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Review

Carbon Dots for Future Prospects: Synthesis, Characterizations and Recent Applications: A Review (2019–2023)

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Abstract: Carbon dots (CDs) have emerged as a promising class of carbon-based nanomaterials due to their unique properties and versatile applications. Carbon dots (CDs), also known as carbon quantum dots (CQDs) or graphene quantum dots (GQDs), are nanoscale carbon-based materials with dimensions typically less than 10 nanometers. They exhibit intriguing optical, electronic, and chemical properties, making them attractive for a wide range of applications, including sensing, imaging, catalysis, and energy conversion, among many others. Both bottom-up and top-down synthesis approaches are utilized for the synthesis of carbon dots, with each method impacting their physicochemical characteristics. Carbon dots can exhibit diverse structures, including amorphous, crystalline, or hybrid structures, depending on the synthesis method and precursor materials used. CDs have diverse chemical structures with modified oxygen, polymer-based, or amino groups on their surface. These structures influence their optical and electronic properties, such as their photoluminescence, bandgap, and charge carrier mobility, making them tunable for specific applications. Various characterization methods such as HRTEM, XPS, and optical analysis (PL, UV) are used to determine the structure of CDs. CDs are cutting-edge fluorescent nanomaterials with remarkable qualities such as biocompatibility, low toxicity, environmental friendliness, high water solubility, and photostability. They are easily adjustable in terms of their optical properties, making them highly versatile in various fields. CDs find applications in bio-imaging, nanomedicine, drug delivery, solar cells, photocatalysis, electrocatalysis, and other related areas. Carbon dots hold great promise in the field of solar cell technology due to their unique properties, including high photoluminescence, high carbon quantum yield (CQY), and excellent charge separation.

Keywords: CDs; synthesis; optical properties; characterization; applications

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1. Introduction

Nanotechnology is a rapidly developing field that has sparked extensive discussions [1,2] and raised concerns about the potential impacts of new nanomaterials on human health and the environment [3,4]. This technology holds significant importance across various technological domains due to its unique and well-defined structures [5]. Since the start of the 21st century, nanotechnology has garnered considerable interest due to its ease of synthesis and its applications in diverse fields, including astronomy and environmental protection [6,7]. Carbon dots, also known as CDs, belong to a novel fluorescent category within the carbon nanomaterial family. They have emerged as a versatile and potent platform with diverse applications [8]. CDs have garnered considerable attention and interest in the field of nanotechnology [9], including bioimaging [10], sensing [11,12], catalysis [13], solar cells [14]. Long-term chemical stability, cost-effectiveness [15], excellent biocompatibility and light-emitting diodes [16], enhanced electron transferability [17], photobleaching, high photoluminescent quantum yield [18], and good aqueous solubility

are all desirable characteristics [6,11,19,20]. Because of their outstanding optical properties, CDs have been developed to replace expensive, heavy-metal-based fluorophores in some photovoltaic solar cells [21]. Various CDs are also used in doping into the photoanode, counter electrode, hole transport layer, and electron transport layer of dye-sensitized solar cells (DSSC) [22–25]. Furthermore, many advantages of CDs have recently been reported regarding their own distinguishing characteristics over other CDs materials (for example, the crystallinity of the core determines the presence (or absence) of quantum confinement in CDs, where quantum confinement is identified in CDs with a crystalline core, but not in CDs with an amorphous core) [8]. Along with different kinds of carbon-based nanomaterials, CDs are new advanced nanomaterials and (zero-dimensional) photolumenescent carbons with typical sizes <10 nm. Recently, significant advances in CD applications have been introduced, including in energy conversion (e.g., super-capacitors, PV, LEDs, etc.), and CDs with optical properties (e.g., anticounterfeiting) and promising biomedical properties have been explored.

According to their virility formation/depending on their composition and structure, many people have previously classified CDs as illustrated in Figure 1. CDs can be classified into four types: graphene quantum dots (GQDs), carbon quantum dots (CQDs), carbon nano-dots (CNDs), and carbonized polymer dots (CPDs) [26,27]. CDs as a special type of fluorescent material with outstanding optical and photoelectric properties and low toxicity [6,28,29]. The difficulties and potential of these nanomaterials are reviewed, with a focus on how carbon dots can be used to improve the efficiency of photovoltaics and white LEDs [26]. Advancements in materials chemistry have significantly impacted human lifestyles, with carbon dots emerging as a promising carbon-based nanomaterial [30–32]. However, further research is needed due to their structural diversity and incomplete field. This review explores the chemistry, history, classification, design fundamentals, applications, and bright futures of carbon dot-based materials [32]. Carbon dots (CDs) are currently one of the most prominent topics in the field of nanomaterials. Typically, their preparation relies on hydrothermal syntheses. However, the resulting materials often exhibit poor repeatability and are difficult to purify [9,33]. Revolutionary advances in materials chemistry have led to the development of carbon-based nanomaterials such as fullerene, carbon nanotubes, and graphene. Carbon dots (CDs), which are small carbon nanoparticles under 10 nm in size, have attracted attention due to their exceptional properties [30]. This article provides a comprehensive review of the synthesis process, characterization methods, optical properties, and current applications of carbon dots. It also explores the impact of doping and surface engineering on the optical properties of carbon dots and their potential future applications.

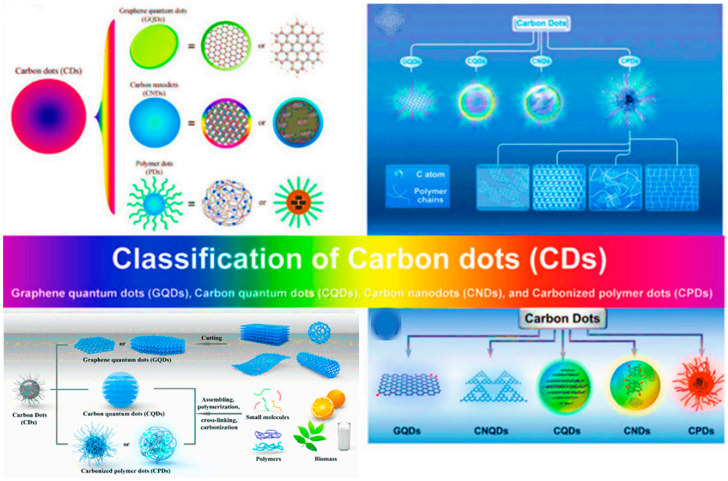

Figure 1. Classification of CDs using different preparation approaches. Reproduced with permission from [34]. Copyright 2022 Wiley.

2. Synthesis Method for Carbon Dots

The bottom-up and top-down approaches (seen in Figure 2) represent two broad categories that encompass the many methods for the synthesis of CDs [35]. CD production offers convenience but comes with significant challenges. These include the tendency of nanoparticles to aggregate during carbonization, the need to control size and homogeneity, and the requirement to modify surface attributes [36]. There are numerous methods for creating CDs from a range of complex-structured raw materials. CDs do not display a suitable graphitic domain, in contrast to GQDs [37]. What is more fascinating is that each synthesis method significantly affects the physicochemical characteristics of CDs [14], enabling their use in a variety of applications, such as size-dependent PL for biological imaging and optoelectronics, etc. Bottom-up synthesis involves the construction of carbon dots from smaller molecular precursors or carbon sources [38,39]. This approach typically involves the following steps: carbonization, surface passivation, size control, and purification [40,41]. Bottom-up synthesis methods offer precise control over the size, surface chemistry, and optical properties of carbon dots [42]. Top-down synthesis involves the fragmentation or exfoliation of larger carbonaceous materials to obtain carbon dots [43]. Top-down synthesis methods offer a scalable and cost-effective approach for the production of carbon dots [44]. They utilize readily available carbon sources and can yield carbon dots in large quantities. However, they may have limited control over the surface chemistry and functionalization compared to bottom-up methods [45]. Both bottom-up and top-down synthesis approaches have their advantages and limitations [46,47]. Bottom-up synthesis starts with gathering specific details, data, or evidence and gradually builds up to broader conclusions. This approach allows for a comprehensive understanding of the topic or problem by examining individual components. Since bottom-up synthesis relies on empirical data and concrete examples, the conclusions drawn are often well supported and grounded in evidence. It offers flexibility in adjusting the scope or focus of the thesis based on the findings obtained during the synthesis process. However, bottom-up synthesis can be time-consuming as it involves gathering, organizing, and analyzing a large amount of data or information. Top-down synthesis begins with overarching concepts or theories and then examines how they apply to specific instances or examples. This approach can be more efficient in identifying key themes or principles and can be utilized to prioritize information that aligns with the overarching framework or theoretical perspective, helping to avoid getting lost in irrelevant details. However, since top-down synthesis starts with broad concepts, there is a possibility of overlooking important nuances or details that may only emerge from a bottom-up analysis. The choice of synthesis method depends on the desired properties, scalability, and specific application requirements of the carbon dots [48]. Researchers employ a combination of these methods and continue to explore new approaches to enhance the synthesis efficiency and tailor the properties of carbon dots for various applications. In top-down techniques, various carbon dots materials such as graphene oxide sheets, graphene, carbon nanotubes, and carbon fibers are processed chemically and electrochemically. This process involves breaking them down into smaller particles using methods like ultrasonic treatment, laser ablation, arc discharge, and electrochemical techniques [49,50].

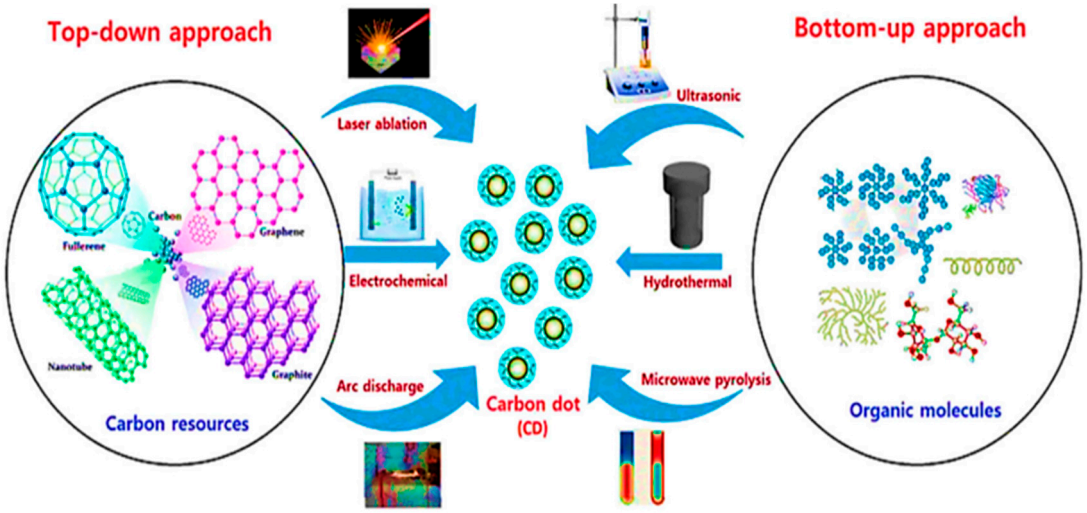

Figure 2. Bottom-up and top-down approaches for carbon dots synthesis. Reproduced with permission from [51]. Copyright 2021 frontiersin.org, 26 April 2021.

2.1. Ultrasonic Approaches

As shown in Figure 3, the ultrasonic approach is one kind of "top-down" technique. It breaks down large carbon molecules into smaller CD particles by applying high-energy ultrasonic sound pulses [52]. This approach has been suggested because of its exceptional advantages, which include being cheap, having strong penetration, being uniform in impact, and being environmentally friendly [53]. Additionally, HH Jing's group discovered that when CDs were functionalized with poly (ethylene oxide), they displayed strong green fluorescence under UV light after being made from cigarette ash via ultrasonication [54]. However, the primary obstacle to CD preparation with ultrasonic treatment is uneven sample heating. This is mostly related to the local thermal effect of ultrasonic waves, which influences reaction efficiency in comparison to direct heating or microwave. Considering these issues, more research is required to enhance CD synthesis using ultrasonic treatment. Ultrasonic approaches are a set of techniques used to synthesize carbon dots (CDs) [37]. Ultrasonic approaches offer several advantages for the synthesis of carbon dots, such as simplicity, low cost, scalability, and control over the size, shape, and surface properties of the resulting CDs [55]. These approaches involve the use of ultrasound, which is a form of mechanical energy in the form of sound waves with frequencies above the audible range (>20 kHz) [56].

