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Progress unveiled: a comprehensive review on non-toxic carbon-based quantum dots - synthesis, unique properties, and diverse applications

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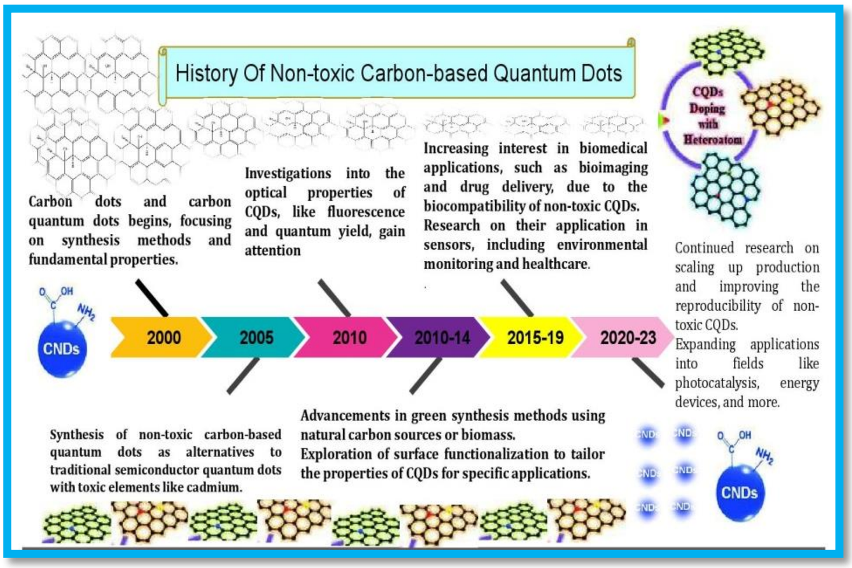
Carbon-based quantum dots (CQDs) represent a highly promising category of nanomaterials due to their distinctive optical, electronic, and chemical characteristics. This review delves into the synthesis methodologies of non-toxic CQDs, with particular emphasis on eco-friendly approaches that minimize environmental impact. The discussion spans their diverse applications across various domains, highlighting their role in pushing the boundaries of sustainability. Notably, the review elucidates the optical attributes of non-toxic CQDs, underscoring their tunable fluorescence, a feature that renders them invaluable for applications in bioimaging, sensors, and optoelectronic devices. Moreover, their non-toxic nature is pivotal for biomedical endeavors, facilitating advancements in drug delivery, photothermal therapy, and bio-labeling. In addition to their biomedical potential, this review delves into the utility of non-toxic CQDs in environmental sensing and catalysis, showcasing their adaptability and multifunctionality. Through an in-depth exploration of recent advancements, challenges, and future prospects, this comprehensive review aims to provide invaluable insights into the burgeoning field of non-toxic CQD research, propelling the development of sustainable and innovative technologies.

Keywords: non-toxic carbon-based quantum dots, synthesis, unique properties, diverse applications.



Carbon dots and carbon quantum dots begins, focusing on synthesis methods and fundamental properties.

Investigations into the optical properties of CQDs, like fluorescence and quantum yield, gain attention

Increasing interest in biomedical applications, such as bioimaging and drug delivery, due to the biocompatibility of non-toxic CQDs. Research on their application in sensors, including environmental monitoring and healthcare.

Continued research on scaling up production and improving the reproducibility of non-toxic CQDs. Expanding applications into fields like photocatalysis, energy devices, and more.

Synthesis of non-toxic carbon-based quantum dots as alternatives to traditional semiconductor quantum dots with toxic elements like cadmium.

Advancements in green synthesis methods using natural carbon sources or biomass. Exploration of surface functionalization to tailor the properties of CQDs for specific applications.

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Introduction

The advent of carbon-based quantum dots (CQDs) has sparked widespread interest across scientific realms, owing to their unique attributes and broad utility. Notably, the emergence of non-toxic CQDs has positioned them at the forefront of sustainable innovation, offering a safe and environmentally friendly alternative for diverse applications [1-6]. Central to their efficacy is the synthesis process, which has undergone a paradigm shift towards green methodologies [7], utilizing organic compounds, biomass, or natural extracts as precursors. This eco-conscious approach not only ensures non-toxicity but also aligns with principles of sustainability, yielding CQDs endowed with a distinctive array of properties. Among these, tunable fluorescence [8], biocompatibility [9], and surface functionalization capabilities [10] stand out, unlocking a realm of possibilities in bioimaging, sensors, and biomedical engineering.

