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# Synthesis and Application of Fluorescent Carbon Dots

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**ABSTRACT** : ***Fluorescent carbon dots (CDs) are emerging nanomaterials with exceptional optical properties, biocompatibility, and versatile applications in biomedical imaging, drug delivery, environmental sensing, and catalysis. CDs, characterized by their small size and unique fluorescence, can be synthesized using top-down or bottom-up approaches, offering control over their size, structure, and surface functionalization. Their ability to provide high-resolution imaging, targeted drug delivery, and efficient pollutant detection highlights their multifunctionality. Despite their vast potential, challenges such as scalability and reproducibility remain barriers to widespread application. activated carbon was chemically prepared using Peach crusts (agriculturalwaste) as renewable resource.The prepared activated carbon wasmodified by introducing two transition metal ions in its framework; Mn and Fe metal ions. This mini-review explores advancements in CDs synthesis methods and highlights their transformative role in nanotechnology, medicine, and environmental science. Unlike green diesel, biodiesel can only be used in diesel engines blended with diesel in order to avoid excessive build-up of carbon in diesel engines. Therefore, production of green fuel from catalytic cracking is getting more attention.***

KEYWORDS: **Fluorescent Carbon Dots; Biomedical Imaging; Synthesis Activated Carbon**.

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## I. INTRODUCTION

Fluorescent carbon dots (CDs) are a class of nanomaterials that have garnered significant attention in recent years due to their unique properties and versatile applications. These nanostructures, typically ranging from 1 to 10 nanometers in size, are composed primarily of carbon and exhibit excellent optical properties [1], including strong photoluminescence, high stability, and low toxicity. The development of carbon dots represents a significant advancement in nanotechnology, bridging the gap between traditional fluorescent materials and carbon-based nanomaterials [2]. The origins of carbon dots can be traced back to the discovery of carbon nanoparticles with fluorescent properties. Initially, these materials were considered byproducts of the carbonization of organic compounds. However, extensive research has led to a deeper understanding of their synthesis, structure, and potential applications [3]{Alas, 2020 #3024}. This has positioned carbon dots as promising candidates for various fields, including biomedical imaging, sensing, drug delivery, and catalysis. The intrinsic properties of carbon dots make them highly attractive for numerous applications. Their strong fluorescence is primarily due to the quantum confinement effect, which occurs when the size of the nanoparticles approaches the exciton Bohr radius. This phenomenon leads to changes in the electronic and optical properties of the material, resulting in enhanced fluorescence. Furthermore, carbon dots exhibit excellent photostability, which is crucial for applications that require prolonged exposure to light without degradation [4-6].

Another significant advantage of carbon dots is their biocompatibility and low cytotoxicity. Unlike traditional semiconductor quantum dots, which often contain heavy metals such as cadmium and lead, carbon dots are composed entirely of carbon, making them safer for biological applications. This characteristic has spurred interest in their use in biomedical fields, particularly in imaging and therapeutic applications. The synthesis of carbon dots can be broadly categorized into two main approaches: top-down and bottom-up methods. Top-down approaches involve the

fragmentation of larger carbon materials into nanoscale dots. Techniques such as laser ablation, electrochemical oxidation, and chemical oxidation fall under this category. These methods typically result in CDs that possess varied sizes and surface properties, requiring further modification for specific applications [7-10].

Conversely, bottom-up approaches involve the assembly of carbon dots from smaller precursors. This includes methods such as hydrothermal synthesis, microwave-assisted synthesis, and thermal pyrolysis. These techniques allow for better control over the size, shape, and surface functionalization of the resulting carbon dots, leading to enhanced optical properties and functionality. The applications of fluorescent carbon dots are vast and varied, spanning multiple disciplines. In the biomedical field, carbon dots have shown great promise, particularly in imaging and drug delivery. Their strong fluorescence enables high-resolution imaging of biological tissues, providing a non-invasive means to monitor cellular processes in real time. Additionally, the surface of carbon dots can be easily functionalized with various biomolecules, enhancing their targeting capabilities for specific cells or tissues. This feature is particularly useful in cancer therapy, where targeted drug delivery can significantly improve treatment efficacy while minimizing side effects [11-14].

Moreover, carbon dots have been explored for use in photothermal therapy. When exposed to near-infrared light, these nanomaterials can generate heat, leading to localized hyperthermia that can destroy cancer cells. This dual function of imaging and therapy, known as theranostics, positions carbon dots as cutting-edge tools in personalized medicine. The unique optical properties of carbon dots also make them ideal candidates for sensing applications. Their fluorescence can be sensitive to environmental changes, such as pH, temperature, and the presence of specific ions or biomolecules. This sensitivity allows for the development of highly selective biosensors capable of detecting pathogens, toxins, and other harmful substances in real time [15-17]. For example, carbon dot-based biosensors have been successfully developed for the detection of heavy metals and biological markers, offering a cost-effective and efficient alternative to traditional sensing methods. The ability to tailor the surface chemistry of carbon dots further enhances their functionality, enabling the design of sensors with specific binding capabilities. In addition to their roles in imaging and sensing, carbon dots have demonstrated significant potential in catalytic applications. Their small size and high surface area facilitate rapid electron transfer, making them effective catalysts in various chemical reactions. Carbon dots have been used in photocatalytic processes to degrade pollutants and in electrocatalytic applications for energy conversion and storage [18-20].

The ability to tune the electronic properties of carbon dots through doping and functionalization opens new avenues for their use in catalysis. For instance, incorporating heteroatoms such as nitrogen, sulfur, or phosphorus can enhance their catalytic activity and selectivity, paving the way for greener and more efficient chemical processes. Despite their promising properties and applications, several challenges must be addressed to fully realize the potential of carbon dots. One major challenge is the scalability of synthesis methods. Many current production techniques are limited to laboratory-scale operations, making it difficult to produce carbon dots in quantities suitable for commercial applications. Developing scalable and cost-effective synthesis routes is crucial for the widespread adoption of carbon dots in industry [20-22].

