Applications of Carbon Dots

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Although there is significant progress in the research of carbon dots (CDs), some challenges such as difficulty in large-scale synthesis, complicated purification, low quantum yield, ambiguity in structure-property correlation, electronic structures, and photophysics are still major obstacles that hinder the commercial use of CDs. The unique properties of CDs, such as good biocompatibility, high photostability, excellent light-harvesting, up-conversion, effective electron transfer, and bandgap narrowing, make the CDs promising nanomaterials for applications in many fields.

Keywords: carbon dot ; Degradation ; CO2 Reduction ; Hydrogen Evolution ; Antimicrobial

1. Introduction

CD is a zero-dimensional (0D) quasi-spherical carbon nanomaterial with a size ranging from 1 to 10 nanometers. Compared with traditional quantum dots, such as metal or semiconductor-based QDs, carbon-based QDs (such as carbon QDs, graphene QDs, and polymer QDs) have excellent biocompatibility and low cytotoxicity. CDs have some unique properties, such as facile synthesis, ease of functionalization, excellent water dispersibility, excellent light-harvesting, sharp fluorescent emission spectrum, up-conversion, tunable photoluminescence properties, effective electron transfer, and good photostability. Therefore, CDs have been applied to a wide range of applications, including bioimaging, biomedical and chemical sensing, therapy, optoelectronics, solar cells, fertilizer, separation, security authentication, food packing, and co-catalyst for environmental remediation applications. The continuous efforts devoted to CDs-related research have significantly explored some important knowledge about CDs-based materials and improved their performance in different fields. However, some serious challenges, such as inadequate and complicated purification, difficulty in large-scale production, low quantum yield, and ambiguity in understanding the structure-property correlation, are still the major obstacles to the commercial use of CDs in various applications.

In 2022, some research have provided useful information about the research of CDs. Đorđević et al. [1] reported the pre-synthetic and post-synthetic approaches for CDs synthesis and the influences of chemical tools on the properties of CDs. Wu et al. [2] reviewed the synthesis of four types of CDs-based composites (metal-CDs, organic-CDs, nonmetallic inorganic-CDs, and multicomponent-CDs composites) and their uses in the bioapplications, such as biosensing, bioimaging, and drug delivery. Zhang et al. [3] reviewed the development of synthetic/modification methods of CDs and CDs-based optical sensors for pesticides, as well as the advantages, possible limits, and challenges for their real-world application. Saini et al. [4] summarized the new findings related to the use of CDs, doped-CDs, and their composites for visible-light-driven photocatalysis. Wang et al. [5] reported the utilization of CDs and CDs-based composites for the detection and adsorption of radioactive ions that may cause long-term influence on the environment and hurt the human body by entering the food chain. Zhai et al. [6] provided a review of the latest study related to the use of CDs for energy storage and electrochemical processes' applications, including CO_2 reduction, H_2/O_2 production, supercapacitors, and batteries. Han et al. [7] summarized the advances in CDs-based ratiometric fluorescent sensors for food safety applications and detection mechanisms. Korah et al. [8] reviewed three aspects of CD-drug interactions, including drug detection, photocatalytic degradation by CDs-based composites, and enhancement of drugs by using CDs. Mohammadi [9] reported the recent progress in using carbon-based QDs as a biosensing and fluorescence imaging platform for the early stage diagnosis of cancers. However, there is still an urgent need for the exploration of some important issues, such as the roles of CDs in different applications, kilogram-scale fabrication of CDs, and doping/surface modification, as well as the correlation among process parameters, structures, compositions, properties, and performances of CDs-based materials.

2. Degradation of Organic Toxicants

2.1. Organic Dyes

The polluting of freshwater sources is a significant threat to providing safe drinking water. Due to unsustainably high development initiatives in construction activities, industrial emissions, and agricultural activities [10], inorganic toxicants such as heavy metals, deposits, and nutrients, and organic toxicants such as dyes, pesticides, pharmaceutical drugs, and endocrine disruptors, are deposited into the environment. The vast majority of these toxicants, mainly inorganic toxicants, will remain in the environment, leading to toxicant bioaccumulation and entry into the food matter. Finally, it has a toxic effect on higher trophic level organisms, which can be lethal. Photocatalysts have been developed for environmental cleanup in recent times [11][12]. CDs have nontoxicity, chemical inertness, photoinduced electron transfer, excellent biocompatibility, and customizable photoluminescence behavior patterns. Since CDs are frequently made from eco-friendly materials, they are inexpensive and environmentally friendly at reducing waste generation.

