

Photocatalysis and electrocatalysis enhanced with carbon quantum dots

Jiko Raut and Prithidipa Sahoo*

Department of Chemistry, Visva-Bharati University, Santiniketan-731235, India

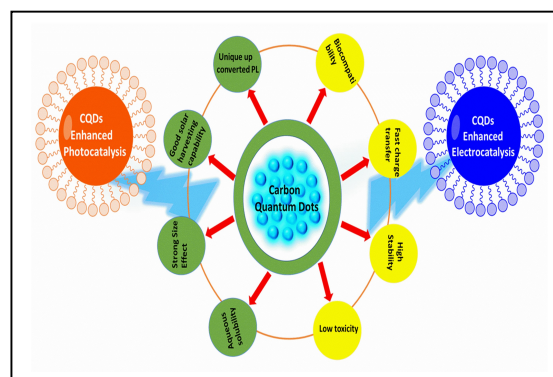
Email: prithidipa.sahoo@visva-bharati.ac.in

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Abstract

Researchers have been sufficiently interested in carbon quantum dots (CQDs), a novel type of nanocarbon material that has potential in the areas of biological imaging, fluorescence sensing, solar cells, drug transport, biomedicine, and catalysis. Excellent physical and chemical characteristics, including high crystallization, good dispersibility, and photoluminescence capabilities, are displayed by CQDs. The CQDs-based composite is especially well-suited for use in photocatalysis and electrocatalysis due to its small size, superconductivity, high tunable photoluminescent, capacity for solar harvesting, and quick charge transfer. The majority of current investigations on CQDs have solely examined their fluorescence characteristics and photocatalytic activities. This review will summarize the major developments of CQDs in terms of synthetic techniques, characteristics, and applications in both photocatalysis and electrocatalysis.

Keywords: Carbon quantum dots, catalytic properties of carbon quantum dots, photocatalysis, electrocatalysis, doped carbon quantum dots



1. Introduction

Small semiconductor particles known as quantum dots are only a few nanometers in size, which makes them different from bulk materials in terms of their optical and electrical characteristics. Semiconductor nanocrystals with physical dimensions less than the Bohr exciton radius are among the QDs that have received substantial research interest.¹ Regardless of the fact that quantum confinement can have a variety of impacts, particularly in relation to photoinduced redox processes, the term "quantum dot" is most frequently used in the literature to refer to the nanoscale objects that exhibit size-dependent multicolor fluorescence emissions.

Due to their remarkable benefits, including strong optical absorptivity, bio-compatibility, chemical stability, and low toxicity, fluorescent carbon-based materials have attracted more and more interest in recent years.² Carbon dots (CDs), carbon nano-tubes, fullerene, nanodiamonds, and fluorescent graphene are the main components of these substances. Among these, carbon quantum dots (CQDs) were originally identified in 2004 while single-walled carbon nanotubes were being purified.³ Carbon quantum dots (C-dots, CDs, or CQDs) are tiny carbon nanoparticles, usually in the range of 1 to 10 nm in size. Their cores are sp² conjugated and sufficiently oxygen-rich to take the forms of several oxygen-containing species, such as hydroxyl, carboxyl, and aldehyde groups.⁴

These materials can be made luminous by carefully adjusting their size and surface chemical groups to tune the electrical structures. The need for surface passivation in order to become photoluminescent made it possible to argue mechanically that the PL from carbon dots may be attributable to surface energy traps that became emissive after stabilization as a result of surface passivation. Brighter fluorescence emissions of carbon dots were shown to be more effectively produced by successful surface passivation, functionalization with polymers or organic molecules, or chemical modification.

The method that is most frequently employed for surface passivation to modify the Photoluminescent characteristics of fluorescent compounds is doping. The most researched method for improving CQD emission is N-doping, S-doping, or metal ion doping which results in an increase in the Fermi level and the number of electrons in the conduction band.⁵ N-doping/S-doping in CQDs is an effective way to change the properties of the material for particular uses, such as fuel cells high-performance supercapacitors, energy-storage devices, ferromagnetic materials, and catalysis. Because of the surface passivation, CQDs not only inherit superior optical properties but also outperform the biohazards and cytotoxicity limitations of conventional semiconductor quantum dots. They have numerous uses in the areas of disease detection, biosensing, bioimaging, and catalysis.^[6-13] Since the discovery of CQDs, many advancements in the

synthesis and its implementation have been made in different fields of applications.

Using the advantages of CQDs as superior photocatalysts and electrocatalysts in comparison to other materials, we will summarise the surface functionalization or passivation techniques to enhance CQDs fluorescence and their application in photocatalysis & electrocatalysis in this review. Despite recent research on the catalytic properties of CQDs, there aren't any publications that particularly discuss the use of CQDs in both photocatalysis and electrocatalysis simultaneously. After that, we go into extensive detail about how CQDs are used in various photocatalytic and electrocatalytic processes.

2. Properties

2.1. Structure

The structures and components of the CQDs determine a variety of attributes. The CQDs' surface's many carboxyl moieties offer high water solubility and biocompatibility. CQDs can also be chemically altered or have their surfaces passivated using a variety of inorganic, organic, biological or polymeric materials. The physical and fluorescence nature of CQDs was enhanced by surface passivation. The ability of CQDs to create tricolor when exposed to diverse pH environments has just been discovered (green, yellow & red).

2.2. Surface Passivation

CQDs have optoelectronic capabilities similar to those of conventional inorganic semiconductors, but they are benign to the environment. They have intricate architectures, and particles as small as 10 nm, and their optoelectronic properties are significantly adjusted and improved by surface passivation and/or functionalization. Both carbon nanodots have remarkable tunable photoluminescence (PL) features that result from quantum confinement processes. Although sufficiently stable aqueous or other solutions of carbon nanoparticles without intentional surface functionalization may also produce fluorescence, the quantum yield (QY) of bare carbon dots is modest (usually 10%) because of the emissive traps on the surface. Therefore, a surface passivation layer is required to increase their stability, long lifespan, and PL. As long as they don't contain visible or near-UV chromophores and are thus non-emissive at visible wavelengths, a variety of organic molecules or polymers have been employed as surface passivation agents. This preserves the observed vibrant luminescence emissions of the passivated CQDs. ^[14-16]

In order to enhance the luminescence, Sun et al. created surface-passivated CQDs with diamine-terminated oligomeric poly-(ethylene glycol). Since then, numerous works using these techniques with minor modifications have been produced. Craciun *et al.* create water-soluble photoluminescent CDs with remarkable physicochemical features by passivating carboxylated carbon nanoparticles surface with p-phenylenediamine.¹⁷ The following passivation agents are widely employed in literature, in brief: 4,7,10-

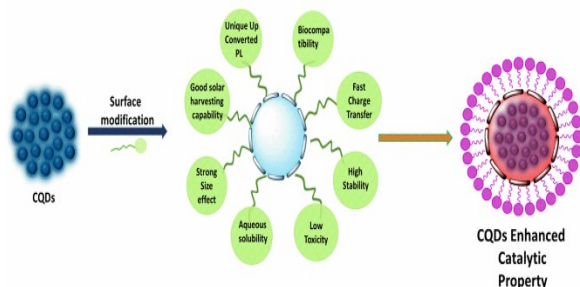
trioxa-1,13-tridecanediamine,^{18,19} poly(ethylenimine)- b-poly(ethylene glycol)-b-poly(ethylenimine) and 4-arm amine terminated PEG²⁰ and PEI²¹.