Another challenge lies in the stability and reproducibility of carbon dots. Variations in synthesis conditions can lead to inconsistencies in the properties of the resulting materials, which can impact their performance in applications. Standardizing synthesis protocols and understanding the underlying mechanisms of carbon dot formation will be key to overcoming this issue. In summary, fluorescent carbon dots represent a remarkable advancement in nanotechnology, offering a plethora of applications across various fields. Their unique properties, including strong fluorescence, low toxicity, and biocompatibility, make them ideal candidates for use in biomedical imaging, sensing, and catalysis. As research continues to uncover new synthesis methods and applications, carbon dots are poised to make significant contributions to the fields of nanomedicine, environmental monitoring, and green catalysis. Addressing the current challenges related to scalability and reproducibility will be essential for unlocking the full potential of these versatile nanomaterials, paving the way for innovative solutions to complex problems in science and technology [22-25].

## II. MATERIALS AND METHODS

### 2.1. Synthesis of Carbon Dots

Carbon dots (CDs), as a class of zero-dimensional nanomaterials, have garnered significant attention due to their outstanding optical properties, chemical stability, biocompatibility, and versatile applications across various fields. Among the synthesis methods for CDs, top-down approaches involve the transformation of larger carbonaceous materials into nanometer-sized particles through different techniques. These methods are versatile, enabling the tailoring of CDs with desired physical and chemical properties. Below, we detail the major top-down approaches, including chemical oxidation, laser ablation, and electrochemical techniques, with examples from the literature. Top-down approaches offer several advantages, such as the ability to use abundant and inexpensive precursors, controllable reaction conditions, and the potential for large-scale production. However, these methods also present limitations, including the generation of waste materials, relatively low quantum yields, and possible structural defects in the CDs.

### 2.2. Chemical Oxidation

Chemical oxidation is a widely used top-down method that involves breaking down bulk carbon-rich materials such as graphite, carbon nanotubes, or activated carbon into CDs through strong oxidizing agents. The process typically results in the introduction of surface functional groups, enhancing the hydrophilicity and luminescence of CDs. For example, ***Tian et al.*** were among the first to synthesize CDs using chemical oxidation, where they oxidized carbon soot with a mixture of nitric acid and sulfuric acid. The resultant CDs exhibited strong blue photoluminescence under UV light [4]. Similarly, ***Cayuela et al*** reported the synthesis of CDs by oxidizing multi-walled carbon nanotubes (MWCNTs) with concentrated nitric acid [5]. The functionalized CDs showed enhanced dispersibility in aqueous solutions, with quantum yields suitable for bioimaging applications [6]. Despite its effectiveness, the chemical oxidation method has limitations, such as prolonged reaction times and the generation of large quantities of acidic waste, which necessitates post-treatment for environmental safety. Furthermore, the method may introduce defects or overoxidation on the CD surface, potentially impacting their luminescence efficiency [7].

### 2.3. 2.3. Laser Ablation

Laser ablation is another top-down method that uses high-energy laser pulses to break down bulk carbon materials into CDs. This technique offers precise control over the size and morphology of the resultant CDs by varying parameters such as laser wavelength, energy, and ablation medium. For instance, ***Habiba et al.*** [8] synthesized CDs by ablating a graphite target submerged in a mixture of water and ethanol using a nanosecond-pulsed Nd:YAG laser. The CDs produced displayed stable photoluminescence and were later functionalized with polyethylene glycol for biocompatibility studies. In another study, ***Zhou et al.*** [9] used laser ablation to synthesize nitrogen-doped CDs from a graphite target in an ammonia solution, resulting in CDs with enhanced photoluminescence and surface passivation. Laser ablation is advantageous because it avoids the use of harsh chemicals and allows for the simultaneous doping of CDs. However, the method is limited by the high cost of laser equipment and the relatively low yield of CDs [10].

## 2.4. Electrochemical Techniques

Electrochemical methods involve applying an electric potential to carbon-rich electrodes immersed in an electrolyte solution to induce the formation of CDs. This approach is known for its simplicity, scalability, and ability to produce CDs with tunable surface properties. For example, ***He et al.*** [11] synthesized CDs by electrochemically exfoliating graphite rods in an aqueous electrolyte solution containing ammonia. The resulting nitrogen-doped CDs exhibited strong blue photoluminescence and potential for bioimaging applications [12]. Similarly, ***Wang et al.*** [13] developed a one-step electrochemical method using graphite as the anode and a platinum wire as the cathode in a phosphate buffer solution. The synthesized CDs showed excellent stability and were applied in the detection of ferric ions ($Fe^{3+}$) [14]. Electrochemical methods provide several advantages, including eco-friendliness, mild reaction conditions, and the ability to incorporate heteroatoms such as nitrogen, sulfur, or phosphorus during the synthesis process. However, the yield of CDs can be limited by the efficiency of the exfoliation process, and optimization of the reaction parameters is often required.

### 2.5. Bottom-Up Approaches

Bottom-up synthesis entails the assembly of carbon dots from smaller precursors. This approach allows for better control over the properties of the resulting dots. The following subsections describe key bottom-up methods, including hydrothermal and solvothermal carbonization, microwave-assisted synthesis, and thermal pyrolysis and template-assisted methods. Bottom-up approaches provide excellent control over the size, morphology, and surface properties of CDs, enabling their use in specialized applications. These methods are generally eco-friendly and scalable. However, challenges include the potential for residual precursor materials and the need for precise control over reaction conditions to achieve uniform properties.

### 2.6. Hydrothermal and Solvothermal Carbonization

These methods involve heating organic precursors in a sealed environment, such as an autoclave, to promote carbonization and the formation of CDs. Common precursors includes citric acid, glucose, and amino acids. Hydrothermal and solvothermal methods are cost-effective and eco-friendly, making them popular in research. For instance, ***Ma et al.*** [15] synthesized CDs by heating citric acid and ethylenediamine in a hydrothermal reactor. The resulting CDs exhibited excellent fluorescence properties and were used for cellular imaging. Similarly, ***Huang et al.*** [16] used solvothermal carbonization to synthesize CDs from urea and phenylenediamine, producing nitrogen-doped CDs with enhanced photoluminescence and quantum yields.

### 2.7. Microwave-Assisted Synthesis

Microwave-assisted synthesis is a rapid and energy-efficient method for producing CDs. This technique uses microwave radiation to heat the precursors, resulting in high yields and uniform properties of CDs. For example, ***Zhu et al.*** [17] developed a microwave-assisted method to synthesize CDs from polyethylene glycol and saccharides. The process was completed within minutes, and the CDs demonstrated strong photoluminescence and biocompatibility. Similarly, ***Fu et al.*** [18] synthesized sulfur-doped CDs using a microwave-assisted approach with thiourea as the dopant. The CDs showed enhanced optical properties and were applied in the detection of heavy metal ions.