The versatility of non-toxic CQDs finds expression in an array of applications, spanning biomedicine [11], environmental sensing [12], and catalysis [13]. In the realm of biomedicine, they emerge as promising candidates for drug delivery, bioimaging, and theranostics, capitalizing on their biocompatibility and tailored surface functionalities. Environmental sensing represents another frontier, where non-toxic CQDs exhibit prowess in detecting heavy metals [14], monitoring water quality, and catalyzing remediation efforts.

Moreover, their application in catalysis holds promise for sustainable chemical transformations, contributing to a greener future.

Despite notable advancements, challenges persist on the path to maximizing the potential of non-toxic CQDs. Standardization of synthesis protocols, comprehensive toxicity assessments, and optimization for specific applications remain imperative. Looking ahead, collaborative interdisciplinary efforts, coupled with a deeper understanding of biological interactions and functionalization strategies, are poised to propel the field forward. Standardization of evaluation criteria and exploration of novel functionalities will further accelerate the adoption of non-toxic CQDs in addressing pressing global challenges [15].

In this review, we embark on a comprehensive journey through the synthesis methodologies, key properties, and diverse applications of non-toxic CQDs. By providing insights into their current status, challenges, and future prospects, we illuminate the path towards sustainable and innovative technologies. As the world navigates towards a greener future, non-toxic CQDs stand poised to revolutionize industries, offering a glimpse into a future where sustainability and innovation converge for the betterment of society.

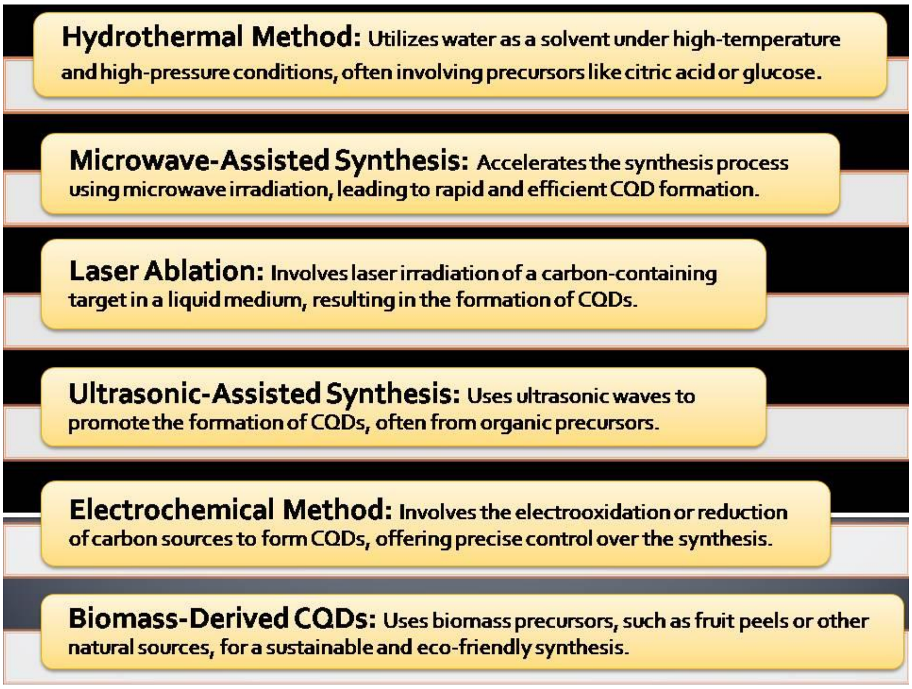
I. Synthesis methodologies

Synthesizing non-toxic carbon quantum dots (CQDs) often involves green and environmentally friendly methods [16-21]. Here's a brief overview of some common synthesis methods (Fig. 1).

1.1. Optical Properties of Non-Toxic CQDs: Tunable Fluorescence for Bioimaging, Sensors, and Optoelectronic Devices

Non-toxic carbon quantum dots (CQDs) have garnered significant attention due to their unique optical properties [22] (Fig. 2), particularly tunable fluorescence [23].

This review provides a comprehensive overview of the optical characteristics of non-toxic CQDs [24], emphasizing their tunable fluorescence and its implications for diverse applications in bioimaging [25] (Fig. 3), sensors [26], and optoelectronic devices [27].



Hydrothermal Method: Utilizes water as a solvent under high-temperature and high-pressure conditions, often involving precursors like citric acid or glucose.

Microwave-Assisted Synthesis: Accelerates the synthesis process using microwave irradiation, leading to rapid and efficient CQD formation.