Surface passivation, which adds functional groups like amines in addition to coating CQDs with a protective layer to promote stability, can be thought of in some ways as a sort of surface functionalization. For instance, the surface passivation of CQDs²² with the addition of amine groups on the surface is equivalent to the surface functionalization of CQDs with PEI and BPEI.²³ At this point, it is evident that the surface functionalization and passivation of CQDs share plenty of similarities in terms of the chemicals, techniques, etc., making these two modification processes almost identical. In order to mitigate the effects of trap sites, surface-attached flaws, and immediate quenching by the environment, all of which are responsible for increasing fluorescence emission, surface passivation creates a protective covering encasing the particles. On the other hand, surface functionalization seeks to introduce different functional groups for a specific chemical or biological reactivity or to generally improve the optoelectronic capabilities of CQDs.

The doped CQDs have broad and strong absorption peaks at 200 and 600 nm, and some of them have distinctive peaks at around 225 nm and 325 nm due to the $\pi-\pi^*$ and $n-\pi^*$ transitions. The absorption/emission of CQDs can be tuned from UV to UV-NIR by changing the doping species. Additionally, under 365 nm UV light, doped CQDs produce a variety of fluorescence, including green, blue-green, blue, yellow, and red due to their broad range of excitation and emission. CQDs also exhibit both excited-dependent and excited-independent PL behaviors, depending on doping. It was shown that the emission peaks produced by doped CQDs significantly redshifted as the excitation wavelength changed from 290 to 490 nm and from 320 to 400 nm, respectively, with a decrease in intensity in the case of excited-dependent PL behavior.

2.3. Surface Functionalization

An innovative method for creating new features on CQDs is surface functionalization. In the past few years, numerous approaches for surface functionalization have been discovered. Hu *et al.* worked using direct laser irradiation of graphite powder within various organic solvents, including diamine hydrate, diethanolamine, or PEG200N-amine-terminated poly-ethylene glycol oligomers with an average molecular weight of 200, while being ultrasonically stirred was one of the representative one-pot syntheses of carbon dots.²⁴ Zhaogan *et al.* designed hydroxyl functionalized CDs by utilizing ethylene glycol to improve the Fluorescence intensity and detection sensitivity.²⁵ Chi's group used a low-temperature mediated bottom-up technique to develop Polyamine-functionalized carbon quantum dots which improve quantum yield.²⁶ Similarly, Yongqiang *et al.* developed polyamine-functionalized carbon quantum dots which improve CQDs detection sensitivity.²⁷



Scheme 1. Schematic diagram of surface-modified CQDs with enhanced catalytic properties.

3. Catalytic properties of Carbon dots

3. 1. Photocatalysis property of C-dots

In Chemistry, Photocatalysis is the acceleration of a photoreaction in the presence of a catalyst. It is an environmentally friendly method that is frequently used in the solar water splitting and environmental remediation industries. The knowledge that solar light is an infinite source of energy has contributed to the interest in photocatalysis.^[28-30] In this context, a photocatalyst is regarded as excellent if it can capture solar energy from the visible and/or near-infrared spectrum. However, as of now, current photocatalytic systems have not yet properly utilized near-infrared (NIR) and infrared (IR) light with long wavelengths. Carbon Quantum dots (CQDs) own many good features, such as good biocompatibility, low toxicity, strong size effect, high aqueous solubility, unique up-converted photoluminescence (PL) behavior, and photo-induced electron transfer property, which indicate that Carbon quantum dots (CQDs) can act as an efficient component in the design of photocatalyst. This section provides a summary of photocatalyst systems based on CQDs.

Yu *et al.* (2012) created a simple solvent-thermal approach in an aqueous solution for the successful preparation of carbon quantum dots (CQDs) and mesoporous hematite (MH) (α - Fe_2O_3) photocatalysts. The presence of mesostructured α - Fe_2O_3 clusters, featuring an extensive surface area and a porous framework, played a pivotal role in shaping the design of the photocatalysts. These structures were instrumental in promoting photon absorption and catalyzing the breakdown of organic contaminants. The photocatalytic activity of the nanocomposite was investigated by using methylene blue (MB). When exposed to visible light, the absorption spectra of MB for MH, MH + H_2O_2 , and CQD/MH solution all significantly decreased from 664 nm, but not for CQD/MH + H_2O_2 solution, suggesting that MB underwent photocatalytic degradation. Mesoporous α - Fe_2O_3 embedded in CQDs demonstrated outstanding photocatalytic performance remarkably increasing the degradation rate up to 97% after three cycles, for the destruction of organic molecules in aqueous conditions, whereas only 56.2 % degradation efficiency was found when assisted with MH + H_2O_2 . More notably, the CQDs in this catalyst are essential for enhancing the photocatalytic activity when exposed to visible light. In

addition to providing more active sites for breaking down MB molecules, the porous structure and wide surface area of the material also effectively facilitate the separation of electron-hole ($e^- - h^+$) pairs.³¹

Through a hydrothermal reaction, Yu *et al.* (2012) fabricated nanocomposites consisting of ZnO and carbon quantum dots (ZnO/CQDs). Remarkably, these nanocomposites proved to be highly efficient photocatalysts for the degradation of noxious gases such as methanol and benzene under visible light exposure at room temperature. The findings demonstrate that these nanocomposites when compared to N-TiO₂ and pure ZnO nanoparticles, display superior photocatalytic activity (degradation efficiency above 80%, 24h). Figure 1 elegantly exemplifies the substantial enhancement in the photocatalytic process of the ZnO/CQD nanocomposites within the present catalyst system, highlighting the indispensable role played by CQDs in these improvements. In order to excite ZnO and produce electron-hole pairs, CQDs exhibit the capability to absorb light with longer wavelengths (above 600 nm) and subsequently emit light with shorter wavelengths (below 400 nm). Subsequently, electron-hole pairs have the capacity to interact with adsorbed oxidants/reducers, often involving O_2 and OH^- to generate a significant quantity of active oxygen radicals with strong oxidation capabilities (for example, O_2^- and $\cdot\text{OH}$ leading to the breakdown of hazardous gas.³²

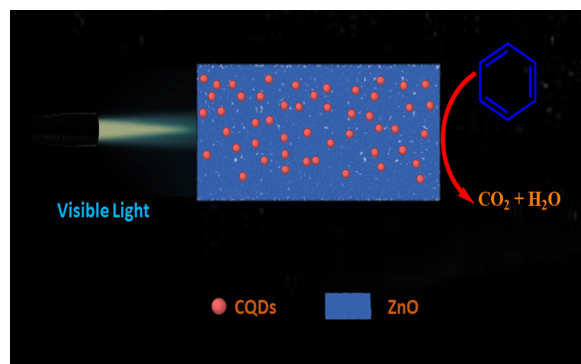


Figure 1. Proposed mechanism for the improvement of photocatalytic activity of the ZnO/CQD nanocomposites.

