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Synthesis and applications of carbon quantum dots derived from biomass waste: a review

Jiayu Wu¹ · Tianyue Chen¹ · Shengbo Ge^{1,2}  · Wei Fan³ · Hui Wang⁴ · Zhongfeng Zhang⁵ · Eric Lichtfouse⁶  · Thuan Van Tran⁷ · Rock Keey Liew^{8,9} · Mashallah Rezakazemi¹⁰ · Runzhou Huang¹

Abstract

In the context of the circular economy and decreasing earth resources, waste should be converted into value-added materials such as carbon quantum dots, which are fluorescent nanomaterials with promising applications in sensing, biological imaging, energy storage, and photocatalysis. Here, we review carbon quantum dots with focus on their synthesis from biomass, factors controlling their performance, properties, and applications in energy, medicine, and environmental science. Applications include energy storage in batteries and supercapacitors, renewable energy, pollutant sensing and degradation, drug delivery, biosensing, and bioimaging.

Keywords Biomass waste · Carbon quantum dots · Synthesis · Application · Optical · Energy · Pollution · Catalysis · Medicine · Quantum yield

Introduction

The unique physical and chemical properties of carbon nanomaterials have attracted considerable research interest since the 1990s. Researchers have investigated multiple types of carbon nanomaterials in recent decades including

graphene, C₆₀, nanotubes, and nanofibres (Fig. 1a). Carbon-based nanomaterials have led to the booming development of various applications due to their superior properties (Liu et al. 2022b). As an emerging carbon nanomaterial, carbon quantum dots, usually defined as small carbon nanoparticles with approximate dimensions below 10 nm (Fig. 1b) (Baker

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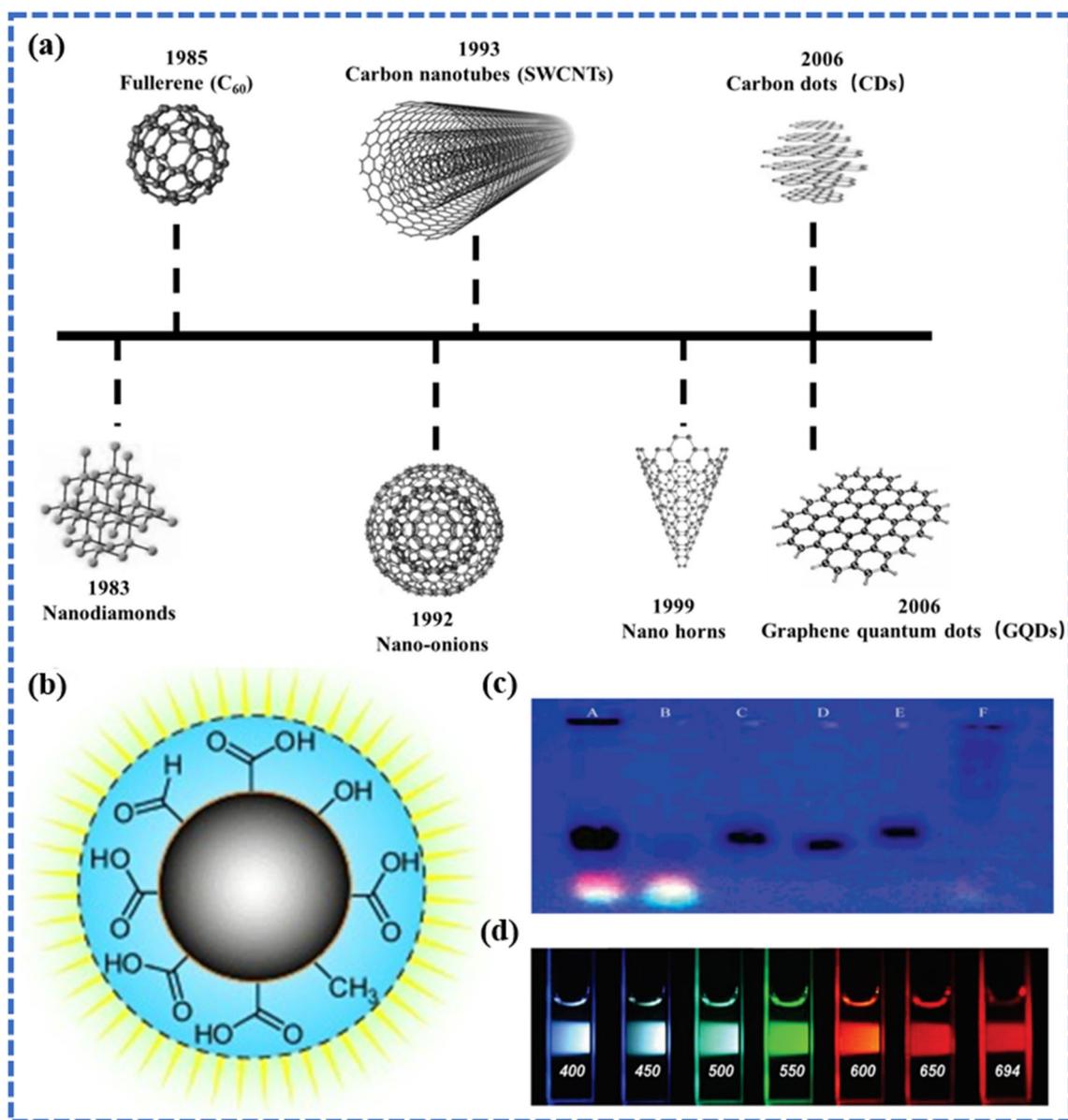


Fig. 1 **a** Structures of the carbon-based nanomaterials in order of discovery, **b** Chemical structure of carbon quantum dots. Reproduced with permission from Baker and Baker (2010); **c** Carbon quantum dots electrophoretic profile in an agarose gel under ultraviolet light

irradiation at 365 nm. Reproduced with permission from Xu et al. (2004); **d** Carbon quantum dots solution excited at different wavelengths. Reproduced with permission from Sun et al. (2006)

and Baker 2010), have drawn tremendous interest thanks to their superior optical properties.

They were accidentally discovered by Xu et al. (2004) while preparing single-walled carbon nanotubes (SWCNTs) purified by electrophoresis. The new material showed fast-moving and highly fluorescent properties in the electrophoresis pattern under 365 nm irradiated UV light (Fig. 1b) (Xu et al. 2004), which led to subsequent studies on the fluorescence properties of the material. It was not officially named "carbon quantum dots" until 2006 by Sun et al. (2006). Since then, studies on carbon quantum dots have gradually begun

to emerge. Early studies focused on the properties of carbon quantum dots and synthetic raw materials. Raw materials for synthesizing carbon quantum dots can be broadly divided into inorganic and organic carbon sources. The quantum dot yield from inorganic carbon sources is usually low, which needs to be further increased by doping or surface passivation (Dong et al. 2013; Joseph and Anappara 2017; Qiao et al. 2010). Organic carbon sources are more widely used for their high yield and low cost. As one of the organic carbon sources, biomass waste has a very extensive application prospect.

Researchers have recently attempted to transform biomass waste into carbon quantum dots to produce value-added materials with environmentally friendly methods (Fig. 2). The first carbon quantum dots was synthesized directly from biomass waste in 2012 (Sahu et al. 2012). Since then, people have tried a variety of biomass waste to synthesis carbon quantum dots, including pig bones (Fu et al. 2022), orange peels (Olmos-Moya et al. 2022), grape skins (Tang et al. 2022a), grassland morning glory (Krishnaiah et al. 2022), ginkgo biloba (Wang et al. 2020a), and guava leaves (Dash et al. 2022). Wang et al. (2016a) hydrothermally treated coffee grounds with hydrazine hydrate at 200 °C for 10 h in a closed vessel yielded carbon quantum dots of 33% (Wang et al. 2016a). After functionalization with polyethyleneimine, the carbon quantum dots demonstrated low toxicity and excellent fluorescence properties that are practical for bioimaging.

In addition to trying different kinds of biomass waste to synthesis carbon quantum dots, researchers have also expanded the application scope of carbon quantum dots. With excellent fluorescence stability and tunability, superior catalytic activity, electrical properties, and low toxicity, carbon quantum dots were used in a wide range of fields including bioimaging (Antaris et al. 2016; Hong et al. 2017; Sahu et al. 2012), ion detection (Wang et al.

2020a), photocatalysis (Huang et al. 2019; Prasannan and Imae 2013), fluorescent labelling (Wang et al. 2012), and energy storage devices (Dordevic et al. 2022; Georgakilas et al. 2016; Wang et al. 2014b) (Fig. 3).

However, the current research on carbon quantum dots in material chemistry is not thorough enough, such as the physical and chemical properties of carbon quantum dots, the influence of experimental parameters on the properties of carbon quantum dots, and the mechanism of different synthesis methods which need to be further studied. Given the above analysis, the synthesis methods and their mechanism are first demonstrated, followed by factors affecting the performance of carbon quantum dots, structural and optical properties of carbon quantum dots and their potential uses in industries. Multiple sources and types of raw materials, synthesis methods, reaction time, and temperature that will influence the performance of biomass waste-derived carbon quantum dots are extensively presented. Besides, the latest progress of carbon quantum dots application in energy, environment, and medicine, emphasizing the advantages of selecting biomass waste as the precursor, is highlighted. Finally, the future perspective and challenges of biomass-derived carbon quantum dots are provided.

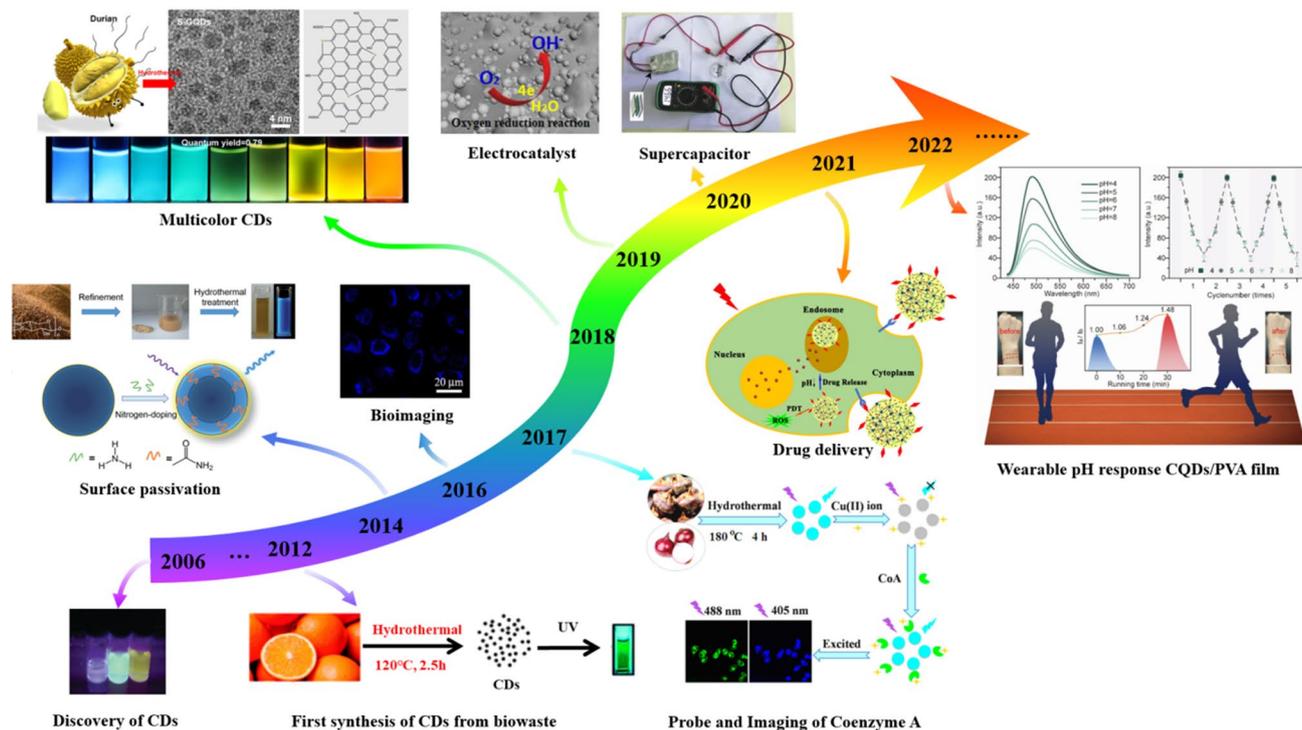


Fig. 2 Timeline showing recent progress in biomass waste-derived carbon quantum dots (CDs). Reproduced with permission from Arthisree and Madhuri (2020), Hu et al. (2017), Sahu et al. (2012),