Laser Ablation: Involves laser irradiation of a carbon-containing target in a liquid medium, resulting in the formation of CQDs.

Ultrasonic-Assisted Synthesis: Uses ultrasonic waves to promote the formation of CQDs, often from organic precursors.

Electrochemical Method: Involves the electrooxidation or reduction of carbon sources to form CQDs, offering precise control over the synthesis.

Biomass-Derived CQDs: Uses biomass precursors, such as fruit peels or other natural sources, for a sustainable and eco-friendly synthesis.

Fig. 1. Green and environmentally friendly synthesis methods of CQDs.

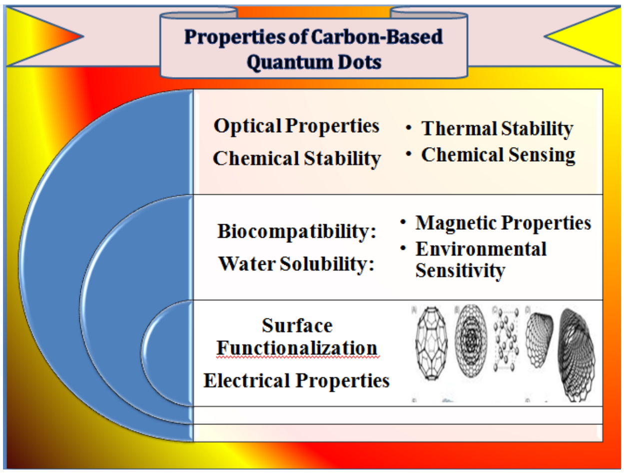


Fig. 2. Properties of Carbon-based quantum dots.

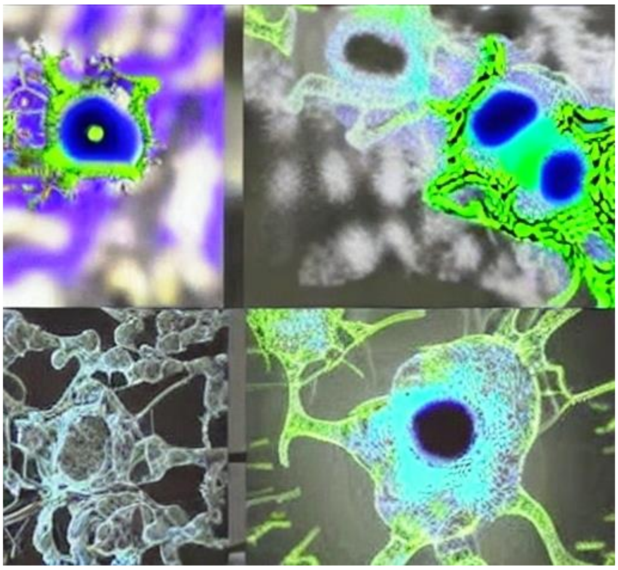


Fig. 3. Small animal bioimaging.

The discussion encompasses the underlying mechanisms governing fluorescence tuning, the influence of synthesis methods on optical properties, and the challenges associated with achieving precise control over emission wavelengths. The tunable fluorescence of non-toxic CQDs opens avenues for enhanced sensitivity in biosensing, superior contrast in bioimaging, and efficient light emission in optoelectronic devices [28]. The review concludes with insights into current research trends and future prospects for harnessing the versatile optical properties of non-toxic CQDs in advancing biotechnology and materials science [29].

II. Applications

Carbon quantum dots (CQDs) have gained prominence in biomedical applications (Fig. 4), especially in the realm of bio-labeling. Their unique properties, including tunable fluorescence, biocompatibility, and ease of functionalization, make them excellent candidates for various labeling and imaging purposes in biological systems [30]. CQDs can be used as fluorescent probes for labeling and imaging cells, enabling researchers to visualize and track cellular structures and behaviors [31]. Functionalized CQDs can be designed to selectively label specific organelles within cells, providing insights into subcellular structures and dynamics. CQDs with appropriate surface modifications exhibit low toxicity and can be employed for in vivo imaging, facilitating non-invasive observation of biological processes [32]. CQDs can be functionalized to act as biosensors, allowing for the detection of specific biomolecules or analytes. Additionally, they can be utilized for diagnostic imaging. Surface functionalization of CQDs allows for the attachment of targeting ligands [33], enhancing their specificity for cancer cells and enabling selective labeling. CQDs can be used for labeling neurons and other neural structures, facilitating neuroimaging studies and providing insights into brain function. CQDs can be incorporated into multimodal imaging platforms, combining different imaging techniques such as fluorescence imaging,

