnO-NWs composite material. This also depicts the fabrication process for flexible SAW devices on a flexible glass wafer.[210] These highlight the significant potential of ZnO-QD based photocatalysts for wastewater treatment and environmental cleanup. By tailoring the properties of QDs and their integration with ZnO, researchers are creating increasingly effective and recyclable photocatalytic materials for a sustainable future.

Developing high-performance ZnO-based photocatalysts is essential for efficient sewage treatment and environmental remediation. Incorporating quantum dots (QDs), particularly graphene and carbon QDs, into ZnO nanocomposites has led to significant enhancements in photocatalytic properties and visible-light degradation efficiency. For example, Figure 23a illustrates how the formation of heterojunctions between graphene quantum dots (GQDs) and ZnO nanorods significantly improves environmental photocatalysis.[207] Zhang et al. established ZnO/N-CQD nanocomposites through a three-step hydrothermal synthesis process (Figure 23b).[77] These nanocomposites exhibit remarkable photostability and recyclability, making them ideal for environmental remediation applications. Sun et al. synthesised ZnO/C-dots nanocomposites using a solvothermal method with PEG 400 (Figure 23c).[211] These composites demonstrate enhanced photocatalytic activity due to extended light absorption. Cheng et al. employed a three-step method to decorate ZnO nanoflowers with CQDs on nanofiber membranes (NFMs) for sewage treatment applications (Figure 23d).[45] This design improves light absorption and promotes effective degradation of pollutants under natural sunlight.

5.4. ZnO/Carbon Quantum Dots for Biomedical Applications

Quantum dots (QDs), particularly those incorporating ZnO and carbon, offer unique optical properties that make them powerful tools for bioimaging. Surface modifications, such as core-shell structures, improve their quantum yield and stability, enabling precise targeting of biomolecules for enhanced imaging capabilities.[212] However, concerns regarding the potential toxicity of traditional QDs, often containing heavy metals, pose a significant challenge.[213] The emergence of graphene quantum dots (GQDs) offers a promising alternative for bioimaging and cancer treatment. These materials address concerns about heavy metal toxicity while maintaining excellent imaging capabilities. However, further research is needed to fully understand the biosafety of QDs and their interaction with biomolecules.[214] Surface modifications, including ligand exchange and polymer functionalisation, play a critical role in enhancing both the luminescence and biocompatibility of QDs.[215,216] Ligand-modified surfaces are particularly important

