CHAPTER THREE

Materials and synthesis of eco-friendly carbon dots for sustainable solutions

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Contents

Abstract

The chapter explores the wide-ranging applications of eco-friendly CDs, showcasing their versatility in various fields. In photovoltaics, they enhance the efficiency of solar cells because of their absorption of light and charge transfer. Their high surface area

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and conductivity make them applicable in supercapacitors, contributing to increased energy storage capacity and stability. In catalytic reduction processes, CDs serve as efficient catalysts for hydrogen generation and carbon dioxide reduction reactions. Additionally, the light-emitting properties of CDs are highlighted in the production of advanced light-emitting diodes (LEDs), while their adsorption capabilities and photocatalytic activity are utilized in environmental remediation. Therefore, the current chapter highlights the potential of eco-friendly CDs in supporting sustainable solutions across multiple technical domains by analysing the nature of these materials, synthesis methodologies, and in-depth applications.

1. Introduction

Carbon dots (CDs) have gained considerable interest due to their combination of remarkable properties. These include biocompatibility, ease of functionalization and negligible toxicity, making them suitable for various applications [1]. Carbon dots (CDs) are tiny carbon nanoparticles, typically described as quasi-spherical carbon-based materials. They were first identified in 2004 by Xu et al. while purifying single-walled carbon nanotubes, where they were found as components of fluorescent nanoparticles (NPs) [2]. The research triggered an increased interest in the properties and behavior of CDs. These nanoscale carbon dots were then named "carbon quantum dots" by Sun and co-workers in 2006 [3]. CDs are typically defined as carbon NPs of 2–8 nm and exhibit distinctive optical properties, viz. photoluminescence (PL), electrochemiluminescence and chemiluminescence [4], rendering them suitable for various applications. These include drug delivery, sensing and bioimaging [5,6,7]. The fluorescence and physical properties of CDs can be altered by modification and surface passivation [8]. CDs' most unique and intriguing optical property is their photoluminescence. Photoluminescence is a process in which CDs absorb photons (light) from external light radiation, causing their energy levels transition to generate fluorescence [9]. CDs also display unique electrical and optoelectronic properties due to their intrinsic band gap [10]. To improve their solubility, sensing, selectivity, and PL qualities as well as expand their range of applications, CDs' carbon surfaces and cores are readily functionalized [11]. Nanomaterials offer many advantages, but their synthesis often involves toxic reagents, limiting their use and making them environmentally unfriendly. The development of eco-friendly CDs has grown significantly given the increased demand for environmentally friendly and sustainable synthesis techniques. Green chemistry methods

such as using natural or waste-derived sources to synthesize eco-friendly CDs are employed to ensure minimal impact on the environment [12]. Renewable, abundant and non-toxic biomass, food waste, and natural materials are examples of sources used in the synthesis of environmentally friendly CDs [13]. This approach addresses environmental and financial concerns by reducing reliance on hazardous chemicals and high-energy processes.

The incorporation of environmentally friendly CDs into commercial products is anticipated to increase as research develops, driving innovation in sustainable nanotechnology and creating new opportunities for study and application. This chapter explores different ways of synthesizing environmentally friendly carbon dots, their distinctive properties, and potential applications in various fields. An overview of carbon dots classifications is presented followed by various synthesis methods derived from green chemistry principles. The characteristics of CDs and the progress made in energy, optics and biomedicine as well as other applications are thoroughly explored. Lastly, the future outlook and recommendations on the use of eco-friendly CDs are discussed. Our goal in highlighting these nanoparticles' functional diversity and the progress made in green synthesis techniques is to emphasize the role that sustainable practices play in the continuous development of nanotechnology.

2. Classification of carbon dots

Carbon dots (CDs) were initially reported by Xu and colleagues in late 2004. These materials are categorized based on their carbon source into carbon quantum dots, graphene carbon quantum dots, carbon nanodots, and carbonized polymer dots [2]. Carbon quantum dots (CQDs) are spherical crystalline particles with numerous functional groups that contribute to their intrinsic luminescence and quantum confinement effects. Graphene carbon quantum dots (GQDs) are anisotropic fragments of graphene composed of single or multiple graphene nanosheet layers [14]. They exhibit quantum confinement and edge effects due to chemical functionalities at the edges and within interlayer defects. These quasi-spherical particles are used as smart probes in environmental, optoelectronic, electrochemical, and biological applications. Their intrinsic luminescence and size-dependent photoluminescence (PL) allow control over emission wavelength by manipulating particle size. GQDs can also form hybrid materials through π-π interactions,

broadening their applications. Recognized for their excellent non-toxicity and biocompatibility, and thus preferably used in biomedical applications [15]. These applications include drug delivery [16,17], wound dressing [18], biosensing [19], tissue engineering [20] and bioimaging [16]. Citric acid is often used as a source for GQD synthesis via a bottom-up approach, where it is heated to 200 °C for 30 min, resulting in 2D sheets with sizes ranging from 1–4 nm and size of ~2.19 nm. AFM images show GQD thicknesses between 0.5–2.0 nm, indicating one to three graphene layers [21]. Carbon nanodots (CNDs) are characterized by a high level of carbonization and edge effects, but they are non-crystalline and lack quantum confinement effects [22]. Carbonized polymer dots (CPDs) feature a cross-linked carbon structure with aggregated polymers. They have a central carbonized core surrounded by polymeric chains or functional groups [22].

3. Synthesis of carbon dot materials

Though there are different methods of synthesizing CDs this chapter focuses on green synthesis methods. Green synthesis methods for CDs production have attracted substantial attention because of their potential to produce these valuable nanomaterials in an eco-friendly and sustainable means [23]. As the demand for CDs grows across various industries such as biomedicine, energy, and environmental monitoring, the need for eco-friendly production techniques has become increasingly important [24–26]. This section discusses the principles, advantages, and specific methods of green synthesis, highlighting the recent advancements and challenges in this area. Green synthesis of CDs revolves around the principles of green chemistry, which aim to minimize the use of hazardous substances, reduce waste, and enhance the efficiency of chemical processes [27]. The fundamental principles guiding green synthesis include; utilizing natural, renewable resources such as plant extracts, fruit and vegetable juices, and biomass instead of synthetic chemicals [28,29]. Employing methods that require lower energy inputs, such as microwave, solar and ultrasonic irradiation, contrary to using high demand of electricity [25]. Avoiding or minimizing toxic and harmful solvents and reagents, thereby reducing the environmental footprint [30]. Ensuring that the synthesized CDs are biocompatible, particularly for applications in biomedicine and environmental monitoring [31]. Designing processes that produce minimal waste and allow for easy recycling or disposal of by-products [32,33].

Green synthesis methods offer several advantages over traditional chemical synthesis approaches such as environmental safety, by avoiding toxic and harmful chemicals and solvents, green synthesis methods are safer for both the environment and human health conditions [34]. Secondly, cost-effectiveness, utilizing readily available natural resources can reduce production costs [35]. Thirdly, simplicity, many green synthesis processes are straightforward and do not require complex instrumentation or conditions

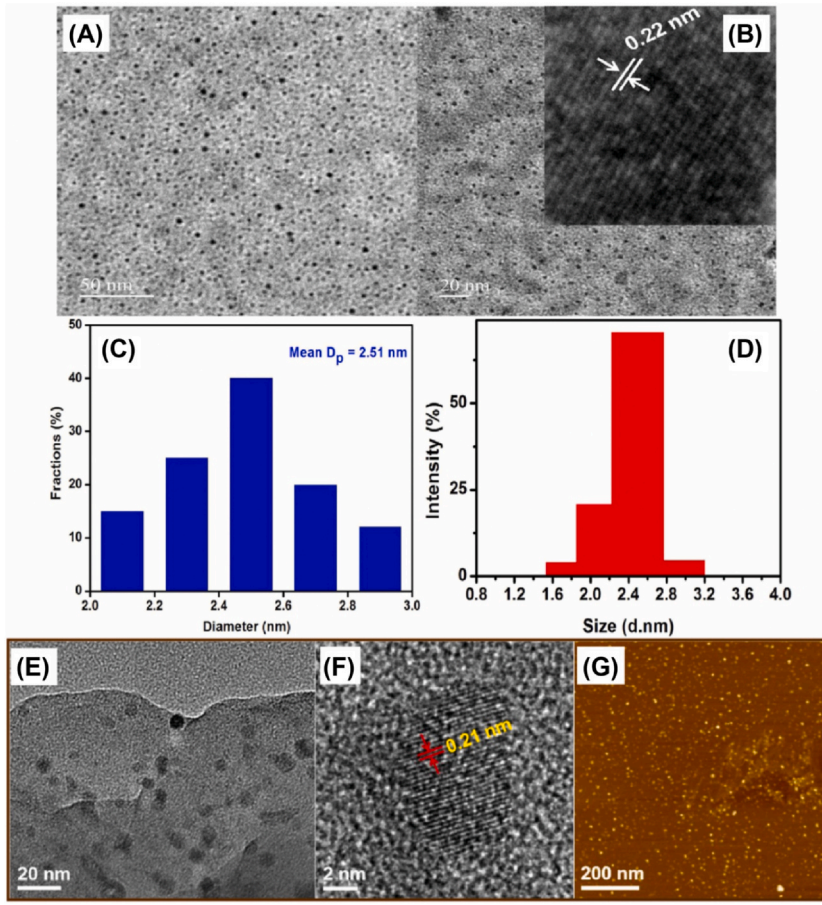

Fig. 1 Hydrothermally synthesized carbon dots (CDs) from banana plant stems are depicted in panels (A) and (B) with TEM images, panel (C) shows their particle size distribution based on TEM measurements, and panel (D) presents dynamic light scattering (DLS) data. CDs synthesized using *M. liliiflora* are illustrated in panels (E) and (F) with TEM images at different magnifications, while panel (G) displays an AFM topography image. *Reproduced from reference [44,45].*

[36]. Fourthly, the scalability factor; green methods can often be scaled up more easily, making them suitable for industrial applications [25]. Lastly, biocompatibility, these CDs produced through green methods are typically more biocompatible, which is crucial for biomedical applications [31,37]. The following section discusses different green synthesis methods for producing CDs.