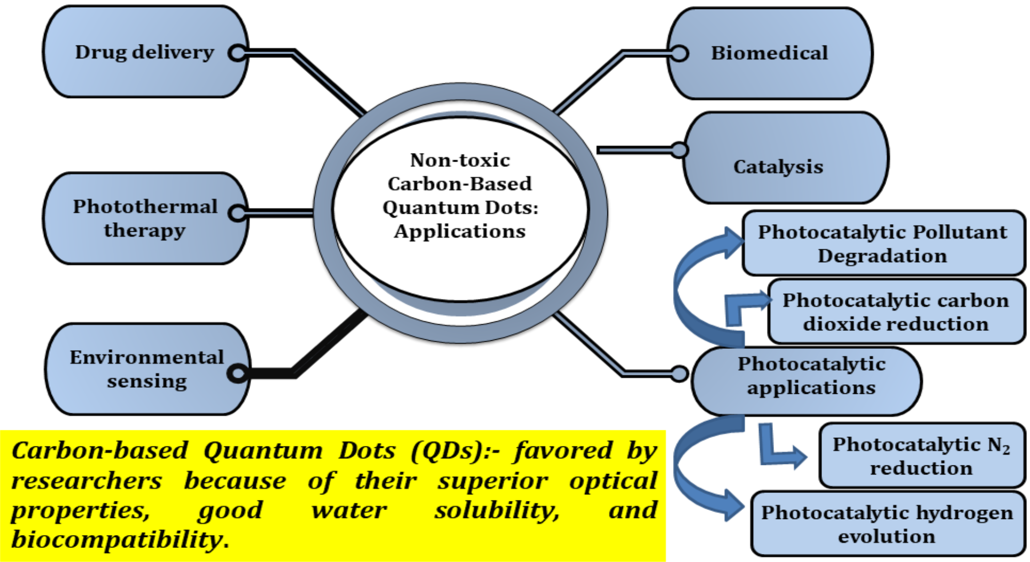


Fig. 4. Non-toxic Carbon-based quantum dots: applications.

magnetic resonance imaging (MRI), and computed tomography (CT). CQDs can be engineered to combine bio-labeling with therapeutic functionalities, allowing for simultaneous imaging and targeted drug delivery [34]. The versatility and biocompatibility of CQDs make them valuable tools for various bio-labeling applications, contributing to advances in cellular and molecular imaging, diagnostics, and targeted therapy. Ongoing research continues to explore novel functionalities and optimize CQD-based bio-labeling strategies.

2.1. Drug delivery.

Carbon quantum dots (CQDs) have gained significant attention in biomedical applications [35], particularly in the field of drug delivery. Their unique properties, such as biocompatibility, tunable fluorescence, and surface functionalization capabilities, make them promising candidates for various drug delivery strategies. CQDs can serve as carriers for various drugs, including small molecules and therapeutic biomolecules [36]. CQDs are generally considered biocompatible, with low toxicity, which is crucial for biomedical applications. Surface functionalization of CQDs allows for the attachment of targeting ligands, enabling specific delivery to diseased cells or tissues. The intrinsic fluorescence of CQDs can be utilized for imaging-guided drug delivery, providing real-time monitoring of drug release. CQDs can be engineered to respond to changes in pH or temperature, enabling controlled drug release in specific environments [34].

2.2. Photothermal therapy (PTT).

CQDs with photothermal properties can be used for combined drug delivery and photothermal therapy(PTT) for enhanced cancer treatment [37]. Carbon quantum dots (CQDs) have shown significant potential in biomedical applications, particularly in the field of photothermal therapy (PTT) [11]. The multifaceted nature of CQDs, combining photothermal properties with imaging capabilities and potential for targeted drug delivery, makes them promising candidates for advancing cancer therapy through photothermal treatment strategies [38]. Ongoing research in this area continues to explore new functionalities and optimize CQD-based photothermal therapy approaches.PTT involves the use of materials that can convert light into heat, leading to localized hyperthermia and targeted destruction of cancer cells. CQDs can serve as efficient photothermal agents due to their strong light absorption in the near-infrared (NIR) region [39]. The ability of CQDs to absorb NIR light allows for deeper tissue penetration, making them suitable for in vivo applications. Surface functionalization of CQDs enables the attachment of targeting ligands, enhancing their accumulation in cancer cells and enabling targeted PTT [40]. CQDs can be integrated with other therapeutic agents (chemotherapeutic drugs, photosensitizers) for synergistic combination therapies. The inherent fluorescence of CQDs allows for imaging-guided photothermal therapy, facilitating real-time monitoring of treatment [41]. CQDs can be part of multifunctional nanoplatforms that integrate imaging, drug delivery, and PTT for comprehensive cancer treatment. The non-invasive nature of PTT using CQDs makes it an attractive option for cancer therapy, minimizing damage to healthy tissues. CQDs can also be utilized for photothermal imaging, providing valuable information on the distribution and efficacy of PTT. CQDs can be functionalized to exhibit antibacterial properties, making them suitable for drug delivery in infections [42]. The versatility of CQDs in drug delivery applications highlights their potential in revolutionizing therapeutic strategies, providing targeted and controlled release of drugs with enhanced efficacy and reduced side effects [43]. Ongoing research in this area continues to explore novel functionalities and optimize CQD-based drug delivery systems.