Kang *et al.* (2013) engineered a highly efficient near-infrared (NIR) light-triggered photocatalyst tailored for the discerning oxidation of benzyl alcohol to benzaldehyde in the presence of H_2O_2 .³³ using an alkali-assisted electrochemical technique, yielding CQDs with diameters of 1-4 nm. The selectivity and conversion efficiency of benzyl alcohol oxidation catalyzed by CQDs can increase to 92% and 100%, respectively, after 12 hours of NIR light exposure. They postulated the subsequent mechanism governing the photocatalytic oxidation of benzyl alcohol to benzaldehyde by CQDs under near-infrared (NIR) light, as illustrated in Figure 2.

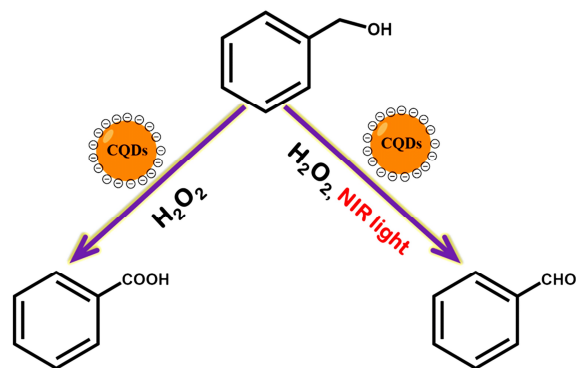


Figure 2. The process of benzyl alcohol selectively oxidizing to benzaldehyde in the presence of CQDs while being exposed to NIR light.

On CQDs, H_2O_2 molecules are adsorbed, and these molecules break down into active oxygen species (HO^\cdot), thereby enabling the oxidation of benzyl alcohol, resulting in the formation of benzaldehyde or benzoic acid. Additionally, the catalytic process is significantly improved by the π - π interaction that takes place between CQDs and benzaldehyde or benzyl alcohol. Only a minor amount of benzaldehyde is formed as the principal catalytic product in the absence of NIR irradiation, indicating that benzoic acid is produced initially by the oxidation of benzyl alcohol before it is further oxidized into benzaldehyde. Notably, the photoinduced electron transfer capability of CQDs serves to inhibit the additional oxidation of the initially formed benzaldehyde within the photo-electron reductive environment, thus resulting in exceptional selectivity (100%) exclusively towards benzaldehyde when exposed to NIR light excitation. Bi_2MoO_6 photocatalysts enhanced with carbon quantum dots (CQDs) were produced by Di *et al.* (2015) using an easy hydrothermal procedure. The photodegradation of four various types of pollutants, including tetracycline hydrochloride (TC), bisphenol A (BPA), ciprofloxacin (CIP), and methylene blue (MB), was sufficient for the evaluation of the photocatalytic effectiveness of the prepared CQD modified Bi_2MoO_6 materials. Enhancing light harvesting, enhancing interfacial charge transfer, suppressing charge recombination, and increasing the number of active adsorption sites and photocatalytic reaction centers are only a few benefits of the CQDs modification. In comparison to pure Bi_2MoO_6 , CQD-modified Bi_2MoO_6 samples exhibited a substantial enhancement in photocatalytic activity when subjected to visible light. Notably, the optimal photocatalytic performance saw an increase of nearly fivefold compared to that of pure Bi_2MoO_6 for the photodegradation of CIP in the CQD-modified Bi_2MoO_6 photocatalysts containing 2 wt% CQDs. It was ascertained that $\cdot\text{OH}$ and $\text{O}^{\cdot-}$ were the principal reactive species. Based on the findings of the experiment, a potential photocatalytic mechanism is suggested in Figure 3.³⁴

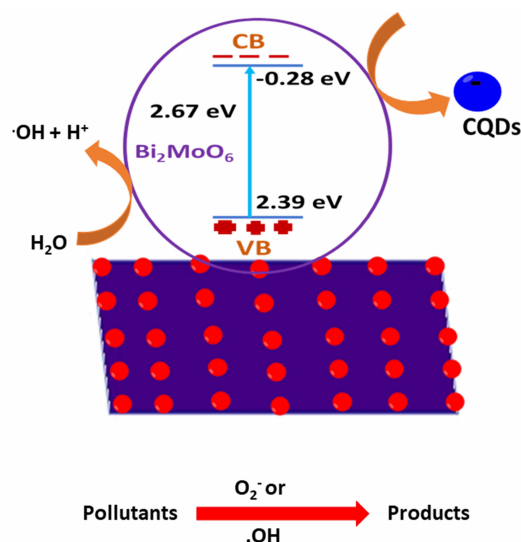


Figure 3. Proposed mechanism of possible photocatalytic activity.

A CQDs/hydrogenated TiO_2 (H- TiO_2) nanobelt heterostructure with broad-spectrum active photocatalytic properties was developed by Tian *et al.* (2015). The enhanced charge carrier entrapment, optical absorption, and suppression of photogenerated electron-hole recombination of oxygen vacancies and Ti^{3+} ions in hydrogenated TiO_2 nanobelts collectively contribute to the augmented UV and visible photocatalytic performance. Since CQDs possess the capability to absorb NIR light, convert it into visible light, and subsequently transfer this visible light to the photoactive H- TiO_2 nanobelts, they exhibit electron storage, photoinduced electron transfer, and up-converted PL properties. The formation of CQDs/H- TiO_2 heterostructures occurs when CQDs adhere to the H- TiO_2 nanobelts. By facilitating the separation of photogenerated holes and electrons, the heterostructure can improve photocatalytic activities. Because of their bigger surface area and more coarsened surface, the CQDs/H- TiO_2 heterostructures are more able to absorb pollutants. These pollutant molecules can be directly degraded by photoinduced electrons and holes, which enhances photocatalytic capabilities. As a result of up-conversion, CQDs may absorb NIR light (>700 nm) and then emit light with lower wavelengths (390–564 nm). This up-conversion then stimulates the H- TiO_2 nanobelt to produce electron/hole (e^- / h^+) pairs. Therefore, the NIR photocatalytic activities of the CQDs/H- TiO_2 heterostructures are caused by the up-converted PL behavior of CQDs. These properties are what give CQDs their NIR photocatalytic activity.³⁵

Du *et al.* (2017) synthesized Cu-doped carbon quantum dots by employing a hydrothermal process utilizing the precursors ethylenediaminetetraacetic acid disodium salt dihydrate (EDTA) and $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$. Additionally, they extensively investigated the catalytic activity and its role as a fluorescence indicator during the catalytic process, utilizing p-nitrophenol reduction as a reference reaction. The results unveiled a notable catalytic activity in the p-nitrophenol hydrogenation reaction, characterized by a pseudo-first-order

rate constant of $1.2 \times 10^{-2} \text{ s}^{-1}$. The observed catalytic activity can likely be attributed to a synergistic interplay between the remarkably efficient catalytic properties of copper and the electron-enhancing effects stemming from the graphite-like CDs.³⁶