CDs have better catalytic performance with enhanced photocatalytic effectiveness and shorter degradation times. CDs were made by a simple one-pot solvothermal process, using ethanol and glyoxal as a precursor (0.26). In the sunlight, indoors, and under dark conditions, the degradation efficiency of indigo carmine (IC) can reach 91% [13]. The *Cornus walteri* leaves were used to synthesize G-CDs that acted as a photocatalyst for the degradation of organic dyes [14]. A hydrothermal procedure was used to make carbon dots containing Fe and N (Fe,N-CDs) as Fenton-like catalysts for the degradation of the MB dye. About 100% of the MB dye (20 mg L^{-1}) was degraded within 60 min [14]. The TiO_2 nanoparticles decorated with a microalgae-based carbon dots (MCDs) (TiO_2-MCDs) composite degraded the MB dye more efficiently than pristine TiO_2. The MCDs in TiO_2-MCDs act as the reservoirs for trapping photogenerated electrons and as photosensitizers for enhancing visible-light absorption [15]. Wang et al. [16] prepared the CDs-based porous europium micro-networks (CDs@P-Eu-MNs). The CDs can alter the morphology of CDs@P-Eu-MNs and result in a huge variety of porous structures. The incorporation of CDs can improve the activity of photocatalysts by increasing both the light absorption and the separation of photogenerated carriers. The visible-light-driven activity of the CDs/TNs (TNs-TiO_2 sheets) photocatalysts was significantly higher than that of bare TNs [17]. The remarkable stability of CDs/TNs was explored by completing repeated Congo red (CR) degradation for five cycles (photocatalytic degradation rate reached 85.9% after irradiation for 120 min). The CDs/MoS_2/p-C_3N_5 composites had outstanding photocatalytic degradation ability (93.51%) toward methylene blue.

CQDs-modified Sb_2WO_6 nanosheets (CQDs/Sb_2WO_6) exhibited a visible-to-near-infrared (Vis-NIR) light-responsive property [18]. The photocatalytic degradation efficiency of RhB by the composite photocatalyst is roughly seven times better than that of Sb_2WO_6. The results of quenching experiments, DFT calculations, and electron spin resonance spectrometry revealed that the hydroxyl radical (•OH) played a dominant role in the photocatalysis reaction.

2.2. Possible Mechanism

The nitrogen-doped carbon dot-modified ZnO composite (N-CDs@ZnO) photocatalyst shows significantly better activity (MB dye degradation efficiency > 99%, 60 min irradiation) than pristine ZnO photocatalysts (75%, 60 min irradiation). The improved photocatalytic activity resulted from increased UV-light absorption and hindered the recombination of photoexcited electron-hole pairs. The hindered carrier recombination may be due to effective electrons trapping by N-CDs. Moreover, loading N-CDs also helped to solve the photocorrosion problem of ZnO in the N-CDs@ZnO photocatalysts. N-CDs were decorated on the ZnO surface and created a complex structure providing the access to photogenerated charge transfer upon light irradiation. The combination of adsorbed O_2 with the electrons in N-CDs leads to the formation of oxygen radicals. Then N-CDs with the up-conversion properties convert the long-wavelength light to the short-wavelength light that can excite ZnO to form separate electrons and holes. During the degradation process of the MB dye, the π-π* interaction between N-CDs and the MB dye can enhance the degradation of MB by the N-CDs@ZnO photocatalyst [19]. The nitrogen-rich carbon nitride (p-C3N5) had exceptional electronic properties. The CDs-modified co-catalyst MoS_2 can significantly improve the photocatalytic activity of p-C3N5 by increasing the transfer rate of photoexcited electrons [20]. The photogenerated electrons in the CB of p-C3N5 are collected and stored by CD particles, transferred across the interface to a MoS_2 cocatalyst, leading to enhanced separation of electron-hole pairs. The electrons transfer to MoS_2 nanosheets and interact with the adsorbed H^+ and evolve H_2. The holes in the VB of p-C_3N_5 are consumed by the reacting with SO_3^{2-} and S^{2-}. CDs attached on MoS_2 act as the electron acceptors, facilitating charge-transfer efficiency and improving the photocatalytic H_2 production activity of the composite photocatalyst. Organic pollutant dyes such as RhB, MB, CR, and fuchsine were removed by using the newly developed Z-scheme C_3N_4-NS/CD/FeOCl ((C_3N_4-NS) g-C_3N_4 nanosheets) photocatalysts [21]. The complete removal of RhB can be achieved within 60 min. The photocatalytic activity of C_3N_4-NS/CD/FeOCl for the removal of RhB, CR, MB, and fuchsine was about 39.7, 15.2, 26.9, and 20.9 times that of pristine

C_3N_4. The C_3N_4-NS/CD/FeOCl sample also displayed high stability. The chemical scavenging studies revealed that the $•O_2^{•-}$, •OH, and h^+ played significant roles in the photocatalytic degradation reaction. The modified CDs-$BiSbO_4$ composite was used for the degradation of RhB effectively up to 90% [22]. The CDs with excellent up-conversion properties can successfully convert long wavelengths (550–900 nm) to short wavelengths (320–500 nm). CDs acted as the electron sink, reducing the recombination of photogenerated carriers originating from the $BiSbO_4$ nanomaterials. When O_2 molecules are deposited on the CDs surface, the electrons in the interlayer will be drawn toward O_2, providing a perfect platform for activating the molecular oxygen.

2.3. Pharmaceutical Pollutant Removal

The increasing persistence of active pharmaceutical residues in water matrices, such as anti-inflammatory medicines (diclofenac, naproxen, indomethacin, etc.) and antibiotics (tetracycline, ciprofloxacin, norfloxacin, etc.), has become a global problem [23]. These harmful substances have negative impacts on the entire living ecosystem and deplete biodiversity. As a result, the development of effective solutions and preventative strategies is urgently needed to reduce the pharmaceutically active developing contaminants from the environmental matrices in a long-term manner. As a result, CD-based photocatalysts are gaining traction as a viable decontamination option for pharmaceutical pollutants. CDs play a vital role in the performance of photocatalysts, due to their unique up-conversion property, electron transfer capabilities, and effective separation of photogenerated carriers [24].