There are different ultrasonic approaches for synthesizing carbon dots, including the direct ultrasonic method and the indirect ultrasonic method [57]. Let us discuss each of these approaches in detail; the direct ultrasonic method involves synthesizing CDs directly from carbon precursor materials using ultrasound [58]. The process typically begins with the preparing of a precursor solution containing carbon sources such as organic molecules, carbohydrates, or polymers [59]. The precursor solution is then subjected to ultrasonic treatment by immersing an ultrasound probe or horn directly into the solution or by using an ultrasonic bath. The ultrasonic waves induce cavitation, which is the formation and implosion of tiny bubbles in the liquid [60]. The collapse of these bubbles generates localized high temperatures and pressures, leading to the fragmentation and carbonization of the precursors. The resulting carbon atoms reassemble into carbon dots due to the rapid cooling and quenching effects of the surrounding liquid. The direct ultrasonic method offers several advantages, including rapid synthesis, high yield, and tunable optical properties of the resulting carbon dots [61,62]. However, it may require the use of toxic or hazardous precursors and may suffer from low stability and reproducibility [63]. The indirect ultrasonic method provides better control over the synthesis process and allows for the incorporation of additional functional groups or dopants into the carbon

dots. It also offers improved stability and reproducibility compared to the direct ultrasonic method. However, it may require more complex reaction conditions and longer reaction times [64,65].

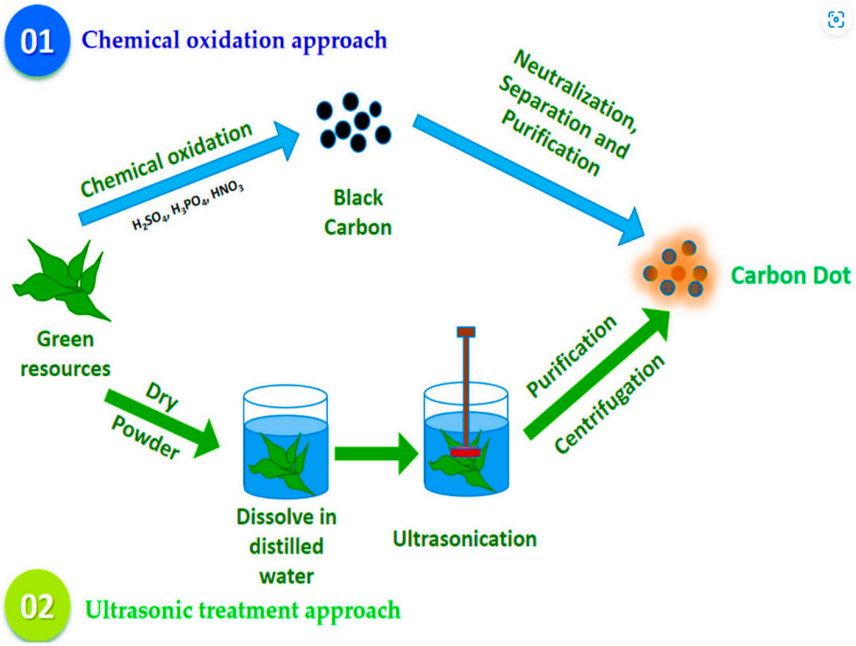

Figure 3. Top-down approaches in the green synthesis of carbon dots. Reproduced with permission from [54]. Copyright 2023 mdpi.com.

2.2. Laser Ablation

Laser ablation is a synthesis approach that comprises the use of a laser beam and a source of carbon to destroy it into a single material (seen in Figure 4). It is an effective, simple method that does not require excessive chemicals. The timescale of material interaction with the laser beam is the most critical factor for creating perfect structures [66]. CD nanomaterials are created using the laser ablation process at a wavelength of 1064 nm. For instance, synthesized CDs by focusing the laser beam on carbon dot (tea) material in colloid toluent for 3 h, as illustrated in Figure 4. The prepared CDs were utilized as fluorescent materials for applications in bioimaging. One of the main advantages of laser ablation is that functional groups can be controlled without requiring hazardous solvents and can be produced using a straightforward, efficient technique that does not require a lot of chemicals [66]. The main limitation is a low quantum yield of 4.5–18% [51].

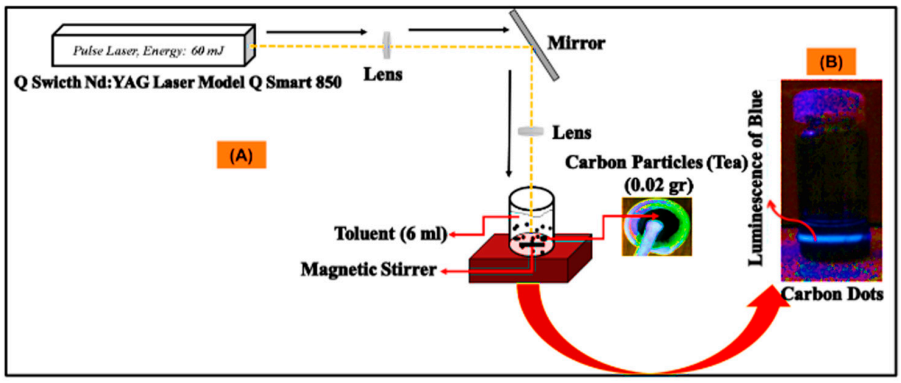

Figure 4. Schematic illustration of (**A**) synthesis of CDs via the laser ablation approach and (**B**) the luminance of CDs [67]. Copyright 2023 Jurnal Ilmu Fisika (JIF).

2.3. Electrochemical Oxidation

As revealed in Figure 5, the electrochemical approach is a facile technique for manufacturing CQDs with controllable optical properties and sizes. Typically, it follows a top-down method, wherein larger carbon materials, like graphite electrodes, are severed under an electrical potential to produce high-quality CQDs [68]. This can be a very effective method and enables heterogeneous redox reactions, in which it is simple to control the potential between two electrodes and monitor the current that passes through an electrolytic cell, and thus use that information as an indicator of certain CDs properties. Furthermore, electrons represent a redox reagent that is inexpensive, inherently non-polluting, and simple to administer. For these reasons, they are regarded as "green" reactants in chemical reactions. CDs made using this method are typically plentiful in functional groups, and they have more extensive uses in sensors. Advantages of this approach include a large production yield, low-cost easy size control, and high purity [69,70]. The main limitation of this approach is that it requires a longer reaction time.

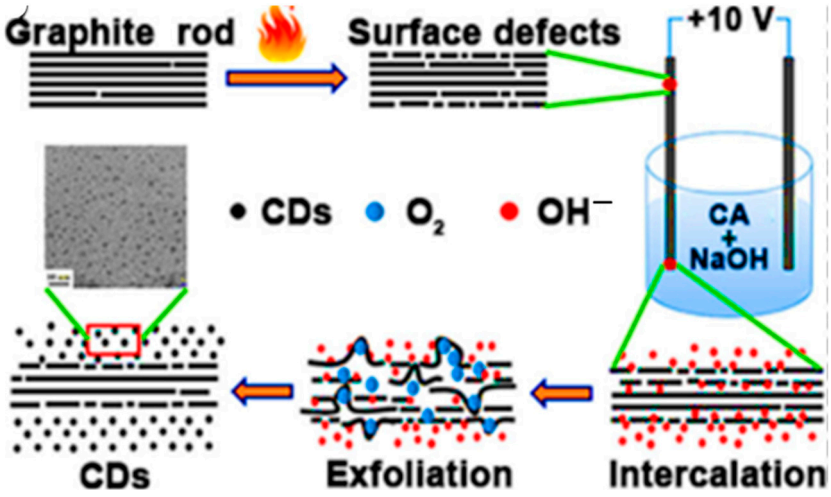

Figure 5. Synthesis of CDs via the top-down method of electrochemical oxidation [70]. Copyright 2022 Wiley.

Arc Discharge

Arc discharge synthesis is a top-down method used to produce carbon dots (CDs). It involves the fragmentation of larger carbon structures through an electric arc discharge. A detailed explanation of the arc discharge synthesis method is provided in [71,72]. Carbon nanoparticles are produced in very small quantities via arc discharge. Arc discharge dust frequently contains a variety of intricate, challenging-to-extract elements [73]. Numerous investigations have been performed on the synthesis of CDs using the arc discharge technique. The limitation of this approach is a low carbon quantum yield of 2.3 to 8.7% [48]. A high voltage is applied between the two electrodes, creating an electric arc discharge. The high electric field generated during the discharge leads to the vaporization and fragmentation of the graphite electrode [74]. Within these carbon nanoparticles, a fraction of the carbon atoms undergo further rearrangement and bond formation, leading to the formation of carbon dots [75]. These dots are typically composed of a core made from sp^2-hybridized carbon atoms and a surface functionalized with various chemical groups [76]. The resulting mixture contains a variety of carbon nanostructures, including carbon dots of different sizes. To isolate and purify the carbon dots, various separation techniques such as centrifugation, filtration, or chromatography can be employed [77,78]. However, the size distribution of the carbon dots produced by arc discharge (Figure 6) is often uneven, making separation and purification challenging [79]. The carbon dots obtained from the arc discharge synthesis method are then characterized using various analytical techniques to understand their properties and structure [57,80]. Arc discharge synthesis has been widely used in the early

stages of carbon dot research [81]. However, other techniques like laser ablation, oxidative cracking, and electrochemical procedures have become more prominent in the synthesis of carbon dots recently due to the difficulties regarding size distribution and purification using arc discharge in the synthesis of CDs [79].

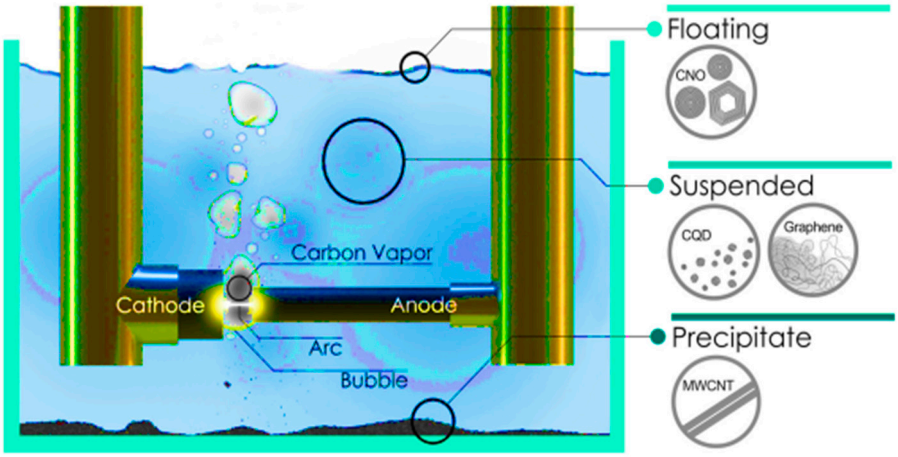

Figure 6. Scheme for the arc discharging synthesis of carbon quantum dots [81]. Copyright 2021 AIP publishing.

The top-down techniques, which include arc discharge, laser ablation, oxidative cracking, and electrochemical oxidation, are predicated on the fragmentation of larger carbon structures [71,82,83]. Be Manoj et al. (2020) found an undiscovered luminous carbon material while purifying single-walled carbon nanotubes made from arc discharge soot. The disadvantage of this approach is that the CDs have inconsistent sizes, which makes separation and purification difficult because differently sized carbon nanostructures coexist [84]. This method's drawback is that the size of the CDs is uneven, making separation and purification challenging because a variety of variously sized carbon nanostructures coexist [85]. Moreover, this method has a very low CD yield. Strong acid passivation of the CD surface is used in laser ablation and oxidative cracking processes. Electrochemical approaches have superseded them due to the hazardous chemicals needed [86]. However, the drawback of this method is the uneven size distribution of the CDs, which makes separation and purification challenging.