Bhati *et al.* (2018) successfully engineered eco-friendly red-emitting magnesium nitrogen-embedded carbon dots (r-Mg-N-CD) using an extract of Bougainvillea leaves. Photoluminescence (PL) measurements revealed that r-Mg-N-CD exhibited excitation-independent emissions at 678 nm, robust photostability, and a notably high quantum yield of 40%. As a cost-effective photocatalyst, r-Mg-N-CD was employed for the photodegradation of methylene blue (MB), a polluting dye, in an aqueous medium. Under artificial visible light from a tungsten bulb, the photodegradation process required approximately 120 minutes, while under sunlight, it proceeded almost six times faster. The calculated band gap of r-MG-MN-CD from Tauc's plot is 1.45 eV, but when exposed to a 100 W light bulb and sunlight, their values reduced to 1.42 eV and 1.38 eV, respectively. This demonstrates how the photocatalytic process for MB degradation was boosted by the decrease in the band gap, especially towards an effective visible light range.³⁷

Guo *et al.* (2018) prepared Nitrogen and Phosphorous co-doped carbon quantum dots (NP-CQDs) by using Citric acid and phosphorylethanolamine as a resource of nitrogen and phosphorus by simple heat treatment. As per the analysis conducted using photoluminescence (PL) spectroscopy, NP-CQDs solution exhibits robust emission of a vibrant blue-green light with a peak wavelength at 475 nm when subjected to 365 nm light irradiation. The NP-CQDs showed excellent photostability, a quantum yield of 8.45%, and great stability in saline environments. Under artificial sunlight, methylene blue (MB) was degraded using the NP-CQDs/TiO₂ nanocomposite as a photocatalyst. In comparison to pure TiO₂, the degradation time of the NP-CQDs/TiO₂ nanocomposite was 15 min. The separation of photoexcited electron-hole pairs and the accelerated carrier migration made possible by NP-CQDs may be the causes of the NP-CQDs' extremely high photocatalytic activity.³⁸

Peng *et al.* (2020) used citric acid, 1, 2-diboranyl ethane, and anhydrous dimethylformamide in a hydrothermal process to create B-doped carbon dots. According to photoluminescence (PL) measurements, the B-doped carbon dots exhibited excitation-dependent emission characteristics, with the peak emission occurring at 450 nm when the excitation wavelength was set to 360 nm. Under the influence of visible light, methylene blue (MB) and rhodamine B (RhB) were degraded using the B-doped C-dots as photocatalysts. In 170 minutes, MB and RhB had entirely broken down. MB and RhB degradation had rate constants of $2.4 \times 10^{-2} \text{ min}^{-1}$ and 1.8×10^{-2} , respectively. In comparison to alternative C-dot photocatalysts and photocatalysts containing metals, the B-doped C-dots exhibited commendable photocatalytic performance.³⁹

By employing palm powders and the hydrothermal procedure, Zhu *et al.* (2020) created S, Cl co-doped biomass-based CDs (Bio-CDs). Bio-CDs displayed excitation-dependent blue fluorescence, with the peak emission observed at 425 nm when excited at 340 nm, according to photoluminescence (PL) spectroscopic measurements. Rhodamine B (RhB) and methylene blue (MB) were degraded using the Bio-CDs as photocatalysts when exposed to visible light. High RhB and MB degrading efficiency was demonstrated by the Bio-CDs, at 71.7% and 94.2%, respectively. Because of the quantum confinement effect and S/Cl co-doping, the photocatalytic activity was outstanding. The presence of S and Cl-related groups led to the creation of a multitude of distinctive defect states, where the efficient separation of electrons from holes and their return to the ground state occurred through diverse radiative recombination pathways. When exposed to visible light, Bio-CDs' electron-hole pair combinations will be somewhat delayed, increasing the number of free electrons on their surfaces, which can then interact with adsorbed oxidants (often O₂) to produce active oxygen radicals. The remaining holes may also be able to produce hydroxyl radicals by oxidizing water and hydroxyl groups that have been absorbed from the surface. As a consequence, the hydroxyl radicals and holes produced on the surface of Bio-CDs have the ability to interact with the dye molecules causing the dye molecules to break down into smaller hydrocarbons. Additionally, tiny Bio-CDs, which have a wide surface area and a low likelihood of absorbing contaminated dyes before being exposed to visible light, nonetheless retain a high degree of catalytic activity.⁴⁰

Using tetrabutyl titanate (TBT) and urea, Ouyang *et al.* (2020) created a nitrogen-doped carbon quantum dots/TiO₂ (N-CDs/TiO₂) composite through hydrothermal processing. As the N-CDs content rose, the emission intensity increased, as shown by the photoluminescence (PL) spectra. Rhodamine B (RhB) was degraded using the N-CDs/TiO₂ composite as a photocatalyst under visible light. RhB was broken down by N-CDs/TiO₂ in 120 minutes, which was 11.42 times faster than pure TiO₂. Further experimentation was conducted by introducing specific radical trapping agents into the reactant solution prior to subjecting it to light irradiation, with the aim of gaining deeper insights into the catalytic mechanism. The OH scavengers tert-butanol (TBA), O₂⁻ radicals scavengers benzoquinone (BQ) as well as the electron and hole trapping properties of EDTA-2Na and AgNO₃ are well known. When benzoquinone (BQ) or EDTA-2Na were introduced to the reaction system under visible-light irradiation, the RhB degradation was dramatically reduced. However, photoactivity was unaffected by other radical scavengers. This suggested that the predominant active species participating in the photodegradation process were the O₂⁻ radical and h⁺.⁴¹

By using a solvothermal technique, Velumani *et al.* (2020) created carbon quantum dots that enabled ZnO hollow spheres (ZnO/C-dots). Photoluminescence (PL) spectra revealed that ZnO/C-dots exhibited their highest emission

when excited at a wavelength of 345 nm. Methylene blue (MB) was broken down using the ZnO/C-dots nanocomposite as a photocatalyst under UV-vis light. 96% of MB was broken down in 30 minutes using the nanocomposite of ZnO and C dots. However, only 63% of MB was destroyed in 30 minutes using pure ZnO. Due to the inclusion of C-dots, the recombination of photogenerated electron-hole pairs was significantly inhibited, and the absorption of visible light was augmented, leading to a considerable enhancement in photocatalytic performance. Five cycles of use were possible for the nanocomposite, which demonstrated great stability.⁴²

Jamila *et al.* (2020) synthesized copper oxide/N-doped carbon quantum dots (CuO/NCQDs) by incorporating NCQDs onto CuO nano leaves. The CuO/NCQDs exhibited lower photoluminescence intensity than CuO, demonstrating less electron-hole recombination, according to the PL data. Methyl orange (MO) was degraded using the CuO/NCQDs as a photocatalyst in the presence of sunshine. More charge carriers are accessible for redox reactions as a result of the nitrogen-doped carbon quantum dots (N-CQDs) acting as electron storage that traps the electrons and inhibits recombination. Following the transformation of molecular oxygen into superoxide anion radical O_2^- by these electrons, water molecules react to form hydroxyl radicals and hydrogen peroxide. The hydroxyl radicals are directly reacted with by the holes on the opposite end and are transformed into $\cdot OH$ radicals, which oxidize the dye. This ensures that the CuO/NCQDs catalyst generated will have enhanced solar-induced photocatalytic activity and that the quantum confinement effects will lower the recombination rate. The maximum degrading efficiency was seen in the CuO/NCQDs with 1.5 ml of NCQDs (92.0%) due to its charge separation efficiency and visible light-harvesting capability.⁴³