3. Treatment of Inorganic Toxicant

The fabrication of CDs from microcrystalline cellulose (MCC) is described in a scalable synthetic approach [25]. Elimination of hazardous Cr^{6+} from wastewater was used to test the effectiveness of the produced CDs. Under sunshine illumination, CDs made from cellulose eliminated 20 ppm of Cr^{6+} in about 120 min. During the control test in dark surroundings, no Cr^{6+} removal was observed by the cellulose material as reference samples. With a half-life of 26 min, Cr^{6+} elimination follows pseudo-first-order dynamics. Furthermore, cyclic voltammetry research confirmed the removal of Cr^{6+} from wastewater. A photocatalytic Z-scheme TiO_2-CDs/polyaniline electrode was constructed to improve photocatalytic activity [26]. The light adsorption was enhanced after loading carbon dots and PANI (polyaniline). Simultaneous carbamazepine degradation (44.67%) and Cr^{6+} reduction (11.94%) was observed because of the decreased bandgap and increased photocurrent density. There is a noticeable improvement in the performance of the carbamazepine degradation (from 77.63% to 83.29%) and Cr^{6+} reduction (from 23.70% to 25.68%). The free-radical •OH (78.63%) is the main active species in the degradation of carbamazepine (CBZ) into small molecules by a process consisting of hydrolysis, dehydration, de-ketonization, deaminization, and ring-opened reactions.

4. CO_2

CO_2 can be utilized as a substrate for the synthesis of fuels or high-value carbon compounds such as $HCOOH/HCOO^-$, CO, CH_4, C_2H_4, CH_3OH, or C_2H_5OH. The specificity toward the formation of certain target products is a significant obstacle for ensuring an effective reduction reaction of CO_2, because of the possible formation of a lot of carbon-containing products, and the competitive side H_2 evolution rate (HER), which also decreases the performance of the entire reduction reaction process of CO_2 in aqueous media. Furthermore, the exceptional inertness and stability of CO_2 molecules pose thermodynamic and kinetic barriers to effective CO_2 activation and conversion. Q. Liang et al. [27] reported that, without using a sacrificial agent or any other photosensitizer, a CD-modified Co_3O_4/In_2O_3 composite catalyst for effective CO_2 photoreduction achieves an excellent CO production activity of 2.05 mmol h^{-1} g^{-1}. The CD catalyst produces 3.2 times more CO than the Ru catalyst based on the same testing conditions, namely without the addition of triethanolamine (TEOA). The transient photovoltage (TPV) measurements explored the interface charge transfer kinetics, suggesting that the CDs participate in the electron and hole transfer procedures, stabilizing charge, and enriching H^+ for the effective reduction of CO_2.

The oxygen vacancy defect results from a loss of oxygen atom from its relative position in the crystal lattice. The introduction of surface oxygen vacancy is a promising method to tune band structure, modify surface chemical states, and accelerate charge separation of photocatalysts. Xiong et al. [28] designed a photocatalyst GQDs/BWO_{6-x}, consisting of graphene quantum dots (GQDs) and surface Vo (oxygen vacancies) with decorated Bi_2WO_6 (BWO). The GQDs/BWO_{6-x} showed improved photocatalytic conversion of CO from CO_2, with a high yield (43.9 μmol g^{-1} h^{-1}), i.e., 1.7 times greater than pristine BWO. The GQDs/BWO_{6-x} generated electrons showed a longer fluorescence lifetime than pristine BWO, indicating an excellent separation efficiency for photoexcited carriers. According to the DFT calculations, the electrons move to Vo-adjacent atoms from Vo-remote atoms of GQDs/BWO_{6-x}. The energy barrier calculation of GQDs/BWO_{6-x} and BWO revealed that a simple transition of *COOH to *CO is the rate-limiting step. The results of DFT calculations of

molecular binding energy (BE) on the surface of photocatalysts were performed to demonstrate the CO_2 activation mechanism by spotting the adsorption energy for intermediates. The CO_2 molecules adsorbed on BWO and GQDs/BWO_{6-x} were first hydrogenated to *COOH, then converted to *CO and *OH, and then rehabilitated to *CO and *H_2O. The *CO intermediate bonded at the Vo-neighboring sites was desorbed from the surface of GQDs/BWO_{6-x} to produce CO (possibility (1)) or hydrogenated to produce *CHO (possibility (2)). The CO desorption energy for GQDs/BWO_{6-x} is comparable to Bi_2WO_6. Therefore, the surfaces of GQDs/BWO_{6-x} and BWO were capable of desorbing *CO to form free CO in a similar manner. Since GQDs/BWO_{6-x} has a lower *CHO generation energy than the bulk BWO, the *CO intermediate for GQDs/BWO_{6-x} is more easily protonated to CH_4. The formation of *CO by the protonation of *COOH is the rate-determining step. In comparison with the conversion of *COOH-BWO to *CO-BWO, the transformation of *COOH-GQDs/BWO_{6-x} to *CO-GQDs/BWO_{6-x} has a lower energy barrier, indicating that the decoration by GQDs and Vo was advantageous for the transformation of *COOH to *CO.