### 2.8. Thermal Pyrolysis and Template-Assisted Methods

Thermal pyrolysis involves heating organic precursors at high temperatures in an inert atmosphere, leading to the formation of CDs. Template-assisted methods use structured materials, such as silica or zeolites, as templates to control the size and morphology of CDs. For instance, ***Wang et al.*** [19] synthesized CDs through thermal pyrolysis of citric acid, achieving tunable fluorescence properties by varying the reaction temperature. Template-assisted methods were employed by ***Wang et al***., [20] who used mesoporous silica as a template to produce size-controlled CDs with uniform morphology. These CDs were applied in drug delivery and bioimaging. **Figure 1** representation comparing various synthesis routes for carbon quantum dots (CQDs) and graphene quantum dots (GQDs). The diagram highlights key techniques, including chemical oxidation, laser ablation, and hydrothermal synthesis, along with their respective characteristics [21].

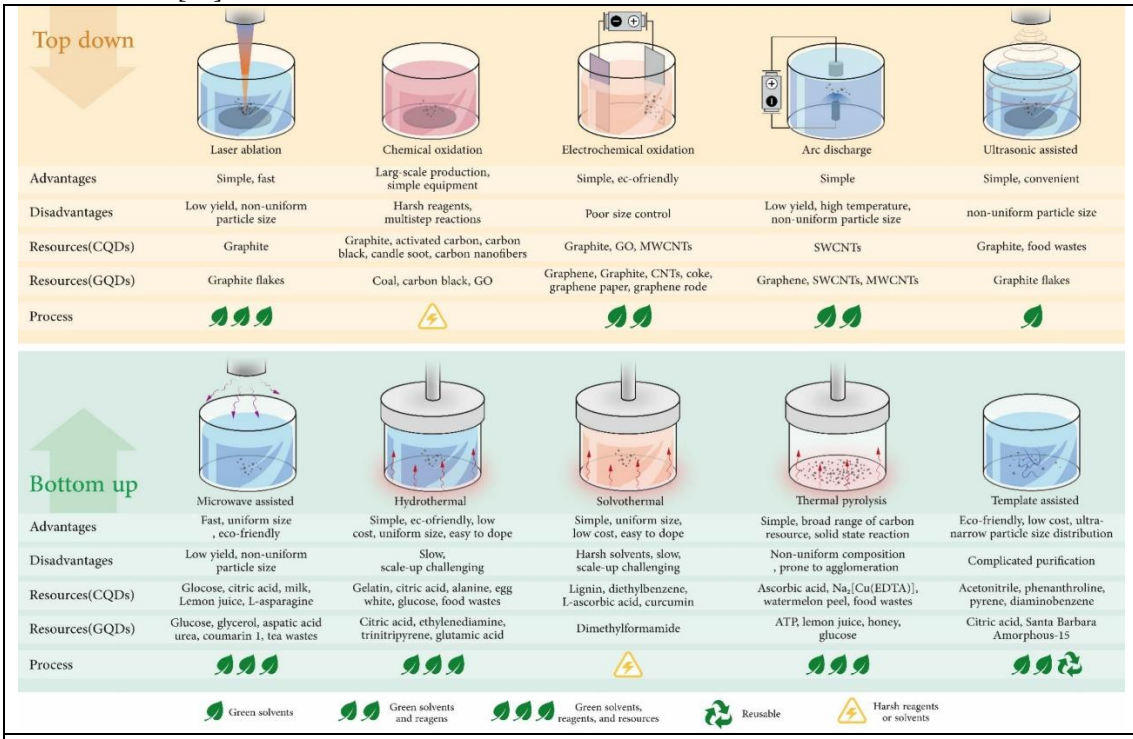


**Figure 1.** Schematic comparison of different routes for synthesizing CQDs and GQDs.

## III. APPLICATIONS OF CARBON DOTS

### 3.1 Biomedical Applications

Fluorescent carbon dots have shown great promise in biomedical applications, particularly in imaging and drug delivery. Their biocompatibility and low toxicity enable their use in vivo.

#### 3.1.1. Bioimaging

Fluorescent carbon dots (CDs) have emerged as a superior alternative to traditional fluorescent dyes and quantum dots in bioimaging due to their exceptional photoluminescence, biocompatibility, low toxicity, and cost-effective synthesis. One of the key advantages of CDs in bioimaging is their tunable emission spectra, which can be adjusted by varying their synthesis conditions or modifying their surface properties. CDs provide stable fluorescence with minimal photobleaching, making them ideal for long-term imaging applications. For example, ***Lei et al.*** [22] demonstrated the potential of CDs as imaging agents in biological systems. CDs synthesized via laser ablation displayed stable fluorescence, which was later enhanced by surface functionalization with polyethylene glycol (PEG). These CDs were successfully used for labeling cancer cells, enabling clear visualization under fluorescence microscopy. Similarly,

***Mao et al.*** [23] reported the synthesis of CDs from citric acid, which were applied in live-cell imaging. The CDs penetrated cell membranes effectively and emitted strong blue fluorescence, providing high-contrast images without harming the cells.
Another remarkable example is the study by ***Zhang et al.*** [24] where nitrogen-doped CDs synthesized via hydrothermal methods were used for real-time imaging of zebrafish embryos. These CDs exhibited multicolor fluorescence, enabling researchers to observe intricate biological processes at different developmental stages. The low toxicity and rapid clearance of CDs from the body further emphasize their potential for in vivo imaging [25].
Moreover, CDs have been explored for deep-tissue imaging due to their near-infrared (NIR) fluorescence. ***Ding et al.*** [26] developed CDs with NIR emission, which were applied for imaging mouse tissues. The CDs provided clear images at depths exceeding those achievable with visible-light-emitting probes, offering a significant advantage in preclinical and clinical diagnostics. Despite their numerous advantages, challenges remain in optimizing CDs for bioimaging. Enhancing their quantum yield, improving their stability in biological environments, and ensuring precise targeting require further research [27]. Surface functionalization with targeting ligands such as antibodies, peptides, or folic acid has shown promise in addressing these limitations. For instance, ***Jurczyk et al.*** [28] functionalized CDs with folic acid to specifically target cancer cells, achieving high imaging precision while minimizing off-target effects.