Rani *et al.* (2021) used a green hydrothermal technique to create 3.6 nm-diameter N-doped carbon quantum dots (NCQDs) utilizing fruit bunches (EFB). When subjected to solar irradiation, NCQDs demonstrated remarkable photocatalytic efficiency, leading to the degradation of 97% of methylene blue (MB) within 180 minutes and 98% of malachite green (MG) within 120 minutes. Only 59% of MB and MG would have deteriorated without NCQDs. Due to the separation of photoinduced charge and the reduced electron-hole recombination, NCQDs have superior photocatalytic activity. The superior photocatalytic activity of NCQDs, achieved through the excellent fluorescent characteristics conferred by N-doping, outperformed that of CQDs. Because of their excellent stability, NCQDs might be utilized at least ten times before showing a noticeable performance decline.⁴⁴

Muhammad *et al.* (2022) created a carbon dot/TiO₂ (CQD/TiO₂) nanocomposite for quick methyl orange degradation under direct and indirect sunlight exposure. Specifically, sol-gel and hydrothermal methods were used to prepare TiO₂ nanosols and CQD. Under direct sunlight exposure at pH 11, the CQD/TiO₂ nanocomposite, synthesized with a weight ratio of 1:10 of CQD and TiO₂, exhibited optimal methyl orange (MO) photodegradation performance, surpassing pure TiO₂ by threefold. The

photocatalytic effectiveness of CQD/TiO₂ is markedly affected by variations in the initial concentration and pH of the MO solution, as well as the loading of the catalyst. With its robust catalytic stability, high visible-light photocatalytic efficiency, and reusability for dye photocatalysis, the CQD/TiO₂ nanohybrid emerges as a promising candidate for the photocatalytic purification of textile and other organic-based wastewater under both direct and indirect solar light exposure conditions.⁴⁵

In order to significantly increase the photocatalytic degradation of Rhodamine B (RhB), Huadong *et al.* (2022) engineered composites of ZnO/N, S co-doped carbon quantum dots (ZnO/N, S-CQDs) designed to be sensitive to visible light. These modifications resulted in an exceptional 98.7% photocatalytic degradation efficiency under visible light, surpassing the performance of the ideal composite. Additionally, the degradation followed a pseudo-first-order kinetics model, featuring a photocatalytic rate constant (k) of 0.0473 min⁻¹, a remarkable 3.71 times higher than that of pure ZnO nanoparticles (0.01273 min⁻¹). Examination of PL and transient photocurrent response data revealed an enhanced efficiency in the separation of charge carriers within the ZnO/N, S-CQDs composite. The elucidation of a potential photocatalytic degradation mechanism was derived from experiments involving the removal of active species. These experiments underscored the significant role played by superoxide radicals ($\cdot O_2^-$) in driving the photocatalytic activities. This further showed that the improved photocatalytic activity of ZnO was considerably influenced by the N, and S-CQDs with various characteristics. Overall, the strategy used in the present method adheres to the green economy principle, and innovative N, S-CQDs offer a workable method for improving ZnO's photocatalytic performance.⁴⁶

NPCT/TiO₂, also known as NPCT, is a photocatalyst created by H. J. *et al.* in 2022 using scaffolded N, P co-doped carbon quantum dots. In comparison to nitrogen-doped CQD/TiO₂, phosphorus-doped CQD/TiO₂, and pure CQD/TiO₂ photocatalysts, the NPCT photocatalyst exhibits significantly enhanced visible-light photocatalytic hydrogen generation, reaching 533 $\mu\text{mol h}^{-1} \text{g}^{-1}$. This remarkable improvement in performance can be attributed to the outstanding synergy between NPCTs and TiO₂ nanoparticles, resulting in the formation of virtual energy levels, a reduction in work function, and the suppression of recombination rates. These factors collectively extend the lifetime of photogenerated electrons, consequently driving the heightened photocatalytic activity observed in the NPCT photocatalyst. The experimental findings, Mott-Schottky graphs, and results from ultraviolet photoelectron spectroscopy are used to suggest a precise explanation for the improvement in visible light-induced hydrogen production achieved by the NPCT photocatalyst. Furthermore, first-principles density functional theory (DFT) simulations have been conducted, revealing that the enhancements in visible light photocatalytic hydrogen production can be attributed to several key factors. These include the reduction in the work

function and band gap, the augmentation of the density of states within the NPCT, and the decreased work function and band gap.⁴⁷

Using a green, one-step hydrothermal process, Ioan-Alexandru *et al.* (2023) synthesized TiO₂ and TiO₂ hybrids with N-CQDs and reduced graphene oxide (rGO). Here they tracked the real-time evolution of methylene blue using a solar light generator in ambient settings without the addition of extra oxygen gas. Utilizing the mixture of reduced graphene and N-CQDs dots and with a photocatalytic rate constant of approximately $25 \times 10^{-5} \text{ s}^{-1}$, N-CQDs were strategically utilized to fine-tune light absorption to align with the solar spectrum. Through the aid of hybrid DFT calculations, it was ascertained that the presence of graphene or carbon dots induced charge transfer and adjustments to the energy band edges of anatase, contributing substantially to the enhancement of photocatalytic efficiency. This remarkable performance is achieved through an environmentally friendly synthetic technique. It not only yields photocatalytic materials with customized visible light absorption, optimal efficiency, and desirable characteristics but also paves the way for potential industrialization.⁴⁸

Preethi *et al.* (2023) employed a hydrothermal approach to synthesize a high surface area nanocomposite consisting of pristine Zn₂SnO₄ (ZTO)/ carbon quantum dots (ZTO/C), utilizing a mineralizer, Na₂CO₃, in conjunction with a precise quantity of sugarcane juice. Under solar irradiation, 84 % and 95 % of methylene blue (MB) were degraded using ZTO and ZTO/C for 150 minutes respectively. CQDs were added to ZTO/C nanocomposites to improve the transit of photoinduced electrons at their interface, whereas holes stayed in the valence band of ZTO and prevented the recombination of photogenerated charge carriers upon photocatalysis. This research implies that ZTO/C is a viable option for photocatalysis powered by sunlight and environmental remediation.⁴⁹

Table 1. The fabrication of CQDs-based materials and their use in photocatalysis techniques.