3.1 Hydrothermal and solvothermal methods

Hydrothermal and solvothermal methods are widely used in green synthesis due to their simplicity and efficiency. These methods involve the reaction of carbon precursors in water or other benign solvents under high pressure and temperature conditions [38]. Common precursors include plant extracts, fruit juices, and waste biomass [39]. The hydrothermal method involves heating the precursor solution in a sealed container (autoclave) at elevated temperatures (typically 150–250 °C) [40]. The high pressure and temperature facilitates the carbonization and formation of CDs [41]. For example, CDs have been synthesized using lemon juice, tea extract, and even waste biomass like orange peel and banana peel [36]. The solvothermal method is akin to the hydrothermal method, but it employs organic solvents rather than water [42]. This method can tailor the surface properties of CDs by using different solvents, thus adjusting their fluorescence and other characteristics [43].

Fig. 1 shows CDs synthesized from banana plant stems and *M. liliiflora* employing hydrothermal technique. Fig. 1A and B display TEM images highlighting their uniform distribution and lattice fringes with an interplanar spacing of ~0.22 nm. Fig. 1C presents the particle size distribution from TEM measurements, indicating a diameter of ~2.51 nm. Fig. 1D shows dynamic light scattering (DLS) measurements, illustrating the intensity distribution with a predominant size around 2.4 nm. Fig. 1E and F feature TEM images of CDs synthesized from *M. liliiflora* at different magnifications, revealing detailed morphology and lattice fringes with a spacing of ~0.21 nm. Lastly, Fig. 1G provides an AFM topography image, depicting the surface distribution of CDs over a larger area. These images collectively detail the structural characteristics and size distribution of the synthesized CDs from both sources.

3.2 Ultrasonic-assisted synthesis

Ultrasonic-assisted synthesis uses ultrasonic waves to generate localized high temperatures and pressures, promoting the formation of CDs, in

addition, this approach is known for its simplicity, efficiency, and ability to produce CDs with high purity [46,47]. The process involves the precursor solution exposed to ultrasonic waves, which create cavitation bubbles. The collapse of these bubbles generates extreme conditions, leading to the formation of CDs [48]. Precursors such as glucose, sucrose, and various plant extracts are commonly used. The advantage of ultrasonic-assisted synthesis is a low-temperature process that produces CDs with excellent

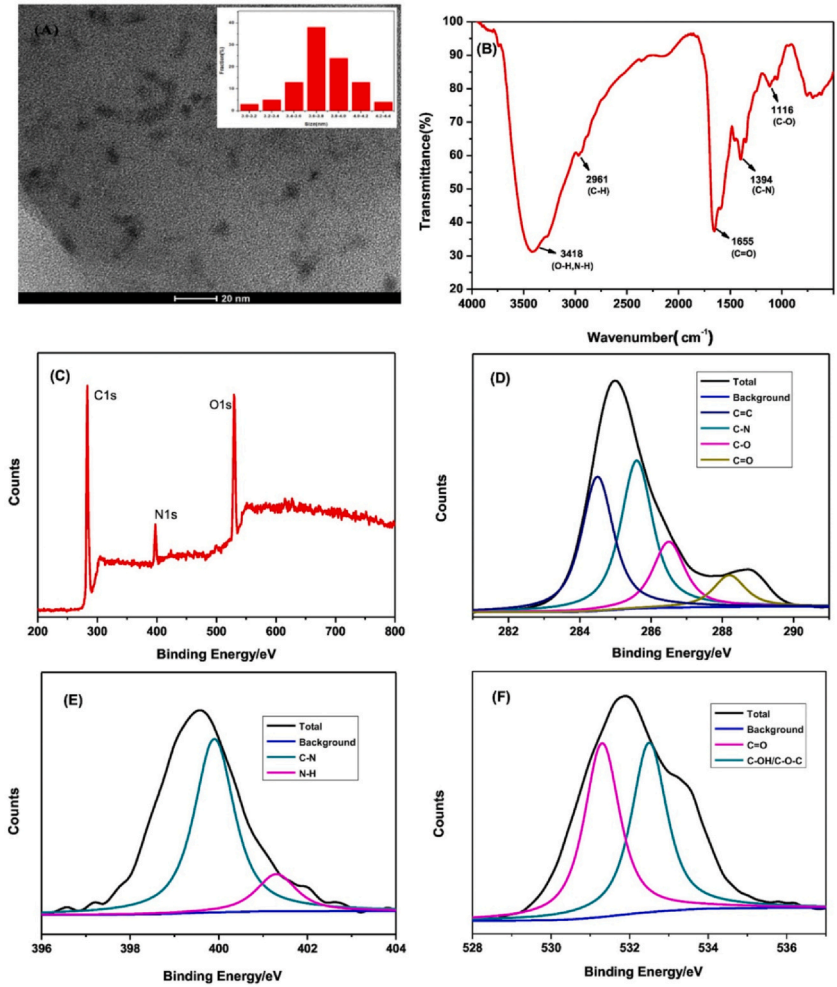

Fig. 2 Transmission electron microscope image and size distribution of carbon dots (A), IR spectrum of the CDs (B), full scan XPS spectrum (C), XPS spectrum of C1s (D), XPS spectrum of N1s (E), and XPS spectrum of O1s (f). *Reproduced from reference [56].*

optical properties [49]. It is also environmentally friendly and suitable for producing CDs with specific functional groups.

3.3 Biopolymer precursor synthesis

Biopolymers including chitosan, cellulose, and starch are renewable and biodegradable materials and can serve as carbon sources for the green synthesis of CDs [50]. These biopolymers not only act as carbon sources but also provide additional functionalities that enhance the properties of resultant CDs. The process includes biopolymers being subjected to pyrolysis or hydrothermal treatment to produce CDs. The type of biopolymer and synthesis conditions can tailor the size, shape, and functional properties of the resulting CDs [51,52]. The advantages are the use of biopolymers ensures biocompatibility and adds value to renewable resources and CDs derived from biopolymers have shown potential in biomedical field, and environmental sensing [53].

3.4 Microwave-assisted synthesis

Microwave-assisted synthesis is yet another popular green method that leverages microwave irradiation to rapidly heat the carbon precursors, leading to the formation of CDs [28]. This approach offers several benefits, including shorter reaction times, energy efficiency, and uniform heating. The process involves a mixture of the carbon precursor and solvent exposed to microwave radiation, and the rapid heating facilitates the carbonization process, resulting in the formation of CDs [54]. Common precursors include honey, citric acid, and polyethylene glycol. The advantages of microwave-assisted synthesis can produce CDs with high quantum yield and tuneable properties and the method is also scalable and can be easily adapted for large-scale production [55].

Fig. 2 presents comprehensive characterization data of CDs. TEM image revealing the morphology of the CDs, along with an inset displaying their size distribution, are shown in Fig. 2A. Fig. 2B provides the Fourier Transform Infra-Red (FTIR) spectrum, indicating surface functionalities of the resultant CDs, with peaks at 3418 cm^{-1} (O-H, N-H), 2961 cm^{-1} (C-H), 1655 cm^{-1} (C═O), 1394 cm^{-1} (C-N), and 1116 cm^{-1} (C-O). Fig. 2C features a full scan X-ray photoelectron spectroscopy (XPS) spectrum, highlighting the elemental composition with peaks for C1s, O1s, and N1s. Fig. 2D–F offer detailed XPS spectra for C1s, N1s, and O1s, respectively. The deconvolution in Fig. 2D shows contributions from C═C, C-N, C-O, and C═O bonds. Fig. 2E indicates the presence of C-N and N-H bonds,

while Fig. 2F identifies C-O and C-OH/C-O-C bonds. These analyses collectively confirm the CDs' structural and chemical composition. The structural and chemical attributes of CDs are reliant on the precursor and the type of method and this have come with several advancements and challenges which are discussed in the following section.