Sun et al. (2006), Tao et al. (2022b), Wang et al. (2016b, 2018b), Ye et al. (2019), Zhang et al. (2021b), Zhu et al. (2014)



Fig. 3 Carbon quantum dots derived from various biomass such as fruit peels, leaves, bones, grass and so on. And this kind of material can be used in different industries including bioimaging, batteries,

anticounterfeiting, photovoltaic devices, catalysis for oxygen evolution reaction (OER) and oxygen reduction reaction and drug delivery (Sharifi et al. 2012)

Synthesis of biomass-derived carbon quantum dots

A tremendous amount of biomass waste is constantly resulting from daily human activities. These wastes can be generally categorized into municipal biomass, agricultural, and livestock manure. Various natural sources of organic carbon in biomass waste include hemicellulose, cellulose, ash, lignin, protein, and other elements. For instance, plant biomass waste contains 30–60% cellulose, 20–40% hemicellulose, and 15–25% lignin. Biomass waste can create carbon

quantum dots due to its renewable characteristics, environmental friendliness, usefulness, and safety. However, most biomass waste is discarded, disposed of, or burned in public, where negative environmental consequences are often associated with resource loss (Kang et al. 2020).

Carbon quantum dots can be synthesized in two ways: top-down and bottom-up. The top-down method decomposes precursors with sp^2 hybrid structure, such as graphite, carbon fibre tube, and fullerene, into fragments by physical or chemical methods (Zhang et al. 2021a). The main methods used to obtain carbon quantum dots with fluorescent properties

include chemical oxidation, arc discharge, and laser pin etching. However, fewer reports relate to this method because of its complexity, the necessity of expensive machines and the lack of alignment with recent advancements in green chemistry. In contrast, the simple and green bottom-up synthesis method has received more attention from researchers. Bottom-up methods usually involve small organic molecules as precursors to generate carbon quantum dots (Lu and Zhao

2017). The bottom-up method is frequently used to prepare biomass-derived carbon quantum dots. The typical synthesis methods are hydrothermal, microwave, and pyrolysis methods. Table 1 shows that biomass-derived carbon quantum dots can be synthesized from sugarcane bagasse (Qiu et al. 2022), bamboo leaves (Liu et al. 2014), straw (Qi et al. 2019), kitchen waste (Himaja et al. 2014), orange peel (Kasouni et al. 2017), banana peel (Atchudan et al. 2021),

Table 1 Properties of biomass carbon quantum dots prepared from different carbon sources and their applications

| Precursors | Synthesis method | Size (nm) | Productivity (%) | Application | References |
|-------------------|------------------------------------|-------------|------------------|---|-----------------------------|
| Orange peels | Hydrothermal | 2.34 | 18.57 | Cr ²⁺ detection | Wang et al. (2020b) |
| Roses | Hydrothermal | 4.51 ± 1.46 | 9.6 | Bioimaging | Sharma et al. (2019) |
| Roses | Microwave | – | 13.45 | Tetracycline (TC) detection | Feng et al. (2015) |
| Lotus root | Microwave | 9.41 | 19 | Fe ³⁺ detection | Gu et al. (2016) |
| Papaya | Microwave | 4.85 ± 0.07 | 8.55 | As ³⁺ detection | Ramezani et al. (2018) |
| Kelp | Microwave | 3.7 | 23.5 | Co ²⁺ detection | Zhao et al. (2019) |
| Bauhinia | Microwave | 3.4 | 27.0 | Fe ³⁺ detection | Huang et al. (2018) |
| Goose feather | Microwave and Hydrothermal | 21.5 | 17.1 | Fe ³⁺ detection | Liu et al. (2015) |
| Fennel seeds | Pyrolysis | 3.90 ± 0.91 | 9.5 | – | Dager et al. (2019) |
| Rice husk | Pyrolysis | 3.8 | 15 | Bioimaging | Wang et al. (2016b) |
| Leaves | Pyrolysis | 3.7 | 15.3 | Fe ³⁺ detection | Zhu et al. (2013) |
| Citrus Peel | Pyrolysis | 6.5 | 16.8 | Fe ³⁺ detection | Chatzimitakos et al. (2017) |
| Grass | Pyrolysis | 2–5 | 30 | – | Krysmann et al. (2012) |
| Grass | Hydrothermal | 7–8 | 7 | Fe ³⁺ , Mn ²⁺ detection | Krishnaiah et al. (2022) |
| Lychee Kernel | Pyrolysis | 1.12 | 8.6 | Bioimaging | Xue et al. (2015) |
| Grapefruit | Hydrothermal | 6.7 | 18.7 | Cr ⁶⁺ detection | Shen et al. (2017) |
| Coffee grounds | Hydrothermal | 2.67 ± 0.81 | 33 | Bioimaging | Wang et al. (2016a) |
| Carp Roe | Hydrothermal | 7.6 | 21 | Tetracycline testing | Tang et al. (2022b) |
| Pork bones | Hydrothermal | 6.7 | 4.9 | Metal ion detection | Fu et al. (2022) |
| Orange peels | Microwave & Solvent thermal method | 1.16 ± 0.1 | – | Electrode material | Olmos-Moya et al. (2022) |
| Grape skins | Hydrothermal | 2.73 ± 0.59 | 15.3 | Huangzen Detection | Tang et al. (2022a) |
| Aloe vera | Pyrolysis | 8 | – | Bioimaging | Raikwar 2022) |
| Guava leaves | Hydrothermal | 3.7 | – | Chlorpyrifos (CHL) detection | Dash et al. (2022) |
| Orange juice | Hydrothermal | 2.5 | 26 | Cell imaging | Sahu et al. (2012) |
| Indian dates | Pyrolysis | 2–4 | 21.3 | Ammonia detection in water | Ganesan et al. (2022) |
| Tobacco leaf | Hydrothermal | 6.3 | 13.7 | Tetracycline testing | Liang et al. (2022a) |
| Sugarcane bagasse | Hydrothermal | 2.79 | 2.24 | Fe ³⁺ detection | Qiu et al. (2022) |
| Birch wood | Hydrothermal | 5.24 | 21.7 | Fe ³⁺ detection | Chen et al. (2021) |
| Marigold | Hydrothermal | 5.7 | – | Supercapacitor | Gupta et al. (2021) |
| Bamboo leaves | Hydrothermal | 3.6 | 7.1 | Cu ²⁺ detection | Liu et al. (2014) |
| Straw | Hydrothermal | 2.7 | 23.48 | Tetracycline testing | Qi et al. (2019) |
| Onion | Hydrothermal | 9 | 28 | Fe ³⁺ detection | Bandi et al. (2016a) |
| Kitchen waste | Hydrothermal | 50 | – | Drug delivery | Himaja et al. (2014) |
| Crab Shell | Ultrasound | – | 14.5 | Targeted imaging of cancer cells | Dehvari et al. (2019) |
| Hair | Heat Treatment | 4.56 | 8.75 | Hg ²⁺ detection | Guo et al. (2016) |
| Onion Skin | Microwave | 2–4 | – | Cell imaging | Bankoti et al. (2017) |
| Silk | Hydrothermal | 45 | 38 | Tissue imaging | Li et al. (2013) |
| Citric acid | Hydrothermal | 5–8 | 75.2 | – | Guo et al. (2016) |

mango peel (Sun et al. 2019), ginkgo biloba (Jiang et al. 2019), waste seaweed (Godavarthi et al. 2017), onion waste (Bandi et al. 2016), heat bran (John et al. 2020), lignin waste (Abdullah Issa et al. 2019), lychee waste (Sahoo et al.,) and other biomass waste materials have been successfully used to synthesize biomass carbon quantum dots (Table 1), and the process of synthesizing carbon quantum dots from different biomass waste carbon sources (Fig. 4).

Hydrothermal method

The hydrothermal method produces carbon quantum dots from biomass feedstock and sub-supercritical water in an autoclave through dehydration, polymerization and carbide nucleation. The use of different biomass feedstocks can impact the synthesis of carbon quantum dots through the hydrothermal method. Biomass feedstocks high in lignin content tend to be larger in size, while those rich in hemicellulose such as sugarcane bagasse and corn cobs are smaller. Therefore, the selection of raw materials and the control of reaction conditions are extremely critical in the synthesis of carbon quantum dots by hydrothermal method. Hydrothermal is the most commonly used approach to synthesize carbon quantum dots from biomass because of environmental friendliness, easy control, and low cost. There is an urgent need to solve the low yield of carbon quantum dots synthesized via a hydrothermal method, as different reaction parameters such as reaction temperature, time, or feedstock can affect the yield. Researchers have extensively discussed this issue over the past few years, but it has yet to be resolved.

Without any surface passivation chemicals, Atchudan et al. (2021) adopted a simple hydrothermal approach for the sustainable synthesis of carbon quantum dots from banana

peel waste, obtaining a quantum yield of 20%. The carbon quantum dots obtained showed narrow particle size distribution with an average size of 5 nm. Under the excitation spectrum of 365 nm, the synthesized carbon quantum dot emits intense blue fluorescence in daylight (Fig. 5a). In spite of being stimulated for 90 min, the emission peak intensity was similar to the one before stimulation, suggesting that the synthesized carbon quantum dot is extremely photosensitive (Fig. 5b). Hence, the synthesized carbon quantum dots that exhibit excellent photostability over long periods could be a good fluorescent probe for living cell imaging, microscopic and analytical applications (Atchudan et al. 2021).

Using corn cob waste combined with silver nanoparticles to construct fluorescent probe CDs@IL-AgNPs, the researchers succeeded in preparing biomass-derived carbon quantum dots by a hydrothermal process using an ionic liquid (1-Allyl-3-methylimidazolium chloride) (Fig. 5c). Several properties of the probe were examined as well as its formation mechanism. The H_2O_2 has been directly detected, while melamine has been indirectly detected. Wang et al. (2020b) synthesized carbon quantum dots from 14 varieties of orange peels by hydrothermal method. An investigation was conducted to determine the relationship between volatile oil content in citrus peels and carbon quantum dot yield (Wang et al. 2020b) (Figs. 4d, 5d). As can be seen, citrus peels of different varieties contain different levels of volatile oils. Based on the trend of fluorescence quantum yield and volatile oil content, it is hypothesized that volatile oil is a carbonization product on the surface of orange peels, affecting quantum dot yield.