Dot type	Method	Photocatalysis application	Ref.
CQD/mesoporous α -Fe ₂ O ₃	Solvent-thermal	methylene blue (MB).	Yu <i>et al.</i> (2012)
ZnO/CQDs	Hydrothermal	benzene and methanol	Yu <i>et al.</i> (2012)
CQDs	Alkali-assisted electrochemical technique	Oxidation of benzyl alcohol to benzaldehyde in the presence of H ₂ O ₂	Kang <i>et al.</i> (2013)
CQDs/Bi ₂ MoO ₆	Hydrothermal	Bisphenol A (BPA), Tetracycline hydrochloride (TC), Ciprofloxacin (CIP), and Methylene blue (MB),	Di <i>et al.</i> (2015)

CQDs/H-TiO ₂	Hydrothermal	Methyl orange	Tian <i>et al.</i> (2015)
Cu-doped carbon quantum dots	Hydrothermal	p-nitrophenol	Du <i>et al.</i> (2017)
r-Mg-N-CD	Microwave	Methylene blue (MB)	Bhati <i>et al.</i> (2018)
NP-CQDs/TiO ₂	Hydrothermal	Methylene blue (MB)	Guo <i>et al.</i> (2018)
B-CDs	Hydrothermal	Methylene blue (MB) and Rhodamine B (rhb)	Peng <i>et al.</i> (2020)
S/Cl co-doped Bio-CDs	Hydrothermal	Rhodamine B (RhB) and Methylene blue (MB)	Zhu <i>et al.</i> (2020)
N-CDs/TiO ₂	Hydrothermal	Rhodamine B (RhB)	Ouyang <i>et al.</i> (2020)
ZnO/C-dots	Solvothermal	Methylene blue (MB)	Velumani <i>et al.</i> (2020)
CuO/NCQDs	Sol-gel	Methyl orange (MO)	Jamila <i>et al.</i> (2020)
NCQDs	Hydrothermal	Malachite green (MG), and Methylene blue (MB)	Rani <i>et al.</i> (2021)
CQD/TiO ₂	Sol-gel and Hydrothermal	Methyl orange (MO)	Muhammad <i>et al.</i> (2022)
ZnO/N, S-CQDs	Hydrothermal	Rhodamine B (RhB)	Huadong <i>et al.</i> (2022)
NPCQD/TiO ₂	Hydrothermal	Visible light photocatalytic hydrogen production	H. J. <i>et al.</i> (2022)
TiO ₂ -NCQDs-rGO	Hydrothermal	Methylene blue	Ioan-Alexandru <i>et al.</i> (2023)

*Carbon quantum dots and their applications in photocatalysis have gained interest in the last decades. Researchers are trying to enhance the photocatalytic properties of CQDs by implementing different synthesis approaches or tuning CQDs surface properties by means of surface passivation or doping or by making nanocomposites with CQDs, and researchers are still trying to generate more efficient CQDs by changing their surface phenomenon for its applications in photocatalysis. Herein, we provide a table-format summary of the pertinent works that may aid in quickly understanding the overall investigations of how to design CQDs and tune their surface properties to make them more fruitful in photocatalysis and serve an inspiration for researchers to come up with novel ideas for developing advanced CQD materials for photocatalytic applications.

3.2. Electrocatalysis property of C-dots:

A catalyst that is involved in electrochemical processes is an electrocatalyst. Chemical reactions can be modified and speeded up with the help of catalyst materials, which do so without being consumed. Catalysts with a specific purpose, electro-catalysts might be the electrode surface itself or work at electrode surfaces. The variable electrode kinetics that results from employing various crystallographic orientations for the electrode surface is one most significant characteristic of electrocatalysis.

Carbon-based materials, notably Carbon Quantum Dots (CQDs), are often characterized by a carbogenic core comprising both amorphous and crystalline components, along with surface functional groups. These materials, particularly CQDs, have garnered significant interest in the fields of energy conversion and storage, primarily due to the increasingly complex environmental challenges we face. The substantial presence of functional groups (-OH, -COOH, -NH₂, etc.) on the surface of CQDs renders them capable of serving as active coordination sites for interacting with transition metal ions. Furthermore, heteroatom-doped CQDs featuring multiple components have the potential to significantly enhance electrocatalytic performance by facilitating electron transfer through internal interactions. Notably, CQDs, when hybridized with other inorganic compounds such as layered double hydroxides (LDHs), metal sulfides, and metal phosphides, among others, exhibit promising utility as efficient electrocatalysts for various reactions including Oxygen Reduction Reaction (ORR), Oxygen Evolution Reaction (OER), Hydrogen Evolution Reaction (HER), and CO₂ Reduction Reaction (CO₂RR), as illustrated in Figure 4.

3.2.1. Oxygen Reduction Reaction (ORR):

As a major method for metal-air batteries and fuel cells, ORR has garnered considerable interest in recent years. In the presence of functional groups rich in oxygen and nitrogen, CQDs are stable in water and various polar organic solvents and make multicomponent photoelectric chemical processes, such as ORR, more convenient.

Modern science has advanced the development of innovative carbon-based ORR catalysts through the integration of Graphene Quantum Dots (GQDs) with graphene nanoribbons (GNR), allowing for reduction reactions. In an alkaline environment, the resulting GQDs-GNR catalyst has showcased impressive performance and exceptional durability in ORR applications. A simple method for the in-situ reduction and assembly of GQDs with S-doped graphitic carbon nitride nanosheets (s-g-C₃N₄) was developed by Xu *et al.* (2015) using hydrothermal processing. In comparison to the pure s-g-C₃N₄ and GQDs, the produced sg-C₃N₄@GQDs nanohybrid dramatically increased catalytic ORR activity, highlighting the promising potential of CQDs in the electrocatalytic application.⁵⁰

Although Pt-based materials are widely acknowledged as highly efficient electrocatalysts for ORR, their utilization is

hampered by the cost and availability constraints associated with platinum. Consequently, there has been a strong impetus to explore the development of exceptionally active catalysts as alternatives. The creation of cost-effective nitrogen containing Co-based materials as potential electrocatalysts for ORR has been the subject of numerous investigations, and it has been discovered that heat-treating macrocyclic compounds under an inert atmosphere is an efficient way to create such catalysts.

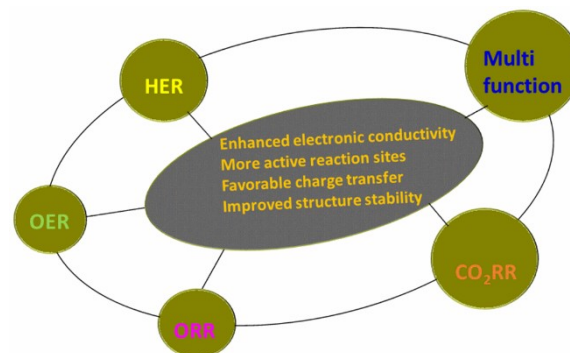


Figure 4. The application of CQDs for electrocatalysis.