On a carbon nitride-like polymer (FAT) adorned with CDs, Wang et al. [29] demonstrated that CO_2 is reduced to methanol (CH_3OH) with 100% selectivity using H_2O as the only electron source and discovered that carbon dots could extract holes in FAT with almost 75% efficiency before they became unreactive due to entrapment using transient absorption spectroscopy. The removal of holes resulted in a higher density of photoelectrons, indicating that shorter-lived reactive electrons recombined less frequently. Lee et al. [30] rationally created a CD/TOH hybrid catalyst consisting of N-doped carbon dots (CD) and hollow TiO_2 spheres (TOH). They used it for the photocatalytic reduction of CO_2 to make CH_4. According to electron microscopy images, the CD/TOH composite has a porous hollow spherical shape that is uniformly loaded with CD. Furthermore, the CD/TOH hybrid exhibits excellent light-harvesting, large surface area, good CO_2 adsorption capabilities, and, most critically, improved separation of photogenerated carriers for CO_2 photoreduction processes. As a result, the CD/TOH with 2 wt.% CD exhibits a high CH_4 generation rate of 26.8 μmol h^{-1} g^{-1}, equal to 98% of CH_4 selectivity over the competitive H_2 generation reaction. Wang et al. [31] designed and fabricated a direct Z-scheme heterojunction composite CPDs/$Bi_4O_5Br_2$, consisting of $Bi_4O_5Br_2$ nanosheets and carbonized polymer dots. It effectively facilitates photogenerated carrier migration and separation efficiency while retaining more negative electron reduction potential of carbonized polymer dots (CPDs) and more positive hole oxidation potential of $Bi_4O_5Br_2$. CPDs also facilitate the adsorption of CO_2 and COOH* intermediates and the desorption of product CO. Under the Xe lamp irradiation, the maximum CO generation of CPDs/$Bi_4O_5Br_2$ is 132.42 μmol h^{-1} g^{-1}, which is 5.43 times higher than that of $Bi_4O_5Br_2$ nanosheets. When the excitation wavelength is higher than 580 nm, CPDs with up-conversion capabilities can extend the light utilization range, resulting in better CO_2 conversion performance in composite materials.

5. Hydrogen Evolution

Photocatalytic H_2 production using semiconductor photocatalysts is an eco-friendly technology for solar energy conversion [32][33][34]. Ding et al. [35] reported the synthesis of a sequence of CDs decorated HCNS-C_x (hollow g-C_3N_4 spheres) with glucose and cyanamide as precursors. The single-step in situ thermal polymerization method was used to synthesize the HCNS-C_x. CDs and g-C_3N_4 were able to maintain a tight bond and enhance the separation of photogenerated carriers. The HER of HCNS-$C_{1.0}$ (2322 μmol g^{-1} h^{-1}) was 1.8 times and 19 times higher than the HCNS and bulk g-C_3N_4, correspondingly.

A non-metallic photocatalyst based on CQDs/covalent triazine-based framework (CQDs/CTF) was made using an impregnation approach for photocatalytic hydrogen generation. In comparison to pristine CTF, the composite with 0.24% CQDs showed a three-fold increase in hydrogen generation rate of 102 μmol g^{-1} h^{-1}. CQDs acted as the electron libraries, facilitating electron capture and promoting the separation of photogenerated carriers in CTF-1, according to photoluminescence and photoelectrochemical research. CQDs' excitation-independent up-conversion fluorescent properties gave the catalysts a wider range of visible-light responses and improved the efficiency of solar energy utilization [36]. Wang et al. [37] reported a CQDs-$CdIn_2S_4$ (CQDs/CIS) heterostructured composite. As the number of CQDs increased, the morphology of the hybrid sample changed from 3D octahedrons to 2D nanosheets. This unique 3D/2D structure and synergistic effects between $CdIn_2S_4$ and CQDs effectively boosted the active reaction sites of the composite, improving quantum yield and photogenerated electron pair separation efficiency. In particular, the CQDs/CIS composite photocatalyst had the highest H_2 production activity of 956.79 μmol g^{-1} h^{-1}, which was 7.57 times higher than the pristine $CdIn_2S_4$.

CQDs modified TiO_2 composites were prepared to coproduce H_2 and arabinose with increased selectivity. The CQDs partially trap the photogenerated electrons and then cause proton reduction to produce H_2, whereas the remaining electrons react with the absorbed oxygen to produce radical •O_2^-. The photogenerated h^+ combines with the absorbed H_2O to form radical •OH. The CQDs/TiO_2 composites with particular colored CQDs can significantly enhance the selectivity of glucose to arabinose conversion (75%) and the H_2 production activity (2.43 mmol h^{-1} g^{-1}) [38].

Xu et al. [39] proposed that the incorporation of nitrogen-doped carbon quantum dots (NCQDs) into composite catalysts not only improved photoabsorption but also allowed effective and rapid migration of photogenerated electrons to NCQDs. The photocatalytic H_2 generation activity can be effectively improved because of reduced photogenerated carrier recombination. The photocatalytic H_2 generation performance of composite photocatalysts was significantly enhanced (2306.1 µmol g^{-1} h^{-1}), which was around seven times that of the sample without NCQDs.