2.4. Hydrothermal Method

According to the literature data of many authors, CDs synthesized by means of the hydrothermal/solvothermal method also have "excellent photoluminescence properties". For example, CDs obtained from citric acid and ethylenediamine as a result of a reaction at a temperature of 190 °C for 2 h had a quantum yield of photoluminescence in aqueous solutions equal to 58% [87]. The hydrothermal synthesis approach is the greenest method of CD preparation. It uses water as a solvent. In typical synthesis, the reaction time and temperature range from 3 to 12 h and from 120 to 240 °C, respectively. It is characterized by the reactions of carbon dot precursors under autoclave conditions at high temperatures and pressures; the temperature should be above the boiling point of water [88]. Because it is straightforward, low-cost, rapid, and requires moderate reaction conditions, this method can be used for large-scale synthesis and yields highly tunable carbon dots. The hydrothermal method is the most widely used technique to synthesize CDs from renewable resources [89]. The solvothermal synthesis procedure is similar to the hydrothermal method, except that organic solvents, like ethanol, are utilized [90]. However, the optical properties, quantum yield florescence (QYF), and purity of CDs greatly depend on the solvent utilized during synthesis [90]. For example, Chen, X. et al. synthesized trichromatic CDs such as green (G), red (R), and blue (B) CDs via the solvothermal method from a single precursor, 2,5-dimethylbenzenesulfonic acid, by selecting different solvents, including NMP, DMF,

and formamide, respectively, and keeping the other conditions the same. Not only the color but also the quantum yield varied as the solvent was changed, as illustrated in Figure 7. The limitations of these approaches include a long reaction time and high energy consumption.

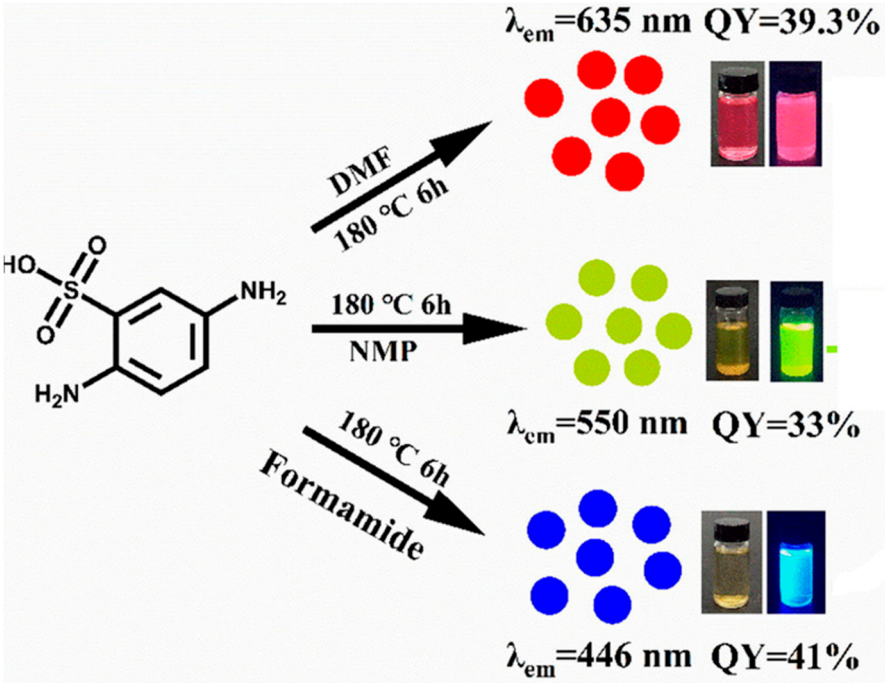

Figure 7. Schematic synthesis and detection of green, red, and blue CDs. Copyright 2023 Elsevier.

As revealed in Figure 8, beyond fruits and vegetables, a wide variety of biomass can be utilized as a carbon source to create BCDs, such as soy milk, black tea, ginkgo leaves, bamboo leaves [91,92] (Figure 8e), grass, and other plants. When BCDs are made using these carbon sources, the size distribution is rather uniform and the dispersion is good. The majority of the particle sizes fall within the range of 1 to 5 nm, while some BCDs made using oats [93] as a carbon source have a size distribution that ranges from 20 to 40 nm. A few years back, Khalifa et al. [94] suggested using bee pollen as a carbon source to increase the synthesis of BCDs; from 10 g of bee pollen, more than 3 g of BCDs could be created (Figure 8b). High-quality BCDs with up-conversion fluorescence were prepared via hydrothermal treatment in an autoclave set at 180 °C using sweet pepper [95] as a carbon source (Figure 8c). BCDs have a diameter dispersion spanning from 2 to 7 nm, with a carbon QY of 19.3% [96]. Simultaneously, cabbage was hydrothermally treated at 140 °C for five hours to produce BCDs [97,98]. These BCDs' CQY was 16.5%, and their limited diameter distribution spanned from 2 to 6 nm [95,98]. The size distribution of BCDs made with sweet pepper and cabbage as carbon sources was comparatively narrower than that of the aforementioned carbon sources, and as a result, their quantum yield was also lower [99,100].

The produced BCDs had a quantum yield of 6.9% and a particle size that varied from 2 to 4 nm [101] (Figure 8d). However, compared to BCDs made from the majority of other carbon sources, the quantum yield of BCDs made from orange juice was 26% greater [102,103]. Additionally, the prepared BCDs have a size of 2.5 nm. Citrus lemon juice was used as a carbon source in NaOH solution to make BCDs with a fluorescence QY (FQY) of 12.1%, as reported by W. Meng et al. [97].

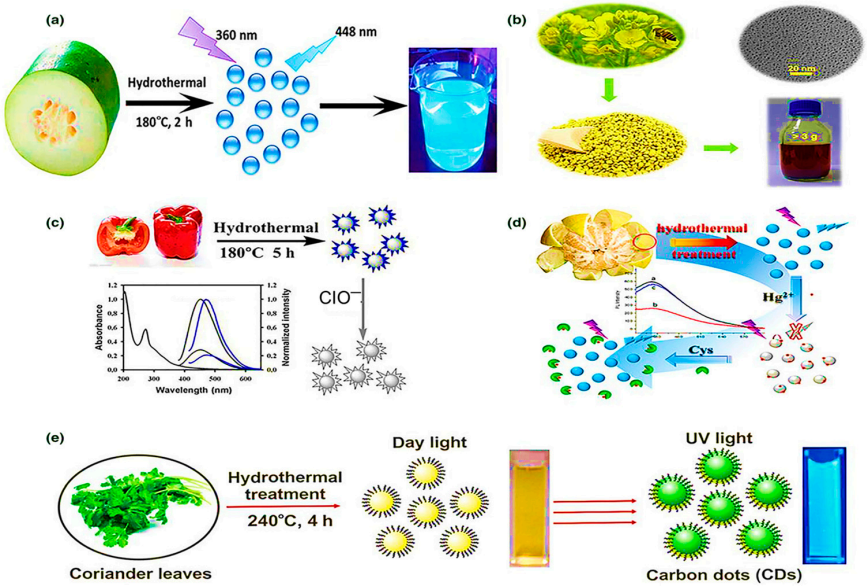

Figure 8. Preparation of biomass carbon dots (BCDs) by means of hydrothermal methods from (**a**) winter melon, (**b**) bee pollens, (**c**) sweet pepper, (**d**) pomelo peel, and (**e**) coriander leaves [97]. Copyright 2019 Wiley.

2.5. Microwave Synthesize Approach

The microwave synthesis approach is a bottom-up process in which CD precursors are mixed with *Bauhinia* flowers, tomatoes, onions and rose flowers to prepare N-CDs through the microwave method in an aqueous solution, as seen in Figure 9. Compared to the hydrothermal process, this technique works at far lower temperatures [104]. For example, Vikneswaran et al. used banana peels to synthesize CDs using the microwave method. The synthesized CDs were used to selectively detect Fe^{3+} ions. These CDs displayed excitation fluorescence in the range of 280–460 nm, with a fluorescence band at 438–521 nm. Rai, S. et al. [105] also reported the microwave-assisted synthesis of fluorescent carbon dots (FCDs) from sulfur-containing lignosulfonate lignin as a carbon source, in which sulfur acts as a doping agent. CDs that have been synthesized can be used to load and release drugs. Due to the many kinds of functional groups that lignin CDs have on their surface, it was verified that the manufactured CDs with a narrow particle size distribution exhibited excellent stability and fluorescence properties.

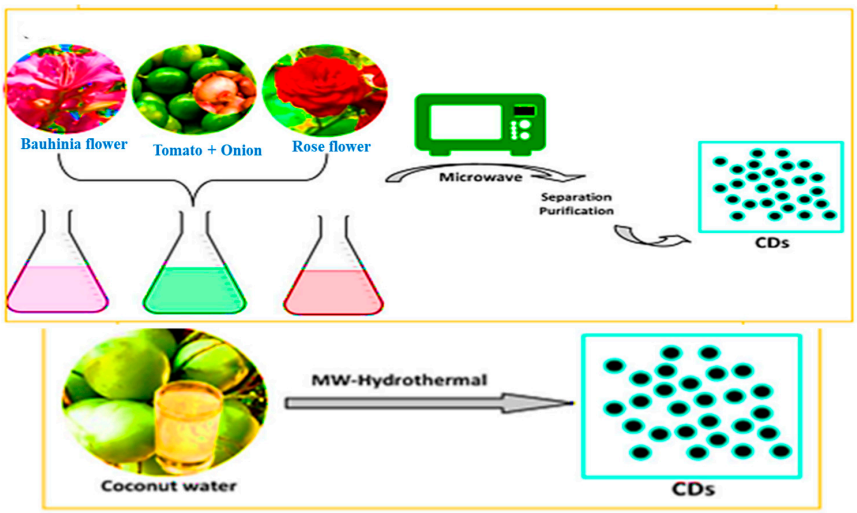

Figure 9. Preparation procedure of reduced carbon dots via the microwave synthesize approach [106]. Copyright 2020 mdpi.com.

2.6. Pyrolysis Synthesis Approach

The most popular "bottom-up" technique, known as carbonization or pyrolysis synthesis, was initially introduced by Xu et al. [107] during the discovery of CDs, and has since been utilized by several researchers. Speight [108] defined carbonization as the thermal breakdown process of carbon-containing materials, particularly natural substances, to produce carbonaceous residue. This process, depicted in Figure 10a,b, involves the high-temperature degradation of solid compounds with a higher CD content from organic sources in an inert atmosphere. The advantages of this approach include easy operation, low cost, solvent-free production, scalability, and a fast reaction time. The main problem with pyrolysis is aggregation, which occurs during carbonization. Here, we present a unique two-step carbonization process (Figure 10c) that allows for the simultaneous extraction of porous carbon (SC) and N-doped fluorescent carbon dots (SCDs) from naturally nitrogen-rich soybean biomass. Fluorescent carbon dots were produced by means of an initial low-temperature carbonization process (20 °C), and porous carbon with a unique network of linked micropores and mesopores and a high specific surface area (1663.1 m^2 g^{-1}) was produced by means of a second high-temperature carbonization process (750 °C). The schematic diagram for the SCD and SC preparation is shown in Figure 10c. The carbonization process consists of two treatment steps: a low-temperature pre-carbonization (200 °C) step that yields fluorescent carbon dots and preserves the microstructure and heteroatoms (such as N, O, and S) of the raw material soybean, and a high-temperature carbonization (750 °C) step that involves KOH activation that partially graphitizes the pre-carbonization residue and yields highly porous active carbon.