Chang *et al.* suggested that the pyrolyzed cobalt-corrin compounds (py-Co-Corrin/C) demonstrated the maximum activity for ORR after studying the impact of the structures of cobalt-based macrocyclic compounds on ORR.⁵¹ Furthermore, Wang *et al.* have extensively showcased the adaptability of pyrolyzed VB12, a non-precious metal catalyst, in various applications of ORR, including polymer electrolyte fuel cells (PEFC) and microbial fuel cells (MFC).⁵² These Co, N co-doped materials have been demonstrated to offer non-precious catalyst potential for ORR, however urgent problems still need to be overcome. For example, the careful regulation and tuning of N and Co concentrations, as they play a pivotal role in enhancing catalytic efficacy and the development of porous structures. Additionally, it is imperative to explore whether Co and N concentrations exert a synergistic influence on electrocatalytic activity for ORR, necessitating further research and examination. Given their diminutive dimensions, highly crystalline composition, and surface functionalization, Carbon Dots (CDs) emerge as promising foundational units for constructing materials characterized by extensive surface areas and well-defined crystalline structures, facilitating efficient electron transport. Through the utilization of CDs, the pyrolytic process involving VB12 and CDs can yield a porous framework with meticulous control over N and Co concentrations. This strategic approach proves advantageous in augmenting the electrocatalytic performance of the catalyst.

By applying straightforward solvent and electrochemical treatments, Dumont *et al.* (2019) developed nitrogen-doped graphene oxide catalysts for the ORR that have higher activity and four electron selectivity. By significantly altering the shape of the functionalized graphene materials, the solvents chosen in accordance with Hansen's solubility parameters help ORR. These catalysts have also been

cycled, which has revealed the diversity of active sites and their varying levels of durability, resulting in a highly selective catalyst with little performance loss over time.⁵³

3.2.2. Oxygen Evolution Reaction (OER):

In their study, Tang *et al.* (2014) harnessed the potential of Carbon Quantum Dots (CQDs) to create hybrid structures with ultrathin nickel-iron layered double-hydroxide (NiFe-LDH) nanoplates. Rapid diffusion of reactants and products as well as a speedy proton-coupled electron transfer process are made possible by the layered and open structure of NiFe-LDH. The synergistic combination of CQDs and NiFe-LDH nanoplates as exceptional electrocatalysts opens up innovative avenues for the design of high-efficiency CQDs-based electrocatalysts. These advancements hold promise for a wide range of applications, including new energy sources, green chemistry, and environmental solutions, owing to the diverse and adaptable structural design capabilities offered by the current CQDs/NiFe-LDH composite system.⁵⁴

Zhao *et al.* (2015) reported the development of a nanocomposite composed of Carbon Quantum Dots (CQDs), SnO₂, and Co₃O₄ (CQDs/SnO₂-Co₃O₄) designed for efficient electrocatalysis in the oxygen evolution reaction (OER). This compound exhibited robust electrocatalytic performance and remarkable stability when operating in an alkaline environment. Furthermore, among the various molar ratios tested for the CQDs/SnO₂-Co₃O₄ composites, the composition with a molar ratio of Sn: Co at 1:3 displayed the highest catalytic activity for OER. According to experimental results, the catalyst was effectively shielded by an insoluble CQDs layer on its surface, the Co atoms served as the active center, and nanoscale SnO₂ improved electronic conductivity. The stability and electrocatalytic activity of this composite structure were excellent.⁵⁵

A CoP/CQDs composite has been found to have increased OER activity, which shows that adding CQDs to a compound based on a transition metal (TM) may boost the catalytic performance of a TM-based catalyst. The availability of functional groups, small dimensions, rapid electron transfer capabilities of CQDs, and excellent conductivity contribute to the augmented electrocatalytic performance of the CoP/CQDs composite. However, multi-step proton-coupled electron transfer mechanism that causes the oxygen evolution reaction (OER) to be kinetically sluggish, electrolysis must demand a higher potential than the thermodynamic potential for water splitting. Due to their adaptable architectures and chemical adaptability, layered double hydroxides (LDHs), a family of layered anionic materials, have drawn a lot of interest. These properties have been used to create materials with applications in chemical sensing, magnetism, electrochemistry and catalysis.⁵⁶

3.2.3. Hydrogen Evolution Reduction (HER):

An essential energy conversion procedure, particularly for some unstable energy systems, is the evolution of hydrogen from water through electrolysis. However, due to its poor

energy conversion efficiency and demand for pricey electrocatalysts, its practical usefulness is constrained. As a result, nanocomposites made of carbon have attracted a lot of attention as potential replacements for the costly precious metal catalysts currently in use. With regard to these, carbon dots (CDs) stand out owing to their adaptable composition, exceptional conductivity, outstanding dispersion, and strong metal coordination. The development of CD-based electrocatalysts for hydrogen evolution has made notable strides in the last ten years. CDs and the hybrids they have produced have displayed excellent performance and vital potential for the use of hydrogen in the future.

Zhao *et al.* (2016), using a simple hydrothermal method developed a carbon quantum dots (CQDs)/ molybdenum disulfide (MoS₂) composite which acts as a hydrogen evolution reduction (HER) catalyst.⁵⁷ The CQDs/MoS₂ catalyst's HER activity was greatly enhanced by the elevated charge transfer efficiency, reduction of S⁴⁺, and rise in S₂²⁻ and S²⁻ content following light exposure. The design of semiconductor catalysts' electrocatalytic properties, whether for experiment operation or component control, is made simple using this type of surface modification technique.

Hybrid materials based on CQDs find successful application in electrocatalytic HER due to their robust electric conductivity and ample active reaction sites. Li *et al.* (2018)⁵⁸ developed an easy thermal disintegration technique for the synthesis of hybrid Ru@CQDs. In alkaline circumstances, synthesized Ru@CQDs showed good HER activity.

A three-dimensional mesoporous sponge-like nanostructure containing nitrogen and sulfur co-doped carbon dots (NSCDs) and CoS hybrid was developed by Wang *et al.* (2018)⁵⁹, and it shows the essential electrocatalytic activity for electrochemical HER. The remarkable electrocatalytic activity of NSCDs/CoS for HER is attributed to the interaction between the two materials, which allowed the NSCDs to shield the CoS from aggregation or dissolution in acidic environments. The performance of the NSCDs/CoS hybrid was further improved by its enlarged surface area and the excellent charge transfer efficiency achieved with Co-S-C bonding between NSCDs and CoS.

A class of sophisticated Ni₅Mo₃P@CQDs electrocatalysts was investigated for their HER activities by Tian *et al.* in 2019.⁶⁰ Their findings revealed that the presence of CQDs not only altered the morphology of the Ni₅Mo₃P composite but also introduced additional catalytic sites with higher reactivity. A greater specific surface area was observed, providing more electrochemical active sites and a wider interface with the electrolyte, resulting in a significant improvement in HER performance. The interaction of CDs with Ni₅Mo₃P is also advantageous for enhancing HER stability.

3.2.4. CO₂ Reduction Reaction

In recent years, there has been a growing focus on electrochemically converting the excess carbon dioxide generated during fossil fuel combustion back into the natural carbon cycle. The electro-reduction of CO₂ into valuable

carbon-based products and feedstocks offers a promising approach to storing intermittent renewable electricity and thus contributes to reducing overall greenhouse gas emissions.⁶¹ While significant progress has been made in the CO₂ reduction reaction (CO₂RR), including achieving low activation over-potentials and improved faradic efficiencies (FEs) through catalyst morphology adjustments, oxidation state manipulation, and dopant introduction, there is still a need for continued efforts to enhance catalytic activity, selectivity, and durability. In catalysis, defect sites are often proposed as crucial active sites because they can reduce the energy barrier for the electrogeneration of desired chemical products.⁶² This suggests a fundamental design principle for developing efficient CO₂RR catalysts with high activity and selectivity using quantum dots (QDs).