2.3. Environmental sensing.

Non-toxic carbon quantum dots (CQDs) have demonstrated excellent potential for environmental sensing due to their unique optical properties, biocompatibility, and surface functionalization capabilities [44]. Here are several applications of non-toxic CQDs in environmental sensing. Non-toxic CQDs can be functionalized to selectively detect heavy metals in water and soil samples. Their fluorescence properties can be quenched or enhanced in the presence of specific heavy metal ions, providing a sensitive detection method. The surface chemistry of non-toxic CQDs can be modified to respond to changes in pH. This property makes them suitable for pH sensing applications in environmental monitoring and biological systems [44]. Non-toxic CQDs can be used for the detection of various water pollutants, including organic compounds and contaminants. Their tunable fluorescence allows for sensitive and selective monitoring of water quality. Non-toxic CQDs can be integrated into gas sensors to detect specific gases [45]. The interaction between gases and the CQDs may lead to changes in their optical properties, enabling gas sensing applications. The fluorescence emission of non-toxic CQDs can be sensitive to temperature changes. This property can be harnessed for temperature sensing applications in environmental monitoring. Non-toxic CQDs can be used to detect a wide range of environmental pollutants, including pesticides, dyes, and other organic contaminants [46]. The specificity of detection can be enhanced through surface functionalization. Non-toxic CQDs can be integrated into biosensors for the detection of specific biological or environmental markers. Their biocompatibility makes them suitable for interfacing with biological systems. Non-toxic CQDs can be applied to monitor soil conditions, including nutrient levels and soil pH. Their versatility allows for the development of sensors tailored to specific environmental parameters. Non-toxic CQDs hold great promise for advancing environmental sensing technologies, providing rapid, sensitive, and cost-effective solutions for monitoring various environmental parameters. Ongoing research in this field continues to explore novel applications and improve the performance of non-toxic CQD-based sensors [47].

2.4. Catalysis.

Non-toxic carbon quantum dots (CQDs) have shown promising applications in catalysis, contributing to advancements in various chemical processes. Their unique properties, such as high surface area, tunable surface chemistry, and catalytic activity, make them versatile candidates for catalytic applications [48]. Here are some notable applications of non-toxic CQDs in catalysis [49]. Non-toxic CQDs, particularly those with enhanced light absorption capabilities, can be employed in photocatalytic reactions [50]. They generate electron-hole pairs upon light absorption, facilitating various chemical transformations. Non-toxic CQDs can serve as efficient electrocatalysts in fuel cells and other electrochemical devices [51]. They can facilitate the electrochemical conversion of various substances, such as oxygen reduction reactions (ORR) and hydrogen evolution reactions (HER) [52]. Non-toxic CQDs can function as metal-free catalysts, providing an alternative to traditional metal-based catalysts [53]. They have been explored in reactions such as the reduction of nitro compounds and oxidation reactions. CQDs can be used as heterogeneous catalysts for various chemical reactions, offering advantages such as easy separation from reaction mixtures and potential reusability. Non-toxic CQDs have been explored in the catalytic conversion of biomass feedstocks [54], facilitating the production of valuable chemicals and biofuels. CQDs can play a role in environmental remediation by catalyzing the degradation of pollutants in air and water, contributing to the treatment of wastewater and air purification [55]. Sulfur-doped CQDs exhibit improved catalytic activity, and they have been explored in reactions such as oxygen reduction reactions (ORR) and hydrogen evolution reactions (HER) [56]. CQDs can act as redox catalysts in various reactions, including oxidation and reduction processes, providing a sustainable and environmentally friendly approach to catalysis. The diverse catalytic applications of non-toxic CQDs highlight their potential in promoting more sustainable and efficient chemical processes. Ongoing research in this field aims to further understand and optimize the catalytic properties of CQDs for a wide range of applications [57].