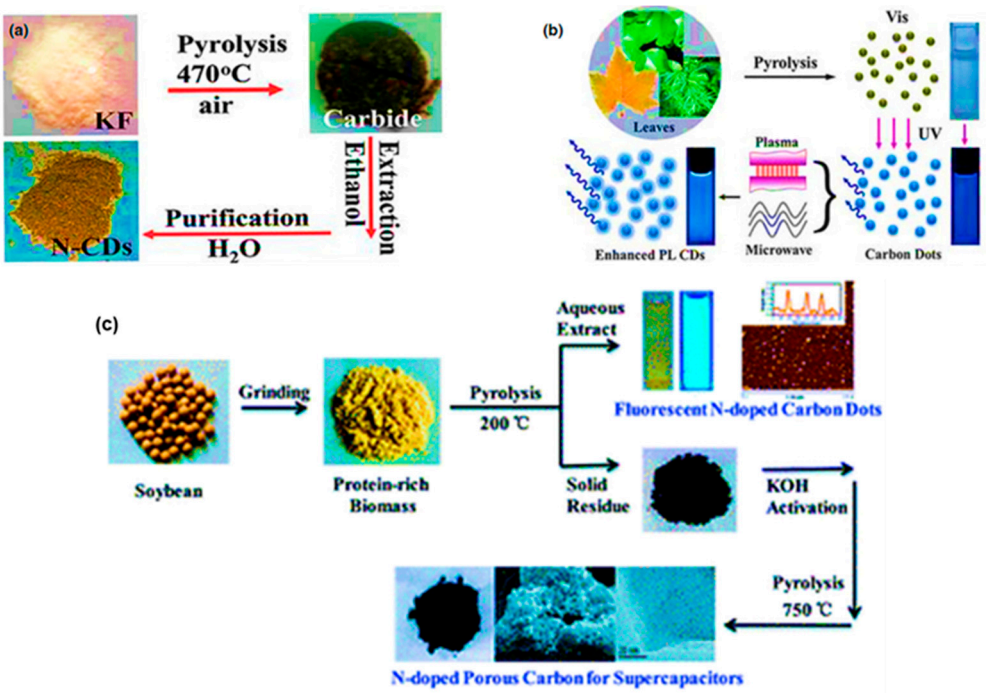

Figure 10. Different pyrolysis synthesis methods of carbon dots (**a**) Konjac flour (**b**) Plant leaves (**c**) Soya beans [97,109,110]. Copyright 2019 Wiley; copyright 2016 Wiley; copyright 2016 pubs.rsc.org.

As shown in Table 1, carbon dots synthesized via hydrothermal methods demonstrate excellent photoluminescence properties, rendering them highly suitable for use in biomedical imaging applications. They can effectively serve as fluorescent probes for imaging various biological structures, including cells, tissues, and specific biomarkers. Hydrothermal synthesis generates carbon dots with distinctive surface properties and functional groups, making them ideal for sensing applications such as chemical and biological sensing. Carbon dots can be deployed as fluorescent probes or integrated into sensing platforms to

detect analytes such as heavy metals, gases, and biomolecules. While carbon dots synthesized through alternative methods may find similar applications, the specific properties and characteristics resulting from hydrothermal synthesis render them particularly well-suited for these uses. Microwave synthesis allows for rapid heating and reactions, resulting in shorter synthesis times compared to other methods. This can be advantageous for large-scale production or time-sensitive applications. Additionally, microwave synthesis affords easy control over reaction parameters including temperature, power, and reaction time. This level of control enables researchers to optimize synthesis conditions to meet specific environmental remediation requirements. By referring to Table 1, researchers can compare the benefits, drawbacks, and applications of different synthesis methods. This information aids in selecting the most appropriate method based on the research goals, cost considerations, equipment availability, and desired properties of carbon dots. It is important to note that these applications are not limited solely to hydrothermally or microwave-synthesized carbon dots.

Table 1. Different approaches to synthesizing CDs, along with their advantages, disadvantages, and applications.

Approach	Methods	Advantages	Disadvantages	Applications	Ref.
Bottom-up	Hydrothermal/ Solvothermal	Simple and cost-effective synthesis method	High reaction temperatures and long reaction times	Biomedical imaging, sensors, drug delivery	[111,112]
	One-Pot Synthesis	Convenient synthesis without additional purification steps	Potential variability in size and properties	Bioimaging, drug delivery	[113,114]
	Pyrolysis	Good stability and tunable properties	High temperatures and lack of control over size distribution	Photodetection, bioimaging	[115,116]
	Microwave	Short reaction times and easy control of parameters	Potential overheating and non-uniform heating	Drug delivery, environmental remediation	[117,118]
	Organic approach	Environmentally friendly synthesis	Limited control over size and properties	Sensing, bioimaging	[70]
Top-down	ultrasonication	Simple and rapid synthesis method	Limited control over size and potential aggregation	Biosensing, antibacterial agents	[57,70]
	Chemical oxidation	Simple and versatile method	Harsh reaction conditions and potential toxic byproducts	Sensing, energy storage	[119,120]
	Arc discharge	High yield of CDs with good FQYs	Complex setup and requirement of a high-power arc discharge	Photovoltaics, optoelectronic devices	[48,121]
	Laser ablation	Precise control over size and excellent FQYs Energy efficient	Expensive laser equipment and potential contamination	Bioimaging, photocatalysis	[122]

3. Characterizations Tools for Carbon Dots and Its Optical Properties

Characterization tools play a crucial role in studying and understanding carbon dots (CDs) [64], which are nanoscale carbon-based materials with unique optical and electronic properties. These tools allow researchers to investigate various aspects of CDs, including their structure, size, surface chemistry, optical properties, and surface morphology [123]. Characterization tools are essential for gaining a comprehensive understanding of carbon dots [124]. They enable researchers to explore the structural, optical, surface, and electrical

properties of CDs, which are crucial for tailoring their properties and optimizing their performance in various applications ranging from optoelectronics and biomedicine to energy storage and sensing. Due to the various synthesis approaches, the chemical structure of each set of CDs will also be different. Nevertheless, all have modified oxygen, polymer-based, or amino groups on their surface. As a result, numerous characterization methods have been developed to determine the structure of CDs [125]. For instance, the outstanding characteristics of CDs include their electrochemical and optical properties. Due to these exceptional qualities, CDs are widely used in several biomedical fields, such as biosensing, bioimaging, and therapeutic development. These attributes make CDs an excellent option for various medical applications, including drug and gene delivery, biosensing, bioimaging, and photodynamic/photothermal therapy. Fluorescent CDs have been widely utilized in various healthcare applications, particularly in the areas of biosensing, bioimaging, and therapeutic development, thanks to their remarkable optical properties. To manufacture a range of CDs for different bio-applications, it is crucial to thoroughly research and understand their optical properties [10].

TEM pictures at a resolution of 50 nm, as shown in Figure 11a, reveal that the manufactured CDs are evenly distributed in aqueous solutions. The inset image in Figure 11a indicates that CD particle sizes range from 1 to 3 nm, with an average size of 2 nm. The high-resolution photo in Figure 11b shows that the CDs are linked to the (1, 0, 0) plane of graphite, with a lattice distance of 0.21 nm (as seen in Figure 11b). The arrangement of carbon atoms within CDs can greatly affect the interlayer spacing. Different planar configurations, such as graphene-like structures or aromatic ring formations, can result in varying distances between layers. For example, if the CD has a highly graphitic structure resembling graphene, the interlayer distance might be closer to the typical spacing of graphite (around 0.21 nm), which is in the same range of 0.21–0.24 for the (001) lattice plane [126]. However, if the structure is more amorphous or contains defects, the interlayer distance may be larger. Higher degrees of carbonization often lead to more ordered and graphitic structures, which tend to have smaller interlayer spacings. Different precursors may undergo varying degrees of carbonization and graphitization, resulting in CDs with different interlayer distances.

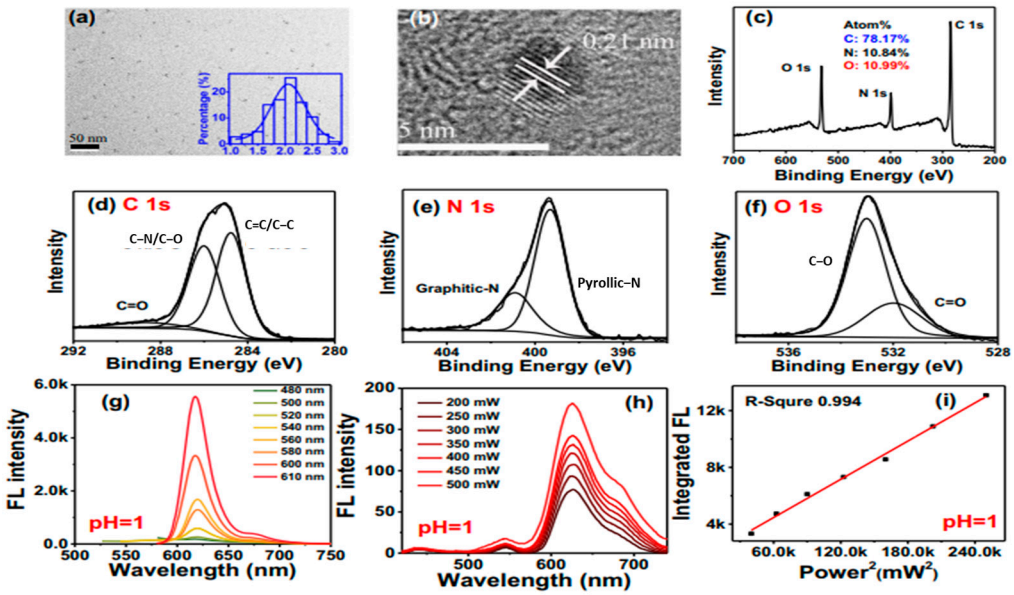

Figure 11. Structure, composition, and optical properties of protonated CDs. (**a**) TEM image of CDs (inset, particle size distribution of CDs); (**b**) high-resolution TEM image of CDs; (**c**–**f**) full scale XPS spectra, high-resolution C 1s, N 1s, and O 1s XPS spectra of CDs; (**g**,**h**) one-photon and two-photon fluorescence (FL) spectra of protonated CDs in deionized water; (**i**) relationship of two-photon FL intensity and femtosecond (fs) laser power [127]. Copyright 2021, Nature Communications.

The chemical composition of the manufactured CDs was analyzed using XPS examination. The full-scale XPS spectra analysis results, shown in Figure 11c, reveal that the CDs have atomic ratios of 78.17%, 10.84%, and 10.99% for the elements carbon (C), nitrogen (N), and oxygen (O), respectively. The high-resolution XPS spectra in Figure 11d–f demonstrate the presence of sp2 C=C carbon (284.76 eV), sp3 C−N/C−O carbon (286.0 eV), and C=O groups (288.6 eV) in the C 1s spectra. The high-resolution N 1s spectra in Figure 11e show two peaks representing graphitic nitrogen (400.9 eV) and pyrrolic nitrogen (399.3 eV). The O 1s band in Figure 11f can be divided into two peaks, which indicate the presence of C=O and C−O−C/C−O−H groups at 531.9 and 533.0 eV, respectively.

The solvent environment can significantly impact the photoluminescence (PL) properties of CDs. Therefore, to better understand the PL properties of the manufactured CDs in biologically water-soluble environments, the FL emission is determined by dissolving the protonated CD samples in deionized water. The red FL emission of protonated CDs, as shown in Figure 11g, occurs at 620 nm with a full width at half maximum (FWHM) of 24 nm, which is 34% narrower than the most recent high-color-purity CDs discovered, with an FWHM of 35 nm. The produced CDs exhibit excitation-independent PL behavior when excited by wavelengths ranging from 480 to 610 nm. Additionally, experiments show that the up-conversion of the FL emission of CDs produces red emission lines at 630 and 680 nm with an FWHM of 70 nm when excited by near-infrared (NIR) light from an 808 nm femtosecond (fs) laser (see Figure 11h). The FL intensity of CDs increases linearly (R = 0.994) as the square of the laser power increase sfrom 200 to 570 mW, as illustrated in Figure 11i. This suggests that the red up-conversion FL of CDs is induced by two-photon excitation.