### 3.1.2. Drug Delivery

Carbon dots have shown tremendous promise in drug delivery systems due to their small size, high surface area, biocompatibility, and ease of functionalization. Their ability to conjugate with therapeutic agents, including small molecules, proteins, and nucleic acids, enables the targeted delivery of drugs to specific cells or tissues, minimizing side effects and enhancing therapeutic efficacy. A key feature of CDs in drug delivery is their ability to cross biological barriers such as cell membranes. This property allows CDs to deliver drugs directly into cells, enhancing treatment outcomes. For instance, ***Li et al.*** [29] developed CDs functionalized with doxorubicin (DOX), a widely used chemotherapy drug. The CD-DOX conjugates showed efficient cellular uptake and selective accumulation in cancer cells, resulting in enhanced cytotoxicity against tumor cells while sparing healthy tissues [30]. Another notable study by ***Qu et al.*** [31] utilized CDs synthesized from glucose for delivering the anti-inflammatory drug ibuprofen. The CDs were conjugated with ibuprofen via ester bonds, ensuring controlled drug release in response to changes in pH. This property was beneficial for targeting inflamed tissues, where the acidic environment triggered drug release, providing localized therapeutic effects [32].

Targeted drug delivery has also been explored using CDs conjugated with specific ligands. For example, ***Cabral Filho et al.*** [33] developed CDs functionalized with transferrin, a protein that binds to transferrin receptors overexpressed on cancer cells. The CDs were loaded with paclitaxel, a chemotherapeutic agent, and showed enhanced uptake by cancer cells, resulting in improved treatment outcomes. Furthermore, CDs have been employed for delivering genetic material, such as small interfering RNA (siRNA) and plasmid DNA, for gene therapy applications [21]. ***Mohammadi et al.*** [34] synthesized cationic CDs that formed stable complexes with siRNA, enabling efficient delivery into cells and effective gene silencing. This approach has potential for treating genetic disorders and cancers.

The surface of CDs can also be modified with stimuli-responsive moieties, enabling controlled drug release [35]. For instance, ***Wang et al.*** [36] developed CDs coated with a thermoresponsive polymer that released drugs upon exposure to elevated temperatures. This feature could be utilized in hyperthermia-based cancer therapies, where localized heating triggers drug release at the tumor site. Despite their advantages, challenges in drug delivery using CDs include potential toxicity at high doses, limited drug-loading capacity, and ensuring stability in biological environments. Addressing these challenges through optimized synthesis and surface engineering will pave the way for broader clinical applications [37]. **Figure 2** demonstration of CQDs for bacterial detection. (A) SEM images of untreated and CQDs-treated *E. coli* and *S. aureus*. (B) Surface-functionalized nanofibers for fluorescence recovery in detecting *S. aureus*. (C) Smartphone-based ECL system for *E. coli* detection. (D) Bacterial shape alterations before and after antibiotic treatment captured on nanoporous alumina membranes.

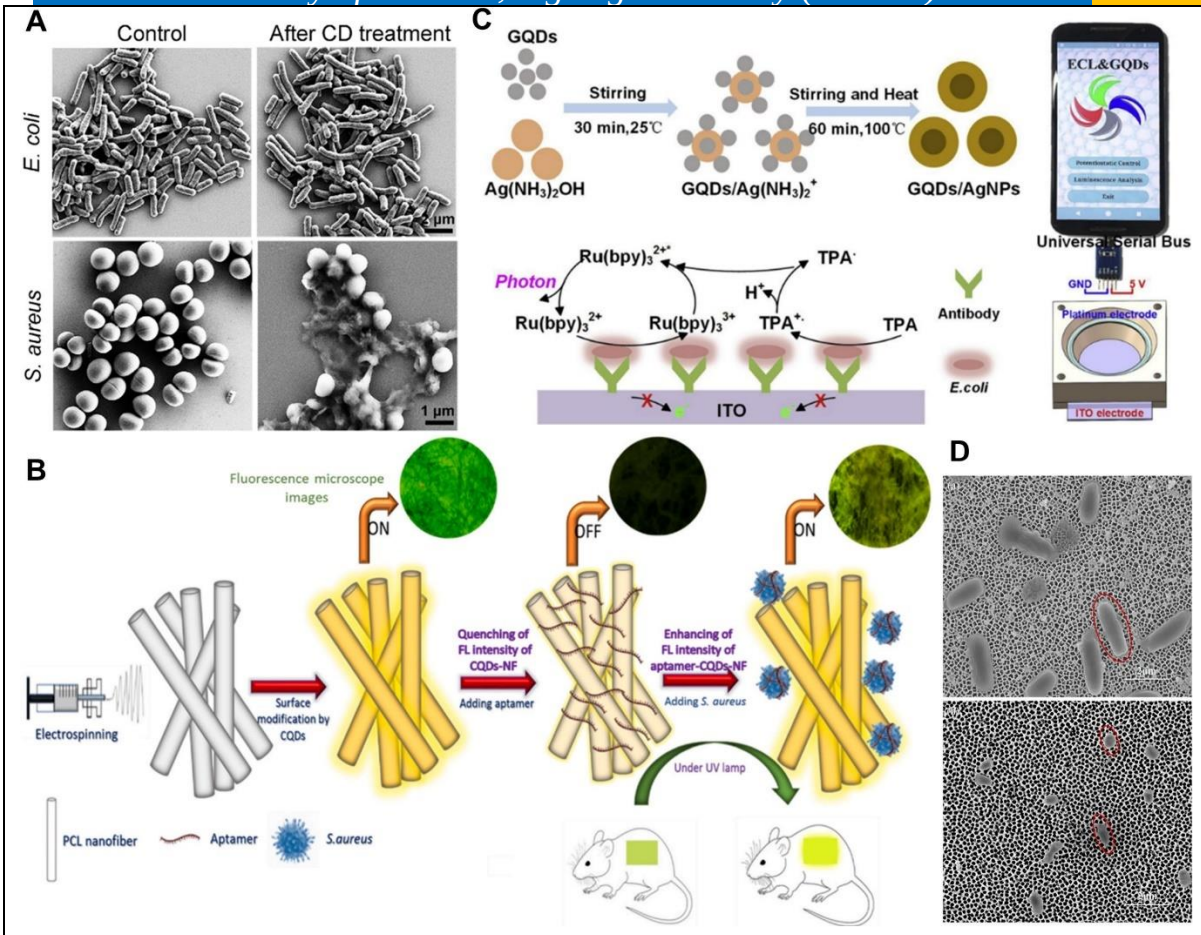


**Figure 2** Use of CQDs for bacterial detection. (A) SEM images of *E. coli* and *S. aureus* cells without (left) or with (right) the treatment of CQDs. (B) Surface functionalize of nano-fibers with CQDs and an aptamer and the recovery of fluorescence intensity in the presence of *S. aureus* bacteria. (C) Smartphone-based ECL system for *E.coli* detection. (D) SEM image of bacteria captured on a nanoporous alumina membrane. The red ellipses indicated the shape changes before and after antibiotics treatment.