3.5 Recent advancements

Recent advancements in the green synthesis of CDs have focused on optimizing the processes, enhancing the chemical and physical properties of CDs, and expanding their applications [57,58]. Some notable developments include multifunctional CDs with multifunctional properties that have been synthesized using green methods [35]. For example, CDs with both antibacterial and fluorescent properties have been produced using natural precursors like garlic and ginger [59]. Secondly, with enhanced quantum yield, researchers have developed green synthesis methods that produce CDs with higher quantum yields, making them more efficient for applications in bioimaging and sensing [60,61]. Thirdly, hybrid nanomaterials involving green synthesis have been used to produce hybrid nanomaterials that combine CDs with other nanomaterials like metal nanoparticles or graphene, resulting in enhanced properties and new functionalities [62].

3.6 Challenges

Despite the significant progress, several challenges remain in the green ecofriendly synthesis of CDs, such as standardization; there is a lack of standardized protocols for the green synthesis of CDs, leading to variability in the properties of CDs produced by different methods [63–65]. The second challenge is the scaling up. Besides most of these methods showing a promise at the labscale, scaling them up for industrial production remains a challenge [66–68]. Thirdly, a deeper understanding of the formation mechanisms and the relationship between synthesis conditions and the resultant CDs' properties is needed to optimize green synthesis methods [49,69,70]. Lastly, functionalization control, meaning that controlling the functionalization of CDs during green synthesis to achieve specific properties and functionalities remains a complex task [71–74]. Green synthesis methods for CDs production represent a promising and environmentally friendly approach to creating these versatile nanomaterials. By leveraging natural resources, minimizing toxic reagents, and enhancing energy efficiency, green eco-friendly synthesis method aligns with the principles of sustainability and offers significant advantages over traditional methods.

Despite the challenges, ongoing research and advancements in this field are poised to unlock the full potential of CDs, paving the way for their widespread application in biomedicine, energy, environmental monitoring, and beyond. As the understanding of green synthesis methods deepens, the future of CDs production looks increasingly sustainable and innovative.

4. Application of carbon dots

4.1 Energy

CDs are a fascinating class of carbon NPs that have gained tremendous attention because of their exceptional attributes and versatile applications. They are typically less than 10 nm in diameter and comprise of a carbon core with a surface passivation shell. The core is primarily responsible for the intrinsic optical properties while the surface passivation shell plays a critical role in enhancing the solubility, stability and biocompatibility of the CDs. Their unique photoluminescence (PL) properties, high solubility, high biocompatibility, and environmental benignity make them particularly attractive for various applications, including renewable energy, and environmental remediation [75–77].

Traditional methods for synthesising CDs often involve harsh chemicals and conditions. However, as discussed earlier in Section 3, eco-friendly green synthesis methods have been developed to overcome these concerns. The use of natural precursors such as fruit extracts, plant leaves, and food waste, affords the synthesis process sustainable, environmentally friendly and most importantly for businesses, economical, making this class of nanomaterials very lucrative. These natural products afford the CDs key organic moieties such as hydroxyl, carboxyl, and amine groups that give CDs their unique properties. Fig. 3 depicts the structure of the quasi-sphere of carbon. The core (gray-brown) contains the crystalline structure of carbon rings while the amorphous sp^3-hybridized carbon matrix is found in the shell (blue). Any dopants present due to synthesis or post synthesis treatment will result functional groups which are located on the outer surface of the CD [78].

In addition to examples mentioned in Section 3 of eco-friendly CDs produced from natural resources, the following precursors have also been explored including brewer's spent grain [79], watermelon peel [63], coffee grounds [80] litchi leaves [69] and rosemary leaves [81] all producing CDs for bio-imaging, sensing, corrosion inhibition and photo absorption renewable energy devices. Fig. 4 presents the synthesis of CDs from collard green leaves

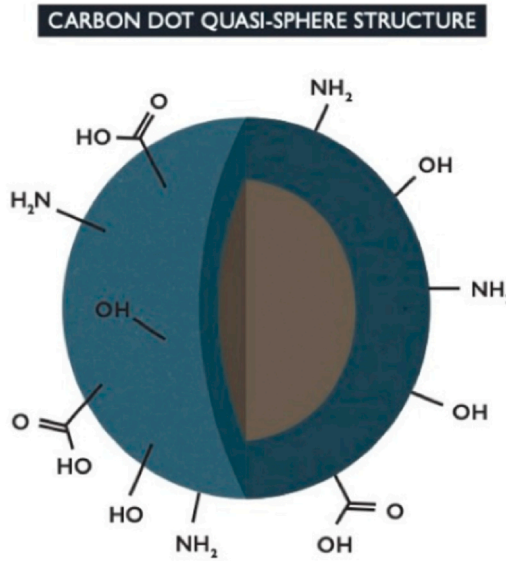

Fig. 3 Presentation of the quasi-sphere structure of carbon dots showing various functional groups in the passivation shell [78].

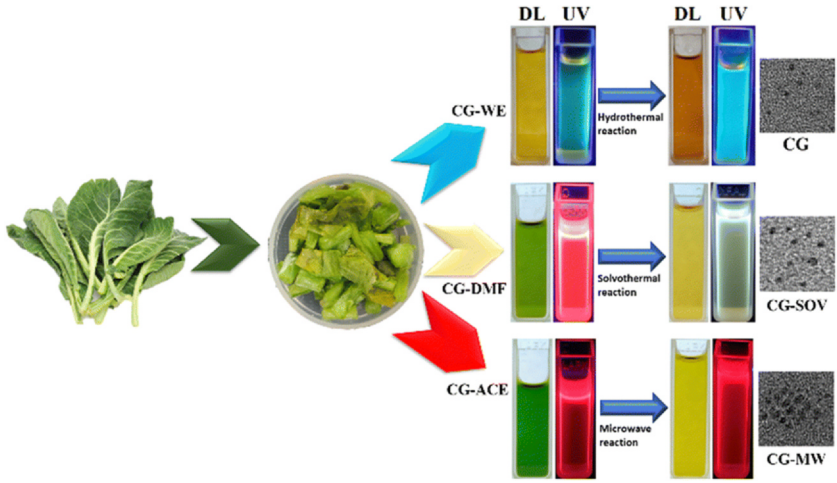

Fig. 4 The representation of the collard green CD synthesis. CG-WE represents collard greens extract in water and ethanol solvent, CG-DMF represents collard greens extract in DMF solvent, and CG-ACE represents collard greens extract in acetone solvent. CG, CG-SOV, and CG-MW are the corresponding CDs prepared by hydrothermal, solvothermal, and microwave methods, respectively. DL stands for daylight, and UV stands for ultra-violet light. *Reproduced with permission from [82].*

using three different procedures i.e. hydrothermal, solvothermal and microwave digestion. The collard green carbon dots were used in a dye-sensitized solar cell (DSSC). The CDs and N719 dye worked together synergistically, resulting in a device with improved efficiency. Additionally, the CDs were capable of harvesting surrounding infrared radiation, enabling the device to operate perfectly even in low-light conditions [82].

The surface passivation also helps in tuning the CDs' electronic and optical properties by preventing non-radiative recombination of electron-hole pairs, thus enhancing their luminescence efficiency [14,83]. The PL emission of CDs can span across the visible spectrum, from blue to red and can be tailored by fine-tuning the surface functional groups or by controlling the synthesis parameters. This tuneable PL makes CDs highly useful for applications in light-absorbing devices, and sensors. The mechanism behind remarkable PL emission is attributed to various factors, including quantum confinement, surface state emission, and the presence of molecular fluorophores on the surface [75,83].

4.2 Photovoltaic applications

Due to their exceptional light-absorbing capabilities, one of the most popular and promising energy applications of CDs is in photovoltaic devices. CDs can be incorporated into solar cells to enhance light absorption and charge transfer efficiency. Their remarkable absorption in the UV–visible range and tuneable emission properties make them suitable for enhancing the overall performance of solar cells [84,85]. In dye-sensitized solar cells (DSSCs), CDs can serve as co-sensitizers or as additives in the photoanode material to boost the photocurrent and overall efficiency of the cells. Studies have shown that CDs enhance charge separation and reduce recombination rates, leading to higher power conversion efficiencies (PCEs). Ghann et al. [86] demonstrated that the incorporation of CDs in a DSSC which had an efficiency (η) of 0.10 %, while that of the N719 dye (Ru-sensitizer) together with the CDs was 0.19 %, showing an increase in the efficiency. This illustrates that the CDs have some sensitizing effect that ensures the capture of photons to generate electric power [86].