2.5. Photocatalytic applications.

Non-toxic carbon-based quantum dots are found to be excellent photocatalysts (Fig. 5) for reduction of CO_2 in the atmosphere [58], degrading the hazardous pollutant [59], production of hydrogen (H_2) [60] as well as nitrogen reduction [61] by the virtue of their up-conversion phenomenon, quantum confinement and boundary effects due to which they possess phenomenal optical properties.

2.6a. Photocatalytic carbon dioxide reduction.

The latest approach to addressing the energy crisis involves utilizing non-toxic carbon-based quantum dots for the photocatalytic reduction of CO_2 into energy fuels. Recently developed phosphorus-doped graphitic carbon nitride quantum dots (g-CNQDs) have emerged as promising catalysts for this purpose [62]. The optical properties of g-CNQDs, spanning from 400 nm to the near-infrared range, significantly enhance parameters such as band gap narrowing and photocatalytic activity [63]. Researchers have explored the potential of these quantum dots by incorporating them into m-CeO_2-modified CNQDs. This modification enhances the photoelectronic response by facilitating the excitation of more oxygen vacancies within the heterostructure, thus increasing CO_2 adsorption and electron photoreduction.

Taking advantage of CNQDs' ability in carrier separation, light energy utilization, and electron transport, novel composites have been developed by combining CNQDs with gold nanoparticles, co-modified with CeO_2/Fe_3O_4 to create highly active photocatalysts [64]. Zeng et al. have demonstrated a significant enhancement in photocatalytic CO_2 reduction activity by heterogeneously coupling Ti_3C_2 quantum dots (TCQDs) with Cu_2O nanowires [65]. This enhancement can be attributed to improved promotion and separation of photogenerated charges, as well as a reduction in band bending edge [66].

Moreover, derivatives of MXenes, known as MQDs, have shown promise in photocatalytic CO_2 reduction [67,68]. He et al. have reported on a $TiO_2/C_3N_4/Ti_3C_2$MXene heterojunction structure with improved stability compared to single precursor catalysts, underscoring the importance of TCQDs in enhancing photocatalytic activity [69]. Furthermore, doping TCQDs with biocompatible 3d transition metals has demonstrated a synergistic effect, resulting in QD modifications with

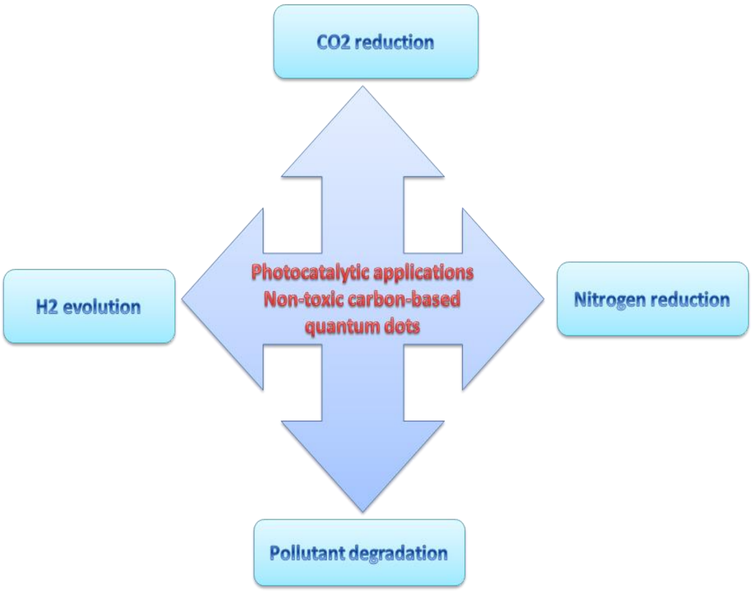


Fig. 5. Photocatalytic applications non-toxic carbon-based quantum dots.

superior light utilization and efficient carrier separation and transfer capabilities, thereby improving CO_2 reduction to CO [70].

2.6b. Photocatalytic pollutant degradation.

A core challenge in photocatalysis revolves around the degradation of organic pollutants in aquatic environments. Graphene quantum dots (GQDs) stand out as primary materials employed for this purpose [71]. GQDs enhance the photocatalytic performance of catalysts by modifying various heterojunctions, thereby reducing electron-hole recombination [72]. Additionally, carbon nitride quantum dots (CNQDs) find widespread use in the photocatalytic degradation of organic compounds. Loaded CNQDs, boasting increased specific surface area and expanded light absorption range, demonstrate superior performance [73].