### 3.2. Sensing Applications

Carbon dots (CDs) have garnered significant attention for their applications in sensing due to their unique optical properties, including strong fluorescence, high photostability, tunable emission, and sensitivity to environmental changes. These attributes make CDs highly suitable for detecting a wide range of biological and chemical analyses with high precision and sensitivity.

#### 3.2.1. Biosensors

CDs are widely utilized as fluorescence probes in biosensors. Their fluorescence can be modulated through quenching, enhancement, or spectral shifts in response to interactions with specific target analytes, enabling sensitive and selective detection. The small size, biocompatibility, and functionalizability of CDs make them ideal candidates for biosensing applications. For example, ***Wang et al.*** [38] reported the development of CDs for glucose detection. CDs functionalized with glucose oxidase exhibited fluorescence quenching upon exposure to glucose due to the production of hydrogen peroxide during the enzymatic reaction. This simple and effective approach enabled rapid and sensitive detection of glucose in biological samples, making it highly applicable in diabetes monitoring. In another study, ***Xu et al.*** [39] demonstrated the use of CDs for detecting dopamine, an important neurotransmitter associated with various neurological disorders. The CDs were synthesized using citric acid and urea and showed fluorescence quenching upon interaction with dopamine due to its electron-donating properties. This biosensor was capable of detecting dopamine at nanomolar concentrations, highlighting its potential in clinical diagnostics. CDs have also been explored for nucleic acid detection, offering high specificity through complementary hybridization. ***Li et al.*** [40] developed CDs

functionalized with single-stranded DNA probes to detect target DNA sequences. The presence of the target DNA induced a conformational change in the probe, resulting in fluorescence enhancement. This approach was successfully applied to detect genetic mutations linked to diseases such as cancer [41].

Additionally, CDs have been used in immunosensors for detecting specific proteins or antigens. For instance, ***Pirsaheb et al.*** [42] developed CDs conjugated with antibodies for detecting carcinoembryonic antigen (CEA), a biomarker for cancer. The interaction between CEA and the antibodies caused fluorescence quenching, enabling quantitative analysis of the biomarker with high sensitivity and specificity. Despite their potential, challenges in biosensing with CDs include ensuring reproducible synthesis, minimizing interference from complex sample matrices, and optimizing their surface chemistry for specific analyses. Ongoing research is focused on addressing these limitations and expanding the range of applications in medical diagnostics and health monitoring [43].

### 3.2.2. Environmental Monitoring

The ability of CDs to detect pollutants, toxins, and heavy metals in environmental samples has positioned them as valuable tools for environmental monitoring. Their fluorescence changes in response to specific contaminants, enabling sensitive and real-time detection in water, soil, and air samples. For instance, CDs have been employed for detecting heavy metals such as mercury ($Hg^{2+}$) and lead ($Pb^{2+}$), which pose significant risks to human health and the environment [44]. ***Yan et al.*** [45] synthesized sulfur-doped CDs that exhibited selective fluorescence quenching in the presence of $Hg^{2+}$ ions. The detection limit was as low as 0.5 nM, making this system suitable for monitoring mercury contamination in water sources. Similarly, ***Atchudan et al.*** developed nitrogen-doped CDs for $Pb^{2+}$ detection. These CDs showed a fluorescence shift upon binding with lead ions, enabling rapid and precise detection in complex environmental samples [46]. The method was successfully applied to analyze water samples from industrial discharge sites. CDs have also been utilized for detecting organic pollutants, such as pesticides and dyes. For example, ***Zhang et al.*** [47] developed CDs functionalized with amino groups to detect paraquat, a widely used herbicide known for its toxicity. The CDs exhibited fluorescence quenching in the presence of paraquat, enabling its detection at micromolar concentrations.

Moreover, CDs have been explored for monitoring air quality by detecting volatile organic compounds (VOCs). ***Tachapermpon et al.*** [48] synthesized CDs that showed fluorescence changes in the presence of formaldehyde, a harmful VOC commonly found in indoor environments. This sensor demonstrated real-time monitoring capabilities, making it useful for ensuring air safety in residential and industrial settings. The versatility of CDs in environmental monitoring extends to detecting multiple analytes simultaneously. By doping CDs with different elements or functional groups, researchers have developed multicolor sensors capable of distinguishing between various pollutants [49]. For instance, ***Hu et al.*** [50] created CDs with dual-emission properties for detecting both nitrite and nitrate ions in water, achieving simultaneous and accurate quantification. **Figure 3:**
highlights CDs use in glucose detection via enzymatic reactions, dopamine sensing through fluorescence quenching, and nucleic acid detection by complementary hybridization. The versatility of CDs as fluorescence probes showcases their potential in medical diagnostics and health monitoring [51].