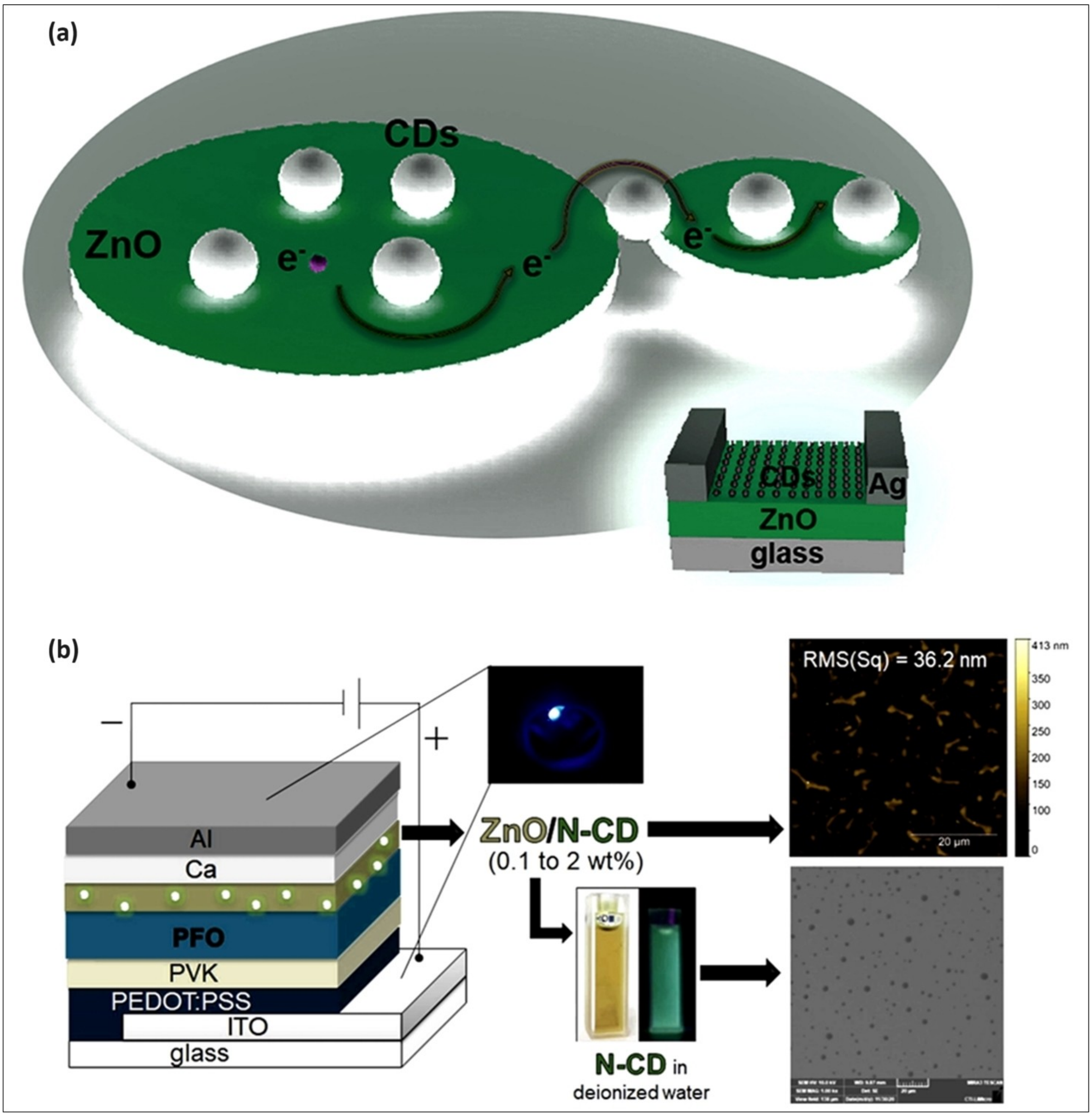


Figure 21. (a) Improved performance achieved by incorporating carbon quantum dots (CDs) in a ZnO photodetector, Adopted with permission from,[204] (b) Anisotropic behaviour of nitrogen-doped carbon dots (N-CD) and the composite film structure deposited between the emissive poly(9,9-dioctylfluorenyl-2,7-diyl) (PFO) layer and the top metal electrode in organic light-emitting diodes (OLEDs), Adopted with permission from.[205]

for ensuring water solubility and reducing toxicity within living organisms. Researchers are also exploring the use of QD-hydrogel composites, which offer advantages in terms of biocompatibility and biodegradability, using various synthesis methods.[217,218] Doping strategies can be used to enhance the properties of carbon-based QDs, while surface functionalisation allows researchers to tailor these materials for specific bioimaging and therapeutic applications.[219] For instance, fluorescent carbon quantum dots (FCQDs) exhibit high photostability and tuneable photoluminescence, making them valuable for diagnostics.[220] Studies by Singh et al. and Led by Nithyakalyani et al. explored ZnO/CQD hybrids, combining the biocompatibility of ZnO with the desirable optical properties of CQDs for enhanced bioimaging applications .[221–223] Safardoust et al. further demonstrated the potential of these hybrids for drug delivery due to their biocompatibility and ability to hold large quantities of therapeutic drugs.[224] Furthermore, the tuneable optical properties of such hybrids make them promising candidates for theranostics, combining diagnostic and therapeutic functionalities.[221] Research by Sarkar et al. focused on improving the bioactivity and UV-shielding properties of ZnO quantum dots using continuous flow synthesis.[225] Yan et al. incorporated ZnO quantum dots (ZnQDs) into orthodontic adhesives, demonstrating antibacterial activity and fluorescence properties.[226] Additionally, ZnO-doped carbon quantum dots (CQDs) have been used to develop novel methods for drug