Elsewhere green-emitting CDs were produced in a solvothermal treatment using citric acid as a source and N, N-dimethylformamide as a solvent. Upon incorporation of the CDs into the photoanode with N719 as the sensitizer, the conversion efficiency of the DSSC improved from 6.28 % to 6.90 % [87]. Ninan et al. recently reported on the deployment of different dyes as sensitizers in their DSSC devices. They used hibiscus dye

and onion peel dye extracts as opposed to the commonly used N719 dye and produced CDs from Citrus medica fruit extract. The device with the unmodified photoanode (TiO_2) gave a PCE of 2 %, while that with carbon dot co-activated photoanode (CD/TiO_2) had a PCE of 3.5 %. This is the highest PCE attained so far through the usage of hibiscus and onion peel dyes as the sensitizer [88].

4.3 Energy storage applications

The application of CDs in energy storage devices, such as supercapacitors and batteries, is another area of active research. CDs can enhance the electrochemical performance of these devices because of their high surface area, remarkable electrical conductivity, and electrochemical stability. In supercapacitors, CDs have been commonly employed as electrode materials or as conductive additives in composites with other carbon materials. For example, CDs combined with graphene oxide have demonstrated enhanced specific capacitance and cycling stability in supercapacitor electrodes [89–91]. In particular, in an experiment conducted by Dang et al., where a graphene-based electrode material for supercapacitors was created by anchoring CDs onto reduced graphene oxide (rGO). This electrode, tested in 1 M H_2SO_4, exhibited a capacitance of ~212 Fg^{-1} at a current density of ~0.5 Ag^{-1}, which is ~74 % higher than the pristine rGO electrode's 121.6 Fg^{-1}. Additionally, the CD/rGO electrode maintained ~93 % of its initial capacitance after 1000 cycles at a CDs-rGO ratio of 5:1, eluding to the composite electrode's stability [92]. This enhancement is due to the synergistic interaction between CDs and graphene oxide, which provide a more efficient charge storage and transfer pathway.

Hybrid supercapacitor devices have stimulated a growing interest among researchers in the field because of their great potential in energy storage applications. A study by Ji et al. prepared N-doped CDs were used to decorate flower-like cobalt sulfide (CoS) structures and rGO nanosheets via a simple hydrothermal method. The N-doped CDs considerably increased the CoS and rGO specific surface areas and pore volumes, enhancing the electrochemical properties of CoS/N-doped CDs and rGO/N-doped CDs electrodes, resulting in high specific capacitances and remarkable cycling stability. During charge-discharge tests the CoS/N-doped CDs-3 electrode exhibited superior cyclic stability, maintaining its performance after 10,000 cycles at 10 $A\,g^{-1}$, whereas the bare CoS retained about 80 % of its capacity. The tests for rGO/N-doped CDs-1.0 composite were carried out through consecutive charge-discharge at 5 $A\,g^{-1}$. The rGO/N-doped CDs-1.0

composite also showed impressive cyclic stability, retaining ~93 % of its initial capacity after 20,000 cycles at 5 Ag^{-1}.

Moreover, CoS/N-doped CDs flowers as the cathode and rGO/N-doped CDs nanosheets as the anode were deployed to produce hybrid supercapacitor device. This device delivered a high energy density of ~37 Wh kg^{-1} at ~800 W kg^{-1}, and demonstrated good cycling stability, retaining ~86 % retention of original value after 10,000 cycles. This study demonstrates the superior role of N-doped CDs and the potential they can provide when incorporated into supercapacitor devices for improved energy storage [93].

In lithium-ion batteries, CDs have been explored as anodes or as coatings on traditional anode materials to enhance capacity and cyclic stability. The presence of CDs can facilitate faster lithium-ion diffusion and provide better structural integrity, thereby improving the overall battery performance [94–96]. Yang et al. reported on N-doped TiO_2 nanorods decorated with carbon dots. The N-TiO_2/CDs composite, used as an anode material for lithium-ion (LIB) and sodium-ion batteries (SIB), showed decreased polarization and improved performance. In the lithium-ion battery, Fig. 5A shows the cyclic voltammetry plots of pure N-TiO_2 and N-TiO_2/CDs composite electrodes at a scan rate of 0.5 mV s^{-1}. The results demonstrate that polarization reduced upon decorating the TiO_2 nanorods with CDs. The N-TiO_2/CDs composite obtained a capacity of ~185 mA h g^{-1} and the retention of ~92 % at 10 C over 1000 cycles, when compared to ~84 % retention for the N-TiO_2 electrode (Fig. 5B). Presented in Fig. 5C, are cyclic voltammetry plots for the N-TiO_2/CDs composite and pure N-TiO_2 electrodes at a scan rate of 0.2 mV s^{-1}. Both the electrodes display broad peaks in a wide potential range of 0.1–1.5 V, similar to that of anatase TiO_2. To evaluate the cyclability of the SIBs, the electrodes were cycled against Na over 300 cycles at 5 C (Fig. 5D). In sodium-ion batteries, the N-TiO_2/CDs composite maintained a capacity of 176 mA h g^{-1} at 5 C with ~94 % retention after 300 cycles, while the pure N-TiO_2 declined to 107 mA h g^{-1} with only ~78 % retention. [97].

4.4 Catalytic applications in energy production

CDs also hold potential in catalytic applications, particularly in energy production processes such as hydrogen generation and carbon dioxide reduction. Due to their tuneable electronic properties and abundant active sites, CDs can act as effective catalysts or co-catalysts [98–100]. For hydrogen generation, CDs have been utilized in photocatalytic water-splitting systems.

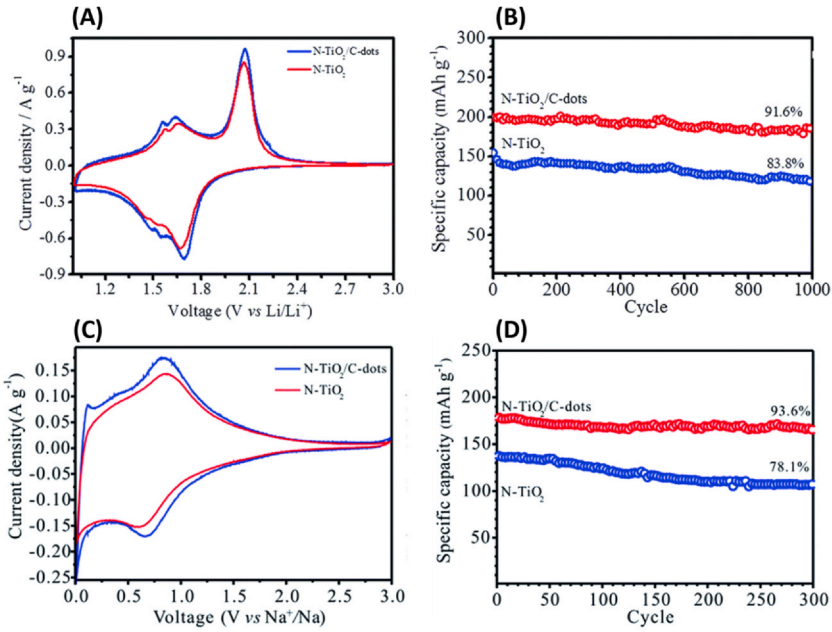

Fig. 5 Cyclic voltammetry plots for LIB using the N-TiO_2 and N-TiO_2/CDs as an anodes at a scan rate of 0.5 mV s^{-1} (A), cycling performance of both anodes at 10 C (B), cyclic voltammetry plots of SIB using the N-TiO_2 and N-TiO_2/CDs anodes at a scan rate of 0.2 mV s^{-1} (C), cycling performance of both anodes at 5 C (D). *Reproduced from [97].*

Their capability to absorb a broad spectrum of light and generate charge carriers efficiently enhances the production of hydrogen. Photocatalytic water splitting presents a promising method for producing sustainable hydrogen. The process is, however, limited by the discrepancy between the rapid transport of photoelectrons to catalyst sites (occurring within picoseconds to nanoseconds) and the much slower proton delivery (which takes approximately microseconds). To enhance hydrogen production, it is crucial to speed up the abstraction of protons from water molecules to match the electron transfer rate. The photobasic effect, which increases proton affinity upon excitation, provides a potential solution to this challenge.