6. Antimicrobial

6.1. Food Storage

The curcumin (Cur) carbon quantum dots (Cur-NRCQDs), as a photosensitizer, can improve the efficiency of reactive oxygen generation and antibacterial performance. Cur-NRCQDs can inactivate 100% Escherichia coli (*E. coli*) and Staphylococcus aureus (*S. aureus*) under xenon lamp irradiation at concentrations of 10 and 15 M, respectively. The reactive oxygen created by Cur-NRCQDs during photodynamic therapy may have disrupted the cell membrane, leading to leakage of the contents [40]. Lin et al. [41] prepared nanosized, spherical, neutral charge, fluorescent carbon dots with good water dispersibility using fish, ginger, onion, and garlic as carbon sources. The fish and ginger CDs contained lower sulfur elements than the onion and garlic CDs. The onion CDs exhibited antibacterial activity against *Pseudomonas fragi* (*P. fragi*), as well as antimicrobial activity against *S. aureus* and *E. coli*. Onion CDs had MIC of 2 mg mL^{-1} and MBC of 4 mg mL^{-1}, against *P. fragi*. The cell membrane and cell-wall integrity were damaged after the light irradiation to CDs, and extracellular alkaline phosphatase (AKP) and ATP activity increased, resulting in a decrease in cell viability and a change in cellular shape in *P. fragi*. These results reveal that onion CDs can be used as a bacteriostatic agent for aquatic products. Ma et al. [42] produced AgNPs by reducing a combination of CDs and silver (Ag) ions with sodium borohydride ($NaBH_4$), employing CDs with numerous chemical groups as ligands. The stable CD-AgNPs (carbon-dot-stabilized silver nanoparticles) give a higher antibacterial performance than AgNPs without CDs. The CD-AgNPs had an MIC of 100 µg mL^{-1} with 0.613 µg mL^{-1} Ag. CD-AgNPs have a broad-spectrum antibacterial activity since they inhibit the growth of six bacteria, namely *S. aureus*, *L. monocytogenes*, *E. coli*, *Vibrio parahaemolyticus*, *S. typhimurium*, and *Shigella castellani*.

6.2. Wound Healing

The quaternized carbon quantum dots (qCQDs) regained the weight of rats in wounds infections caused by mixed bacteria, significantly decreased the death of rats from a serious infection, and also improved the healing of infected wounds in rat models. Biosafety tests revealed that qCQDs had no apparent toxic or adverse reactions during the testing phase. The quantification proteomics analysis showed that qCQDs primarily acted on ribosomal proteins in S. aureus and downregulated the citrate cycle proteins in *E. coli* [43].

Wu et al. [44] reported that the levofloxacin (antibiotic medicine)-based carbon dots (LCDs) improved the antibacterial activity and reduced drug resistance. The results showed that LCDs have effective antibacterial properties due to the active groups of levofloxacin being preserved. LCDs had a dual-antibacterial mode that distorted microorganisms because of the reactive species and positive surface charge generation at the same time. The LCDs in vivo antibacterial effects were evaluated in the infected wounds with *E. coli* or *S. aureus* of ICR mice. The abscess was visible in infected wounds after 48 h of infection with *E. coli* or *S. aureus*. When the infected wounds were treated with levofloxacin hydrochloride, LCDs, and normal saline, from day 1 to day 10. The scab appeared after treatment in the LCDs and levofloxacin hydrochloride (LC-HCl) groups, but in the negative control group, the exudates and pus remained. The exudates and pus remained in the negative control group after seven days of treatment, although the area of infected wounds in the LCD groups was substantially reduced compared to the LC-HCl groups.

The sulfur (S) functionalized turmeric-derived carbon dots (S-CDs) showed high antibacterial and antioxidant action against mouse fibroblast L929 cells with minimal cytotoxicity [45]. The UV protection capabilities of the CDs-added film were increased without affecting the transparency of the pectin/gelatin film. The hydrophobicity, mechanical, and water vapor permeability of the film were all changed by the addition of CDs. Furthermore, the DPPH and ABTS techniques revealed that CDs-loaded pectin/gelatin films had high antioxidant properties. Moreover, the film with sulfur functionalized CDs demonstrated high antibacterial action against foodborne pathogenic bacteria such as *E. coli* and *L. monocytogenes*. S-CDs embedded pectin/gelatin films can be employed in food packaging-related applications to increase the shelf life of foods and assure food safety. Glucose carbon dots (GCDs) were made by utilizing glucose as the carbon source and doped with sulfur, nitrogen, and boron to improve their functioning [46]. The NGCD, in particular, has the highest antioxidant activity of all the GCD. The S-doped GCD (SGCD) and B-doped GCD (BGCD) showed higher antibacterial activity against *L. monocytogenes* and *E. coli*. Both bacterial strains are susceptible to the NGCD, which has the strongest antibacterial action. The NGCD possesses substantial antifungal activity against *P. citrinum*, *Ammophilus fumigatus*, *R.*