Prasannan et al. (2013) treated the orange peel via mild-temperature hydrothermal carbonization at 180 °C. A photocatalyst composed of ZnO and fluorescent carbon quantum dots was used to degrade naphthol blue-black azo dyes under

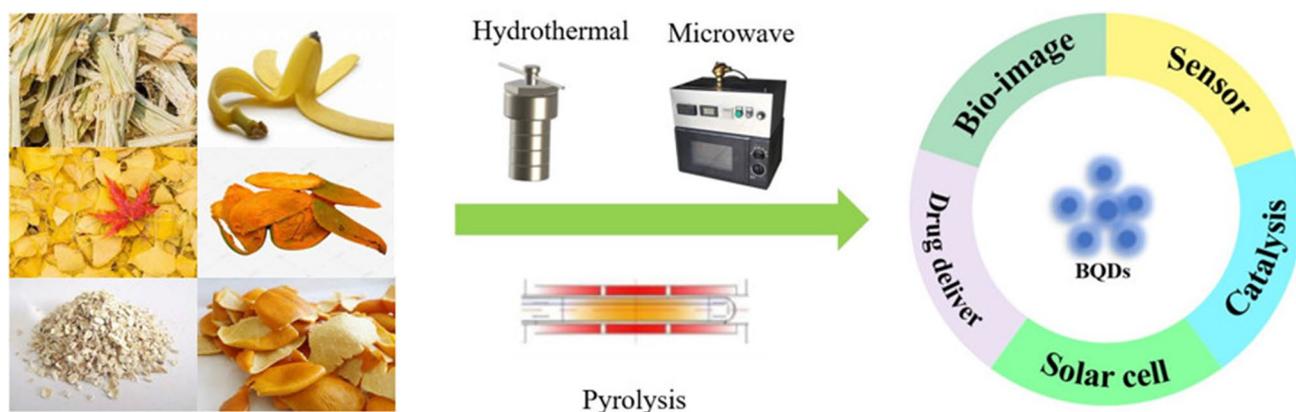


Fig. 4 Biomass carbon quantum dots (BQD) are carbon dots prepared from biomass as a carbon source. As the most widely available and least expensive source of carbon, biomass can easily introduce heteroatoms in the preparation of carbon dots, making it an ideal platform for a variety of important environmental, biological, and

energy-related applications. Synthesis of carbon quantum dots by hydrothermal, microwave and pyrolysis methods using biomass waste such as bagasse, orange peel and banana peel. The carbon quantum dots is promising for potentially use in bioimaging, sensing, and drug delivery

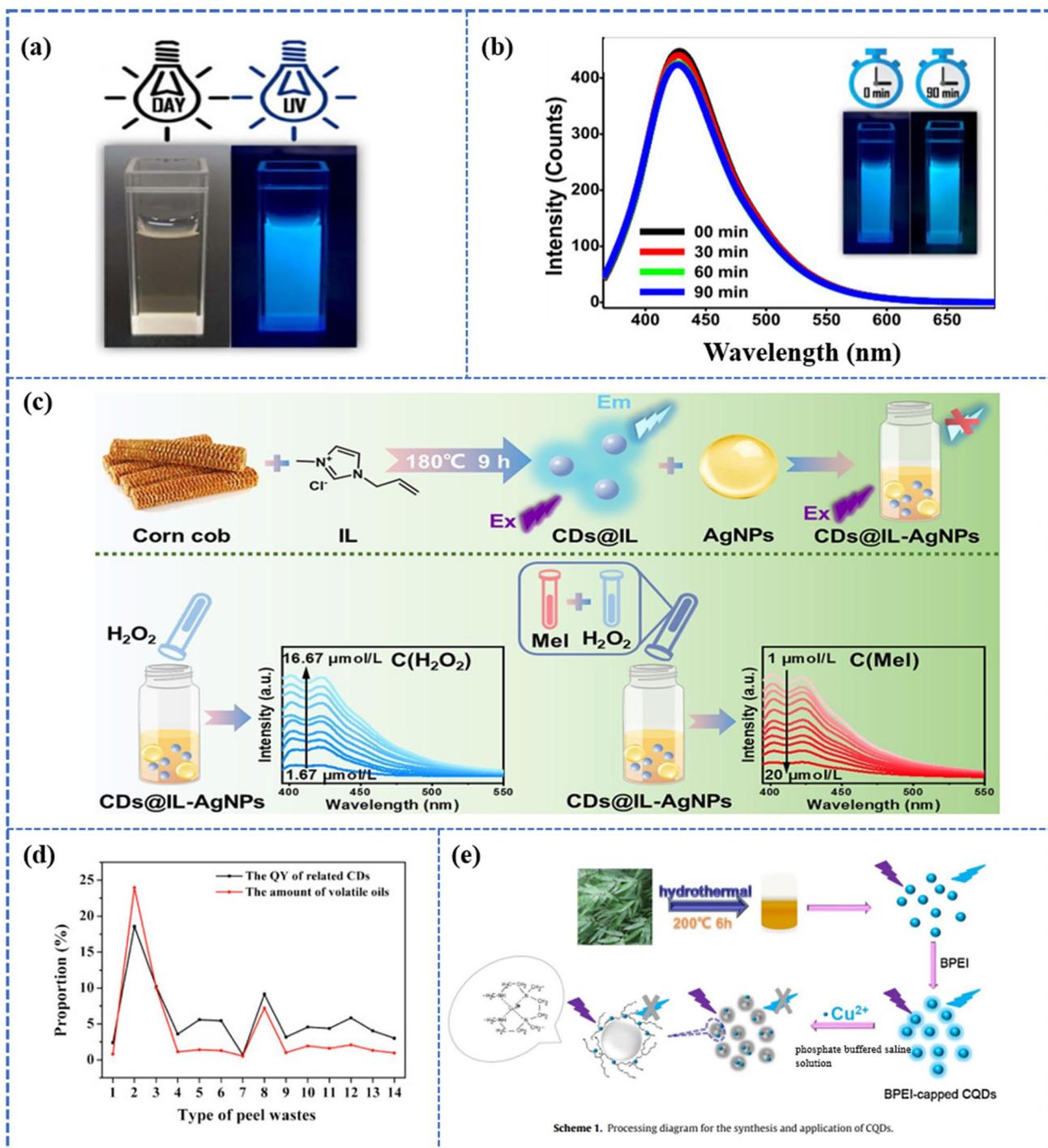


Fig. 5 **a** Synthetic carbon quantum dot optical images in ultra-violet light (UV light) and daylight; **b** Aqueous carbon quantum dot fluorescence spectra under 365 nm UV light at different irradiation times (inset: optical images of aqueous carbon quantum dot at 0 and 90 min irradiation). Reproduced with permission from Atchudan et al. (2021); **c** Using a fluorescent probe made of corn cob carbon quantum dots, ionic liquid, and silver nanoparticles (AgNPs), H₂O₂-assisted melamine detection was achieved. Reproduced with permission from Zheng et al. (2022); **d** Volatile oil content of dif-

ferent varieties of citrus peels vs quantum yield. Reproduced with permission from Wang et al. (Wang et al. 2020b); **e** An overview of the synthesis and application of carbon quantum dots. Branched polyethyleneimine (BPEI)-capped CQDs (BPEI-CQDs) are prepared by coating the CQDs with BPEI via electrostatic adsorption. The BPEI-CQDs are then employed as fluorescent probes for sensitive and selective Cu²⁺ detection. Reproduced with permission from Liu et al. (2014a)

UV irradiation, demonstrating their excellent photocatalytic activity and the contribution of nanoparticles to the catalytic behaviour (Prasannan et al. 2013). The study by Wang et al. (2020b) focused more on the quantum yield of carbon quantum dots and the effect of reaction conditions such as temperature on the quantum yield during the synthesis process, while Prasannan's work focused more on the photocatalytic properties of the prepared carbon quantum dots and did not describe the synthesis process in sufficient detail.

Liu et al. (2014) used a hydrothermal method with bamboo leaves as a carbon source to successfully produce carbon quantum dots with excellent quantum yield (Liu et al. 2014) (Fig. 5e). The carbon quantum dots surface was altered with branched polyethyleneimine to be used as fluorescent nanoprobes for Cu^{2+} detection. The Cu^{2+} sensing system based on the synthesized modified carbon quantum dot ensures a simple, green, reliable, and sensitive approach for detecting Cu^{2+} in environmental water (Liu et al. 2014).

Overall, the application of the hydrothermal approach for preparing carbon quantum dots gives high quantum yields and good photostability, and the preparation method is simple. However, controlling the particle sizes of carbon quantum dots remains challenging.

Microwave-assisted method

The microwave method uses the rapid and large amount of energy generated by microwaves to break the chemical bonds within the biomass material, causing dehydration, polymerization, and eventually carbonization to form carbon nanostructures. Carbon quantum dots can be produced efficiently with microwave technology at a relatively low cost, reducing reaction times. Recent years have seen increased interest in this technology of preparing carbon quantum dots.

Eggshells, a common biological waste in life, have attracted the attention of many researchers in carbon quantum dots. Eggshell nanocomposites and quantum dots can efficiently extract polycyclic aromatic hydrocarbons from water. At the same time, eggshells are an excellent carbon source for synthesizing carbon quantum dots (Razmi et al. 2016). Zuo et al. (2016) devised a green, rapid, environmentally friendly waste recovery method to synthesize water-soluble and fluorescent carbon quantum dots from eggshell membrane ashes. Eggshell membranes are protein-rich waste products that are readily available and inexpensive. The carbon quantum dots yielded from microwave heating have a 14% fluorescence quantum yield and show a maximum fluorescence emission peak at 450 nm. The researchers further designed a fluorescence off-and-on glutathione-sensitive probe based on the carbon quantum dots/ Cu^{2+} system with a detection limit of 0.48 mmol L^{-1} and a linear range of $0.5\text{--}80 \text{ mmol L}^{-1}$. Overall, the carbon quantum dots from the eggshell membrane showed exceptional

fluorescence properties and applicability in sample detection and biotechnology (Zuo et al. 2016). In addition, researchers prepared carbon quantum dots using biomass waste such as mango peels as a precursor (Kumawat et al. 2017). The microwave method is also essential for synthesizing carbon quantum dots with hydrothermal or pyrolysis systems. Liu et al. (2015) utilized goose feathers as the precursor to synthesize carbon quantum dots for ferric ion detection by microwave-hydrothermal method, achieving 196 nM of the lowest detection limit (Liu et al. 2015).

Although biomass-derived carbon quantum dots can be prepared via microwave methods rapidly, the microwave equipment size hinders its application in large-scale industrial production (Khairol Anuar et al. 2021). As a result, developing a microwave method for preparing biomass carbon quantum dots with a high fluorescence quantum dot yield and relatively uniform size distribution is critical.

Pyrolysis

Pyrolysis represents another common method for preparing biomass carbon quantum dots, where biomass precursor is heated above $500 \text{ }^\circ\text{C}$ and then condensed and nucleated to produce carbon nanostructures. The biomass feedstock undergoes cracking and loses water and other reactions to obtain carbide. Pyrolysis can be performed using microwave heating with the advantages of rapid heat generation and simple operation, while the equipment size is also suitable for industrial mass production. Pyrolysis generally uses a high concentration of acid or base to cleave the carbon precursor into nanoparticles. Pyrolysis can produce carbon quantum dots from various biomass materials, including sago waste, watermelon rind, plant leaves and coffee grounds. By adjusting the pyrolysis conditions, for example, reaction duration, pH, and process temperature, the carbon quantum dots can be tailored in their properties (Zuo et al. 2016). Zhou et al. (2012) utilized watermelon rind to synthesize high-quality fluorescent carbon quantum dots via simple filtration and low-temperature carbonization. The prepared carbon quantum dots show intense blue luminescence, a small particle size ($\sim 2.0 \text{ nm}$), good stability over a wide pH range of 2–11 and a considerable fluorescence lifetime. In addition, the carbon quantum dots produced have been successfully used for living cell imaging, demonstrating that a high-performance optical imaging probe can be made from these carbon quantum dots (Zhou et al. 2012).