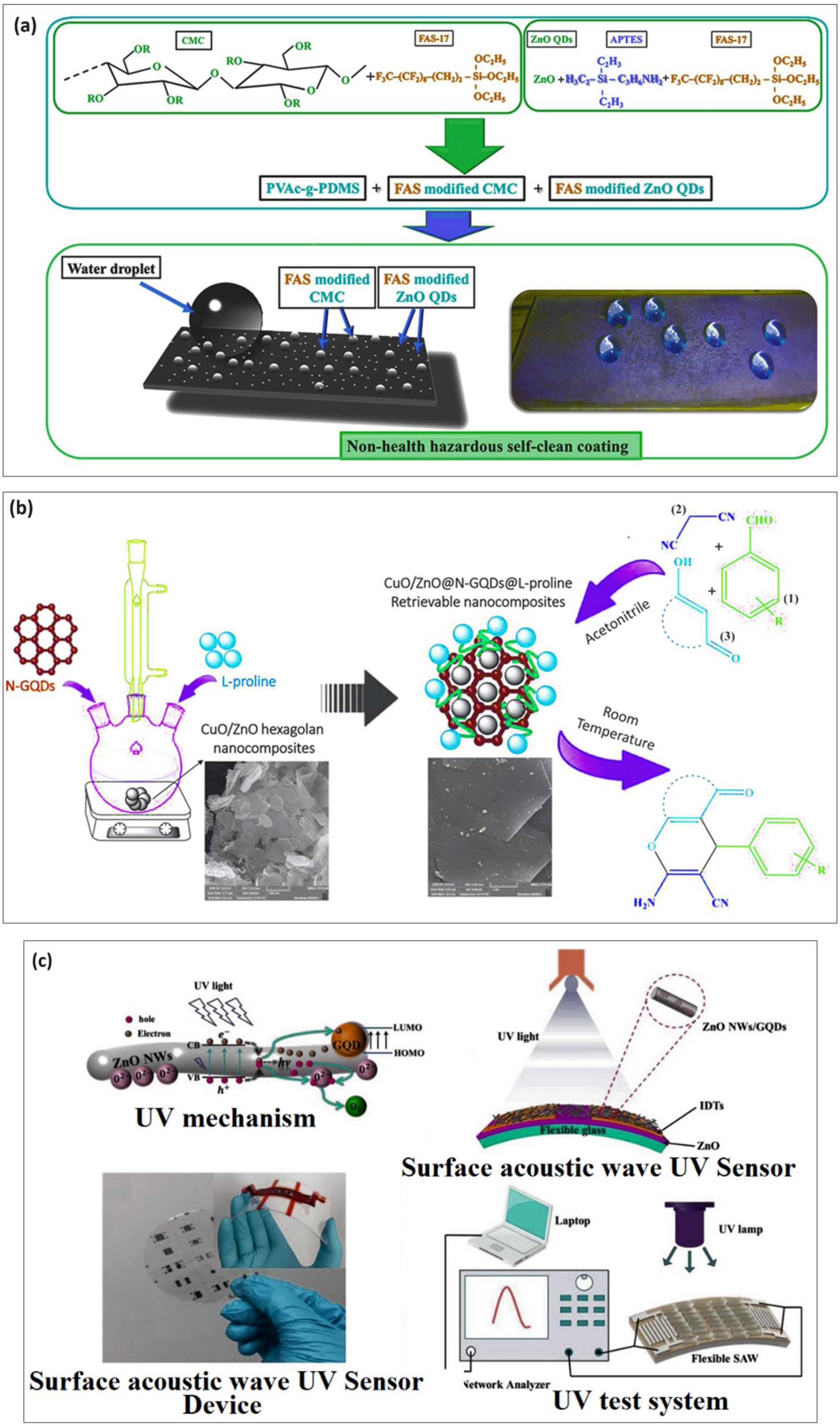


Figure 22. (a) Processing and structure of the carboxymethylcellulose (CMC) and ZnO quantum dots (QDs) coating, Adopted with permission from,[208] (b) Structural and compositional analysis of l-proline-assisted CuO/ZnO@N-GQDs hexagonal nanocomposites for robust multicomponent reactions, Adopted with permission from,[209](c) The schematic diagram of UV mechanisms of surface acoustic wave (SAW) UV sensor setup using GQDs@ZnO-NWs composite nanomaterials, and the fabrication process of flexible SAW devices on a 3-inch flexible glass wafer, Adopted with permission from.[210]