rubra, and *C. albicans*, but the SGCD effectively inhibits the *F. solani* growth. When mouse fibroblast L929 cells are exposed to a high dosage of 500 g/mL for 72 h, 80% of cells remained alive, indicating the low toxicity of CDs. The Ag,NCQDs are efficient antimicrobials against *E. coli* and *S. aureus* [47]. Antibacterial activity was evaluated by using *S. aureus* and *E. coli* colonies, and the morphologies of the bacteria were investigated by using SEM. The inhibitory effect is sequenced in spread plate tests: NCQDs > Ag,NCQDs > Ag-CQDs > NCQDs > Ag solution. As a result, doping Ag into N-CQDs is a more effective technique to improve antibacterial activity than mixing N-CQDs and Ag. Furthermore, Ag,NCQDs have antibacterial activity against both bacteria colonies, whereas the NCQDs counterpart has an inhibitory effect solely on *E. coli*. The lowest Ag,NCQDs preventive concentrations against *E. coli* and *S. aureus* are 250 and 200 µg mL^{-1}, respectively.

7. Cell Imaging

The development of fluorescent tools can improve the ability to probe biological dynamics [48]. The CDs-HS18 was employed as the fluorescent dyes for cell imaging study in the *Saccharomyces cerevisiae* (*S. cerevisiae*) bacteria, *Jasminum mesnyi* Hance (JMH) leaf, onion skin, and microworms via in vivo and in vitro methods, respectively [49]. The fluorescence signals found in JMH are in the leaf veins, revealing the supply tendency to the tip from the petiole, which is constant with the movement of H_2O in the leaves, indicating the distribution of CDs in the leaves is mainly driven by transpiration. The confocal laser scanning microscopy (CLSM) data show that multicolored fluorescent signals can be found in the pharynx, somatic cells, pseudocoelom, and digestive system of the microworms. However, the signal strength in the mouth cavity and the tail is lower than in other organs. Wang et al. [49] assume that CDs are ingested by microworms by ingestion. Due to the exceptional biocompatibility of CDs, CDs enter the gastrointestinal tract through the oral cavity and pharynx, spreading to the somatic cells and pseudocoelom, and eventually being expelled through the anus. Microworm deaths were not seen during the test, implying that the regular metabolic activities of microworms were maintained.

The level of folic acid in the human body can be a useful indicator for evaluating the body's normal physiological activities and can provide information about cell growth and reproduction [50]. A high level of FA can cause a variety of diseases. The fluorescence spectra of N-CDs were quenched after the addition of folic acid due to the synergistic effects of the static quenching mechanism and internal filtering effect (IFE). Within the folic acid concentration range of 0–200.0 M, the LOD was 28.0 nM (S/N = 3) under optimal conditions. Furthermore, N-CDs were used to sense folic acid in the real samples, including urine and fetal bovine serum, with a quantitative addition recovery rate of 99.6–100.7%. The experimental results revealed that N-CDs exhibit low toxicity, excellent cell imaging performance, and quantitative folic acid analysis. In the daylight, aqueous dispersions of Morus nigra CDs (M-CDs) exhibit a brownish-yellow color and cyan-blue light emission under UV light irradiation [51]. M-CDs show characteristic excitation-dependent emission with a high QY of 24%. M-CDs exhibit a high QY of 24% in a characteristic excitation-dependent emission manner. M-CDs were used as fluorescent sensors for the sensitive and selective Fe^{3+} sensing via fluorescence quenching, with a detection ranging from 5 to 30 µm, and an LOD of 0.47 µM. Furthermore, M-CDs were applied to stain human colon cancer (HTC-116) cells for cell viability and microscopic analysis. The M-CDs-conjugated HTC-116 cells emitted blue, green, and red light when excited through 405, 488, and 555 nm filters, respectively. An efficient and environmentally friendly process for the preparation of nitrogen-doped carbon dots (N-CDs) was reported, using chicken waste Galli Gigerii Endothelium Corneum (GGEC) as a precursor [52]. Surprisingly, N-CDs can be used as a sensor for the selective and sensitive detection of nitroimidazoles, such as metronidazole, tinidazole, ornidazole, and secnidazole, using internal filtration effect (IFE) and static quenching mechanisms. N-CDs were proved to be effective for detecting nitroimidazoles in some real samples (e.g., chicken, plasma, and tablets). Moreover, N-CDs also showed great potential in the bioimaging application. The Kiwi-fruit-peel carbon dots (KFP-CDs) were successfully prepared from kiwi fruit peels without using a capping/passivation agent [53]. KFP-CDs were useful for the fabrication of novel fluorescent inks. When exposed to UV light, the images and words were instantly visible. Furthermore, when evaluated for the cell-imaging application in human cell lines, KFP-CDs are biocompatible and have low cytotoxicity. The findings suggest that KFP-CDs can be used as a cell labeling agent for the in vitro imaging of cancer cells and normal cells.

Most CDs that can discriminate between live and dead cells exhibit excitation-wavelength-dependent fluorescence and low photoluminescence quantum yields [54]. It may cause problems such as possible fluorescence overlap with the other fluorescent probe. Meanwhile, it is not feasible for dual-color live/dead staining. Therefore, developing CDs with high photoluminescence quantum yields and excitation-wavelength-independent emission becomes an important task. Excitation-wavelength-independent sulfur-doped CDs (S-CDs) were used to demonstrate that the S-CDs could distinguish dead cells from live cells for fungal, bacterial, and animal cells. Yu et al. [54] found that S-CDs could reach the interior of the dead cells, allowing the visualization of these cells. On the other hand, live cells cannot be stained by S-CDs because

S-CDs cannot enter the live cells. Moreover, compared with the commercial live/dead staining dye propidium iodide, S-CDs showed better photostability and biocompatibility, indicating a promising future in cell viability assessment and cell-imaging applications.