Compared to hydrothermal methods, pyrolysis usually yields large distributions of carbon quantum dots. Biomass-derived carbon quantum dots with bright luminescent properties were synthesized by heating rice husk as a precursor at $700 \text{ }^\circ\text{C}$ for 2 h under a nitrogen atmosphere (Wang et al. 2016b). The prepared carbon quantum dots exhibited strong blue luminescence at 365 nm, and the luminescence

intensity remained stable after three months, indicating their potential application in bioimaging. The pyrolysis approach could realize high-value biomass waste utilization with great economic and environmental benefits. Both studies show how cost-effective and environmentally friendly the microwave method is in preparation. There has been no assessment of whether the production of carbon quantum dots can be scaled up further. Biomass such as leaves (Zhu et al. 2013), citrus peels (Chatzimitakos et al. 2017), grass (Krysmann et al. 2012), and lychee kernel (Xue et al. 2015) can also be processed by pyrolysis to produce biomass carbon quantum dots for potential application in cell imaging and fluorescence sensing.

Other methods

Ultrasonic-assisted method and electrochemical methods have received considerable attention from researchers in recent years due to their green and efficient advantages, in addition to the common synthetic methods of hydrothermal, microwave, and pyrolysis. Chemical oxidation has also attracted the attention of many researchers due to its simplicity and ease of use and its highly adjustable nature. The chemical oxidation method refers to the preparation of carbon quantum dots by oxidizing cut macromolecular carbon materials with strong oxidants such as nitric acid. The method is simple to use, does not require large equipment, and can produce large quantities of carbon quantum dots; however, the preparation process is more dangerous, and the large amount of waste acid produced can harm the environment. Liu et al. (2007) prepared carbon quantum dots with fluorescence properties from candle ash using an oxidation acid treatment. The carbon quantum dots had a particle size of less than 2 nm and a quantum yield of 0.8–1.9%. The fluorescence properties of the prepared carbon quantum dots were found to be affected by the pH of the solution, with a significant decrease in fluorescence intensity when the solution was changed from neutral to acidic or alkaline (Liu et al. 2007).

Ultrasound-assisted methods use alternating high and low-pressure waves generated by ultrasound to cavitate, resulting in a brief high-energy environment that can initiate chemical reactions in reactants or crush big particulate materials. The ultrasound-assisted approach is inexpensive, simple to use, and adaptable in terms of experimental settings, allowing for the production of carbon quantum dots with desirable features. Using food waste as the carbon source, Park et al. successfully synthesized green carbon quantum dots with water solubility using an ultrasonic-aided technique. Carbon quantum dots have a surface rich in oxygen-containing functional groups and strong photostability. The researchers demonstrated the low cytotoxicity of the produced carbon quantum dots by injecting them

individually into mouse cells for cell viability experiments (Park et al. 2014).

Electrochemical preparation is a green, efficient, practical, and high-quality method for the synthesis of carbon quantum dots. The basic idea is to use a conductive carbon material as a working electrode, such as graphite rods, graphene, and carbon fibres. The large carbon material is then exfoliated into very small carbon nanoparticles by applying a direct current voltage, a process occurs via anodic oxidation of the electrode and the entry of ions from the electrolyte into the graphite layer (Rocco et al. 2023). Hou et al. utilized a sodium citrate and urea aqueous solution as an electrolyte, along with a platinum sheet as an electrode, to carry out the electrochemical carbonization reaction at 5 V for 1 h. Afterwards, carbon dots were extracted from the electrolyte via dialysis. Experimental results showed that the carbon dots synthesized using this method had a high quantum yield (11.9%), excellent photostability, and could effectively detect Hg^{2+} ions in water samples. This method presents an efficient, environmentally friendly, and cost-effective technique for the synthesis of carbon dots, thereby providing a new avenue for developing carbon dot materials (Hou et al. 2015). The electrochemical method allows the prepared carbon quantum dots to be monitored during the synthesis process, and by changing the electrolyte solution, such as ionic liquids, the mechanism of formation of the carbon quantum dots may be altered, resulting in changes to their morphology and chemical structure. The method is low cost and high yield, but the range of carbon sources available is narrow, the choice of heteroatom doping is limited and the operation is more complex. Liu et al. (2016) prepared carbon quantum dots with an average diameter of 4.0 ± 0.2 nm using graphite as the electrode and alkaline alcohol as the electrolyte solution using an electrochemical method. The prepared carbon quantum dots can be used for the specific and sensitive detection of Fe^{3+} (Liu et al. 2016).

Main factors affecting the performance of carbon quantum dots

Compared to traditional fluorescent dyes, the advantages of biomass carbon quantum dots are affordability and environmental friendliness. However, the quantum yield of carbon quantum dots is low without treatment, making it difficult to use widely. Currently, the fluorescence properties of carbon quantum dots are affected by four factors: surface defect state, quantum size effect, band gap jumping, and surface passivation. Surface passivation treatment and metal or non-metal atom doping treatment can effectively solve the limitations of biomass carbon quantum dots, such as uneven quantum size distribution, low fluorescence quantum dot yield and easy agglomeration of reaction products

(Thangaraj et al. 2019). Biomass carbon quantum dots have been produced via this method with high fluorescence quantum yields (Wang et al. 2018b).

By further doping heteroatoms into the carbonaceous framework and passing the surface through passivation, the fluorescence activity of carbon quantum dots can be significantly increased. Highly fluorescent carbon quantum dots can be more easily prepared if hetero-element doping and passivation can be performed simultaneously. However, as biomass waste is typically populated with multiple heteroatoms, diverse surface groups from these materials are present in carbon quantum dots, giving them unique properties that do not require further passivation or modification. As opposed to being determined solely by one of the four factors, the luminescent behaviour of carbon quantum dots is determined by a combination of two or more. Carbon quantum dots are modulated primarily by changes in the synthesis conditions; therefore, different synthesis conditions have extensive effects on their properties.

Impact of raw materials

The raw materials used would somewhat affect the fluorescence properties of the resulting carbon quantum dots. For example, banana juice was used to prepare carbon quantum dots with a quantum yield of 8.95% by hydrothermal heating at 150 °C and 4 h of process time (De and Karak 2013). Atchudan et al. (2021) used banana peel waste as the carbon source and hydrothermally synthesized carbon quantum dots with a 20% yield that exhibited excellent water solubility and photostability (Atchudan et al. 2021). Chatzimitakos et al. (2017) used lemon and orange peels to produce carbon quantum dots via a hydrothermal approach. The fluorescence properties showed that orange and lemon peels exhibited similar photostability, whereas the quantum yields obtained were 16.8 and 15.5%, respectively. In addition, the fluorescence emission spectra of citrus peel carbon quantum dots under various excitation wavelengths show a narrow and symmetric fluorescence spectrum when excited at 365 nm and peak at 455 nm. The fluorescence spectrum of the lemon peel carbon quantum dot shows double peaks at 390 (violet) and 435 nm (blue) (Chatzimitakos et al. 2017).

For the degree of bursting, both showed different changes with increasing Fe^{3+} concentration (A et al. 2017). The degree of burst extinction of carbon quantum dots derived from orange peel decreased with increasing Fe^{3+} concentration, which was in contrast to the increasing trend of the stern–Volmer curve for lemon peel. The reason for this is that the carbon quantum dots obtained from lemon peel cannot be excluded from both the dynamic and static aspects of the burst process, and lemon yellow also induces fluorescence bursts to some extent. The carbon quantum dots yield made with different raw materials also vary greatly.

For instance, the carbon quantum dots yields prepared from wheat bran (John et al. 2020), ginkgo biloba (Jiang et al. 2019), and cabbage (Alam et al. 2015) as carbon sources were 33.23, 22.8, and 16.5%, respectively.

Impact of preparation temperature

The synthesis of fluorescent carbon quantum dots using biomass waste as a carbon source requires carbonization to control the structure, morphology, and size, so the pyrolysis temperature is critical in this case (Zhu et al. 2020). The effect of different pyrolysis temperatures on the fluorescence properties of carbon quantum dots was investigated. The lotus, pine, and sycamore leaves were pyrolysed under the nitrogen atmosphere at 250, 350 and 400 °C to produce carbon quantum dots. The results showed the best fluorescence properties when the pyrolysis temperature was set at 350 °C. When the temperature is low, the prepared carbon quantum dots leaves cannot be completely carbonized, while the carbon quantum dots are oxidized and the photoluminescence intensity is reduced when the temperature is too high (Zhu et al. 2013). Sahoo et al. (2020) heated the litchi waste at various temperatures (150, 180, and 280 °C) and studied the UV–Vis and fluorescence spectra of the carbon quantum dots. It was determined that 180 °C was the optimal temperature for synthesis. Figure 5 depicts that fluorescence intensity increased continuously with temperature from 150 to 180 °C and reached its maximum value at 180 °C, which began to weaken as the temperature increased. The findings revealed that the organic functional groups on the surface of carbon quantum dots are destroyed under high-temperature conditions, reducing the fluorescence intensity (Sahoo et al.).

Impact of process time

To some extent, temperature influences the optical properties of carbon quantum dots during the synthesis process as well as the reaction time. Under the premise that the reaction temperature is suitable, incomplete carbonization of the carbon source will result from a short reaction time. However, if the reaction time is too long, the surface structure of the carbon quantum dots will be destroyed. Therefore, researching the optimal reaction time through controlled experiments to prepare carbon quantum dots with excellent optical properties represents an important focus. With ginkgo biloba as a precursor, Jiang et al. (2019) synthesized nitrogen-doped carbon quantum dots using a simple and economical hydrothermal synthesis. The maximal burst efficiency was obtained with a reaction time of 1 min (Jiang et al. 2019). In a study by Sun et al. (2019), carbon quantum dots were investigated in terms of fluorescence properties as a function of reaction time. The fluorescence

intensity of carbon quantum dots increased with increasing reaction time from 1 to 4 h at a temperature of 200 °C. Nevertheless, fluorescence intensity levelled off after 4 h of reaction (Sun et al. 2019).

Many biomass wastes are available for synthesizing carbon quantum dots via many synthetic methods. However, no systematic research has been conducted. To date, the preparation method and the type of biomass used for carbon sources remain subject to a high level of randomness. As a result, there is uncertainty about the properties and quantum yields of the carbon quantum dots produced. The properties of carbon quantum dots should be studied from the carbon source and preparation method. Through the identification of the elements that affect the properties of carbon quantum dots, a more purposeful selection of carbon sources will be possible.

Properties of carbon quantum dots derived from biomass waste

Compared with the carbon quantum dots prepared by traditional chemical carbon sources, the carbon quantum dots synthesized by green biomass waste have the advantages of rich raw materials, low cost, good biocompatibility and water solubility. In addition, due to the rich elements contained in biomass waste, it usually does not need additional doping or surface modification when used to prepare carbon quantum dots but rather self-doping, which makes it widely used in medical treatment, real-time imaging, biosensors, energy storage and other fields. Next, the structural and unique optical properties of carbon quantum dots derived from biomass wastes will be discussed.

Structural properties

Carbon quantum dots are new spherical nanomaterials that use carbon as the skeleton. The inner part usually comprises sp^2 and a small amount of sp^3 hybrid nanocrystalline carbon, with the carboxyl and hydroxyl groups unevenly distributing on the surface. The surface functional groups of carbon quantum dots synthesized from different biomass waste precursors are different, which makes them extensively used in different fields. Because the size of carbon quantum dots is generally between 2–10 nm, it shows a "quantum size effect"; that is, the maximum fluorescence emission wavelength of carbon quantum dots will change with its particle size. Compared with non-biomass carbon quantum dots, biomass waste-derived carbon quantum dots have excellent biocompatibility and smaller size, making them better applied to cell imaging and drug delivery.