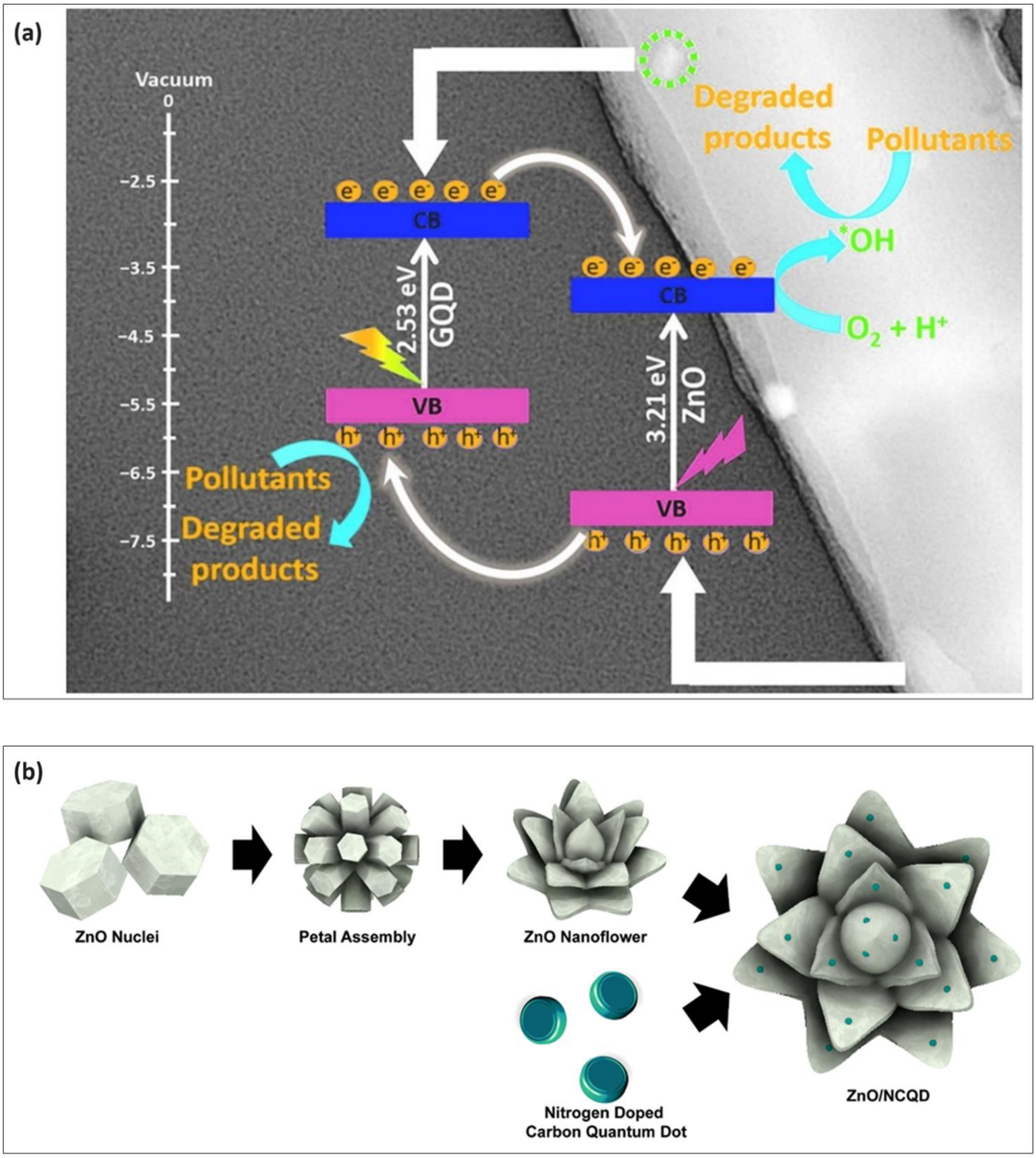
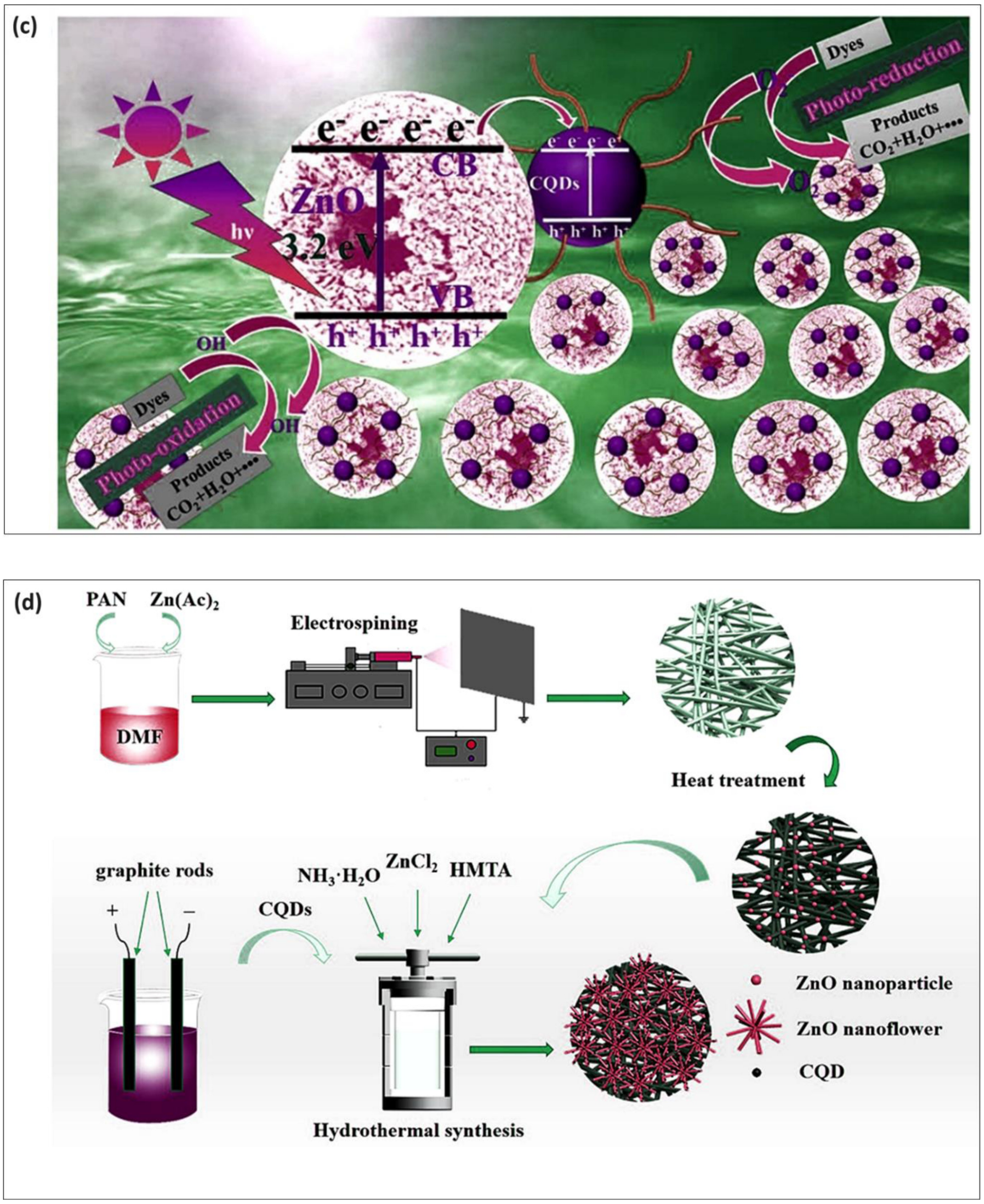