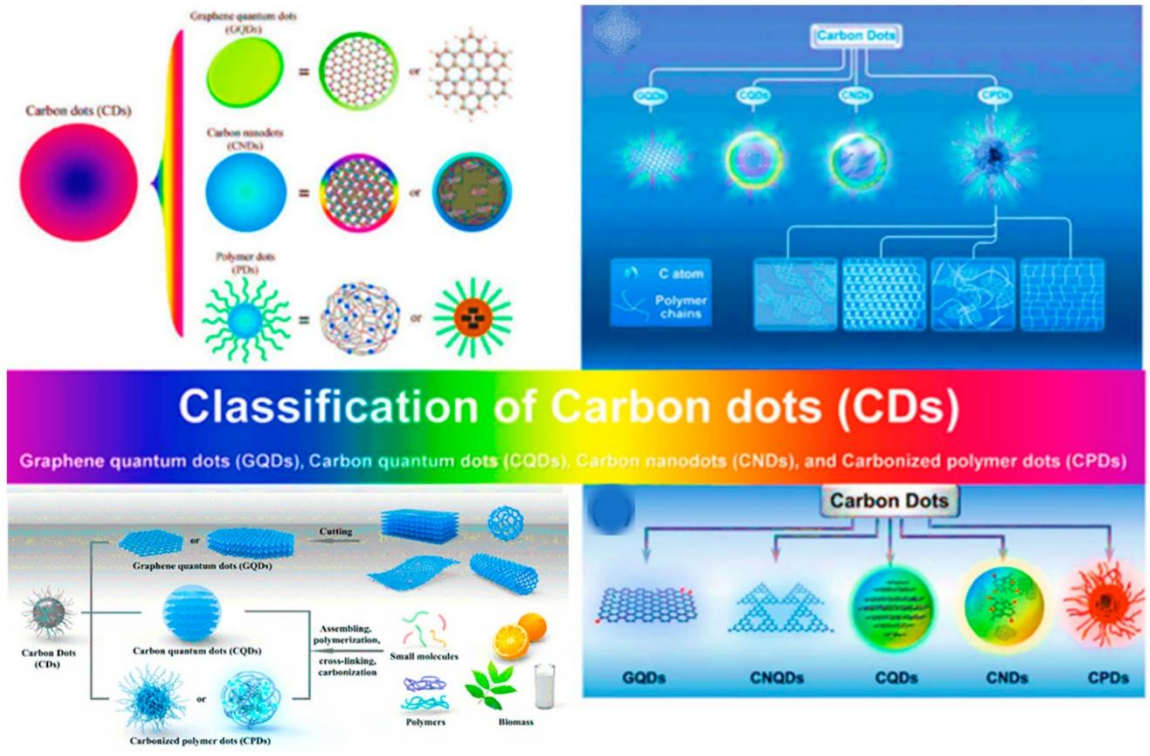


**Figure 3.** Classification of CDs using different preparation approaches.

### 3.3. Catalytic application

Fluorescent carbon dots (CDs) exhibit remarkable catalytic properties that enable their use in various chemical reactions, particularly in photocatalysis and electrocatalysis. Their small size, tunable bandgap, excellent photostability, and electrical conductivity make them versatile catalysts for energy and environmental applications.

3.3.1. **Photocatalysis**:

Carbon dots can function as effective photocatalysts under light irradiation, facilitating chemical transformations such as pollutant degradation, water splitting, and organic synthesis [52]. For instance, nitrogen-doped carbon dots have been shown to degrade dyes like rhodamine B and methylene blue under visible light. This photocatalytic activity arises from the ability of CDs to generate reactive oxygen species (ROS), such as hydroxyl radicals and singlet oxygen, which break down pollutants into non-toxic by-products [53]. Another application includes using CDs in hydrogen generation via water splitting, where they act as co-catalysts to enhance solar energy conversion efficiency. Studies have demonstrated that carbon dots, when coupled with semiconductors like titanium dioxide ($TiO_2$), improve the light-harvesting ability and overall photocatalytic performance.

3.3.2. **Electrocatalysis**:

The high conductivity of carbon dots enables their use as electrocatalysts in applications such as fuel cells and sensors. In the oxygen reduction reaction (ORR), a critical process in fuel cells, CDs functionalized with heteroatoms (e.g., nitrogen, sulfur) exhibit high activity and durability, offering a cost-effective alternative to traditional platinum-based catalysts. Additionally, carbon dots have been integrated into electrochemical sensors to detect biomolecules like dopamine, glucose, and uric acid, with impressive sensitivity and selectivity. **Figure 4** Illustration of CDs' synthesis mechanism and optical properties. (a) Overview of synthesis methods with red emissive CDs' PL spectrum. (b) Multicolor emissive CDs. (c) Optical properties across multiple fluorescence types. Images reproduced with permission from referenced sources [54].

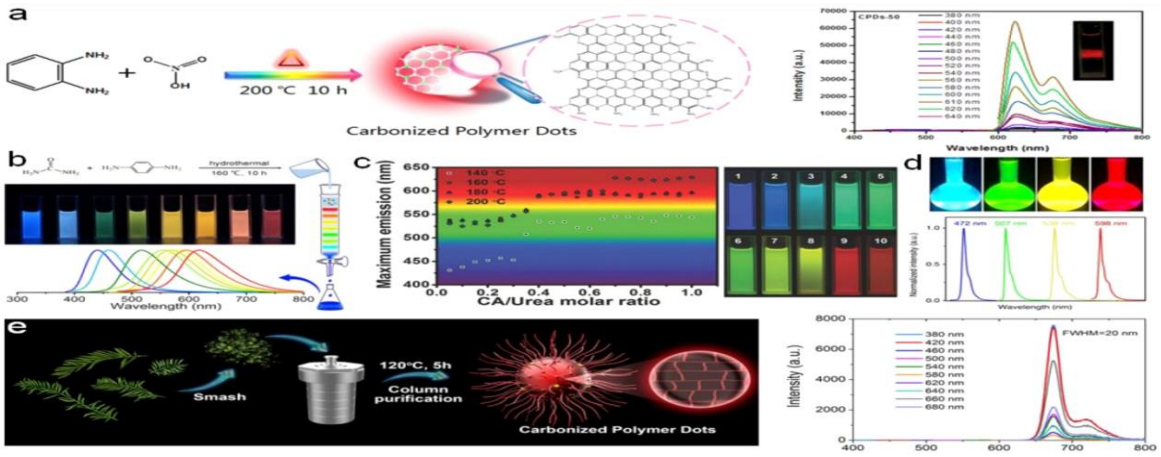


**Figure 4** Synthesis mechanism and optical characteristics of CDs. (a) synthesis method and PL spectrum of red emissive type CPDs as well as (b) multicolor type CPDs . Optical characteristics of (c) multicolor emissive CPDs as well as CQDs . Synthesis method and PL spectrum of deep red emissive type CPDs .