CDs typically exhibit optical absorption in the UV range, with a tail that extends into the visible spectrum. Regardless of their manufacturing process, most CDs have an absorption band ranging from 260 to 323 nm [128]. However, the absorption spectra of CDs may show absorption shoulders related to the π–π* transition of the C=C bonds or the n-π* transition of the C=O bonds. It has been demonstrated that surface passivation of CDs with different molecules can alter their absorption properties, causing a shift towards longer wavelengths [129]. Currently, there is significant research interest in the optical characteristics of CDs, such as red/NIR emission, up-conversion photoluminescence (UCPL), high fluorescence quantum yields (FQYs), and NIR-driven applications (as shown in Figure 12a). The use of CDs in biology and biomedicine includes applications involving photothermal heating and chiral luminescence. High FQYs are advantageous for tracking CDs in vivo. Due to the poor penetration of short-wavelength light in biological tissues, most CDs absorb in the UV range and emit blue-green light, which makes their detection challenging. This limitation can be partially overcome by using blue-green emission CDs with high FQYs. By exploiting the acidophilic characteristics of CDs, lysosomes in living cells can be passively visualized. For instance, by using branched polyethyleneimine (bPEI) and rose bengal (RB) as precursors, green-emitting CDs with a FQY of 90.49% were produced. As shown in Figure 12b, there is currently significant interest in red and NIR-emitting CDs due to their low autofluorescence interference, deep tissue penetration, and minimal tissue absorption. Numerous applications related to in vitro and in vivo observation of biological systems have been investigated. Red/NIR-CDs have been cultured with different cancer cells to evaluate their potential for labeling applications in in vitro cell imaging. According to the data [99], red/NIR-CDs primarily aggregate in the cytoplasm and cell membrane [99]. Our lab successfully synthesized red-emitting CDs with high FQYs using o-phenylenediamine as the precursor [130,131]. These CDs were employed as fluorescent probes for both in vitro and in vivo imaging. We also developed a range of red-emissive CDs based on o-phenylenediamine, enabling bioimaging. As shown in Figure 12c, the resulting L-CDs are suitable for long-term in situ imaging of the Golgi apparatus due to their high light stability and biocompatibility. The dynamic changes of the Golgi apparatus during the early stages of viral infection can be observed using these L-CDs. Furthermore, chiral cysteine has been extensively used as a chiral ligand and stabilizer to modify the properties of nanomaterials. When chiral CDs generated using L (or D)-cysteine were

tested on human bladder cancer T24 cells, L-CDs exhibited up-regulated glycolysis, while D-CDs had no such effect (Figure 12c). For example, D-proline with inverted chirality preferentially interacts with liposome mimics or the cell membrane (Figure 12d).

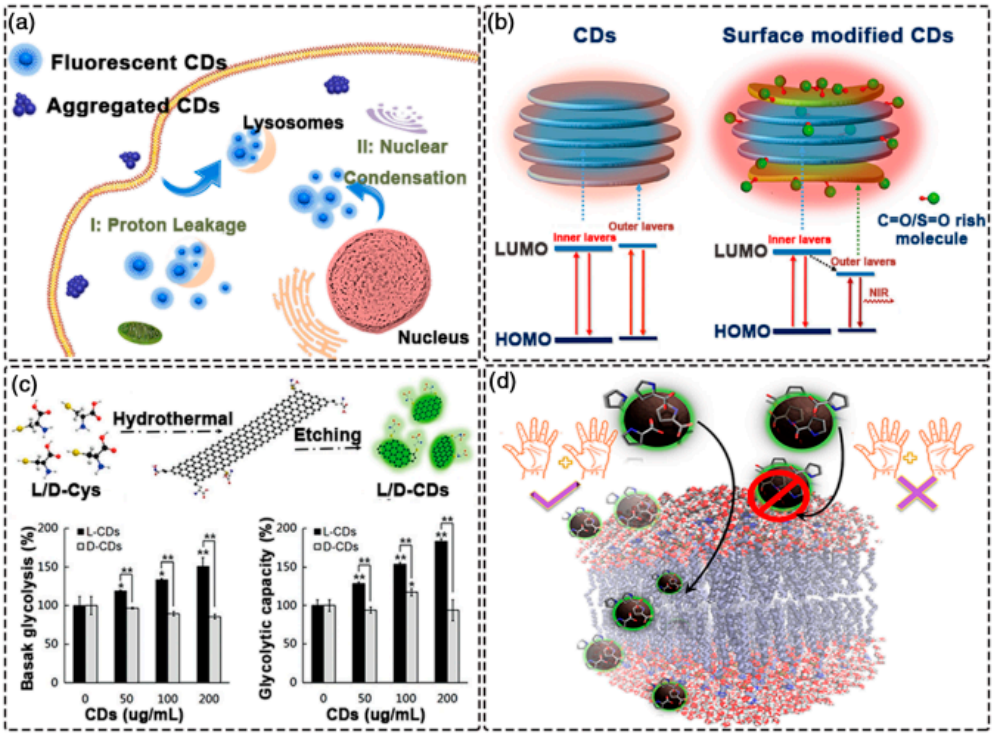

Figure 12. Optical properties of CDs. (**a**) High-quantum-yield CDs for the visualization of lysosomes; (**b**) NIR-emitting CDs for bio-imaging; (**c**) chiral CDs for the treatment of T24 cells; (**d**) chiral CDs demonstrating high selectivity for cell membranes [70]. Copyright 2022 Wiley.

Excitation-dependent photoluminescence, or excitation-dependent fluorescence emission, is one of the most remarkable characteristics of CQDs (seen in Figure 13). Dependence on the emission wavelength and intensity is a characteristic of the PL for CQDs generally [132]. Zhang's group conducted a study to explore the emission behavior of carbon quantum dots (CQDs) when exposed to light with a wavelength of 470 nm at different concentrations [133]. They discovered that when the excitation wavelength and CD concentration were raised, the PL intensity of the yellow-emitting CQDs first climbed to a maximum λex and then declined. This work demonstrated that CDs exhibit similar excitation-dependent photoluminescence activity to other luminous carbon nanoparticles [134]. Similarly, by heating o-phenylenediamine under the catalysis of KCl, a series of CDs with a tunable PL emission from 442 to 621 nm, an FQY of 23–56%, and a production yield within 34–72% were produced by Ding, H. et al. [135]. Extensive analyses reveal that the variations among these CDs concerning the extent of graphitization, the amount of graphitic nitrogen in them, and the functional groups that contain oxygen determine their unique optical characteristics, as illustrated in Figure 13. These variations can be adjusted by managing the deamination and dehydrogenation procedures that take place during reactions. To create blue, green, yellow, and red emissive films and LEDs, the appropriate CDs are dispersed into polyvinyl alcohol (PVA). Red, green, and blue emissive CDs are also mixed to create all varieties of warm, standard, and cool white LEDs (WLEDs) with a high color rendering index (CRI).

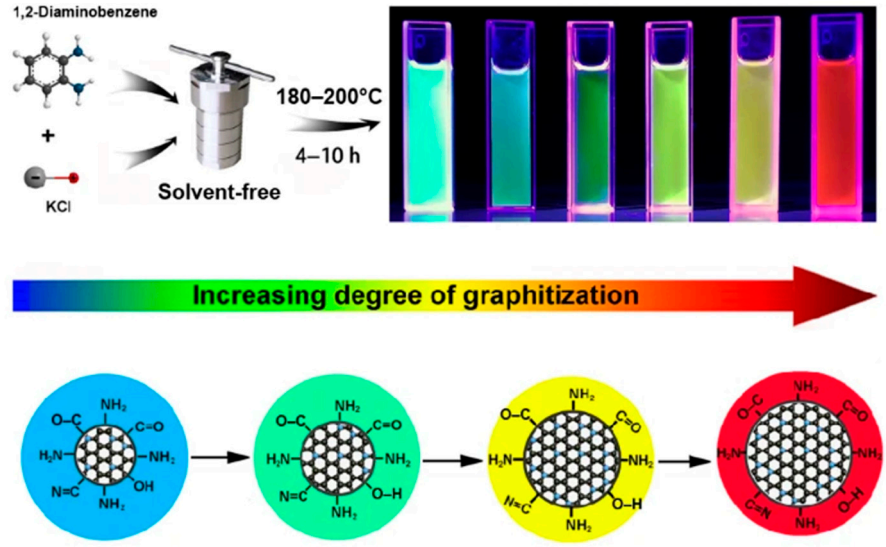

Figure 13. A CDs with a tunable PL emission range from 442–621 nm [135]. Copyright2022 Springer.

4. Application of Carbon Dots

As a cutting-edge fluorescent nanomaterial, CDs display remarkable qualities such as biocompatibility, low toxicity, environmental friendliness, high water solubility, and photostability. Additionally, CDs can be easily and quickly made in accordance with green chemistry concepts. Given their easily adjustable optical properties, CDs find applications in various fields including bio-imaging, nanomedicine, drug delivery, solar cells, energy storage, photocatalysis, electrocatalysis, and other closely related areas [23,29,82,136,137].

4.1. Solar Cell

The I–V curves for dye-sensitized solar cells (DSSCs) shown in Figure 14A [138] and B [139] demonstrate the significant impact of varying weight percentages (in mg) of CDs deposited on ZnO NPs and NiO NPs on the performance enhancement of dye-sensitized solar cells (DSSCs). To investigate this, we tested composite DSSCs consisting of ZnO@CDs/dye nanostructures under blue light illumination with an intensity of 156 w/m^2. They conducted comparisons by adjusting the concentrations of CDs and the mole ratios of ethylenediamine/citric acid. Figure 14A shows the I–V characteristics of different DSSC combinations using ZnO@CDs (1) as sensitizers, while varying the weight percentage of CDs content from 0 to 50. The I–V curves show varying strengths depending on the CDs content, with weaker curves observed for weight percentages above a certain threshold and more intense curves within the range of 0 to 10 weight percent. Notably, the ZnO(20)@CDs DSSCs sensitized with N719 demonstrated the highest performance among all combinations. Additionally, the ZnO(20)@CDs DSSCs exhibited a current 1.2–1.5 times higher than that of the ZnO(100)@CDs DSSCs. Furthermore, when the sensitizer was changed from RhB to N719, both ZnO(100)@CD and ZnO(20)@CD DSSCs experienced an increase in both voltage (1.3–2.0 times) and current (almost one order of magnitude). These observations highlight the superior efficiency achieved by optimizing the conditions. Figure 14B presents the I–V curves for NiO@CD DSSCs with a 12.5 weight percent CD content, but with different EDA/CA molar ratios for the N719 and Rh6G sensitizers (0.5:1, 1.0:1, 1.5:1, 2.0:1, and 2.5:1). The electrochemical parameters determined from these I–V curves are provided [139]. The EDA/CA molar ratio for both sensitizers affected four parameters: since the rise in the EDA/CA molar ratio enhances the amine content relative to the carboxylic acid content, all metrics were usually at their maximum at an EDA/CA molar ratio of 1.5:1 and higher for N719 DSSC than for Rh6G DSSC, suggesting the effect of the amine (NH2) moiety in the CDs. Overall, the experimental results demonstrated that optimizing the weight percentages of CDs deposited on ZnO NPs and NiO NPs, as

well as the EDA/CA molar ratio, can significantly enhance the performance of DSSCs by improving current, voltage, and overall efficiency.