Optical properties

UV–visible absorption properties

UV–visible absorption is one of the unique optical properties of carbon quantum dots. UV absorption between 260 and 320 nm is usually ascribed to the π – π^* leap of the C=C bonds, which effectively allowing carbon quantum dots to trap photons in the short wavelength region (Zheng et al. 2015). On the other hand, absorption at 320–380 nm is generally caused by an n – π^* leap of the C=O and C=N bonds. A UV absorption peak at 270 nm was observed for the carbon quantum dots obtained from microwave pyrolysis of Indian dates, which confirms the existence of the corresponding π – π^* transition (Ganesan et al. 2022).

Carbon quantum dots produced by different synthetic routes exhibit different UV–visible absorption spectra. Orange peel was transformed into carbon quantum dots with an absorption peak of 268 nm using a hydrothermal method at 180 °C and 12 h of process time (Prasanna and Imae 2013). The carbon quantum dots derived from orange peel displayed the UV absorption peak red-shifted to 280 nm at 200 °C and 4 h of process time (Wang et al. 2020b). In addition, the physical state of the raw material also affects the UV absorption peak shifting. Sahu et al. (2012) obtained the UV absorption peak of the carbon quantum dots at 288 nm by pretreating the raw material with orange juice hydrothermally at 120 °C and 2.5 h of process time. In short, the types of raw material, physical state, reaction temperature, time, and pH value will affect the position of the ultraviolet absorption peak of carbon quantum dots, and its specific mechanism still needs further study.

Tunable fluorescence emissions

In comparison with other materials, carbon quantum dots have tunable fluorescence emissions. Excitation light wavelength, quantum dot size, pH value, surface defects of quantum dots, and other conditions can affect the intensity and wavelength of the fluorescence emission of carbon quantum dots. Currently, the discussion on fluorescence tunability is mostly accompanied by multicolour or panchromatic luminescence research.

One of the most unique optical properties of carbon quantum dots compared with conventional semiconductor quantum dots was their tunable fluorescence emissions (that is, the emission wavelength of carbon quantum dots was red-shifted with the increase of the excitation wavelength, and the fluorescence emission was easy to adjust). From the tunable fluorescence emissions phenomenon of carbon quantum dots first reported by Sun et al. (2006), it can be found that carbon quantum dots passivated by polyethylene glycol (PEG) have strong fluorescence emission, and the

fluorescence emission of 450–690 nm can be obtained under a fixed 400 nm wavelength excitation. There was strong fluorescence emission in the range of 500–600 nm. When the excitation wavelength was different (400–694 nm), the emission peak extended from the visible to the near-infrared region, showing the characteristic of excitation wavelength dependence, and the fluorescence intensity was higher under the optimal wavelength excitation than the former. In addition, with the increase of excitation wavelength of 20 nm, the emission wavelength also shows an equal interval increase, accompanied by a significant decrease in fluorescence intensity (Fig. 6a) (Sun et al. 2006). A large difference between the intensity of light emitted at different wavelengths is not expected in practical applications. Pan et al. (2015) produced panchromatic light-emitting carbon quantum dots by

microwave heating methylamine citrate at 160 °C for 1 h. However, no significant difference exists in the intensity of light emitted by different wavelengths of this panchromatic carbon point (Fig. 6b) (Pan et al. 2015). It is believed that the difference in the emitted light wavelength results from the electron transition of different chemical bonds could be attributed to the superposition of multiple emissions induced by the reactivation of emitted light as excitation light. Besides, the fluorescence emission from carbon quantum dots is mostly tunable using monochromatic light. Hu et al. (2015) successfully synthesized a tunable fluorescence emission of carbon quantum dots within the visible spectrum under white light excitation for the first time. They mixed citric acid and ethylenediamine solution to prepare different kinds of carbon quantum dots at 180 °C with various

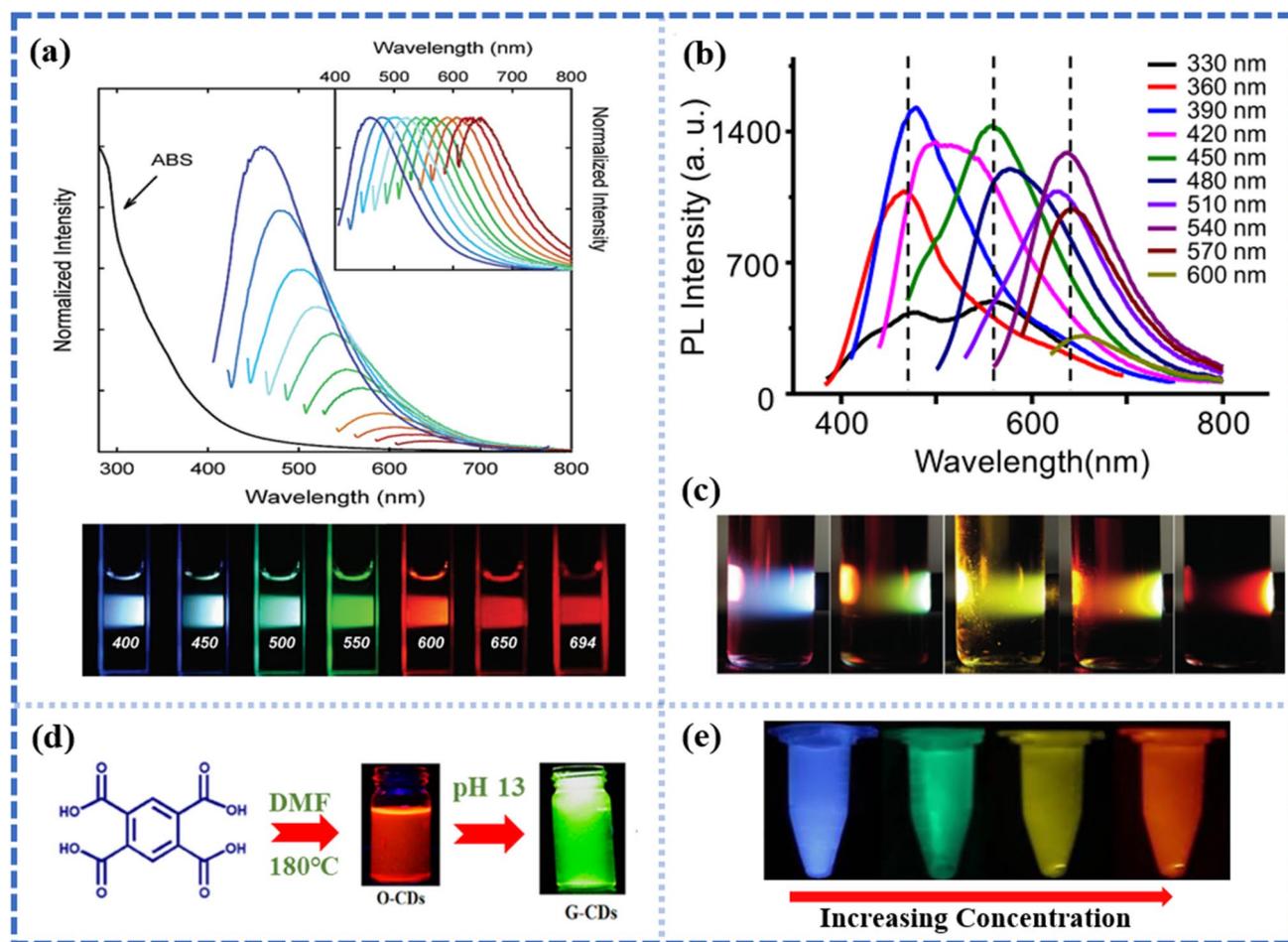


Fig. 6 **a** Carbon quantum dots aqueous solution exhibits luminescence and absorption spectra. Quantum yields are normalized to spectral emission intensities (The spectral peak in the inset is normalized). Reproduced with permission from Sun et al. (2006); **b** Fluorescent spectra of the carbon quantum dots under various excitation wavelengths. Reproduced with permission from Pan et al. (2015); **c** Emission of various carbon quantum dots excited by white light. Reproduced with permission from (Hu et al. 2015); **d** Orange fluores-

cent carbon quantum dots (O-CDs) synthesized via the solvothermal in dimethylformamide (DMF) solution turn to green fluorescent carbon quantum dots (G-CDs) in a high pH environment. Reproduced with permission from Kumari et al. (2019); **e** Emission from N-doped carbon quantum dots excited at a maximum wavelength with varying concentrations. Reproduced with permission from Wang et al. (2018a)

proportions of H_3PO_4 and NaBH_4 (Fig. 6c) (Hu et al. 2015). The addition of H_3PO_4 and NaBH_4 has affected the dehydrogenation reaction in the carbonization process, thus making the absorption peak blue or red-shifted, which is in sharp contrast to the previous excitation-dependent fluorescence.

The concentration, pH, and average particle size of the carbon quantum dots solution could also affect the emitted light. Li et al. (2010) obtained a series of carbon quantum dots with different sizes by electrolysis of graphite rods under alkaline conditions. Fluorescence of red, yellow and green can be observed when carbon quantum dots are sized from 1.2 to 3.8 nm. This luminescence is likely caused by quantum size effects rather than changes in oxygen-containing functional groups. In addition, the excitation wavelength of each carbon quantum dot also depends on the above factors (Li et al. 2010).

Wang et al. (2018a) obtained orange fluorescent carbon quantum dots by adding phthalic acid and manganese chloride to a dimethylformamide solution through sonication, followed by oven heating. Carbon quantum dots exhibited bright green when the pH was raised to 13 using NaOH (Fig. 6d) (Kumari et al. 2019). When the pH is increased, there is a blue shift in the fluorescence emission band of synthetic carbon quantum dots which could be due to the conversion of the acid anhydride to a carboxylate salt that increases the electron density of the system and widens the energy band gap to enhance the emission light energy. N-doped carbon quantum dots was obtained via the microwave approach combined citric acid and ammonia as precursors. Then, the resulted N-doped carbon quantum dots were configured to different concentrations ($0.78\text{--}10.42\text{ mg mL}^{-1}$). The fluorescence emission wavelengths at the optimal excitation wavelength increased gradually (450–600 nm) with the carbon quantum dot concentration (Fig. 6e) (Wang et al. 2018a). Spectral analysis revealed that the carbon quantum dots at all concentrations showed excitation wavelength dependence. The concentration-influenced luminescence changes were most likely due to the re-emission and re-absorption caused by the shorter distance between the particles of the carbon quantum dots at higher concentrations.

Several studies reported successfully preparing multi-colour or panchromatic light-emitting carbon quantum dots excited by monochromatic light. The findings suggest that the requirements for light sources could be reduced and surmount the limitations of traditional quantum dots in terms of narrow emission wavelength range and unobvious near-infrared excitation. The emission of near-infrared light greatly impacts biological imaging due to its ability to penetrate biological tissues better than other wavebands, minimize interference caused by blue-green autofluorescence in the background, and achieve a high-quality signal. There is little research on near-infrared emission carbon quantum dots, and further research is needed to explore its red

emission mechanism and the influence of pH, precursor concentration, and reaction temperature on luminous intensity.