Figure 23. (a) Heterojunctions formed by incorporating graphene quantum dots (GQD) into ZnO nanorods for efficient environmental photocatalysis, Adopted with permission from,[207] (b) Schematic representation of the three-step hydrothermal synthesis process for ZnO/N-CQD nanocomposite, Adopted with permission from,[77] (c) Enhanced photocatalytic activity of ZnO Hollow Spheres by C-dots, Adopted with permission from,[211] (d) Preparation of carbon quantum dots (CQDs)-decorated ZnO nanoflowers on nanofiber membranes (NFMs), Adopted with permission from.[45]

detection.[227] Tadesse et al. explored improved ZnO/N-doped carbon quantum dots (NCQDs) for applications in both environmental and biomedical fields.[228] Zhang et al. introduced a device for monitoring leukaemia cells using aptamers and ZnO@carbon quantum dots.[229] While the focus of this section has been on bioimaging and related applications, it's worth noting that Yashwanth et al. also investigated NPCQDs/ZnO (NPCZ) nanohybrids for hydrogen production, highlighting potential applications in renewable energy.[47] Similarly, Shetti et al. developed ZnO-based nanostructured electrodes for use in electrochemical sensors and biosensors, demonstrating the broad applicability of these materials.[230,231] Table 3 provides a comprehensive overview of the various biomedical applications of quantum dots.



5.5. ZnO/Carbon Quantum Dots for Sensing

Quantum dots (QDs) and carbon quantum dots (CQDs) are revolutionizing sensing applications, including gas sensing, photodetection, and environmental monitoring. Their unique properties, especially when combined with zinc oxide (ZnO), lead to significant improvements in sensor performance. Truskewycz et al. developed a novel method for integrating quantum carbon dots into a PVP/ZnO hydrogel for effective hexavalent chromium sensing.[251] This composite material achieved a remarkable quantum yield of 62.5 %, leading to enhanced sensitivity in detecting this harmful pollutant. Nithyakalyani and Christ explored the controlled synthesis of size-dependent ZnO QDs dispersed on nitrogen and sulfur co-doped porous carbon nanosheets.[223] This research paves the way for promising chemi-resistive gas sensing capabilities, particularly for detecting lung cancer biomarkers in exhaled breath. Li et al. further contributed by creating a multifunctional hydrogel (ZCH-2) using amino-modified carbon quantum dots, ZnO, and cellulose nanofibers. This hydrogel exhibits enhanced adsorption, synergistic photoreduction, and a notable reversible fluorescence response.[252] To et al. demonstrated the excellent performance of 10 nm ZnO quantum dots for detecting NO_2 and H_2S, surpassing their sensitivity to other toxic gases.[253] This finding highlights the significant role of ZnO QDs in gas sensing applications. Serkjan et al. introduced organic-inorganic face-to-face ZnO nanorods (NRs) for self-powered UV photodetectors. Modifying these NRs with carbon quantum dots (CQDs)

Table 3. Application of QDs in Biomedicals.

QD Material	Drug/Therapeutic Agent	Key Findings	Reference
Pt-loaded and PEG-modified graphene QDs	Clopidogrel	Hypoxia-mediated chemoresistance in oral squamous cell carcinoma. Increased Pt accumulation in tumours. Reduced systemic toxicity.	[232]
Graphene QDs and doxorubicin (DOX)	Doxorubicin (DOX)	pH-dependent and prolonged release of DOX from nanocomposite hydrogel films.	[233]
CdS-modified chitosan	Sesamol	Increased bioavailability of sesamol for enhanced anticancer activity.	[234]
CdSe/ZnS QDs	Erlotinib (OSI-420)	Reduction of drug resistance and side effects in non-small cell lung cancer treatment. Increased cytotoxicity and efficiency.	[235]
PLGA – SPION – Mn: ZnS QDs	Busulfan	Enhanced localised contrast for cancer diagnosis. In vivo MRI and fluorescence in vitro imaging. Efficient drug delivery.	[236]
ZnO QDs	Doxorubicin hydrochloride (DOX)	pH sensitive ZnO@polymer QDs nanocomposites for drug delivery to glioblastoma cells. Controlled release of DOX.	[237]
SiO_2-coated CdTe QDs	Doxorubicin (DOX)	pH-responsive drug release from CdTe@MSNs nanocomposites. Simultaneous cancer diagnosis and therapy.	[238]
Fe_3O_4/SiO_2–QDs	Methotrexate (MTX)	Photothermal delivery system for MTX. Near-infrared light-triggered release of MTX.	[239]
CdTe QDs	Doxorubicin (DOX)	pH-triggered drug release and apoptosis induction in pancreatic human cancer cells. Theranostic nanocomposite.	[240]
N-doped graphene QDs	Ephrin receptor-A_2-siRNA	Internalisation into cells and dose-dependent cell viability. DNA and mRNA breakage for tumour suppression.	[241]
Ag_2S QDs	5-Fluorouracil (5FU)	Near-infrared imaging and targeting of 5FU to EGFR-positive lung cancer cells. Overcoming drug resistance.	[242]
Ag_2S QDs	Cetuximab and DOX	Targeted drug delivery to ovarian cancer cells. Selective delivery and increased cell death.	[243]
Graphene QDs	Cathepsin D-responsive peptide and DOX-Cy	Near-infrared imaging and drug delivery for tumour cell apoptosis monitoring. Improved therapeutic efficiency.	[19]
CdSe QDs	Clopidogrel detection	Clopidogrel detection at 7.55×10^{-8} M in serum, high sensitivity for cardiovascular drug monitoring.	[244]
CS–Ag/N-GQD–Au electrode	Detection of benzodiazepines	Detection of benzodiazepines in serum using an electrode with high sensitivity (DPV/SWV).	[245]
CdSe@ZnS	Efficient detection of glutathione	Efficient detection of glutathione at 0.1 mM in HeLa cell extracts, potential exploitations in cellular analysis.	[246]
Graphene quantum dots	Cholesterol detection	Cholesterol detection at 35 nmol L^{-1} in human serum, sensitive chemiluminescence-based analytical approach.	[247]
Boron nitride quantum dots	Cardiac troponin-I detection	Cardiac troponin-I detection at 0.0005 ng mL^{-1} in plasma, high sensitivity for cardiac biomarker analysis.	[248]
CdSe	Streptavidin detection	Streptavidin detection at a remarkable limit of 0.65 pg mL^{-1}, potential in bioanalytical applications.	[249]
NH_2@SiQDs	Glucose detection	Glucose detection at 0.3 μM in human serum, promise for fluorescence quenching-based glucose sensing.	[250]