## IV. CONCIUSIONS

The advancements in the synthesis and application of fluorescent carbon dots highlight their potential in various fields. Continued research is necessary to optimize synthesis methods and explore new applications. Future studies should focus on integrating carbon dots with other nanomaterials to enhance their properties and functionalities. As challenges such as scalability and stability are addressed, carbon dots are poised to play a crucial role in the future of nanotechnology and its applications in medicine, sensing, and catalysis.

## VI.REFERENCES

1. **Zuo J., Jiang T., Zhao X., Xiong X., Xiao S., Zhu Z. (2015).** Preparation and application of fluorescent carbon dots. Journal of Nanomaterials, 2015 (1), 787862.
2. **Alas M.O., Alkas F.B., Sukuroglu A.A., Alturk R.G., Battal D. (2020).** Fluorescent carbon dots are the new quantum dots: an overview of their potential in emerging technologies and nanosafety, Journal of Materials Science, **55**, 15074-15105.
3. **Zheng X. T., Ananthanarayanan A., Luo K.Q., Chen P. (2015).** Glowing graphene quantum dots and carbon dots: properties, syntheses, and biological applications, Small, **11**(14), 1620-1636.
4. **Tian X.T., Yin X.B. (2019).** Carbon dots unconventional preparation strategies, and applications beyond photoluminescence, Small, **15**(48), 1901803.
5. **Cayuela A., Soriano M.L., Valcárcel M. (2015).** Photoluminescent carbon dot sensor for carboxylated multiwalled carbon nanotube detection in river water, Sensors and Actuators B: Chemical, **207**, 596-601.
6. **Zebibula A., Alifu N., Xia L., Sun C., Yu X., Xue D., Liu L., Li G., Qian J. (2018).** Ultrastable and biocompatible NIR-II quantum dots for functional bioimaging, Advanced Functional Materials, **28**(9), 1703451.
7. **Xu Q., Li B., Ye Y., Cai W., Li W., Yang C., Chen Y., Xu M., Li N., Zheng X., Street J., Luo Y., Cai L. (2018).** Synthesis, mechanical investigation, and application of nitrogen and phosphorus co-doped carbon dots with a high photoluminescent quantum yield, Nano Research, 11, 3691-3701.
8. **Habiba K., Makarov V. I., Weiner B. R., Morell G. (2014).** Fabrication of nanomaterials by pulsed laser synthesis. In W. Ahmed (Ed.), Manufacturing Nanostructures (Chapter 10, pp. 263–292). One Central

Press.
9. **Zhou J., Zhou H., Tang J., Deng S., Yan F., Li W., Qu M. (2017).** Carbon dots doped with heteroatoms for fluorescent bioimaging: a review, Microchimica Acta, 184(2), 343–368.
10. **Zhang Y., Lu S. (2024).** Lasing of carbon dots: Chemical design, mechanisms, and bright future, Chem, 10(1), 134–171.
11. **He C., Xu P., Zhang X., Long W.-J. (2022).** The synthetic strategies, photoluminescence mechanisms and promising applications of carbon dots: Current state and future perspective, Carbon, 186, 91–127.
12. **Liao J., Cheng Z., Zhou L. (2016).** Nitrogen-doping enhanced fluorescent carbon dots: Green synthesis and their applications for bioimaging and label-free detection of $Au^{3+}$ ions, *ACS Sustainable Chemistry & Engineering*, 4(6), 3053–3061.
13. **Wang Q., Zhang J., Xu Y., Wang Y., Wu L., Weng X., You C., Feng J. (2021).** A one-step electrochemically reduced graphene oxide based sensor for sensitive voltammetric determination of furfural in milk products, Analytical Methods, 13(1), 56–63.
14. **Hashemi N., Mousazadeh M. H. (2021).** Preparation of fluorescent nitrogen-doped carbon dots for highly selective on-off detection of $Fe^{3+}$ ions in real samples, Optical Materials, 121, 111515.
15. **Ma C., Gemma F., Shi L., Bingjie L. (2024).** Exploration of the Synthesis, Properties, and Biological Applications of B-CDs Materials. *TechRxiv*.
16. **Huang Z.Y., Wu W.Z., Li Z.X., Wu Y., Wu C. B., Gao J., Guo J., Chen Y., Hu Y., Huang, C. (2022).** Solvothermal production of tea residue derived carbon dots by the pretreatment of choline chloride/urea and its application for cadmium detection, Industrial Crops and Products, 184, 115085.
17. **Zhu, Y.J., Chen, F. (2014).** Microwave-assisted preparation of inorganic nanostructures in liquid phase, Chemical Reviews, 114(12), 6462–6555.
18. **Fu Q., Li N., Lu K., Dong Z., Yang, Y. (2024).** The emerging development of nitrogen and sulfur co-doped carbon dots: Synthesis methods, influencing factors and applications, Materials Today Chemistry, 37, 102032.
19. **Wang Y., Zhu Y., Yu S., Jiang C. (2017).** Fluorescent carbon dots: rational synthesis, tunable optical properties and analytical applications. *RSC Advances*, 7(65), 40973–40989.
20. **Wang K., Zhang Y., Li J., Zhang W., Li X. (2021).** Current trends in smart mesoporous silica-based nanovehicles for photoactivated cancer therapy, Journal of Controlled Release, 339, 445-472.
21. **Zare I., Kesharwani P., Asgarian M. (2025).** Antimicrobial carbon materials-based quantum dots: From synthesis strategies to antibacterial properties for diagnostic and therapeutic applications in wound healing, Coordination Chemistry Reviews, 522, 216211.
22. **LeCroy G.E., Yang S.T., Wang H. (2016).** Functionalized carbon nanoparticles: Syntheses and applications in optical bioimaging and energy conversion, Coordination Chemistry Reviews, 320, 66-81.
23. **Mao Q., Zhang J., Liu F. (2024).** Organelle imaging with fluorescent carbon dots: Strategies, challenges, and perspectives, Inorganic Chemistry Frontiers.
24. **Zhang J.H., Liu C., Li Z. (2016).** In vivo characterization of hair and skin derived carbon quantum dots with high quantum yield as long-term bioprobes in zebrafish, Scientific Reports, *6*(1), 37860.
25. Ma K., Li Y., Zhang H. (2025). Recent advances of versatile fluorophores for multifunctional biomedical imaging in the NIR-II region, Journal of Materials Chemistry B.
26. **Ding H., Xu J., Wang L. (2020).** Carbon dots with red/near-infrared emissions and their intrinsic merits for biomedical applications, Carbon, 167, 322-344.
27. **Yao J., Yang M., Duan Y. (2014).** Chemistry, biology, and medicine of fluorescent nanomaterials and related systems: New insights into biosensing, bioimaging, genomics, diagnostics, and therapy, Chemical Reviews, 114(12), 6130-6178.
28. **Jurczyk M., Chrzanowski W., Gromadzka-Ostrowska J. (2021).** Single-versus dual-targeted nanoparticles with folic acid and biotin for anticancer drug delivery, Pharmaceutics, 13(3), 326.
29. **Li D., Li J., Xu J. (2019).** Design of dual drug-loaded dendrimer/carbon dot nanohybrids for fluorescence imaging and enhanced chemotherapy of cancer cells. Journal of Materials Chemistry B, 7(2), 277-285.
30. **Lakkakula J., Challa S.R., Kumar K. (2024).** Revolutionizing cancer treatment: Enhancing photodynamic therapy with cyclodextrin nanoparticles and synergistic combination therapies, Materials Today Sustainability, 100958.
31. **Qu Z., Zhou H., Wang D. (2020).** Synthesis of bifunctional carbon quantum dots for bioimaging and anti-inflammation, Nanotechnology, 31(17), 175102.
32. **Dou Y., Zhang W., Wang X. (2020).** Bioresponsive drug delivery systems for the treatment of inflammatory diseases, Journal of Controlled Release, 327, 641-666.
33. **Cabral Filho P.E., Carvalho R.S., Lima L.M. (2018).** Multimodal highly fluorescent-magnetic