In the design of catalysts, defect sites are frequently suggested as major active sites. Achieving a high density of uniformly scattered atomic flaws is a viable method for enhancing activity; however, metals rarely achieve this. We postulate that during the CO₂ reduction reaction, the formation of quantum dots (QDs) and their electrochemical reduction could lead to the production of vacancy-rich catalysts (CO₂RR).

In order to create nitrogen-doped graphitic quantum dots-wrapped single crystalline Au nanoparticles (NGQDs-SCAu NPs) for effective CO₂ reduction, Fu and Zhu (2018) established a unique method. The NGQDs-SCAu NPs that were created showed improved CO₂ reduction capability. The enhanced COOH adsorption on the pyridine N site of NGQDs due to the synergistic impact between SCAu and NGQDs was explained by the higher catalytic activity of NGQDs-SCAu NPs for reducing CO₂ into CO.⁶³

Liu et al. (2019) describe the electrosynthesis of carbon monoxide, formate, and ethylene at low potentials of -0.2, -0.3, and -0.9 V versus reversible hydrogen electrode (RHE), respectively, at record current densities of 16, 19, and 25 mAcm⁻² with high faradic efficiencies. Despite 80 hours of CO₂RR, the materials are still stable. This CO₂RR in aqueous solution performances are 2x times better than those of earlier reported catalysts. X-ray absorption spectroscopy and computational investigations demonstrate that the vacancies provide a localised atomic and electronic structure that improves CO₂RR.⁶⁴

3.2.5. Bifunctional Catalyst

Bifunctional catalysts can catalyze two distinct types of reactions and have two different types of catalytic sites. This particular class of catalysts has the distinct advantage of also being able to transform highly reactive intermediates, which typically result in carbonaceous deposits and a loss of yield, increasing the selectivity of the desired products. By including more functional groups and surrounding edges, CQDs can offer additional catalytically active locations for electrocatalysis. Le et al. (2022) created Co, N-doped CDs from EDTA-Co using a low-temperature polymerization-solvent extraction technique. The catalytic property of Co-CDs may be enhanced by Co doping. The presence of cobalt

(Co) in the precursor plays a crucial role in generating a higher number of pyridinic-N-active sites, which leads to the enhancement of ORR performance. This is evident from the significant increase in the pyridinic N atom content of Co-CDs, which rose from 4.2 to 11.27 at% when compared to CDs. The easy hydrothermal approach, which can reveal many active sites than the aggregation state, evenly distributes Co-CDs across the surface of carbon black (CB) to create Co-CDs@CB. By restricting the catalyst's current density in the direction of the ORR, the Co-greatest CDs@CB's graphite N concentration was discovered. The remarkable catalytic efficiency of Co-CDs@CB can be attributed to the synergistic effect of Co and N resulting from the Co doping process, which introduced a novel method for obtaining advanced electrocatalysts.⁶⁵

Table 2. The synthesis and application of materials based on carbon quantum dots (CQDs) in electrocatalysis processes.

Dot type	Method	Electrocatalysis application	Ref.
sg-C ₃ N ₄ @GQDs	Hydrothermal	Oxygen Reduction Reaction (ORR)	Xu et al. (2015)
NrGO	Solvent and Electrochemical treatments	ORR	Dumont et al. (2019)
CDs/NiFe-LDH	Solvothermal	Oxygen Evolution Reaction (OER)	Tang et al. (2014)
CQDs/SnO ₂ -Co ₃ O ₄	Hydrothermal	OER	Zhao et al. (2015)
CoP/CQDs	Electrochemical etching	OER	Zhu et al. (2018)
CQDs/MoS ₂	Hydrothermal	Hydrogen Evolution Reaction (HER)	Zhao et al. (2016)
Ru@CQDs	Thermal decomposition	HER	Li et al. (2018)
NSCDs/CoS	Hydrothermal	HER	Wang et al. (2018)
Ni ₃ Mo ₃ P@CQDs	Thermal decomposition	HER	Tian et al. (2019)
NGQDs-SCAu NPs	Hydrothermal	CO ₂ Reduction Reaction (CO ₂ RR)	Fu and Zhu (2018)
QDDCs	In situ electrochemical reduction	CO ₂ RR	Liu et al. (2019)
Co-CDs	Hydrothermal	Bifunctional Catalyst	Le et al. (2022)

*Like photocatalysis, carbon quantum dots and their implementation in electrocatalysis have also raised interest in recent years. The continuous effort and hard work of researchers are gradually improving the targeted CQDs and hence their electrocatalytic properties by tuning CQDs surface characteristics by means of surface passivation or doping or by making nanocomposites with CQDs, and trying to produce some proficient dots and their novel applications in electrocatalysis. To concise together here we provide a table-format summary of the works regarding the electrocatalysis approach that may help future research to develop advanced CQD materials.

4. Conclusions

This review concentrates on the latest developments in the synthesis, characteristics, and catalytic properties of carbon quantum dots. CQDs possess the ability to serve as both photocatalysts and electrocatalysts, due to their excellent tunable PL, capability for solar harvesting, and fast charge transfer. Even if things have advanced significantly over the past decade, many problems still need to be thoroughly investigated. Photocatalytic CQDs have a poor ability to capture light due to UV absorption. The activity of the photocatalytic reaction may be impacted by oxygen groups on the surfaces of CQDs. The photostability of photocatalysts based on CQDs is a subject of debate, as oxygenic functional groups tend to be lost during photocatalysis. Since CQD-based nanocomposites are challenging to make, there haven't been many investigations on their photostability. More work is urgently required to create innovative photocatalysis and electrocatalysts based on CQDs. CQDs modification by functionalization or doping enhances its PL and also enhances its photocatalytic and electrocatalytic activity. In addition to being essential for designing the electronic structures of the nearby carbon atoms in CQDs, the hetero atoms (i.e., N, S, and P) also serve as reactive sites during the catalytic reaction.

In the near future, we envision the development of more economical, cost-effective, and creative simple synthetic methodologies as well as the exploration of unique and promising applications for CQDs.

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6. Notes and References

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About the author(s):



Prithidipa Sahoo obtained her MS degree in Organic Chemistry major from Vidyasagar University in 2003 and her Ph.D. degree from Indian Institute of Engineering, Science and Technology in the field of Molecular Recognition in 2010. After a post-doctoral study at Rutgers University, USA, she joined in Visva-Bharati as an Assistant Professor in 2012.



Jiko Raut received his M.Sc. degree in Chemistry from The University of Burdwan in 2016 and is currently pursuing his Ph.D. under the guidance of Dr. Prithidipa Sahoo, in the Department of Chemistry at Visva-Bharati University. His research interests encompass the utilization of Carbon Quantum Dots as sensors for bioassays, antibiotic detection, and drug delivery applications.

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