significantly enhanced device performance.[254] In a different approach, Seangyai et al. developed a magnetic sensing probe for food safety applications. This probe combines nitrogen-doped graphene quantum dots (N-GQDs), zinc oxide decorated carbon foam, and a selective polymer.[255] Thyda et al. employed a sol-gel spin-coating process to create N-CQDs/ZnO hybrid thin films. Their research revealed an exciting energy transfer phenomenon between N-CQDs and ZnO, enhancing the ZnO band-edge emission.[63] Qi et al. explored GQD functionalized Ce-ZnO hybrid nanofibers, demonstrating efficient and selective electrochemical detection of mercury ions (Hg^{2+}) with high reproducibility.[256] Busarello et al. synthesised nanocomposites combining ZnO QDs and graphene oxide (GO) for photocatalysis of dyes. Their work focused on tuning the aqueous stability of the quantum dots, offering a sustainable solution for wastewater treatment.[257] Zhang et al. explored semiconductor metal oxide (MOS) nanocomposites modified by N-doped graphene quantum dots (N-GQDs). These composites exhibited excellent sensing performance for nitrogen dioxide (NO_2) at low temperatures, demonstrating the versatility of these materials in various sensing applications.[258] Li et al. investigated nitrogen-doped carbon quantum dots and ZnO composites (N-CQDs/ZnO) for enhanced electrochemiluminescence (ECL) detection of copper ions (Cu^{2+}), contributing to the expanding field of electrochemical sensing.[92] Liu et al. presented a flexible gas sensor based on carbon quantum dot decorated TiO_2 nanofibers (CQD/TiO_2), highlighting the potential for flexible and efficient gas sensors.[206] Table 4 summarises the unique properties of these nanostructured materials across various sensor types. The combination of QDs, CQDs, and ZnO nano-

Table 4. ZnO-Carbon Quantum Dots sensors from electrochemiluminescence sensing and fluorescent detection of environmental contaminants.

Sensor Type	Key Findings	References
ZnO Quantum Dots/N-doped Ti_3C_2 Mxene	One-pot synthesis enables tuneable nitrogen-doping properties, facilitating efficient electrochemiluminescence sensing.	[259]
ZnO Quantum Dots	Synthesised in one pot, exhibit efficient electrochemiluminescence sensing, particularly in the fluorescent detection of environmental contaminants.	[34]
Carbon Quantum Dots	Serve as a fluorescence and electrochemical sensing platform for picric acid, with noncytotoxic applications in food storage.	[260]
Carbon Quantum Dots	Associated with state-of-the-art developments, finding applications in photo-catalysis, bio-imaging, and bio-sensing.	[261]
Nitrogen-doped Graphene Quantum Dots, Zinc Oxide Decorated Carbon Foam	Function as an ultrasensitive and highly selective fluorescence probe for sparfloxacin determination.	[104]
ZnO Nanostructures Decorated with Graphene Quantum Dots	Serve as highly selective room temperature ammonia sensors.	[262]
Europium-grafted ZnO Quantum Dots	Function as a ratiometric fluorescence sensor, enabling visual and colorimetric detection of tetracycline.	[263]
Carbon Quantum Dots	Contribute to lychee-like SnO_2 hollow microspheres, sensitised for a high-sensitivity ethanol sensor.	[264]
ZnO-mono/Multilayer Graphene Core–Shell Quantum Dots	Demonstrate adsorption behaviour of NO_2 molecules, serving as an NO_2 gas sensor.	[265]
B, N co-doped Graphene	Synergistic catalysed ZnO Quantum Dots for fabricating microcystin-LR aptasensor.	[266]
CdS Quantum Dots Sensitising ZnO Nanorod Arrays	Create a signal-on photoelectrochemical sensing platform.	[267]
Graphene Oxide-Zinc Oxide Quantum Dots Nanocomposite	Create a signal-on photoelectrochemical sensing platform.	[268]
ZnO/CQDs Nanocomposite	Acts as a long-wavelength emissive phosphor and enables sensitive detection of cadmium (II).	[95]

materials holds immense promise for the future of multifunctional sensing applications. These materials offer exciting possibilities for advancements in gas sensing, environmental monitoring, and beyond.