8. CDs for Pollutant Sensing

Compared with conventional analysis techniques, fluorescence-based sensing has attracted attention because it has some advantages, including great sensitivity, rapid response time, easy operation, low cost, and efficiency [55][56]. Among the various fluorescent carbon nanomaterials, CDs have captivated scientists' interest due to their ability to combine the essential selective receptors on their surface. Due to the ease with which CDs can be surface modified to employ a wide range of intrinsic functional groups, they can rapidly improve their selectivity against specific targets. Theoretically, any fluorescence changes attributed to the concentration of various analytes, such as wavelength, intensity, anisotropy, or longevity, have the possibilities to be used as sensors.

Ji et al. [57] studied the N-doped carbon dots mediated by cetyltrimethylammonium bromide (CTAB/NCDs). The spatial structure created by CTAB/NCDs can selectively collect Hg^{2+} and cause fluorescence quenching by interacting with the surface functional groups of NCDs. The N-doped carbon dots (NCDs) were made in a hydrothermal synthesis. The NCDs were discovered to offer potential as a fluorescence sensor for detecting Hg^{2+} [58]. Static quenching of NCDs by Hg^{2+} could be a viable detection technique. The findings suggested that an NCDs-based sensor could detect Hg^{2+} in a real beverage sample. Zhang et al. [59] reported that red fluorescent InP/ZnS quantum dots (InPQDs), MOFs (ZIF-8), and blue-fluorescent carbon dots (CDs) were merged into nanosensor CDs/InPQDs@ZIF-8 for the successive optical detection of Hg^{2+}, utilizing an in situ synthesis approach. The nano-low-sensor's detection limit and its high specificity and accuracy meet the requirements for safe Hg^{2+} regulating and checking in environmental and drinking water. Furthermore, color recognition and processing software put on a smartphone may detect Hg^{2+} in real time and at a high rate. The CDs doped with Eu^{3+} ions (Eu-CDs) were produced hydrothermally, utilizing citric acid and urea as precursors and $Eu(NO_3)_3$ as a europium source by Correia et al. [60]. The Eu^{3+} ions are strongly linked to the carboxylate groups on the CDs' surfaces and incorporated into the carbon core's nanographene network. CDs doped with Eu^{3+} have higher diameters than CDs that are not doped, but they are split into smaller sp^2 carbon domains. Hg^{2+} and Ag^{+} greatly quench the CDs' luminescence, but other cations had no effect. Depending on the ion's nature, the quenching mechanism varies greatly. The blue emission of CDs is affected by the presence of Ag^{+}. In the case of Hg^{2+}, the blue emission of CDs and the red emission of Eu^{3+} are quenched. Shen et al. [61] used Shewanella oneidensis MR-1 to make fluorescent carbon dots (CDs@MR-1) via a hydrothermal procedure to detect Hg^{2+} and tetracycline water samples. The limits of detection for Hg^{2+} and tetracycline were 0.43 and 0.21 $\mu g \cdot mL^{-1}$, respectively. The internal filtration effect (IFE) causes the fluorescence quenching for tetracycline. On the other hand, along with IFE, dynamic quenching and static quenching mechanisms are involved in detecting Hg^{2+}. The CDs@MR-1 can also identify Gram-positive bacteria from Gram-negative bacteria.

An Fe/N-doped CDs (CDBFe) catalytic amplification Apt method was developed for sensitive and fast SERS/RRS/Abs tri-mode sensing of ultra-trace Pb(II) ions [62]. There is an excellent linear relationship between the SERS intensity and Pb(II) concentration between 1.3 and 16 pM (picomole). Moreover, As(III) and Hg(II) can also be monitored by this assay. A dual-emission ratio fluorescent sensor, N-CDs/R-CDs@ZIF-8, was prepared by mixing N-doped blue fluorescence carbon dots and red fluorescence carbon dots in the environment of ZIF-8 [63]. The addition of Pb^{2+} has a great effect on inhibiting the fluorescence of N-CDs, while showing little influence on the fluorescence of R-CDs. As a result, N-CDs/R-CDs@ZIF-8 can act as a ratiometric fluorescence probe for Pb^{2+} sensing. The functionalized-GQD (F-GQD) was prepared by the edge functionalization of graphene quantum dots (GQDs) by 2,6-diaminopyridine molecules and served as a fluorescent nanoprobe [64]. The F-GQD is a suitable pH sensor in the 2–6 pH range because its fluorescence is very sensitive to the pH of the medium. With the addition of Pb^{2+}, F-GQD exhibits fluorescence turn-on performance. The fluorescence enhancement could be due to nanodot aggregation caused by Pb^{2+}. A fluorescent NCDs (nitrogen-doped carbon dots) sensor can detect the presence of divalent heavy metal ions. The detection limits of Pb^{2+} and Cu^{2+} can reach 3 and 15 ppb, respectively [65]. Additionally, the UV absorbance spectra of NCDs were used to detect Pb^{2+} in a dose-dependent manner.