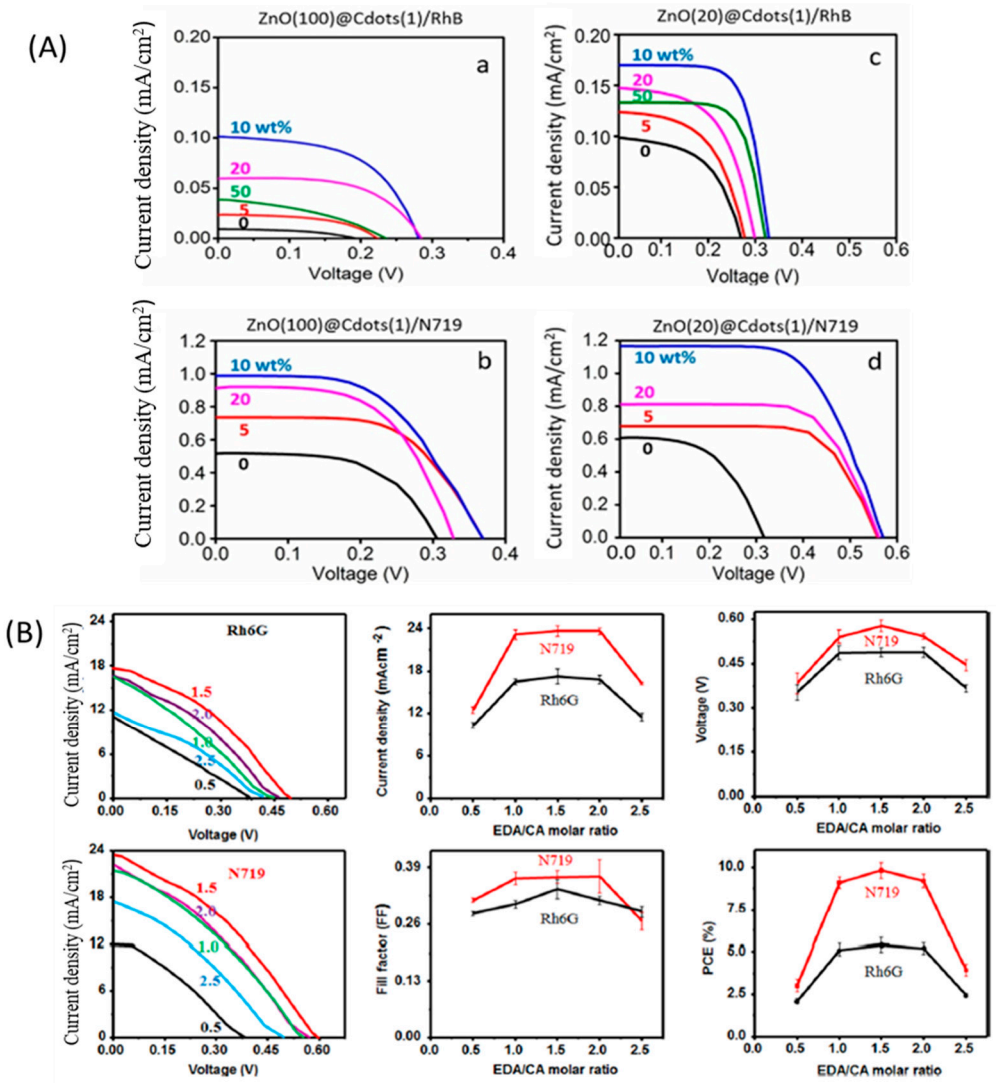

Figure 14. (**A**) CD content's dependency on the I–V characteristics of ZnO@CD DSSCs (**a**) ZnO(100)@Cdots(1)/RhB, (**b**) ZnO(100)@Cdots(1)/N719, (**c**) ZnO(20)@Cdots(1)/RhB and (**d**) ZnO(20)@Cdots(1)/N719. Cdots content: 0, 5, 10, 20 and 50 wt%. (**B**) I−V curves and calculated electrochemical parameters of NiO@CD DSSCs at different EDA/CA molar ratios at 12.5 wt% CD content. The numerals in the I−V curves indicate the EDA/CA molar ratio [138,139]. Copyright 2019 Elsevier; copyright 2020 American Chemical Society.

4.2. Photo Catalysis

Through the environmentally benign and sustainable process of photocatalysis, light stimulates a catalyst to produce energetic electrons and holes that initiate other reactions. Energy and environmental applications have seen the most widespread use of this process. Numerous studies have been conducted to investigate the photocatalytic potential of carbon dots (CDs) due to their broad light absorption, photoluminescent (PL) characteristics, and electron transfer capabilities. CDs can function as a single photocatalyst on their own or combine with other materials to create composite catalysts, such as conventional semiconductor photocatalysts.

The rapid population growth and increasing demand for everyday consumables have led to two main obstacles for human sustainable development: the energy crisis and

environmental pollution. Modern and sustainable technologies can help to resolve these problems. The pure nature of photocatalysis and the endless supply of solar energy make it an attractive solution that will not add to the already heavy environmental load. Typically, photocatalysts are semiconductors that can be activated by light irradiation to produce highly oxidative hole charge carriers and reductive electron charge carriers for various redox processes. The most promising choices for photocatalysis are thought to be II-VI group quantum dots (QDs) and cadmium (Cd)-free I-III-VI carbon QDs (CQDs) due to their exceptional optical capabilities, large surface area, and unique quantum confinement effect. However, certain conventional QDs have garnered increased interest in photocatalysis due to their composition-tunable bandgap. These photocatalysts, however, suffer from poor stability and low production efficiency. This deficiency can be attributed to the limited charge separation and photo-corrosion capabilities of I-III-VI QDs.

According to Figure 15a, fraction 3 (or around 2 nm CDs) was able to rapidly degrade MB (60%) and RhB (20%) through photocatalysis in less than 60 min. It is interesting to note that visible light exposure can cause RhB molecules to change into RhB* radicals. When CdS and CDs were combined (as seen in Figure 15b), the resulting nanocomposites significantly improved the production of hydrogen and oxygen from water splitting and improved the catalytic stability without the need for sacrificial agents. By regulating the CD content in the CDs-CdS composite, the evolution of hydrogen and oxygen was achieved at approximately 2.55 and 0.52 μmol h^{-1}, respectively. These findings did not demonstrate a 2:1 stoichiometric ratio (H2:O2). Additionally, the CDs-CdS nanocomposite outperformed the previously published CdS catalyst in terms of cyclic stability (eight cycles of catalytic tests). The suggested reaction mechanism of CDs-CdS is depicted in Figure 15b. Following the incorporation of carbon dots with CdS, the reaction demonstrates good stability due to enhanced light absorption and electron–hole pair separation. This approach opens up a new avenue for the development and investigation of stable CdS photocatalysts, despite their ongoing shortcomings (such as limited gas generation).

Dyes are compounds that impart color to materials, and they are widely used in various industries, including textiles, cosmetics, food, and biomedical research. The designation of a dye serves as a unique identifier that helps researchers and practitioners to accurately identify and refer to a particular dye compound [140]. Rhodamine B (RhB) is a versatile fluorescent dye widely used in various scientific and industrial applications. Its vibrant pink to red color and strong fluorescence make it a popular choice in fields such as biology, chemistry, materials science, and nanotechnology. RhB belongs to the rhodamine dye family, which encompasses a range of structurally related compounds with similar properties [141]. According to a study by Liu et al., Rhodamine B (RhB) underwent photodegradation, and CDs effectively trap electrons and prevent photoexcited electrons and holes from recombining. The degrading efficiency of RhB by pure CdS after one hour of radiation exposure was approximately 50%, while the efficiency was increased to 90% by 1% CDs/CdS nanocomposites. It is anticipated that the hydrothermal approach of integrating carbon dots with Bi_2MoO_6 nanosheets will improve the nanosheet structure's photocatalytic activity (seen in Figure 15c). How the structure and photocatalytic activity relate to each other was also investigated. They discovered that the as-prepared CD-modified Bi_2MoO_6 had a larger specific surface area (as measured using Brunauer−Emmett−Teller (BET)), which increased the amount of photocatalyst–pollutant interaction and the amount of active species absorbed. This is demonstrated by the photodegradation of ciprofloxacin (CIP), where 2 wt% CD-modified Bi_2MoO_6 showed a 5-fold increase over pure Bi_2MoO_6. The wider visible light absorption zone, slower electron–hole recombination rate, and more active adsorption sites and photocatalytic reaction centers are only a few benefits of this change.

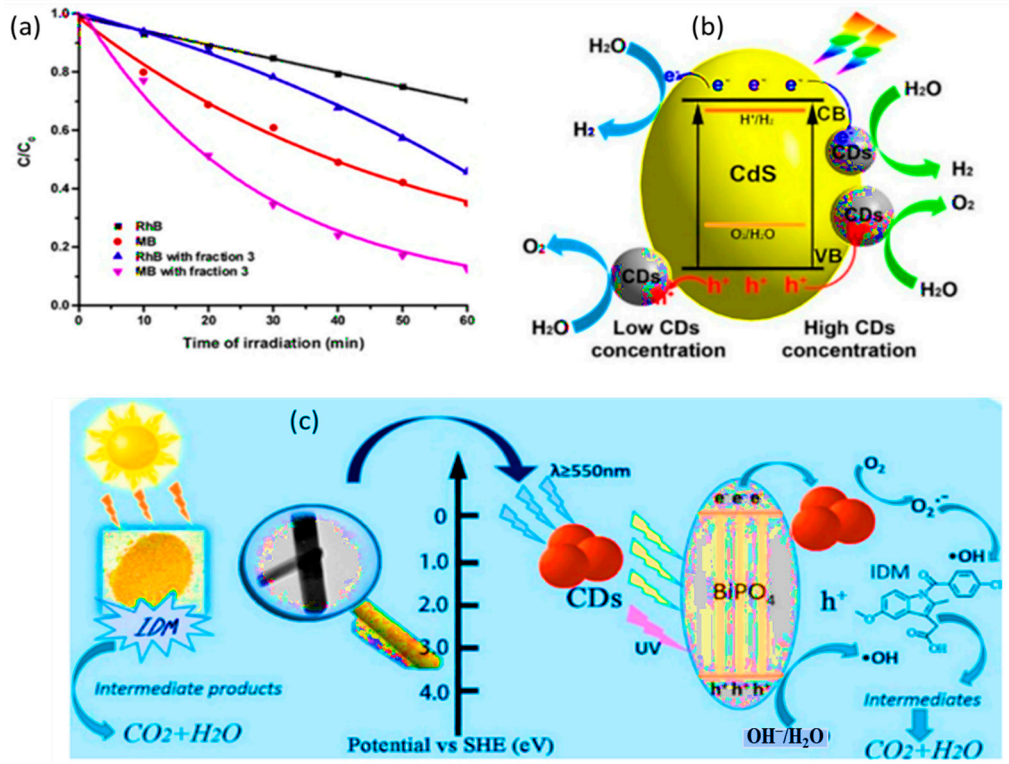

Figure 15. (**a**) Photocatalytic degradation of MB and RhB along with illuminating time [142,143]; (**b**) the proposed reaction mechanism of carbon dots–cadmium sulfide (CDs–CdS) under [142]; (**c**) the schematic photocatalytic mechanism of indometacin (IDM) degradation by the CD-doped BiPO4 composite under irradiation of simulation visible light irradiation [142]. Copyright 2019 mdpi.com.

4.3. Biomass

Biomass carbon dots (BCDs), which are made from discarded organic materials or biomass, are currently being researched for their potential application in solar cells. This is because BCDs are small in size and their fluorescence emission depends on excitation. Zhang et al. [115] reported a fluorescence quenching mechanism that greatly improves the conversion efficiency of BCD-sensitized aqueous solar cells. To test this theory, synthetic BCDs derived from grass were used as a case study to verify the effectiveness of improving fluorescence quenching [144]. It involves converting organic material in a carbon source into carbon dots through heating, dehydration, degradation, and carbonization under high temperatures in a vacuum or inert atmosphere. The pyrolysis method typically utilizes high-concentration acid or alkali to break down the carbon precursors into nanoparticles [93]. Various biomass materials, such as watermelon peel, sago waste, coffee grounds, and plant leaves, can be used as carbon sources for producing CDs through pyrolysis. The properties of the resulting CDs can be adjusted by changing the pyrolysis conditions, including the temperature, duration, and pH value of the reaction system [145]. The resulting CDs have outstanding water solubility, intense blue luminescence, and strong stability in solutions with high salinity and a broad pH range. HeLa cell imaging was accomplished successfully using the carbon dots when prepared (Figure 16a). Pyrolysis of lychee seeds produced fluorescence CDs with low intrinsic cytotoxicity and a quantum yield of 10.6%, which were then utilized for the fluorescence imaging of living $HepG_2$ cells (Figure 16b). A straightforward and affordable pyrolysis technique for the production of fluorescent CDs from peanut shell waste was presented by Xue et al. [53].