5.6. ZnO/Carbon Quantum Dots for Energy Storage

The search for innovative energy storage and conversion solutions has propelled research into ZnO-based nanomaterials combined with quantum dots (QDs) and carbon quantum dots (CQDs). These hybrid materials hold promise for significant advancements in the field. Ma et al. introduced a unique 0D/2D heterostructure (ZnO@NPCF) by confining ZnO quantum dots (ZnO-QDs) within a nitrogen-doped porous carbon sponge. This design exhibited improved energy storage capacity for lithium-ion batteries.[269] Sinha et al. achieved a noteworthy breakthrough with SWCNT/ZnO, promoting promising photoresponsive attributes and achieving an impressive areal energy density of 1.53 mF/cm^2 at a current density of 1.25 $\mu A/cm^2$.[270] Yang et al. employed a self-poring technique to synthesise a composite embedding ZnO-QDs within porous carbon nanosheets. This approach holds promise for high-capacity and stable lithium-ion battery anodes.[27] Tu et al. explored amorphous ZnO quantum dot/mesoporous carbon bubble composites, demonstrating their potential for high-performance lithium-ion battery anodes.[271] Sinha et al. achieved a breakthrough with SWCNT/ZnO, promoting promising photo responsive attributes and achieving an impressive areal energy density in supercapacitors.[270] Phetcharee et al. integrated gamma-irradiated, amine-passivated carbon dots into ZnO composites, leading to enhanced specific capacitance, cycling stability, and seamless integration.[271] Zhang et al. presented improvements in energy and power density for all-solid-state asymmetric supercapacitors using ZnO quantum dots/carbon/CNT and porous N-doped carbon/CNT electrodes.[272] Tyagi et al. explored alternative energy sources with ZnO/graphene oxide (GO) and ZnO/CQDs hybrid solar cells.[43] Wang et al. significantly enhanced the performance of organic solar cells by introducing nitrogen and sulfur-doped carbon quantum dots as modifiers to ZnO.[273] Geleta and Imae incorporated a p-NiO/n-ZnO heterojunction and carbon quantum dot additives in the development of nanocomposite photoanodes for dye-sensitised solar cells.[131] Yashwanth et al. proposed a synergistic approach using nitrogen and phosphorus co-doped carbon quantum dots anchored on ZnO nanorods for enhanced hydrogen production.[47] Lee et al. developed high-performance energy storage electrodes comprising ZnO quantum dot-decorated carbon nanofibers derived from electrospun ZIF-8/PVA nanofibers.[274] Table 5 summarises the properties of these ZnO-based nanomaterials across various energy storage and conversion applications, highlighting their potential for future advancements. ZnO nanomaterials combined with QDs and CQDs highlights potential in developing next-generation energy storage and conversion technologies. These materials offer

Table 5. Overview of Nanostructured Materials for Energy Storage and Conversion.