Che and colleagues have demonstrated the remarkable photocatalytic degradation activity of Z-type g-C_3N_4/Bi_2WO_6 heterojunction, effectively removing various antibiotics such as tetracycline, ciprofloxacin, and oxytetracycline [74]. Yan et al. prepared nitrogen-doped GQDs and elucidated the influence of chemical composition on photocatalytic degradation, highlighting their role in accelerating carrier separation and achieving high degradation activity [75].

Lin et al. reported on the photo-catalytic activity of a hybrid of g-C_3N_4 quantum dots and TiO_2, capable of capturing visible light and delaying the recombination of photogenerated electron-hole pairs for degradation under visible light irradiation [76]. Li reported significant photo-catalytic degradation facilitated by the CNQD/$BiVO_4$ composite, attributing it to enhanced specific surface area, directional charge transfer, and accelerated carrier separation efficiency resulting from CNQD introduction [77].

Zhao's composite material CNQD/FeOOH exhibited highly efficient photo-Fenton effect in degrading organic pollutants, thereby enhancing photocatalytic efficacy [78]. In addition to GQDs and CNQDs, MXenes quantum dots (MQDs) are also reported as suitable for photocatalytic pollutant degradation. Wang reported on coupling Ti_3C_2 quantum dots onto SiC material, resulting in significant improvement in carrier separation efficiency, attributed to enhanced photocatalytic degradation rate through the generation of superoxide radicals [79].

These advancements in non-toxic carbon-based quantum dots, which efficiently convert solar energy into chemical energy, hold great promise for photocatalytic pollutant degradation and contribute significantly to environmental remediation efforts.

3.6c. Photocatalytic hydrogen evolution (PHE).

Non-toxic carbon-based quantum dots (QDs) hold significant promise in photoelectrochemical (PHE) applications [80-81]. For instance, Zou et al. introduced a series of innovative N-GQD/g-C3N4 photocatalysts, among which sample 15N-CNU exhibited the highest photocatalytic hydrogen evolution rate, nearly double that of the initial g-C_3N_4[82]. Gliniak et al. developed metal-free and cost-effective S-GQDs with the highest hydrogen production rate among carbon-based QDs [83].

Wang et al. reported on boron-doped g-C_3N_4 QDs (BCNQDs), noting that the PHE efficiency of the g-C_3N_4/BCNQD heterojunction significantly surpassed that of BCNQDs alone, attributed to boron doping's role in narrowing energy bands, enhancing charge separation, and promoting transfer efficiency [84]. Zheng et al. showcased the outstanding electrocatalytic hydrogen evolution reduction activity of Ti_2CT_x MQDs for alkaline electrocatalytic hydrogen evolution, facilitated by the adsorption and dissociation of H_2O molecules promoted by charge transfer at the MQDs-Cu_2O interface [85].

Kong et al., using density functional theory, illustrated slight distortion post-hybridization of graphene with QDs, altering the electronic structure of QDs [86]. The Z-scheme Ti-MOF/QD/ZIS photocatalyst achieved a high hydrogen production rate, with the Ti-MOF/QD/ZIS composite photocatalyst demonstrating high stability in cycling tests [87]. The remarkable enhancement in PHE rate is attributed to the synergistic effect of flower-shaped microspheres, amorphous Ti(IV), and active sites of MQDs[88].

This research demonstrates that MQDs outperform NGQDs by about three times and BCNQDs by two times, offering a novel approach to efficient photocatalysts leveraging surface-induced effects and expanding possibilities for practical applications of non-toxic carbon-based QD photocatalysis technology.

3.6d. Photocatalytic N_2 reduction.

The extensive utilization of ammonia in industries and agricultural sectors has propelled the conversion of nitrogen into ammonia, a process further facilitated by the environmentally friendly nature of nitrogen and efficient photocatalytic reduction of N_2. Qin and colleagues introduced a non-toxic carbon-based quantum dots (QDs) Ti_3C_2 QD/Ni-MOF heterostructure, demonstrating a notably high product yield [89]. Gao et al. developed a catalyst to enhance the resolution ability of ammonia, marking the first instance of promoting the process of photocatalytic N_2 reduction—an undoubtedly significant advancement in the realm of carbon-based QD photocatalytic nitrogen reduction [90].

Numerous such studies underscore the significant growth potential of non-toxic carbon-based QDs in the field of photocatalysis [91-92]. With continued scientific advancements, there is little doubt that non-toxic carbon-based QDs will exhibit broad application prospects in the near future.