Fang et al. demostrated on the production of photobasic CDs with pyridinic nitrogen. They illustrated that the as-prepared CDs are able to remove protons from water within a few picoseconds after excitation. The pyridinic N-containing CDs with their ultrafast proton transfer thus facilitates the photocatalytic hydrogen production process. The photobasic effect of resultant *N*-containing CDs is depicted in Fig. 6. To investigate

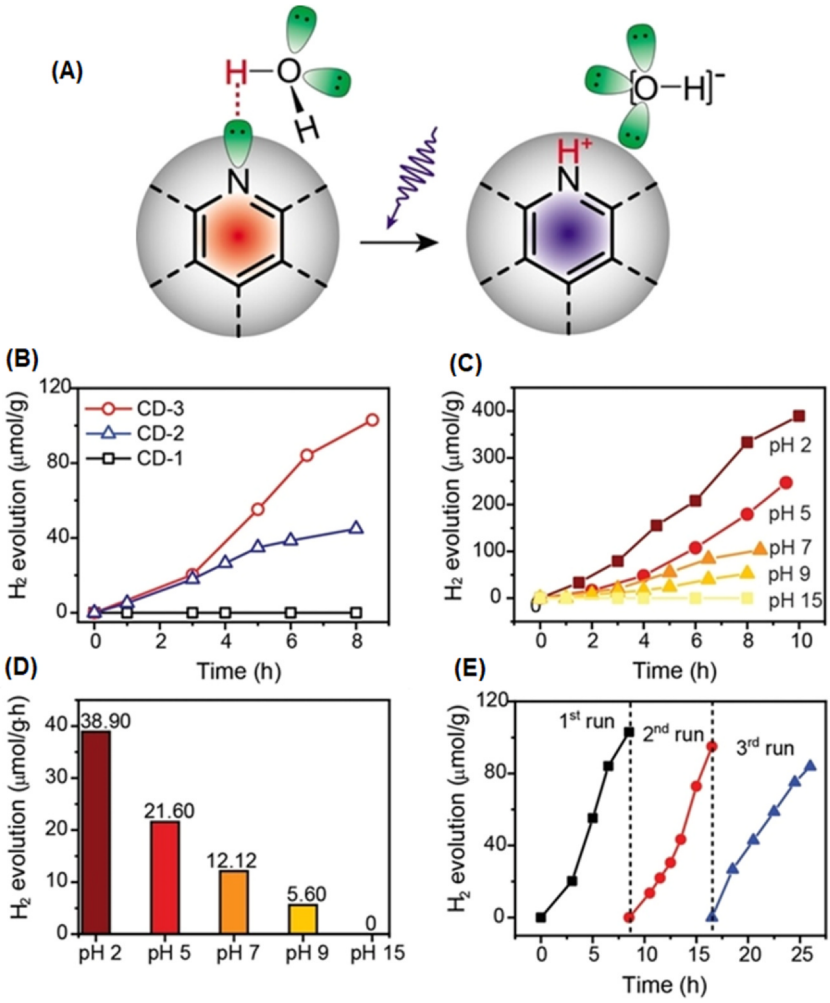

Fig. 6 Schematic representation of the photobasic effect of N-containing carbon dots (A), the rate of photocatalytic hydrogen (H_2) production for three distinct types of carbon dots (B), The photocatalytic performance of the CD-3 at various pH levels showing (C) hydrogen production and the average hydrogen production rate (D). Long-term photocatalytic hydrogen production rate of the CD-3 over 3 separate trials (E). *Reproduced from [101].*

the impact of nitrogen species in the resulting CDs on proton reduction activity, the hydrogen evolution rate (HER) of CDs with varying nitrogen doping levels was measured under solar simulator irradiation. Fig. 6B shows that CD-1 produced negligible hydrogen at neutral pH, showing no

activity due to insufficient photobasic nitrogen active sites to extract protons. In contrast, the authors observed as the pyridinic nitrogen content increased, the HER for CD-2 achieved ~7 μmol g^{-1} h^{-1}, and further increased to ~12 μmol g^{-1} h^{-1} for CD-3. Therefore, the enhancement of proton extraction correlates with the increase in pyridinic nitrogen sites present on the carbon dots.

To further explore the influence of the photobase effect, the hydrogen evolution rate (HER) of CD-3 over a pH range of 2 to 15 was performed. As seen in Fig. 6B–D, at neutral pH, the CD sample showed a HER of ~12 μmol g^{-1} h^{-1} that decreased as the pH values increased. Negligible hydrogen production was observed when pH values are above seven. This was attributed to limited photobasic protonation process. The higher HER activity at pH 7 compared to pH 9 or pH 15 is due to easier proton access at neutral pH. Conversely, in acidic conditions, the hydrogen evolution significantly increased, reaching a rate of 38.9 μmol g^{-1} h^{-1}. Long-term photocatalytic H_2 production experiments, Fig. 6E, demonstrated a fairly high formation rate over three separate trials, demonstrating the potential and excellent durability of the CD-3 as a catalyst [101].

In the reduction of carbon dioxide to valuable fuels, CDs can serve as catalysts to convert CO_2 into hydrocarbons or alcohols. Their high surface area and functional groups facilitate the adsorption and activation of CO_2 molecules, making the reduction process more efficient. Studies have demonstrated that CDs can significantly lower the overpotential required for CO_2 reduction, thus making the process more energy-efficient [75,102,103]. Lui et al. investigated carbon dots without any metal loading and proved that they can be used as an effective and efficient photocatalyst for CO_2 reduction. The as-prepared CD catalysts exhibited good reduction efficiency of CO_2 to form CH_4 with ~75 % electronic selectivity [104]. R Kim et al. reported the reduction of aqueous CO2 to syngas (CO and H2), an important industrial fuel, using CDs as the sole light harvester along with a molecular cobalt bis(terpyridine) CO2 reduction co-catalyst. The photocatalytic system demonstrated an activity of 7.7 ± 0.2 mmol syngas gCDs−1 (3.6 ± 0.2 mmol CO gCDs−1 and 4.1 ± 0.1 mmol H2 gCDs−1) after 24 h of full-simulated solar spectrum irradiation (AM 1.5 G) [105].

4.5 Optics

4.5.1 Light-emitting diodes

The light-emitting properties of CDs are another aspect that makes them highly valuable. CDs can emit light of different colors when excited by light

of a specific wavelength. This property is not only beneficial for developing light-emitting diodes (LEDs) but also for creating fluorescent probes for bioimaging [106–108]. The emission intensity and wavelength can be fine-tuned through surface functionalization and co-doping with a wide variety of heteroatoms (e.g., nitrogen, sulfur, phosphorus), which introduce new energy states and enhance the emission properties. Fig. 7 shows how a carbon dot with different passivating agents/functional groups can emit different colors when excited by light of different wavelengths [109].

In light-emitting diodes, a study by Song et al. showcases a high production yield (60–85 %) of CDs achieved through a one-step solvothermal approach using waste-expanded polystyrene as the starting material. Changing the volume of HNO_3 lead to the increase of oxidation on the CDs' surface, thus producing solid-state CDs with tuneable photoluminescence (PL) from white, warm-white, warm-yellow to orange [110]. Elsewhere, the O, N co-doped CDs having a strong blue PL emission were synthesized via hydrothermal technique using perylene-3,4,9,10-tetracarboxylic dianhydride (PTCDA) and 2,3-diaminophenazine (DAP). The as-prepared CDs PL emission center peaked at ~447 nm in ethanol and they were further incorporated into poly(vinyl carbazole) (PVK) to fabricate emission layer in the virgin blue CDs LEDs. The fabricated LED device using these blue CDs showed a brightness of ~648 cd m^{-2}, a long half-lifetime (T_{50}) of 200 h and a favorable current efficiency of ~2.0 cd A^{-1} [111]. Due to scope limitations, extensive details of the light-emitting ability of CDs in biomedical applications were not covered in this chapter. However, it is worth noting the remarkable contribution that these nanomaterials have in the biomedical field such as in the work of Zheng et al., where CDs synthesised via pyrolysis method using $_D$-glucose and $_L$-aspartic acid were

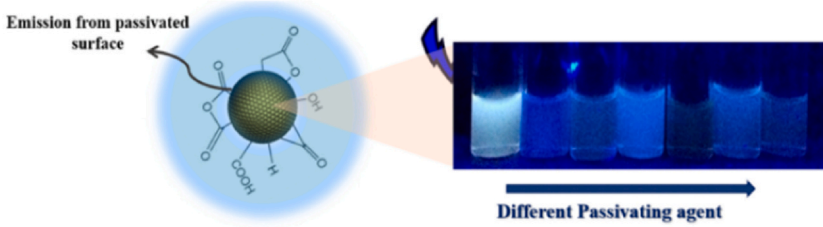

Fig. 7 Image showing different luminescence properties of the different passivating agents under UV radiation [109].

used to target brain cancer glioma, showing another important use of these environmentally friendly and biocompatible class of nanomaterials [112].

In conclusion, eco-friendly synthesized CDs represent a promising class of nanomaterials with exceptional UV/visible light absorption, turnable photoluminescence, and versatile light-emitting properties. These attributes, combined with their sustainable production methods, position CDs as a key material for future applications in energy. The ongoing research into their synthesis and functionalization continues to expand their potential and opens new avenues for innovative applications.

4.6 Environmental remediation

Abundantly available biomass, agricultural products (fruits and vegetables) and other waste materials have been precursors for synthesising CDs. The aforementioned, precursors usually come with a structural backbone mainly made of carbon, making such materials eco-friendly or environmentally friendly because they are biodegradable [113]. Such attributes contribute to the wide application of CD such as already discussed energy, optical and biomedical applications. Other applications include environmental applications that involves pollution remediation by way of pollution removal and reduction whilst utilizing adsorption and photocatalysis, respectively. This is owed to the availability of active surface functionalities, that could act as active sites [10] and their ability to donate or accept electron (e^-) pairs and the generation of holes (h^+) [114]. Therefore, the next section will be about the application of CD materials in adsorption, photocatalysis and separation membranes respectively.