Materials	Properties and Features	Applications	References
Semiconductor quantum dots (CdSe, PbS, InAs)	Tuneable dimensions, outstanding optoelectronic traits, size confinement inducing quantum effects, anisotropic geometry.	Enhance batteries, improve capacitors, optimise optoelectronic devices, enable sensors, serve as biomedical imaging contrast agents.	[275]
Graphene quantum dots (GQDs)	Hexagonal lattice of carbon atoms in a single layer, distinctive electronic and structural properties. Size-dependent electronic and optical properties.	Boost supercapacitor energy storage, enhance battery performance, increase charge storage capacity, faster electrochemical reactions.	[276]
Carbon quantum dots (CQDs) and graphene quantum dots (GQDs)	Environmentally friendly, non-toxic carbon materials. Unique physicochemical properties, environmentally friendly, and non-toxic.	Utilised in fuel cells to enhance energy conversion devices.	[277]
Semiconducting quantum dots (QDs)	Quantum size effect, multiple exciton generation effect, large surface-to-volume ratio, high density of active sites.	Find applications in photocatalysis, electrocatalysis, solar cells, batteries, and supercapacitors.	[278]
Graphene quantum dots (GQDs)	Green precursors, eco-friendly synthesis (hydrothermal, solvothermal, microwave methods).	Applied in supercapacitors, batteries, fuel cells, and solar cells, enhancing energy storage and conversion technologies.	[279]
Carbon quantum dots (CQDs) with polymer	CQDs in polymer composites exhibit tuneable electronic properties, enhanced dielectric properties, charge storage mechanism.	Utilised for energy storage in electronic devices, improving performance and efficiency.	[280]
Composites of graphene oxide/Mg-doped ZnO/tungsten oxide QDs	Photocatalytic activity, optical memory ability, enhanced performance.	Used in photocatalysis for environmental remediation, supercapacitors, and secondary batteries, enhancing energy storage capabilities.	[281]
Zinc Oxide (ZnO)	High sensitivity, large specific area, non-toxicity, excellent compatibility, high isoelectric point.	Utilised in nanostructure-based electrochemical sensors, energy devices, health diagnosis, pharmaceutical evaluation, food hygiene, and environmental monitoring.	[282]
Carbon Quantum Dots (CQDs), Zinc Oxide Nanoflowers (ZnO-NFs), and Poly CTAB	Achieve heightened sensitivity and selectivity for Paracetamol (PAR) and Ciprofloxacin (CIP) through multi-signal amplification.	Electrochemical sensor for simultaneous detection of PAR and CIP in biological samples, also used in energy storage and conversion devices.	[283]
N, S-doped Carbon Dots (TU-CQDs)	Regulate zinc deposition, inhibit zinc dendrites, provide a feasible route for controlling zinc anode reversibility in alkaline electrolyte.	Inhibit zinc dendrites, regulate deposition in KOH, offer a feasible route for controlling zinc anode reversibility.	[284]
Amine-Incorporated Zinc Complex/Carbon Dot Composites	Exhibit improved charge transfer, achieve high specific capacitance, enhance charge storage.	Used as supercapacitor electrodes, enhancing charge transfer and providing higher capacitance for energy storage applications.	[285]
Zinc Oxide Embedded Nitrogen-Doped Carbon (ZnO@N-doped C) hybrid	Synthesised at different temperatures, achieves high capacitance at 1 $A \cdot g^{-1}$.	Employed as an electrode material for a hybrid supercapacitor, displaying high capacitance suitable for energy storage applications.	[286]
Polyhedral ZnO Nanoparticles, CNT-Decorated Cotton Fabric, CNTs	Grown with low-temperature hydrothermal method, offer a wearable, cost-effective substrate, enhance electron transfer, show mechanical durability.	Used in lightweight supercapacitors for health monitoring and wearable electronics, improving electrochemical performance.	[287]
N-doped Carbon Concave-Dodecahedron and ZnO/Co_3ZnC hybrid	Synthesised from ZnCo-ZIF, shows exceptional mechanical tolerance, ultralong cyclability, and high-rate capacity.	Employed as supercapacitor electrodes, ensuring prolonged battery life, demonstrating remarkable electrochemical performance.	[288]

exciting possibilities for enhanced capacity, improved performance, and exploration of alternative energy sources.

6. Conclusions

Zinc oxide-carbon quantum dot (ZnO-CQD) nanocomposites offer a promising approach to address challenges in energy storage and conversion. Synthesised through techniques such as hydrothermal treatment, thermal treatment, and electrospinning, these nanocomposites demonstrate superior properties due to their well-dispersed structures. Control over size, morphology, and composition directly impacts their performance, with advanced characterisation techniques like spectroscopy, microscopy, and electrochemical analysis playing a crucial role in understanding structural, optical, and electrochemical interactions between ZnO and CQDs. Such insights inform the optimisation of composite properties for targeted energy applications. These nanocomposites provide significant advantages in seasonal energy storage, integrating seamlessly into devices like lithium-ion batteries, supercapacitors, and photocatalytic systems to enhance energy and power density, facilitating long-term energy storage solutions. Notably, the utilisation of nitrogen and sulfur-doped CQDs helps mitigate the light-soaking effect in organic solar cells, thereby improving efficiency. Moreover, optimising hybrid solar cell parameters underscores the potential of ZnO-CQD nanocomposites as alternative energy sources. Beyond photovoltaics, these nanocomposites show promise in synergistic catalysis for hydrogen production, paving the way for clean energy generation. Both zinc oxide (ZnO) and carbon quantum dots (CQDs) hold significant potential for energy storage applications due to their unique properties and tunability. CQDs, with their potential for high specific capacitance, energy density, and long-term durability, offer valuable avenues for enhancing supercapacitor performance. On the other hand, doping ZnO nanoparticles, such as with chromium, has shown potential in improving energy storage device performance. Tailoring ZnO through doping offers various benefits depending on the specific battery technology employed. Aqueous Zinc-Ion Batteries (ZIBs) stand out for large-scale energy storage due to their safety, cost-effectiveness, environmental friendliness, and robust electrochemical performance. Integrating ZnO and CQDs holds promise in further enhancing ZIB performance by optimising factors like conductivity and ion diffusion. The versatility of ZnO and CQDs lies in their customisable properties through synthesis, doping, and composite formation, enabling researchers to explore diverse energy storage solutions with enhanced performance characteristics. Continuous multidisciplinary research efforts are poised to yield further breakthroughs, driving the widespread adoption of these materials for sustainable energy solutions.

Conflict of Interests

The authors declare no conflict of interest.

Keywords: Nanostructured Zinc Oxide (ZnO) · Carbon Quantum Dots (CQDs) · Heterostructures · Hybrid Nanocomposites · Sustainability

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REVIEW

This article provides an overview of ZnO-CQD quantum dot hybrid nanocomposite heterostructures. It focuses on synthesis methods, unique properties, and applications in fields such as solar cells, LEDs, catalysis, biomedicine, sensing, and energy storage. The conclusion highlights the research's broader significance.

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