nanoplatform to target transferrin receptors in cancer cells. Biochimica et Biophysica Acta (BBA)-General Subjects, 1862(12), 2788-2796.
34. **Mohammadinejad R., Mirkhani V., Fadaei R. (2019).** Shedding light on gene therapy: Carbon dots for the minimally invasive image-guided delivery of plasmids and noncoding RNAs—A review, Journal of Advanced Research, 18, 81-93.
35. **Acharya B., Sen S., Majumdar S. (2025).** Fluorescent carbon nanoparticles in cancer diagnostic and therapy systems. In *Fluorescent Carbon Nanoparticles* (pp. 367-415). Elsevier.
36. **Wang L., Zhang H., Liu Z. (2022).** A composite system combining self-targeted carbon dots and thermosensitive hydrogels for challenging ocular drug delivery. Journal of Pharmaceutical Sciences, 111(5), 1391-1400.
37. **Gao S., Li X., Han B. (2025).** Bacterial and bacterial derivatives-based drug delivery systems: A novel approach for treating central nervous system disorders, Expert Opinion on Drug Delivery.
38. **Wang H., Zhang X., Li Q. (2015).** Immobilization of carbon dots in molecularly imprinted microgels for optical sensing of glucose at physiological pH, ACS Applied Materials & Interfaces, 7(29), 15735-15745.
39. **Xu J., Li X., Zhang W. (2021).** A critical review of carbon quantum dots: From synthesis toward applications in electrochemical biosensors for the determination of a depression-related neurotransmitter, Materials, 14(14), 3987.
40. **Li N., Yang M., Chen L. (2017).** Tuning gold nanoparticles growth via DNA and carbon dots for nucleic acid and protein detection, Sensors and Actuators B: Chemical, 251, 455-461.
41. **Fan M., Zhang X., Liu Z. (2025).** A DNA conformational nanoswitch for amplification of both low-abundance protein imaging in living cells and photodynamic therapy, Analytical Methods.
42. **Pirsaheb M., Mohammadi S., Salimi A. (2019).** Current advances of carbon dots based biosensors for tumor marker detection, cancer cells analysis, and bioimaging, *TrAC Trends in Analytical Chemistry*, 115, 83-99.
43. **Javed H., El-Sappagh S., Abuhmed T. (2025).** Robustness in deep learning models for medical diagnostics: Security and adversarial challenges towards robust AI applications, Artificial Intelligence Review, *58*(1), 1-107.
44. **Alipour, A. (2025).** Journal of Chemical, Biological and Medicinal Sciences, J. Chem, 1(3), 125-132.
45. **Yan X. (2021).** Preparation of N-doped carbon quantum dots and their applications in the selective sensing of Mercury (II), Journal of Luminescence.
46. **Atchudan R., Sankar S., Manikandan E. (2024).** Sustainable synthesis of multi-functional carbon dots as optical nanoprobe for selective sensing of heavy metal ions. Journal of the Taiwan Institute of Chemical Engineers, 165, 105770.
47. **Zhang X., Li Q., Wu Y. (2022).** Recent advances in synthesis and modification of carbon dots for optical sensing of pesticides, Journal of Hazardous Materials, 422, 126881.
48. **Tachapermpon Y., Wang Z., Li H. (2022).** Fluorescent carbon dots based phytosensor for indoor formaldehyde pollution monitoring, Plant Nano Biology, *2*, 100015.
49. **Qureshi Z.A., Zhang J., Zhou Y. (2024).** Carbon dots as versatile nanomaterials in sensing and imaging: Efficiency and beyond, Heliyon, 10 (11).
50. **Hu H., Li J., Li Q. (2024).** Lateral flow assay with dual-emission nitrogen-doped carbon dots for ratiometric fluorescent determination of nitrite in food, Microchemical Journal, 205, 111247.
51. **Etefa H.F., Tessema A.A., Dejene F.B. (2024).** Carbon dots for future prospects: Synthesis, characterizations and recent applications: A review (2019–2023). *C*, 10(3), 60.
52. **Akbar K., Moretti E., Vomiero A. (2021).** Carbon dots for photocatalytic degradation of aqueous pollutants: Recent advancements, Advanced Optical Materials, *9*(17), 2100532.
53. **Singh P., Kumar S., Kumar K. (2023).** Biogenic synthesis of Allium cepa derived magnetic carbon dots for enhanced photocatalytic degradation of methylene blue and rhodamine B dyes, Biomass Conversion and Biorefinery, 1-19.
54. **Khansili N. (2024).** Review on synthesis and properties of carbon dots with emphasis to combat environmental toxins, Environmental Advances, 100542.