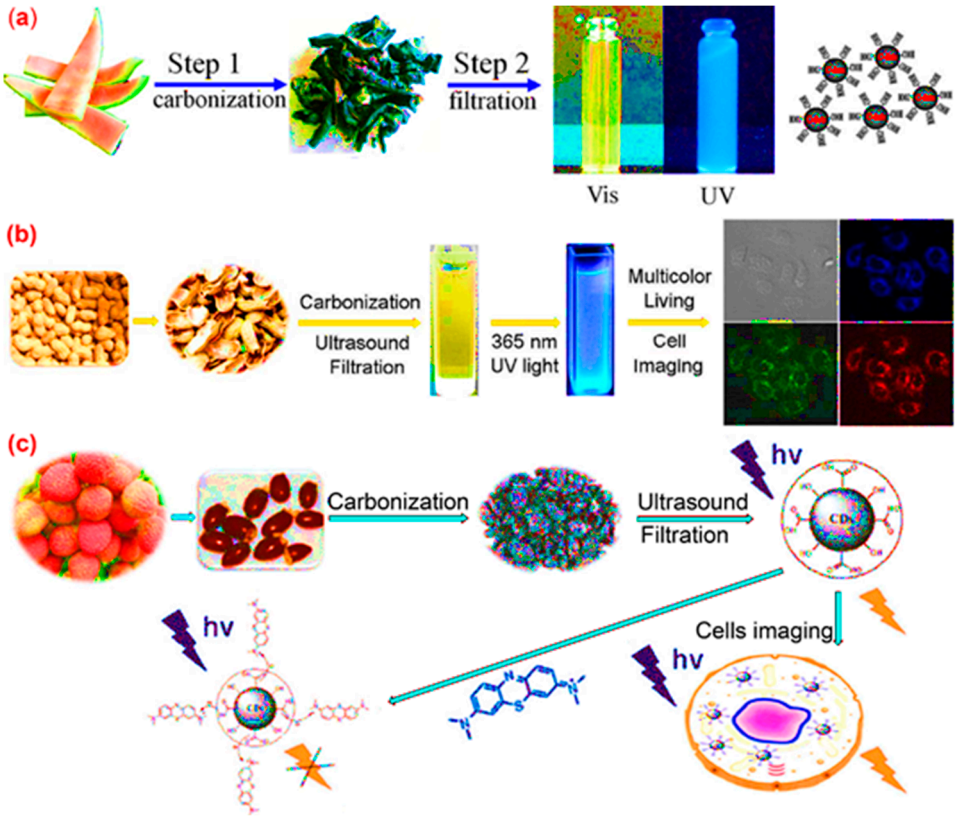

Figure 16. Preparation of fluorescence CDs from agriculture wastes via the pyrolysis method. (**a**) Synthesis of water-soluble CDs from watermelon peel; (**b**) the preparation and application of fluorescent CDs from lychee seeds; (**c**) the preparation and application of CDs from peanut shells [146]. Copyright 2020 mdpi.com.

4.4. Biomedical

CDs have demonstrated excellent properties, including good photostability, excellent photoluminescence, high chemical inertness, and outstanding dispersibility in both organic and aqueous media. These remarkable features, coupled with their facile synthesis, excellent biocompatibility, and low toxicity, have attracted significant attention in bioimaging research. CDs are commonly used in bioimaging applications with confocal laser scanning microscopy (CLSM). Microscopy (CLSM) measures the intensity of light emission or fluorescence absorbed by cells after stimulation with red, blue, and green wavelengths [18]. For instance, zebrafish have been utilized in several important medical fields, such as illness progression, improved mechanisms, and pattern formation due to their clearly defined developmental stages and suitability for optical imaging. Zebrafish were chosen as a fluorescent imaging model, and it was found that CDs preferentially accumulate in the yolk sac and eyes. The integrity of CDs was maintained for over 60 h, making them suitable for studying the long-term stages of zebrafish development, as shown in Figure 17(a–h). Zhang et al. also obtained urine-based CDs through the hydrothermal route and the Sephadex filtration approach, as depicted in Figure 17(i–m). Zebrafish were used to study several important medical sciences, including illness progression, improved mechanisms, and pattern formation, because of their clearly defined developmental stages and optical imaging amenability. Zebrafish were chosen for the fluorescence imaging model because CDs were discovered to accumulate specifically in the yolk sac and eyes. Since CDs were maintained for more than 60 h, they can be used to observe the long-term developmental stages of zebrafish. Despite their blue and green fluorescence, which made them unsuitable for in vivo imaging, PEGpassivated CDs and Zns-doped CDs (CZns-dots-PEG)

were utilized for in vivo imaging. Tissues and organs showed no signs of apparent toxicity under various excitations.

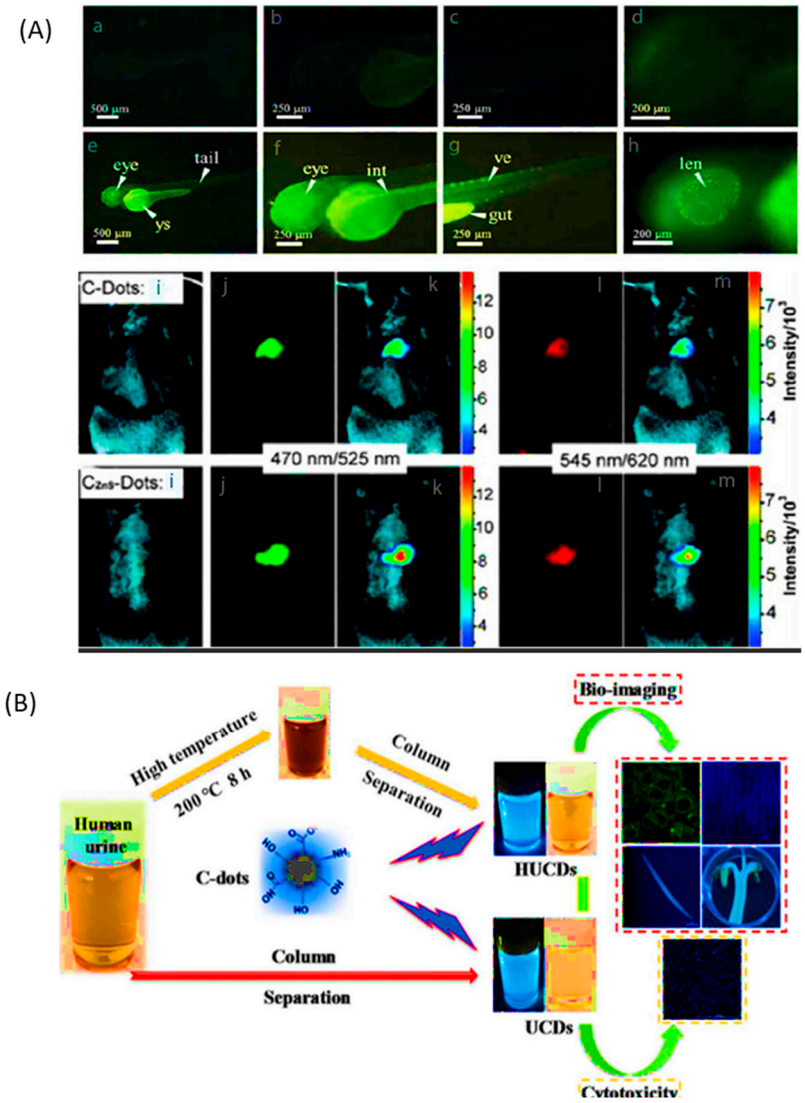

Figure 17. (**A**) (**a**–**h**) Fluorescence image of zebrafish with CDs and (**i**–**m**) fluorescence image of rat injected with CDs (**B**) Graphical representation of how CDs are made from human urine and used in bioimaging [147]. Copyright 2022 beilstein-journals.org.

Various characterizations revealed that both types of CDs contained oxygen and carbon, indicating the presence of several functional groups, including carboxylate, amino, hydroxy, and carbonyl. Cytotoxicity studies demonstrated good applicability and biocompatibility for both in vivo and in vitro imaging. As shown in Figure 17B, within a controlled laboratory environment, the purified urine undergoes a synthesis process. This typically involves heating or chemical treatment to break down the organic compounds present in urine into carbon-rich structures, forming carbon dots. The emitted fluorescent signals from the carbon dots are captured using imaging equipment such as fluorescence microscopes. This allows for the visualization and analysis of biological structures or processes with high sensitivity and resolution.

4.5. Antibacterial Applications of CDs

In recent years, CDs have been studied for their antimicrobial activity. This refers to their ability to inhibit the growth of microorganisms like bacteria, fungi, and viruses.

Figure 18a illustrates the various physical and chemical interactions involved in the antimicrobial mechanism of CDs. The surface of CDs can carry positive or negative charges depending on their surface functional groups. These charged surfaces can interact with the negatively charged cell membranes of microorganisms, resulting in membrane disruption and cell death. Figure 18b shows that the generated CDs exhibit good antibacterial action against a range of Gram-negative bacteria due to their high positive charge potential (45 mV). When locally administered to rabbits' corneal epithelial cells, CDs opened close connections and had a strong antibacterial effect on *Staphylococcus aureus*. Additionally, CDs can be used in combination with Ag, ZnO, and other antibacterial active nanoparticles for broad-spectrum antibacterial action.

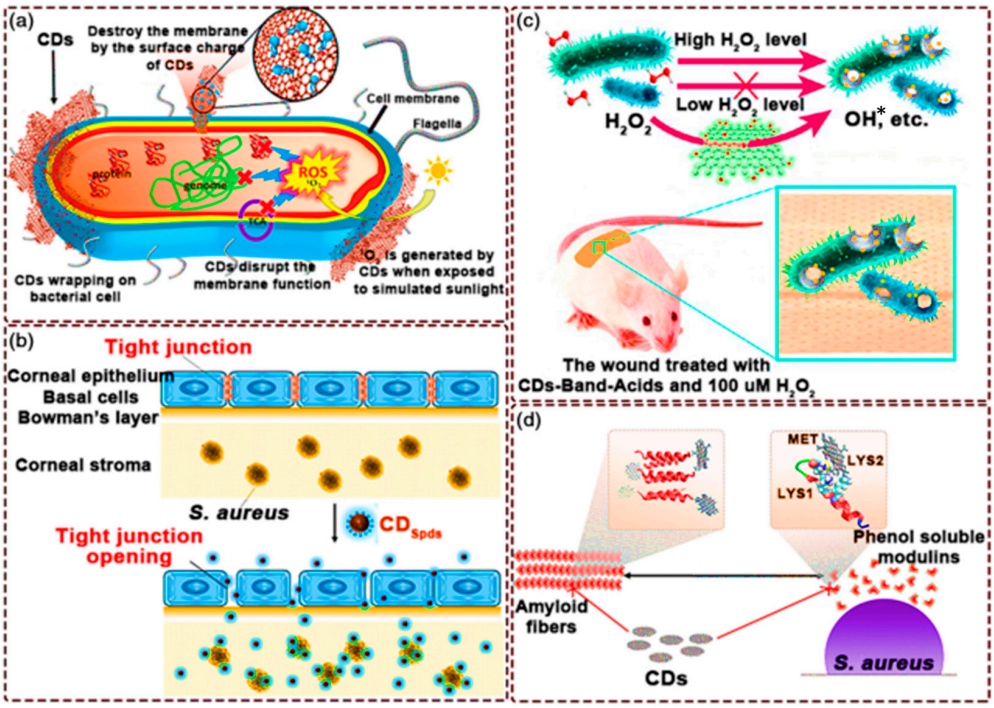

Figure 18. (**a**) Antimicrobial activity mechanism of CDs through various physical and chemical interactions. (**b**) Antibacterial activity using the surface charge on CDs. (**c**) Antibacterial activity using ROS produced by CDs. (**d**) Antibacterial activity using the anti-biofilm properties of CDs [70] Copyright 2022 Wiley.

CDs can have various chemical functional groups on their surface, such as carboxyl, amino, hydroxyl, or sulfhydryl groups. These functional groups can interact with microbial cells through chemical reactions, interfering with their vital processes and inhibiting their growth. CDs can also interact with the cell membrane of microorganisms, causing disruption and destabilization. They can penetrate the lipid bilayer of the membrane, resulting in leakage of intracellular contents and ultimately cell death. When exposed to light or in the presence of oxygen, CDs can generate reactive oxygen species (ROS) like singlet oxygen, hydroxyl radicals, and superoxide ions. These ROS induce oxidative stress in microorganisms, damaging their DNA, proteins, and lipids, and impairing their viability (Figure 18c). Some CDs can also bind to metal ions present in microorganisms, exhibiting metal ion chelation properties. This disrupts essential metal-dependent enzymatic processes in microorganisms, leading to their inactivation. It is important to note that the antimicrobial mechanism of CDs can vary depending on their size, surface chemistry, and the type of microorganism they target.