Following table shows the Photocatalytic CO_2 reduction efficiency, Photocatalytic pollutant degradation efficiency, Photocatalytic hydrogen vvolution efficiency and Photocatalytic N_2 reduction efficiency of various carbon-based quantum dots.

Conclusion

In conclusion, the review of non-toxic carbon quantum dots (CQDs) underscores their remarkable potential in diverse fields, from biomedical applications to environmental sensing and catalysis. The advancements in non-toxic CQD research have demonstrated their unique properties, such as tunable fluorescence, biocompatibility, and surface functionalization, making them versatile

Table 1.

Photocatalytic properties of various carbon-based quantum dots

Carbon-based Quantum Dot	Photocatalytic CO_2 Reduction Efficiency	Photocatalytic Pollutant Degradation Efficiency	Photocatalytic Hydrogen Evolution Efficiency	Photocatalytic N2 Reduction Efficiency
Graphene Quantum Dots[93]	High	High	High	Moderate-High
Carbon Nitride Quantum Dots [94]	Moderate-High	Moderate-High	Moderate-High	Moderate
Carbon Quantum Dots[95]	Moderate	Moderate	Moderate	Moderate
Nitrogen-doped Carbon Dots [96]	High	High	High	High

materials for various applications. Addressing the challenges in non-toxic CQD research, including achieving precise control over synthesis, understanding their long-term toxicity, and optimizing their performance in specific applications, remains an ongoing endeavor. Researchers have made significant strides in developing green synthesis methods, enhancing their stability, and expanding their functionalities. The investigation of toxicity profiles and biodegradability is crucial for ensuring their safe use in biomedical and environmental applications. Looking forward, the future directions for non-toxic CQDs involve their integration into sustainable and innovative technologies. In the biomedical realm, non-toxic CQDs hold promise for advancing drug delivery systems, bio-imaging, and theranostics. Further exploration of their interaction with biological systems and the development of targeted delivery strategies are avenues for future research.

In environmental applications, non-toxic CQDs offer solutions for sensing and catalysis, contributing to the development of efficient sensors, catalysts, and remediation methods. Their use in renewable energy technologies, such as photovoltaics and photocatalysis, could pave the way for sustainable energy solutions.

To fully harness the potential of non-toxic CQDs, interdisciplinary collaboration between researchers in chemistry, biology, materials science, and engineering is essential. Standardization of synthesis protocols, toxicity assessment methods, and evaluation criteria will facilitate comparison and reproducibility of results across studies.

In summary, the advancements in non-toxic CQD research have laid a foundation for their integration into sustainable and innovative technologies. Addressing current challenges and exploring new avenues for utilization will propel non-toxic CQDs towards practical applications, contributing to the development of solutions for pressing global challenges in healthcare, environment, and energy. As research in this field progresses, non-toxic CQDs are poised to play a pivotal role in shaping the future of materials science and technology.

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Повідомлення про новітні результати. Огляд нетоксичних квантових точок на основі вуглецю: синтез, унікальні властивості та широкий спектр застосування

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Вуглецеві квантові точки (ВКТ) є перспективною категорієюнаноматеріалів завдяки своїм відмінним оптичним, електронним і хімічним характеристикам. У цьому огляді розглядаються методики синтезу нетоксичних ВКТ, з особливим наголосом на екологічно чистих підходах, які мінімізують вплив на навколишнє середовище. Обговорення охоплює їх широке застосування у різних сферах, підкреслюючи роль у розширенні меж сталого розвитку. Примітно, що огляд пояснює оптичні властивості нетоксичних ВКТ, вказуючи на їх регульовану флуоресценцію, особливість, яка робить такі об’єкти безцінними для застосування в біовізуалізації, датчиках та оптоелектронних пристроях. Крім того, їх нетоксична природа є ключовою для біомедичних застосувань, сприяючи прогресу в доставці ліків, фототермічній терапії та біомаркуванні. На додаток до біомедичного потенціалу, цей огляд заглиблюється в корисність нетоксичних ВКТу зондуванні навколишнього середовища та каталізі, демонструючи їх адаптивність і багатофункціональність. Завдяки глибокому вивченню останніх досягнень, викликів і майбутніх перспектив, цей огляд має на меті надати безцінне уявлення про зростаючу сферу досліджень нетоксичнихВКТ, що сприяє розвитку стійких та інноваційних технологій.

Ключові слова: вуглецеві нетоксичні квантові точки, синтез, широкий спектр застосування.