Up-conversion fluorescence

Besides the conventional down-conversion fluorescence emission, some of the synthesized carbon quantum dots exhibit up-conversion fluorescence characteristics (Cao et al. 2007; Cui et al. 2014; Jia et al. 2012; Li et al. 2019a; Shen et al. 2011). Up-conversion fluorescence or anti-Stokes luminescence, in which the energy of the emitted light is higher than that of the excitation light; that is, the wavelength of the emitted light is shorter than the excitation light. Most carbon quantum dots synthesized without surface passivation or doping will emit blue light under UV irradiation. The up-conversion fluorescence of carbon quantum dots is therefore highly promising for bioimaging applications since biological tissues also emit blue light (Wang et al. 2014a). Shortly after the carbon quantum dots were named, the carbon quantum dots with up-conversion properties under an 800 nm femtosecond pulsed laser were discovered and applied to cell imaging (Fig. 7a) (Cao et al. 2007).

Jia et al. (2012) also produced carbon quantum dots with up-conversion fluorescent properties using a one-pot heating method to heat an ascorbic acid solution to $90\text{ }^\circ\text{C}$ and maintain it for 5 h. Their up-conversion spectra are shown in Fig. 7(b) (Jia et al. 2012). The carbon quantum dots produced a fixed emission of 540 nm under 805 to 1035 nm excitation light. Cui et al. (2014) added H_2O_2 to the hydrothermal process to make the up-conversion fluorescence of carbon quantum dots more significant. A clear up-conversion emission peak at around 483 nm was noted after adding H_2O_2 (Fig. 7c) (Cui et al. 2014). Shen et al. (2011) investigated the luminescence mechanism of up-conversion fluorescence, which differs from the left side of the down-conversion fluorescence diagram (Fig. 7d). The electrons in the low-energy electron beam in the π orbital tend to leap to a higher energy level, such as the lowest unoccupied molecular orbital (LUMO). Then, the energy of the electron decreases and returns to the lower energy level, namely the highest occupied molecular orbital (HOMO). The difference in energy between the emitted and exciting light during up-conversion in this study (1.1 eV) is close to the energy difference between σ orbitals and π orbitals (dE) (Shen et al. 2011).

In addition to the above studies, some researchers have suggested that the up-conversion luminescence property could be caused by multiphoton activity or the leakage of the second diffraction spectrophotometer of conventional fluorescence emission. It is still unclear what mechanism is responsible for the phenomenon and more research is necessary. Additionally, it is possible to achieve stable emission of carbon quantum dots in the near-infrared region by correctly

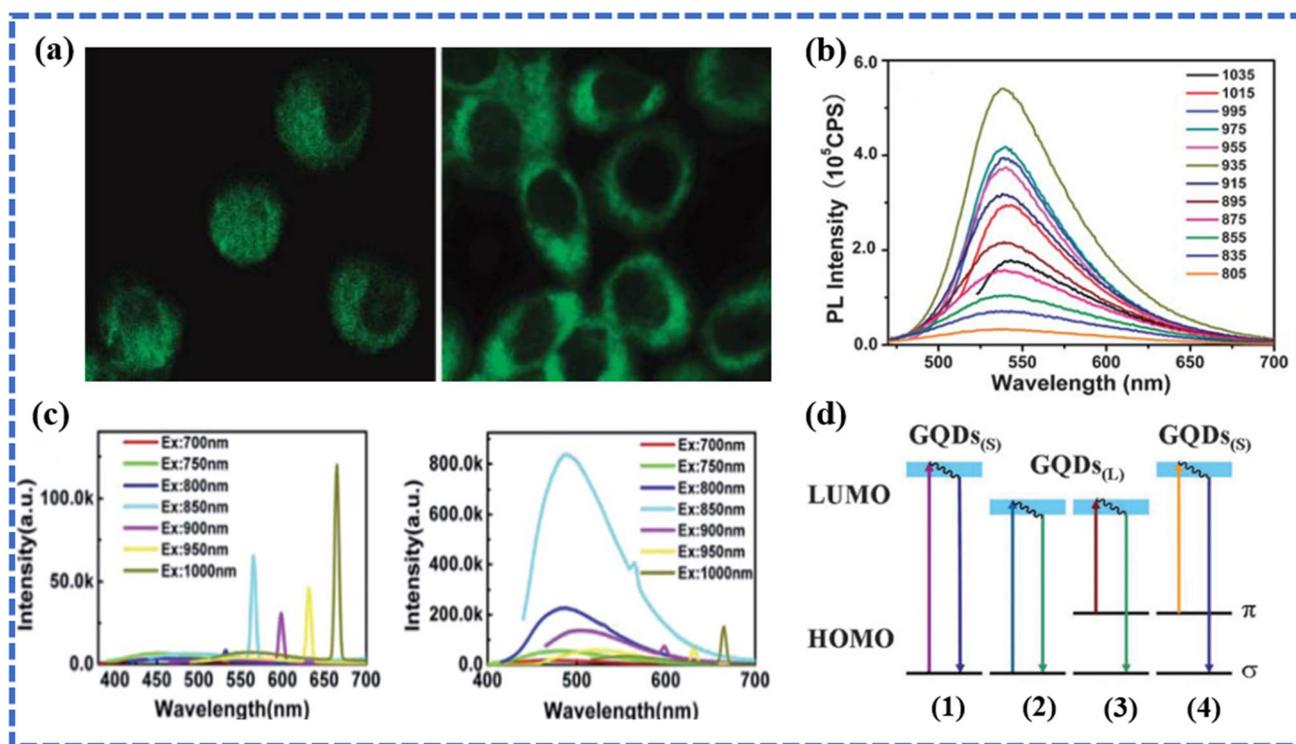


Fig. 7 **a** Two-photon luminescence image of human breast cancer cells with internalized carbon quantum dots. Reproduced with permission from Cao et al. (2007); **b** Photoluminescence emission spectra of carbon quantum dots solution excited from 805 to 1035 nm. Reproduced with permission from (Jia et al. 2012); **c** Fluorescence emission spectra for the carbon quantum dots before (left) and after (right) adding H₂O₂. Reproduced with permission from Cui et al.

(2014); **d** Normal photoluminescence mechanisms in graphene quantum dots for small size (GQDs_(S)) (1) and large size (GQDs_(L)) (2); Up-conversion photoluminescence mechanisms in graphene quantum dots for large size (3) and small size (4). While HOMO and LUMO are indicated to highest occupied molecular orbital and the lowest unoccupied molecular orbital. Reproduced with permission from Shen et al. (2011)

utilizing the special luminous properties of carbon quantum dots combined with the adjustable fluorescence emission, which is of paramount significance for using real-time imaging in organisms.

Fluorescence stability

Good fluorescence stability is a major property that distinguishes carbon quantum dots from traditional fluorescent materials and determines their possible applicability in biological research. Atchudan et al. (2019) dispersed the N-carbon quantum dots in deionized water. After one year of storage, the colour and luminescence intensity of the aqueous N-carbon quantum dots were insignificantly different under daylight and UV light compared with those before storage (Fig. 8a), indicating that the aqueous N-carbon quantum dots possess certain stability (Atchudan et al. 2019). Carbon quantum dots also show stability in broad pH values or high NaCl concentrations (Fig. 8b & c) (Li et al. 2021b). The stability of carbon quantum dots could overcome the rapid decline of the emission intensity of traditional fluorescent dyes. As a result of its excellent luminescence stability, it

can be used in medical imaging, including long-term fluorescent labelling of sensors and organisms without the necessity of keeping them in the dark.

In short, carbon quantum dots have the characteristics of high fluorescence intensity, wide excitation spectrum, tunable emission light, stable fluorescence, low molecular weight and up-conversion fluorescence. The biomedical applications for carbon quantum dots with these properties are extensive, including biological imaging, biosensors, and tumour therapy. As yet, the actual mechanism of fluorescence emissions is unclear and disputable. Various product structures and uncertain surface functional groups due to the great differences in precursors, methods and paths of carbon quantum dots synthesis are the direct impediments. At present, three mechanisms have been proposed for fluorescence emission. The first mechanism is that the band transition of the delocalized π structure contributes to the laser emission (Dai et al. 2022). The second is the quantum domain limiting effect of carbon points (Zhu et al. 2015), whereas the third mechanism is the cavity recombination behaviour caused by surface defects (Li et al. 2021a; Lim et al. 2015). In recent years, researchers have tended to believe that a synergistic

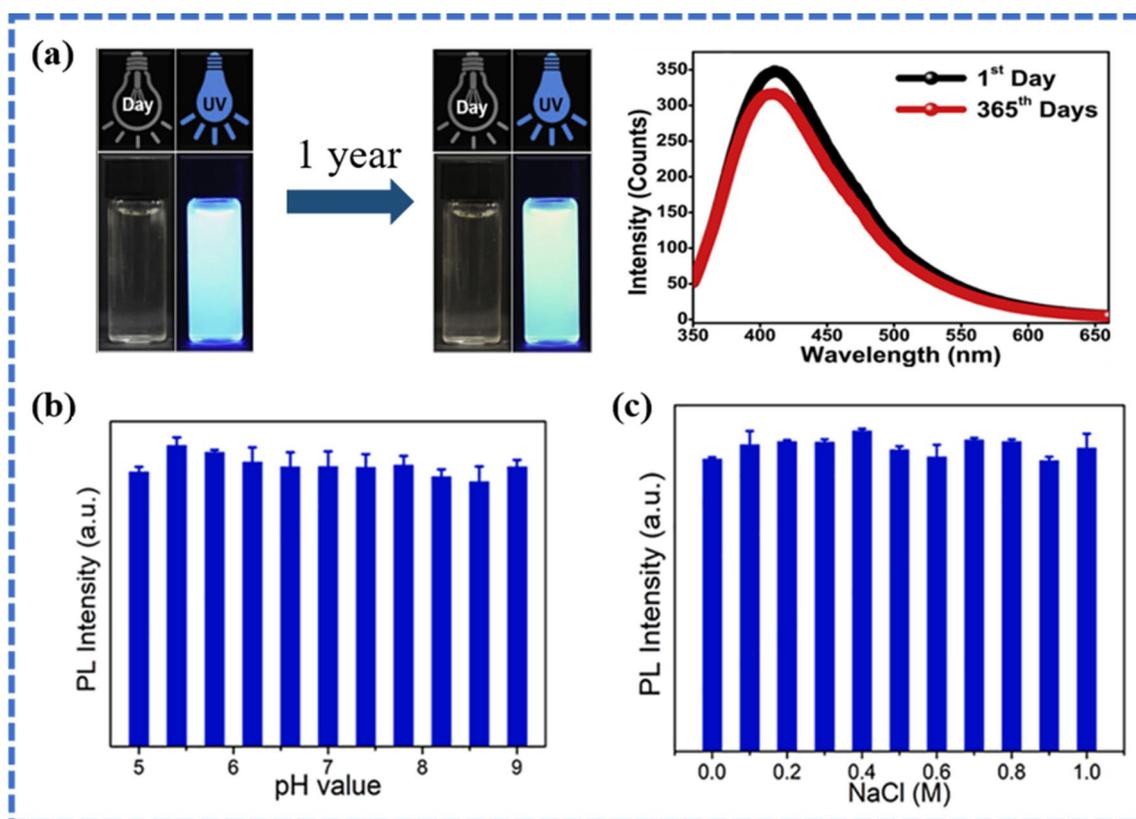


Fig. 8 a Fluorescence intensity of aqueous carbon quantum dots under natural light and ultraviolet light after storing for 1 day and 365 days. Reproduced with permission from Atchudan et al. (2019);

Photoluminescence intensity of aqueous carbon quantum dots at different pH values (b) and NaCl concentration (c). Reproduced with permission from Li et al. (2021b)

effect between these mechanisms may have resulted in the luminescence properties of carbon quantum dots. Hence, a representative understanding of the luminescence mechanism of carbon quantum dots is of great help for their extensive application.