Cr^{6+} is a toxic heavy metal that bacteria cannot decompose or consume. As a result, the development of a highly selective and sensitive method to detect Cr^{6+} is urgently needed. Wang et al. [49] designed the fluorescence CDs-HS18, prepared from Ureibacillus thermosphaericus, using a hydrothermal method. The CDs-HS18-based fast and selective sensing platform displayed an outstanding linear relation for Cr^{6+} between 0 and 9 μM, with a limit of detection of 36 nM. A majority of reported Cr^{6+} sensors are based on the fluorescence quenching method, whereas the one reported by Chen et al. [66] is performed by the fluorescence enhancement mechanism. Results of TEM, FTIR, X-ray photoelectron spectroscopy, and XRD analysis revealed that Cr^{6+} could increase the probe's fluorescence. The detection phenomenon was established by

conferring the affiliation between the quenching efficiency of CDs-Kan fluorescence intensity and the concentration of Cr^{6+} [67].

N-and-S-co-doped carbon dots (NSCDs) can act as fluorescent probes to detect Cr^{3+}. These NSCDs exhibited strong fluorescence that was quickly quenched by Cr^{3+} even in the presence of other competing ions, demonstrating that NSCD probes have outstanding selectivity and anti-interference ability. The mechanism of fluorescence quenching of NSCD by Cr^{3+} ion may result from the increased non-radiation emission due to the deteriorated NSCD surface. These non-toxic and biocompatible NSCDs could be used to detect Cr^{3+} in living cells [68]. An orange-emission carbon dots (OCDs) were created by using a hydrothermal method. According to TEM analysis, the new OCDs were similar in size, with an average particle size of 4–7 nm [69]. The fluorescence of OCDs was effectively quenched by Cr^{3+}. Notably, OCDs were effectively used for cell-level fluorescence detection of Cr^{3+} ions. N-doped carbon quantum dots (N-CQDs) were created by a top-down method, i.e., •OH radical opening of fullerene with H_2O_2 in a basic environment with ammonia for two different reaction times [70]. N-CQDs were tested for metal ion detection in aqueous solutions and during bioimaging. They exhibited a shift in Cu^{2+} and Cr^{3+} selectivity at a greater extent of $-NH_2$ functionalization.

The copper-doped CDs (Cu-CDs) prepared by a pyrolysis approach were found to have peroxidase-mimicking activity, which reduced the fluorescent intensity of the Cu-CDs-mediated o-phenylenediamine (OPD) oxidized to a fluorescent 2,3-diaminophenazine (DAP) in the presence of H_2O_2 via the generation of •OH radicals. The Cr^{6+} species were reduced to Cr^{3+} by using the reductant 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonate) (ABTS). Moreover, the fluorescent intensity of DAP is proportional to the Cr^{3+} content within the range of 5×10^{-6} to 1.5×10^{-4} M. It can be used to determine Cr^{6+} and Cr^{3+} levels in water samples[71].

Fluorescent CQDs synthesized from crab-shell waste by a hydrothermal process exhibited excellent Cd^{2+} sensing and antibacterial activity. CQDs exhibited bright green fluorescence and exorbitant quenching of Cd^{2+} ions in aqueous media under UV light irradiation [72]. Wang et al. [73] reported gold nanoclusters (AuNCs) as fluorescence molecules with red emission, while N-and-S-co-doped CDs (N,S-CDs) were reported as signaling molecules. The fluorescence quenching is caused by the fluorescence resonance energy transfer (FRET) effect between N,S-CDs and AuNCs. The added Cd^{2+} can interact with AuNCs to form complexes and interact with the O atoms in the carboxyl and hydroxyl groups of N,S-CDs, resulting in a stable complex, causing N,S-CDs/AuNCs to aggregate, and then resulting in enhanced fluorescence. The addition of Cd^{2+} led to increased fluorescence intensities of N,S-CDs (F435) and AuNCs (F630).

Wu et al. [74] synthesized green fluorescence CDs (GCDs) by using 1,4-dihydroxyanthraquinone. The GCDs based sensor is used as a dual-mode visual sensor based on “off-on” fluorescence analysis to detect Cu^{2+} and glyphosate. Turn-off fluorescence was observed when adding Cu^{2+} to GCDs, indicating a strong binding interaction between GCDs and Cu^{2+} ions. While turn-on fluorescence was observed after adding glyphosate to GCDs/Cu^{2+}, these studies suggest that Cu^{2+} has more binding sites to glyphosate than other competing pesticides. A GCDs-based smart-sensing membrane was applied to detect glyphosate on vegetable surfaces. The QY of NCDs can be elevated by liquid-liquid extraction and purification. NCDs have the potential to be an excellent multifunctional sensing platform for Cu^{2+} and tetracycline antibiotics (TCs) such as oxytetracycline (OTC), tetracycline hydrochloride (TC), demeclocycline hydrochloride (DMC), doxycycline hydrochloride (DC), and minocycline hydrochloride (MC). Compared to other coexisting metal ions and antibiotics, this platform responded differently to Cu^{2+} and TCs. IFE and static quenching were identified as the fluorescent quenching mechanisms of Cu^{2+} , TC, NCD。

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