Biofilms on the surface of bacteria often reduce the effectiveness of fungicides. Figure 18d demonstrates how the protective network of biofilms prevents antibacterial agents from entering the bacterial community. Many small-molecule-based anti-biofilm agents are quickly

broken down by bacteria, diminishing their effectiveness. Furthermore, the biological toxicity of some anti-biofilm drugs presents additional challenges for their applicability. However, due to their small size, CDs can effectively penetrate Gram-positive and Gram-negative bacterial biofilms. They selectively interact with Gram-positive bacteria through hydrophobic and electrostatic interactions, ultimately eliminating the biofilm. Nonetheless, further research is needed to fully understand and optimize the antimicrobial properties of CDs.

4.6. Drug Delivery

Due to their strong fluorescence, minimal toxicity, chemical inertness, and exceptional biocompatibility, CDs are considered to be versatile drug delivery devices. These CDs have been used to transport and deliver medication to specific locations for therapeutic purposes. Due to their superior qualities, CDs have recently gained attention in the field of medicine delivery. The drug-loaded CDs aggregate and travel to the nucleus and cytoplasm of cancer cells. Irradiation is then used to release the medication at these designated locations. To examine medication delivery (as shown in Figure 19a,b), Ding and colleagues produced BCDs using genomic DNA as a carbon source, as illustrated in Figure 8a. Furthermore, CDs with micro/nanopore architectures have become more interesting for medication delivery due to their effectiveness. Micro/nanopore CDs were loaded with the common medication doxorubicin and the CD-DOX was released in cells by adjusting pH. Ding et al. [148] created a DOX-loaded CD-based theranostic agent for medication administration. The internalization of the nanoagent was monitored by the PL emission signal from CDs, as seen in Figure 8b.

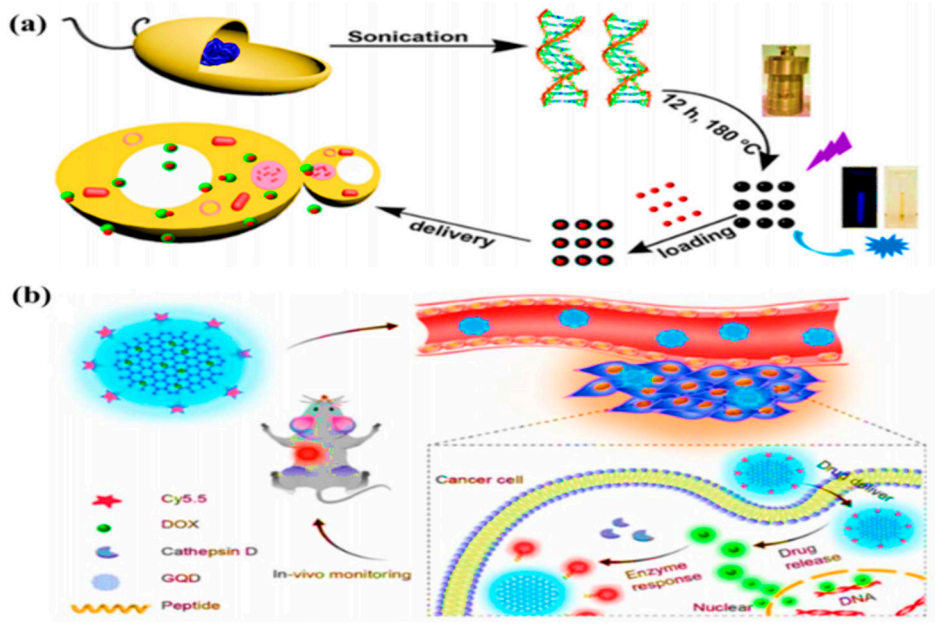

Figure 19. (**a**) Diagram showing the manufacture of DNA-BCD and its use in medication delivery; (**b**) theranostic agent strategy based on CD for in vivo monitoring [148]. Copyright 2020 Springer Nature.

4.7. Energy Storage

There has been a boom in interest in materials for energy applications, specifically for energy conversion and storage. To assure their large-scale application, materials of this kind must be abundant, low-cost, durable in their uses, chemically stable, easily prepared, and non-toxic. Because of their intrinsic qualities, carbon dots, or CDs, seem to be the most promising materials in this context. The discovery of CDs, which are discrete, quasispherical particles with diameters less than 10 nm, dates back to 2004. Since

then, there have been several attempts by researchers to investigate the special qualities of CDs and to use them for energy-related purposes. Recently, attention has focused on the application of the carbon dot (CD) family of quasi-0D carbon-based materials. CDs have been identified as intriguing materials for environmental and energy applications spanning from chemical catalysis, photocatalysis, and electrocatalysis to energy storage such as batteries and capacitors due to their non-toxic nature, availability, and low cost. CDs are made up of discrete, quasispherical particles that are less than 10 nm in size [149].

Recently, Fan and colleagues developed edge-nitrogen-rich CD pillared graphene blocks (N-CDGBs) for sodium ion storage. These N-CDGBs demonstrated exceptional cycle stability and high volumetric/gravimetric capacity. To manufacture the N-CDGBs, the researchers self-polymerized aniline monomers into graphene oxide blocks, which were then carbonized. This process resulted in the creation of edge-rich CDs with nitrogen, evenly spaced throughout the graphene sheets. The introduction of negative electron densities by the embedded CDs increased the sodium ion adsorption energy, as predicted by theory. The N-CDGBs, functioning as anodes, exhibited volumetric and gravimetric capacities of 780 mA h cm^3 and 520 mA h g^{-1}, respectively, at 0.02 A g^{-1}. These impressive properties were attributed to the high bulk density (1.5 g cm^{-3}) and extensive edge-nitrogen doping (95%) in the CD pillared graphene structure of the N-CDGBs. In addition to their remarkable performance, the N-CDGBs also demonstrated excellent cycle stability [150].

As revealed in Figure 20 [149], CV curves show that the I3 reduction has a better catalytic performance when there is an increase in reduction current densities and a minimal potential gap between the oxidation and reduction peaks. The cathodic peak current densities, or CVs, are displayed in Figure 20 and have been used to evaluate the electrocatalytic activity of CEs. The current densities on CEs for PANI and PANI/CDs are −6.18 and −7.66 mA cm^{-2}, respectively. In comparison to pristine PANI, the current density value for PANI/CDs is higher. Additionally, the PANI/CDs CE exhibits a superior peak-to-peak voltage separation (Epp) compared to the PANI CE.

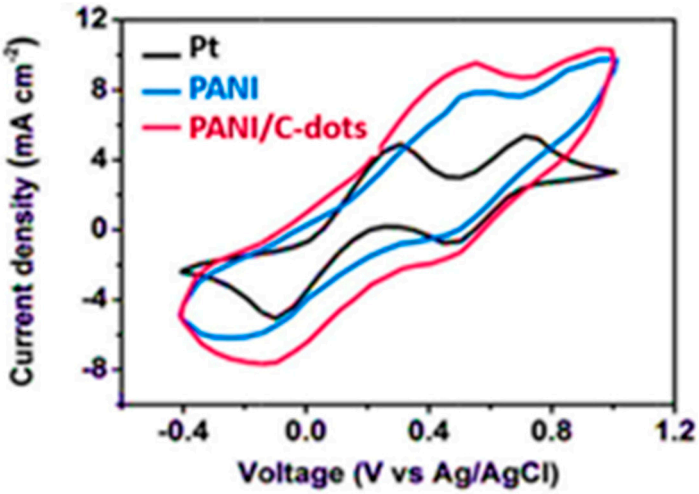

Figure 20. CV in I_3^-/I^- electrolyte composed of 10 mM LiI, 1.0 mM I_2, and 0.1 M $LiClO_4$ in acetonitrile at a scan rate of 50 mV s^{-1} [149]. Copyright 2021 Elsevier.

5. Challenges and Future Perspectives

CDs have emerged as promising nanomaterials in various fields due to their unique properties [34,151]. While there are multiple methods for synthesizing CDs, including physical, chemical, and biological approaches, priority should be given to the biological route due to its cost-effectiveness and environmental friendliness [152,153]. Furthermore, biologically synthesized carbon dots exhibit biocompatibility, enhancing their potential application in biomedicine, particularly in drug delivery [86,154]. In recent years, carbon dots have garnered significant attention for their potential applications in optoelectronics,

bioimaging, sensing, energy storage, and catalysis [34,155]. However, there are still several challenges and future perspectives associated with carbon dots [48]. One such challenge is the synthesis techniques employed [156]. To enable their widespread use, it is crucial to develop efficient and scalable synthesis methods for carbon dots [48]. Although various techniques, such as hydrothermal/solvothermal methods, microwave-assisted synthesis, and pyrolysis, have been utilized, precise control over the size, shape, and surface chemistry of carbon dots remains a necessity [79,157]. The diverse properties exhibited by CDs depend on their synthesis conditions and surface functionalization. To ensure reproducibility and reliability, it is crucial to standardize of synthesis protocols and characterization methods, including transmission electron microscopy (TEM), spectroscopy (UV-Vis, fluorescence), and elemental analysis [158,159]. The photoluminescence mechanism of carbon dots is not yet fully understood. Their emission properties stem from the quantum confinement effect, surface states, and functional groups on their surface. Additional research is needed to elucidate the underlying mechanisms and optimize the photoluminescence properties for specific applications. CDs often encounter stability issues when exposed to environmental factors such as heat, light, and moisture. Enhancing the stability and photostability of CDs is essential for prolonged performance and practical applications. Although carbon dots show promise for biomedical applications, such as bioimaging and drug delivery, a comprehensive investigation into their potential toxicity and biocompatibility is necessary to ensure their safe implementation in biological systems. To translate the potential of carbon dots into practical applications, their integration into devices and the scaling up of their production are imperative. This endeavor involves addressing challenges related to device fabrication, compatibility with existing technologies, and cost-effective large-scale synthesis. In terms of future perspectives, carbon dots hold tremendous potential for advanced applications, solar cells, sensors, and catalysts. Continued research and development will facilitate the exploration of new applications and the optimization of carbon dots for specific functionalities. CDs combine the special optical qualities of semiconductor quantum dots with the electrical features of carbon materials, and they show distinct advantages in applications related to energy. CDs can serve as both a sensitizer and a light absorber during the sunlight-harvesting process.

6. Conclusions

This review covering the period from 2019 to 2023 significantly advanced our understanding of carbon dots (CDs), an emerging nanomaterial. Research during this period led to developments in the synthesis, characterization, and applications of CDs. They find use in optoelectronics, bioimaging, sensing, antibacterial, biomedical, energy storage, and catalysis. CD synthesis saw progress through methods such as hydrothermal, solvothermal, microwave-assisted, and electrochemical techniques. These methods allowed for precise control over size, morphology, surface functionalization, and optical properties. Environmentally friendly routes using renewable precursors and non-toxic reagents increased their appeal. Characterization techniques played a crucial role in understanding CDs. Spectroscopic, microscopic, and analytical tools provided insights into structure, composition, surface chemistry, and photophysical properties. This knowledge guided synthesis optimization and the development of applications. CDs showcased a wide range of applications. They excelled in optoelectronic devices such as LEDs, photovoltaics, and displays due to their strong fluorescence, tunable emission, and high photostability. Future research aims to achieve better control over CDs' properties and scalable synthesis. Understanding the photophysical properties and mechanisms through spectroscopic and theoretical studies is crucial. Further research is needed to bridge the gap between lab-scale demonstrations and practical implementation. Integrating CDs into efficient devices like LEDs, solar cells, and displays is important. Exploring their potential in imaging, drug delivery, and theranostics can revolutionize medicine. Enhancing the sensitivity, selectivity, and stability of CD-based sensors for real-time monitoring is crucial. Optimizing CDs' performance and commercial viability in energy storage and catalysis is promising. Finally,

this review highlights significant progress in CDs from 2019 to 2023. They show versatility and immense potential in various fields. With further research, CDs can become key components in next-generation technologies, advancing electronics, healthcare, environmental monitoring, and energy storage.

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