Applications

The use of biomass waste as a carbon source for the preparation of carbon quantum dots not only solves a portion of the waste problem, but it is also more environmentally friendly and in line with sustainable development. Furthermore, carbon quantum dots have a high fluorescence intensity and a rich surface functional group composition, making them useful in biosensing and other fields. Carbon quantum dots can be used in bioimaging applications due to their low cytotoxicity and excellent biocompatibility. Because of their small size, good electrochemical conductivity, unique fluorescence properties, and electronic properties, carbon quantum dots can be used as energy storage devices. Recent advances in bioimaging, fluorescent labelling, drug delivery, fluorescent probes for environmental

metal ions, photodegradation of organic pollutants and hydrogen photocatalysts from photolysed water, and biosensors will be presented from three perspectives: energy, environment, and medicine.

Energy-related applications

With the continued use of traditional nonrenewable fossil energy sources, the energy crisis and environmental pollution are worsening, and the development of new energy sources is receiving increased attention. In this context, electrochemical energy storage technology, such as rechargeable batteries or capacitors, has become an important development direction for energy storage systems due to its safety, low cost, and high-efficiency features. Carbon quantum dots have become a hot topic in energy storage recently. Among them, carbon quantum dots synthesized from biomass waste are becoming an important development direction for future electrochemical energy storage technology due to its green and simple preparation method and effective use of waste.

Energy storage batteries

Carbon quantum dot-based electrodes prepared from biomass waste are attractive for electrochemical energy storage due to their ideal structure, physicochemical properties, tunability of doped heteroatoms, and good electrical conductivity. They are also economically accessible and non-polluting to the environment, which has gained widespread interest. The electrode material of the battery largely

affects the battery performance. Various carbon quantum dot composite electrode materials have been studied in depth recently, with increasing interest in using carbon quantum dots (Fig. 9a) for constructing high-performance composite materials (Guo et al. 2021).

Balogun et al. (2016) coated the produced carbon quantum dots on the surface of VO₂ nanowires to achieve a surface-engineered VO₂ interwoven nanowire electrode for carbon quantum dots. The introduction of carbon quantum

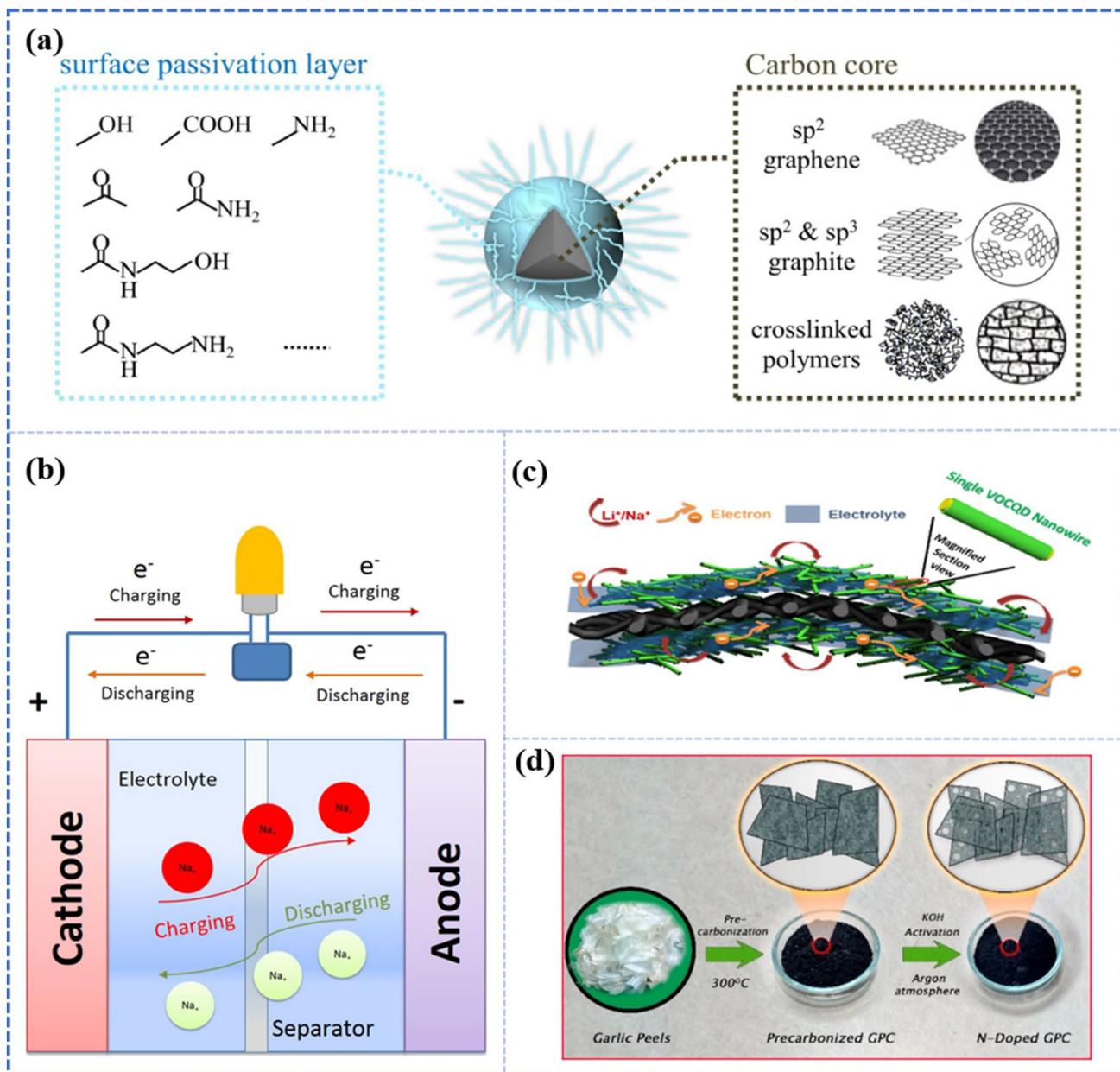


Fig. 9 a Various carbon quantum dots composites electrode materials for different batteries. Reproduced with permission from Guo et al. (2021); b Schematic diagram of a Na-ion battery. Reproduced with permission from Thangaraj et al. (2021); c Schematic representation of the C-VOCQD interwoven nanowire electrode with steady elec-

tron and Li/Na-ion transfer routes. Reproduced with permission from Balogun et al. (2016); d Flowchart for synthesizing carbon quantum dots using garlic peel as a precursor. Reproduced with permission from Selvamani et al. (2016)

dots protected the nanowire surface and increased the electrode capacity. The researchers used nanometer-sized carbon quantum dots interwoven nanowires engineered on the surface to allow for faster and less obstructive ion transport through the structure, resulting in increased electrochemical activity and conductivity. Furthermore, it acts as a sensitizer and protector, enhancing the electrochemical properties of the engineered VO₂ nanowires (Fig. 9c). Carbon quantum dots also improve conductivity, increase capacity and enhance charge transfer resistance. In addition, carbon quantum dots protect the interwoven nanowires from rapid aggregation, imparting excellent structural stability to the VO₂ nanowires and increasing the storage properties of Li and Na (Balogun et al. 2016).

Selvamani et al. (2016) used the synthesized carbon quantum dots as anode materials for sodium-ion and lithium-ion batteries using garlic peel as a precursor (Fig. 9d). The synthesized materials were mesoporous with a specific surface area of 178 m² g⁻¹. Transmission electron microscopy and field emission scanning electron microscopy analyses revealed interconnected micropores and voids. The N-doped carbon quantum dots demonstrated excellent rates and steady-state performances for sodium and lithium-ion exchange. Different current densities, e.g., 0.5, 1.0, 2.0, and 4.0 Ag⁻¹, resulted in discharge capacities of about 142, 89, 58, and 37 mAh g⁻¹ in CR2032-type sodium-ion batteries. At different current densities of 1.0, 2.0, 4.0, and 8.0 Ag⁻¹, Li-ion batteries delivered reversible capacities of 320, 280, 215, and 145 mAh g⁻¹. Due to the nitrogen content within the matrix and mesopores of the carbon quantum dots combined with their large surface area, N-doped carbon quantum dots exhibit high electrochemical performance (Selvamani et al. 2016). Compared to graphene quantum dots, biomass carbon quantum dots use renewable biomass resources and are therefore more environmentally friendly. However, in contrast, graphene quantum dots typically have higher specific energy density and electrical conductivity, so they have greater potential for high energy density energy storage and high power applications (Yuvaraj et al. 2020). Future research and development can continue to explore the advantages and strengths of both materials to further promote the development of the energy storage battery field through reasonable combinations or combined applications.

Energy storage supercapacitors

The development of clean energy sources for sustainable development is urgent. As a potential energy storage device utilizing carbon electrodes, ultracapacitors, or supercapacitors, are considered highly efficient. Using natural waste to synthesize carbon quantum dots to prepare supercapacitors with high electrochemical performance has attracted increasing interest from researchers (Saikia et al. 2020).

Sahoo et al. (2018) synthesized carbon quantum dots using lemon juice as a carbon source and doped them with nickel sulphide to enhance the supercapacitor performance. The pure capacitive properties of the bilayer capacitance measurement were obtained by recording cyclic voltammetry at various scan rates in the bilayer region. NiS pristine shows a greater capacitive current density than composite in the capacitive region. Subsequent impedance measurements at different applied potentials (0.16, 0.46, 0.56 and 0 V) show that the NiS/carbon quantum dot composite (at 456 Ω, 0 V) has a lower charge transfer resistance compared to the pristine form of NiS (690 Ω, 0 V) and that the reduction in charge transfer resistance is due to increased charge transfer through the introduction of highly conductive carbon quantum dots. These results suggest that adding carbon quantum dots to the NiS base improves the charge transfer process and thus enhances the performance of the supercapacitor (Sahoo et al. 2018).

Oskueyan et al. (2020) used carrot juice as a biomass carbon source and prepared carbon quantum dots by hydrothermal method, followed by polyaniline-carbon quantum dots by in situ polymerization. The electrochemical properties of polyaniline with different carbon dot contents were investigated and polyaniline nanocomposites with a carbon dot content of 10 wt% were selected to be mixed with polypyrrole-graphene to prepare high-potential window supercapacitors. The polyaniline-(10%) carrot-derived carbon dot/polypyrrole-graphene nanocomposite exhibited the best electrochemical performance with a maximum specific capacitance of 396 F g⁻¹ at 1 A g⁻¹. This nanocomposite has a current density of 5 A g⁻¹. The specific capacitance can still reach 62% of the initial capacitance and retain 65% of the specific capacitance after 1000 cycles. This work provides a new class of bifunctional nanocomposites for supercapacitors. In short, the study not only utilizes natural materials to produce supercapacitor electrodes with low material cost but also combines conducting polymers with biomass carbon for supercapacitor applications, demonstrating the potential application of biomass waste carbon quantum dots in energy storage devices (Oskueyan et al. 2020).

Renewable energy

Hydrogen has been considered a possible energy carrier for storing renewable energy. Hydrogen is gaining attention as a clean energy source. Carbon quantum dots have been extensively studied for their ability to produce hydrogen. Carbon quantum dots derived from biomass have also received much attention in the photocatalytic hydrogen production field. As the common photocatalyst for hydrogen precipitation reactions, TiO₂ has a wide forbidden band, making it difficult to separate electrons from holes generated during the reaction. Additionally, it requires precious metals such as Pt,

Au, and Ag as co-catalysts. Recent research has increasingly focused on developing nonmetallic photocatalysts with low cost and high efficiency. Typically, photocatalytic systems in organic solvents or purified water rely on toxic and non-scalable photocatalysts to perform catalysis.