4.6.1 Adsorption

Briefly, adsorption is a surface phenomenon involving molecules' adherence to a substrate. In this case, the molecules could be any targeted pollutant in solution or liquid form such as dyes and heavy metals normally called adsorbate [115]. The substrate could be any solid material such as a carbon-rich material and a mono, bi or multi-element metallic material [116]. A combination of carbon and metallic material in the form of a composite has also been used as a substrate, the substrate is normally referred to as the adsorbent. Several adsorption experimental parameters such be considered for optimum pollutant removal conditions. This includes the pH of the solution, time of the reaction, initial adsorbate concentration, temperature of the reaction, volume of the adsorbate, mass of the adsorbent etc. [117]. Another way of enhancing pollutant removal is to modify or functionalize

the surface of the adsorbent through chemical, physical, mechanical and biological modification. The adsorption process has eco-friendly principles due to the use of abundantly available materials as substrate or adsorbent [118]. Adsorption as a pollutant removal process is appealing due to its versatility brought in part by its aptitude or prospect of being cost-effective, scalable, selective, efficient and simple operation. Table 1 is a representation of different adsorbents and adsorbates, it provides some of the advantages of adsorption as a pollutant removal process. The applicability or effectiveness of an adsorbent is generally measured by the adsorption capacity (mg/g) and/ removal percentage as denoted by Eqs. 1 and 2.

$$R\,(\%) = \frac{C_O - C_e}{C_O} X100 \tag{1}$$

$$q_e = \frac{C_O - C_e}{m} V \tag{2}$$

where: C_O (mg/L) represent the initial adosrbate concetration, C_e (mg/L) represent the equilibrium adsorbate concentration, V (L) represent the volume of the adsorbate, m (g) represent the mass of the adsorbent q_e (mg/g) represent the adsorption capacity and R (%) is the removal percentage.

CDs are useful in the adsorption process, particularly in removing pollutants or remediating the environment [55].

For example, Pundza et al. synthesised fluorescent CDs via the hydrothermal method and tapioca flour (starch from cassava plant) as a precursor. Where the flour was suspended in an acetone-NaOH solution. The solution was heated at 175 °C for less than two hours. During the hydrolysis of the starch glucose and disaccharides were the resulting products. The disaccharides reacted to form polysaccharides through cross-linking and they were separated by centrifugation. The remaining glucose was carbonized and the carbonization of the glucose yielded the CDs. Several characterization techniques were used to characterize the CDs. This included the IR spectroscopy and the X-ray photoelectron spectroscopy (XPS) for the determination of surface functional groups. The morphological characteristics and average size diameter of the NPs were determined using high-resolution transmission electron microscopy (HrTEM).

The IR spectra of the CDs confirmed the availability of surface functional groups that are usually linked to CDs including carboxyl, hydroxyl and amino moieties. The XPS data showed that the CDs predominantly

Table 1 Adsorption of different pollutants using carbon-based materials.

Adsorbent	Adsorbate	q_e (mg/g)	R (%)	Comments	References
Carbon quantum dots	Pb(II)	-	80.6	Low-cost, environmentally friendly	[70]
				High removal at pH > 7	
Agricultural waste	Cr(VI)	39.43	98	Alkaline-modified adsorbent performed	[119]
				better than other adsorbents	
				High removal at pH < 7	
Cu-carbon dots	Congo red	437.4	90.1	Synthesized via hydrothermal method	[120]
				Good adsorption efficiency	
				Regenerated 5 times	
				High removal at pH 6	
Carbon quantum dots	Congo red	375.94	77	Oxygenated functional moieties	[121]
				played a role in the removal of the dyes	
	Methylene	451.54	75	pH > 7 more removals for methylene blue	
	blue			pH < 7 more removals for congo red	

consisted of carbon (99.05 %) and oxygen (21.35 %) atomic percentages as part of their structure. The data indicates that the precursor used was a carbon-oxygen-rich material and thus able to yield a carbon-oxygen-rich product (CDs). The HrTEM data showed that CDs were successfully synthesized and had an average diameter size ranging in between 3–5 nm and they were spherical [70]. The CDs from tapioca were then used for the adsorption of Pb(II) in a typical batch adsorption process at room temperature. The adsorption of Pb(II) also increased with an increase in the initial Pb(II) concentration and when the adsorption time was increased Fig. 8A. This was attributed to the availability of active adsorption sites that accommodated the Pb(II). These sites were the results of the oxygen moieties on the CDs' surface [70]. It was reported that the adsorption of Pb (II) was affected by the pH value of the Pb(II) solution and the adsorption efficiency increased as the pH values increased from pH 3 to pH 12 Fig. 8B. This was attributed to the predominantly negatively charged surface and the positive charge of the Pb(II) resulting in electrostatic attraction. The study demonstrate the efficiency and effectiveness of fluorescent CDs on the adsorbate for Pb(II). However, the impact of the fluorescent property on the adsorption efficiency for Pb(II) was not demonstrated. Another issue was the high adsorption at pH 12 because, at such pH levels, Pb(II) tend to precipitate [122]. Therefore to conclude

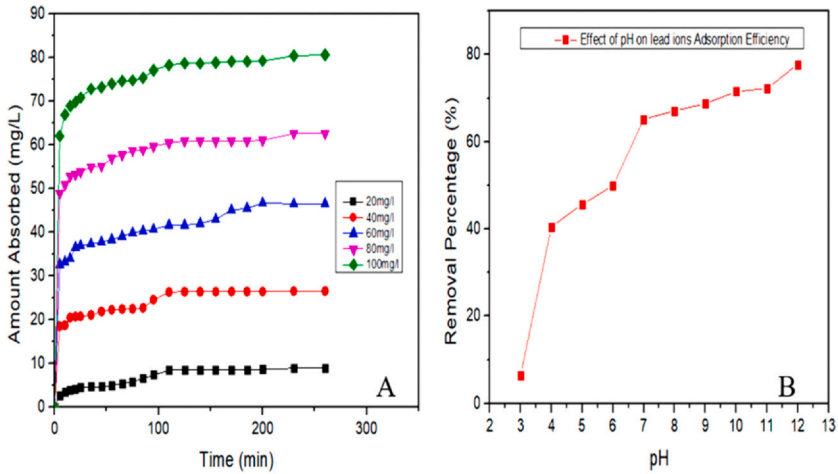

Fig. 8 Effect of adsorption time at different initial concentrations of Pb(II) (A) and effect of solution pH (B). *Reprinted with permission from [70].*

that the high removal at pH 12 is attributed to adsorption and disregard the effect of surface precipitation may not present a comprehensive removal mechanism.

Methylene blue (MB) and Congo red (CR) were successfully removed from wastewater using CDs as adsorbents. Where it was reported that rubber seed shells were utilized as a precursor for the fabrication of CDs. The obtained CDs were proven to have carbonyl and hydroxyl functional moieties on their surface as shown by their FTIR spectra (Fig. 9). It was interesting to note that even though the CDs had the potential to adsorb both dyes at a removal percentage of 77 % (CR) and 75 % (MB) and adsorption efficacy of ~376 mg g^{-1} (CR) and ~452 mg g^{-1} (MB) respectively. The removal mechanism was different, CR was adsorbed more at acidic conditions pH < 7 and MB at more alkaline conditions pH > 7. Because at acidic conditions the H^+ ions compete with the cations of the cationic dye (MB) and the OH^- ions compete with the anions of the anionic dye (CR) [121]. The results indicate that the surface properties of the CDs and the targeted polluted play an essential role in the adsorption efficiency of different pollutants using CDs. This is why surface modification cannot be ignored and should be carefully considered in synthesizing CD materials with high removal percentages and high adsorption

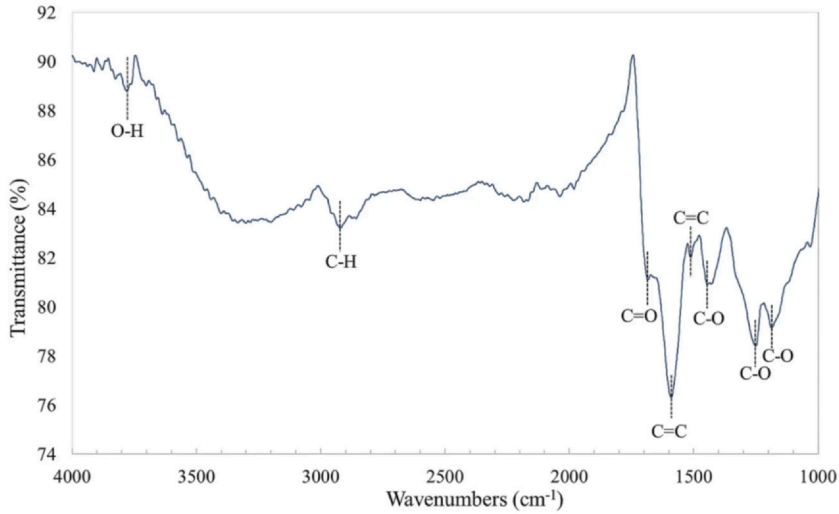

Fig. 9 FTIR spectra of CDs derived from rubber seed shells. *Reprinted with permission from [121].*

capacities. It is to be noted that though the CDs show promise as adsorbents their selectivity remains a contentious issue. Adsorption as a process works hand in hand with photocatalysis, particularly in the photodegradation of pollutants, which is why the next Section discusses the use of CDs in the photocatalytic degradation of pollutants.

4.6.2 Photocatalysis

In terms of photocatalytic degradation or reduction, photocatalysis uses light energy to facilitate chemical reactions. This is done by using a catalyst that can absorb light at the desired range (ultraviolet or visible) depending on the light source guided by the bandgap energy of the catalyst [123]. Some of the most used catalysts and their bandgaps include TiO_2 (3.2 eV for anatase phase and 3.0 eV for rutile phases) [124], ZnO (3.2 eV) [125], CdS (2.4 eV) [126], graphitic carbon nitride (g-C_3N_4) 2.7 eV [127], bismuth oxyhalides (2.5–3.5 eV) [128] and perovskite (1.5–3.5 eV) [129]. Some of the considerations for a suitable catalyst are the bandgap energy, charge separation, stability, environmental impact, surface area sustainability, scalability and cost. The photodegradation or photoreduction is guided by photocatalytic principles, including the excitation of the catalyst by a light source. Where the electrons (e^-) are excited and migrate from the valance band (VB) to the conduction band (CB). In the process create electron-hole pairs (h^+), both the e^- and h^+ migrate to the catalyst's surface where they take part in the oxidation or reduction reactions. The h^+ takes part in the oxidation reactions and the e^- in the reduction reactions. Figs. 10 and 11 illustrate how photocatalytic degradation [123] or reduction [130] could be used for environmental remediation. Where pollutants could be degraded to less harmful products and could also be reduced to valuable products as shown by Figs. 10 and 11. Fig. 10 is an illustration of the photocatalytic degradation of dyes and Fig. 11 is an illustration of the photocatalytic reduction of CO_2 to form different chemicals and products.

The attributes of CDs including high surface area, surface functional groups, chemical and physical tenability, absorption of light from the ultraviolet, visible and near-infrared spectrum, make them attractive as catalysts for the photocatalytic degradation of dyes. They could be applied as-synthesised (bare) or combined with semiconductors, carbon materials and other atoms for a more effective catalyst [131]. A unique form of CDs (gel-like CDs) was synthesised using the solvothermal method, where a reaction flask was filled with Ar gas for 5 min to flush

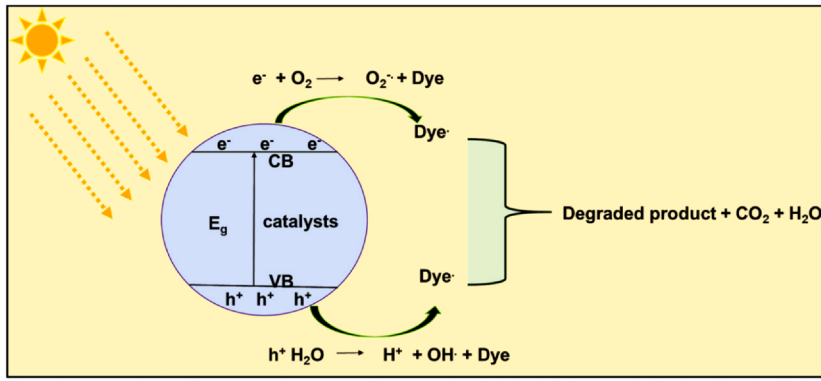

Fig. 10 Photocatalytic degradation of dye.

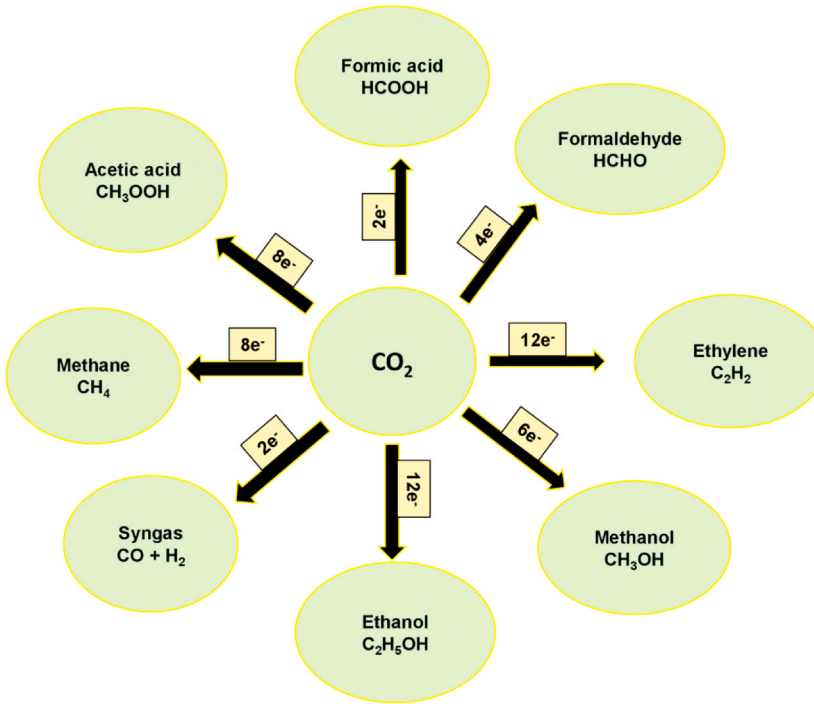

Fig. 11 Photocatalytic reduction of CO_2 to useful products.

out O_2 gas. Thereafter, 30 mL of ethylenediamine was added to the flask and heated to 160 °C, followed by the addition of citric acid, the reaction was allowed for 50 min. The same method was followed for synthesizing CDs modified with g-C_3N_4 (g-CDs), with the difference

being the addition of 50 mg of g-C_3N_4. The obtained CDs were deployed as catalysts for the degrading rhodamine b (RhB), methylene blue (MB) and methyl orange (MO).

It was reported that the g-CDs were more efficient than the bare CDs showing complete degradation of the three dyes in a relatively short reaction time of 20 min (MB), 40 min (MO) and 60 min (RhB). This was supported by the high degradation rate with values of 0.29 (MB), 0.12 (MO) and 0.06 min^{-1} (RhB). The degradation was positively enhanced by the addition of g-C_3N_4 showing 3 times higher efficiency compared to unmodified CDs. The purpose of adding the g-C_3N_4 was to create synergistic adsorption and photocatalytic effect resulting in enhanced photocatalytic performance [132]. Table 2 summarizes diverse CDs derived from different sources or precursors for the degradation of several pollutants. The data from Table 2 indicates that CDs are efficient catalysts for environmental remediation through photocatalytic degradation. This is facilitated through the CDs' physico-chemical properties that include functional groups, light harvesting and size diameter of the catalyst. Some of the precursors are abundantly and naturally available and could be used as catalysts without any added modification. However, Surface modification such as the introduction of atomic doping, chemical functionalization or modification and the addition of carbon materials and other nanoparticles, has a huge potential to enhance the overall CDs' photocatalytic performance [131].

As effective as CDs are in the degradation of pollutants, issues regarding scalability, recombination and sustainability remain challenging. Thus the introduction of composite material to take advantage of the synergy between materials and sustainability. Selectivity is another challenge that research is focused on this is due to the uniqueness of each catalyst which may include cost, structural complexity, stability environmental influence and the absorption of light [131]. It is therefore imperative to synthesize CDs on a case-by-case basis to ensure that the photocatalytic process is controlled at optimum levels. Photocatalytic reduction plays a vital role in the environmental remediation of pollutants by reducing CO_2 to valuable chemicals and products as shown in Fig. 11. The thermocatalysis and electrocatalysis techniques could be used in the reduction of CO_2. Thermocatalysis of CO_2 is the conversion of CO_2 to fuels and chemicals through the use of heat in the presence of a catalyst [138]. The following Equations represent some of the reactions involved in the thermocatalysis including the reverse water gas shift (Eq. 3) [139].

Table 2 Carbon bots as catalyst for pollutant degradation.

Catalyst	Precursor	Pollutant	Efficiency (%)	Time (min)	Comments	References
N-CDs	Diethylenetriamine and Citric acid	MB	97	360	Nitrogen (N) doping N-dopant improved photocatalytic efficiency	[133]
CDs	Eggshell membrane ashes	MB	43	600	Un-modified CDs 3.9 nm diameter size degrade MB under sunlight irradiation	[134]
CDs/TiO_2	Graphite	MB	100	25	Alkaline environment essential to quality CDs CDs-TiO_2 synergy in degradation performance	[135]
Ag-CDs	Graphite	MO	100	10	Alkaline environment essential to quality CDs Ag-CDs synergy in degradation performance	[136]
CDs/H-γ-TaON	Glucose	RhB	98	140	Heterojunctions heterostructures inhibit the recombination rate for improved degradation	[137]

The production of methane from CO_2 and H_2 (Eq. 4) [140], and the synthesis of methanol (Eq. 5) [141] are some of the products of CO_2 thermocatalysis.

$$CO_2 + H_2 \rightarrow CO + H_2O \tag{3}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{4}$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{5}$$

Electrocatalysis could be used in the reduction of CO_2 through the utilization of electrical energy in the presence of a catalyst at the electrolyte and electrode interface, where the reduction of CO_2 occurs at the cathode and the oxidation of H_2O takes place at the anode as shown by Eq. 6 [142].

$$CO_2 + 2H_2O + 2e^- \rightarrow CO + H_2 + 2OH^- \tag{6}$$

In electrocatalysis and thermocatalysis CDs have a role to play owing to their properties which include surface area, turnable surface and conductivity. These could be improved by supporting nanoparticles and carbon nanomaterials alike, in fostering a synergistic effect between materials [143]. A biomass CDs catalyst was synthesized using the hydrothermal method and sodium phytate, potassium iodide and polyethylenimene as precursors. The produced catalyst was used for the conversion of CO_2 to cyclic carbonates. The produced biomass CDs catalyst was reported to be of high catalytic activity. This was supported by the 98 % yield of cyclic carbonates after recycling the catalyst twice. The catalytic activity was reduced after recycling three times, however, an 85 % yield even after recycling five times was reported. This was attributed to the synergistic effect, stability of the catalyst, high reusability rate and high catalytic efficacy [144]. The presented data was obtained from the different applications of CDs has indicated that not only are CDs sourced from abundantly available sources, but they also have a huge potential to be applied in different fields due to their properties. Further applications of the CDs could be exploring the photoluminescence properties in synergistic response to their surface properties and light absorption properties in creating super smart materials for environmental remediation, food security, medicine and other industries.

4.6.3 Separation membranes

Carbon dots (CDs) possess attractive features such as non-toxicity, inherent hydrophilicity, abundant surface functionalities, excellent photoluminescence, and fast proton conductivity, making them suitable for filtration applications [145–147]. Incorporating CDs into various separation membrane technologies,

such as forward osmosis, nanofiltration, and reverse osmosis, can significantly enhance overall performance. There are three main methods to incorporate CDs into separation membranes: grafting, doping, and layer-by-layer self-assembly [145–148]. The grafting technique involves coating the membrane with a coating agent. The doping approach incorporates CDs into polymeric materials before membrane preparation. In layer-by-layer self-assembly, a multifunctional membrane is created by sequentially incorporating multilayer materials via electrostatic interactions, hydrogen bonding, and coordination bonding interactions.

For instance, superhydrophilic CDs with diameter of ~7.0 nm were fused into the polyamide layer of a thin composite reverse osmosis (RO) membrane to improve efficiency [149]. The incorporation of 0.02 % CDs resulted in high desalination performance, with a water flux of ~87 $Lm^{-2}h^{-1}$ and a salt rejection rate of ~99 % when compared to a control thin-film composite (TFC) membrane under conditions of 2000 ppm NaCl, 25 °C, and 1.55 MPa. This improvement was due to enhanced hydrophilicity, reduced thickness, and increased density of the selective layer from the presence of CDs.

Xu et al. [21] also incorporated graphene quantum dots (GQDs) into a forward osmosis (FO) thin composite membrane for desalination as shown in Fig. 12. In this case, a polyacrylonitrile (PAN) ultrafiltration membrane was immersed in a mixture of GQDs and polyethyleneimine (PEI), followed by immersion in a trimesoyl chloride (TMC) solution to form a polyamide (PA) layer on the surface of the ultrafiltration membrane. The GQDs covalently bonded to the PA chains, resulting in a PA active layer thickness of 60 nm. With an optimal loading of 0.05 % GQDs, the water flux reached 12.9 $Lm^{-2}h^{-1}$, and the salt flux was 1.41 $gm^{-2}h^{-1}$ when

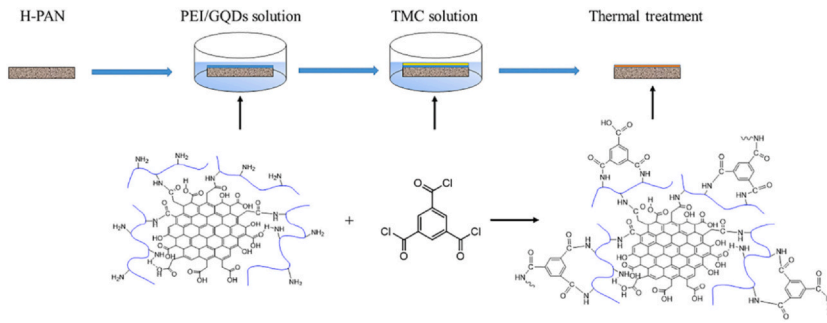

Fig. 12 Schematic representation of incorporation of GQDs into TFC membrane and the reaction mechanism of PEI/GDQs and trimesoyl chloride (TMC) [21].

deionized water and 0.5 M $MgCl_2$ were used as the feed and draw solutions, respectively. Additionally, the TFC exhibited good antifouling properties, demonstrating that incorporating GQDs can produce novel membranes with improved overall performance.

Zhang et al. [150] prepared a TFC membrane through interfacial polymerization to be used in low-pressure nanofiltration. Graphene quantum dots (GQDs) were dispersed within a tannic acid (TA) film, creating a smooth, more hydrophilic, negatively charged active layer. The membrane displayed adequate water flux, viz. 23.33 $Lm^{-1}h^{-1}$ at ~0.2 MPa that is 1.5 times higher than the TA-based membrane. The rejection rates for CR and MB dyes were 99.8 % and 97.6 %, respectively.

The performance of separation membranes based on quantum dots as fillers can be further improved by functionalizing the quantum dots [151,152]. For instance, Shen et al. [151] decorated GQDs with amine and sulfonic groups to incorporated into a PA-based TFC membrane. The resulting TFC membrane displayed a water flux permeance of 5.89 $Lm^{-2}h^{-1}bar^{-1}$, which is three times higher than that of the neat TFC membrane (1.88 $Lm^{-2}h^{-1}bar^{-1}$), while maintaining high salt rejection (97.1 %).

In another instance, CDs can be decorated with other fillers to maximize their performance and introduce multifunctionalities to the resultant membrane. Yu et al. [153] decorated GQDs with silver nanoparticles (AgNPs) to enhance the antimicrobial efficacy of the resultant TFC membrane. The GQDs/Ag were then introduced into PA to develop a selective active layer using interfacial polymerization. The resultant membrane displayed a higher water flux, i.e. about 39 $Lm^{-2}h^{-1}$ while maintaining NaCl rejection of ~99 % at 16 bar, viz. ~ 44.3 % higher flux than that of the neat TFC membrane. The membrane displayed satisfactory antibacterial efficacy against gram-negative *Escherichia coli* (~99 %) and gram-positive *Staphylococcus aureus* (~97 %), demonstrating that through the synergy between GQDs and other fillers, superior RO membranes can be prepared with good separation efficacy and good antibacterial and antifouling activities.

5. Future outlook

As more research opens up new possibilities and uses, the future for environmentally friendly carbon dots in sustainable solutions seems promising. With advancements in green synthesis methods, the CDs' production is

becoming increasingly cost-effective and environmentally benign, paving the way for their widespread adoption. Future advancements are anticipated to significantly improve the overall CDs' performance in a variety of applications, including boosting the effectiveness of supercapacitors and solar cells as well as developing catalytic processes for the hydrogen production and the carbon dioxide reduction. Surface functionalization and doping methods advancements will probably result in CDs with customized features for particular uses, increasing their usefulness in environmental monitoring, drug delivery, and bioimaging. Furthermore, as the world's need for renewable and sustainable technologies grows, the integration of CDs into commercial products and industrial processes is anticipated to grow, driving significant contributions to green energy, environmental remediation, and beyond. To fully realize the promise of eco-friendly CDs, the chapter imagines a future in which they are essential to the advancement of sustainable technology. To that aim, it emphasizes the necessity for ongoing multidisciplinary study and collaboration.

6. Conclusions

In summary, there has been tremendous progress in synthesizing and applying carbon dots (CDs) demonstrating their importance across various fields. With the use of efficient and effective synthesis techniques, such as hydrothermal and ultrasonic-assisted techniques result in high quality and high-purity CDs with unique features, including small particle size and functionalities that broaden their applicability. The CDs structural and chemical attributes of CDs, tuneable through the use of different precursors and synthesis methods, facilitate their use in different environmental remediation, biomedical applications, and as efficient fluorescent materials. With continuous research and development emphasize on the significance of CDs in addressing current global challenges, such as pollution and resource sustainability. With more and more understanding of CDs unique properties and functionalities grows, CDs are set to play essential role in developing innovative solutions for green sustainable future.

Acknowledgments

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