Achilleos et al. (2020) used lignin waste to yield carbon quantum dots by heating α -cellulose, xylan and lignin at 320, 250 and 300 °C, respectively. The α -cellulose derived carbon quantum dots light absorbers were prepared, where the one derived from α -cellulose was the most photoactive. The photocatalytic properties of the materials in pure water and untreated seawater were analysed. The hydrogen yields in river water and seawater were greater than those in pure water. It is speculated that untreated seawater contains a

mixture of organic chemicals that can act as sacrificial electron donors. While untreated river water is rich in pesticides and herbicides, prostryn and terbutryn can burst photogenerated cavities. Based on nickel co-catalysts and biomass-derived carbon quantum dots, a photocatalytic system for hydrogen production was developed, and the system could also be used for pollutant oxidation without requiring external electron donors (Achilleos et al. 2020).

Wang et al. designed an efficient and stable photoelectrochemical (PEC) device using carbon quantum dot-sensitized TiO_2 as the photoanode, glucose solution as the electrolyte, and Pt/carbon nanofibers (CNFs) as a cost-effective counter electrode for hydrogen production, and a typical three-electrode structure was used for PEC hydrogen production,

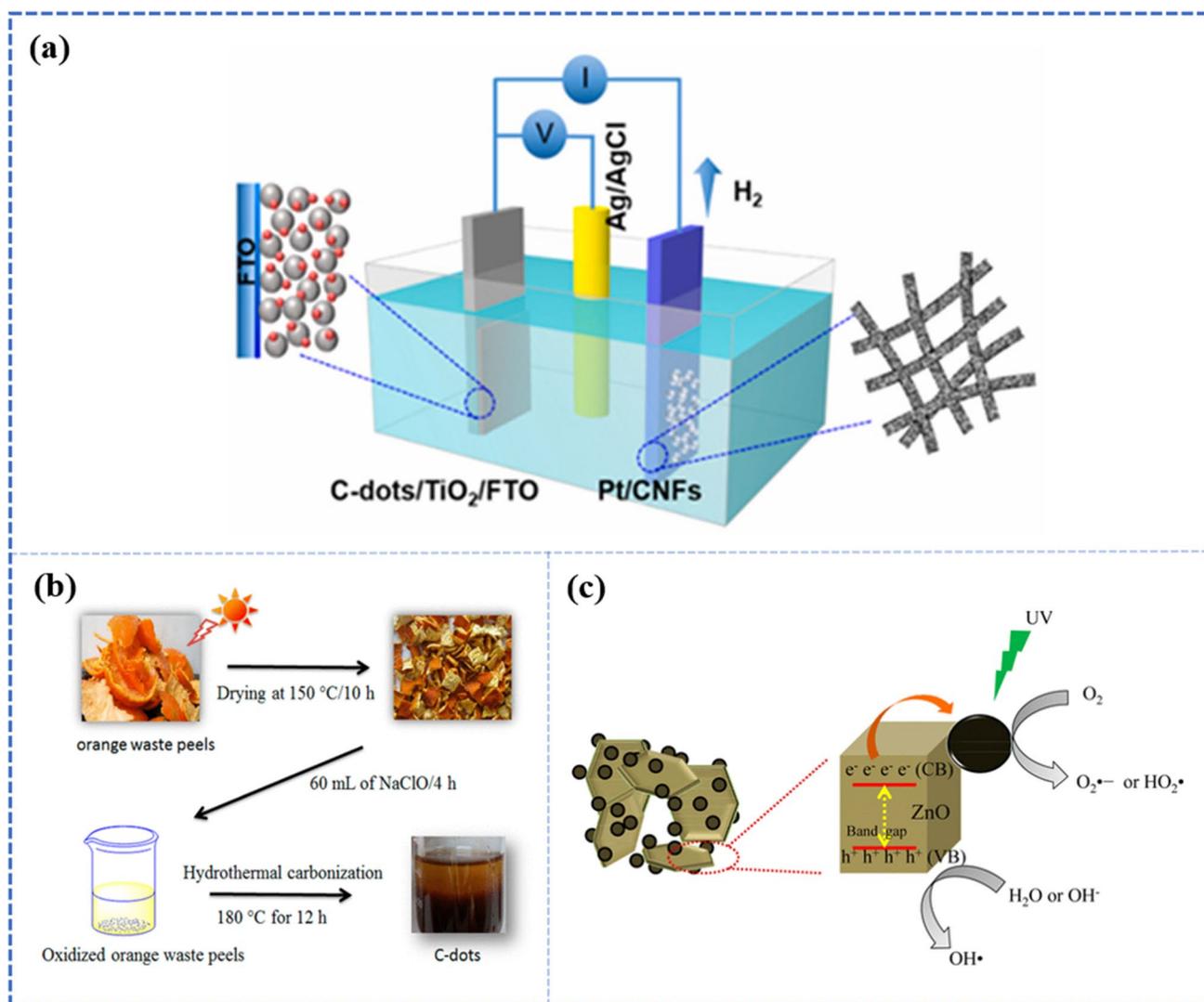


Fig.10 a A typical photoelectrochemical (PEC) device using C-dots/ TiO_2 as anode, Pt/carbon nanofibers (CNFs) as counter electrode, Ag/AgCl as reference electrode, and glucose aqueous solution as electrolyte. Reproduced with permission from Wang et al. (2021). **b** For-

mation of C-dots from the hydrothermal treatment of orange waste peels. Reproduced with permission from Prasannan et al. **c** The photocatalytic process on C-dots/ZnO. Reproduced with permission from Prasannan et al. (2013)

as shown in Fig. 10a. The red carbon quantum dots scattered on the surface of TiO₂ can absorb light energy in the visible range and convert it into electrical energy, and the photoanode of this structure can improve the photoelectric conversion efficiency and stability of the PEC device (Wang et al. 2021).

Biomass is a valuable long-term energy source, especially for hydrogen production. Biomass waste is widely available and inexpensive, and biomass to hydrogen has many advantages over photochemical or thermochemical methods. However, biomass carbon quantum dots have several limitations for photochemical hydrogen generation applications. Because the light absorption range of biomass carbon quantum dots is often confined to the visible spectrum, they can only form electron–hole pairs using visible light and not UV or IR light. Furthermore, while the photoelectric conversion efficiency of biomass carbon quantum dots has improved, it is still lower than that of other conventional semiconductor materials, such as titanium dioxide. Because biomass carbon quantum dots have a higher photoelectric conversion efficiency and catalytic aptitude for electrochemical reactions, they are typically used as photoanodes rather than photocathodes, which may limit their application in photochemical hydrogen production. Despite the fact that there has been limited research on biomass carbon quantum dots as photocathodes, they have been discovered to be potentially interesting for use in photochemical reactions. Future research can go more into their mechanism and performance in photocatalytic reactions, as well as explore a broader spectrum of applications.

Environment-related applications

Pollutant sensing

Water pollution has become a worldwide issue due to the serious threat that metal ions released by anthropogenic activities pose to human health and the environment (Sharma et al. 2021). Pollution emissions from the steel, plastics and battery manufacturing industries and heavy metal ions such as iron, copper and lead ions discharged with wastewater can accumulate in algae and substrates, even in small concentrations, and are adsorbed by the body surfaces of fish and shellfish, creating a food chain concentration and thus causing a public hazard. Therefore, metal ion detection becomes a defence for human safety and environmental safety (Liu et al. 2022a). For example, Cu²⁺ is required for important physiological functions. However, excess Cu²⁺ in the human body carries the risk of inducing disease. Li et al. (2019c) made a biosensor for detecting Cu²⁺ by synthesizing nitrogen-doped carbon quantum dots from lignocellulosic waste. The resulting carbon quantum dots demonstrated a long lifetime, excellent photoluminescence stability, and

pH-dependent characteristics towards Cu²⁺ with a maximum excitation and emission wavelength of 350 and 465.5 nm, respectively. The obtained N-doped carbon quantum dot was further used as a fluorescent probe. Since the Cu²⁺ response to the N-chelating group on its surface affinity and the metal–ligand binding kinetics of the fluorescent probe are particularly high, the probe was successfully applied to detect Cu²⁺ in real water. Some functional groups on the surface of the carbon quantum dots will specifically bind to metal ions and thus produce a fluorescence burst (Li et al. 2019c); this leads to highly sensitive and selective detection of the target. Other researchers have conducted extensive studies on the detection of heavy metal ions such as Fe³⁺ (Lee et al. 2014, Sahoo et al. 2020), Hg²⁺ (Li et al. 2019b), Cr³⁺ (Shen et al. 2017, Singh et al. 2019, Wang et al. 2020b), and Cu²⁺ (Shi et al. 2016) using biomass carbon quantum dots as ion probes.

In another study, carbon quantum dots highly stable over a wide pH range (5–11) and excellent selectivity for Hg²⁺ were hydrothermally prepared (Guo et al. 2016). It is worth mentioning that Shi et al. (2016) found a gap in the burst mechanism of carbon quantum dots between the fluorescence lifetime in the presence and absence of Hg²⁺, implying the existence of a dynamic burst process (Shi et al. 2016). The performance of biomass carbon quantum dots and other fluorescent probes in detecting Hg²⁺ is shown in Table 2. Compared with the traditional metal ion detection methods, the biomass carbon quantum dot fluorescent probes showed advantages in terms of environmental friendliness, low energy consumption in the synthesis process, and detectable range and minimum detection limit.

In addition to detecting heavy metal ions, carbon quantum dots for detecting Fe³⁺ was fabricated by a solvothermal method using lychee peel as the raw material. Various process factors that impact the sensing system, such as reaction time, pH, and salt concentration were optimized, and the best detection conditions were at pH 7 (Sahoo et al.). The fluorescent quantum dot yield of 28% and the yield of 6.06% reported are higher than those in the literature for onion waste carbon quantum dots used for detecting Fe³⁺ (Lee et al. 2014). The mechanism of Fe³⁺ burst fluorescence may be related to the transfer of electrons in the excited state in carbon quantum dots to Fe³⁺, resulting in a non-radiative electron/hole complex of excited state electrons, which exhibits a fluorescence burst effect (Wu et al. 2019). Subsequent fluorescence lifetime tests showed that the burst of Fe³⁺ on the carbon quantum dots was dynamic, further confirming this speculation. The detection of other common metal ions is shown in Table 2.

Table 2 Common metal ion detection

| Biomass carbon source | Preparation method | Testing scope (μM) | Detection limit | References |
|----------------------------------|-------------------------|---------------------------------|---------------------|--------------------------|
| Hg²⁺ detection | | | | |
| Flour | Microwave | 0.0005–0.01 | 0.5 nM | Qin et al. (2013) |
| Hair | Hydrothermal | 0–75 | 8 nM | Guo et al. (2016) |
| Jinhua Bergamot | Hydrothermal | 0.01–80 | 5.5 nM | Yu et al. (2015) |
| Pigeon feathers | Pyrolytic carbonization | 0–1 | 8.3 nM | Ye et al. (2017) |
| Fe³⁺ detection | | | | |
| Bauhinia | Microwave | 40–350 | 0.01 μM | Huang et al. (2018) |
| Onion | Hydrothermal | 0–20 | 0.31 μM | Bandi et al. (2016a) |
| Grass | Hydrothermal | 0–25 | 1.4 μM | Krishnaiah et al. (2022) |
| Cassava stalks | Hydrothermal | 15.6–62.5 | 0.91 μM | Qiu et al. (2022) |
| Cr⁶⁺ detection | | | | |
| Citrus Peel | Hydrothermal | 1–50 | 0.1 μM | Wang et al. (2020b) |
| Grapefruit | Hydrothermal | 1–40 | 0.52 μM | Shen et al. (2017) |
| Algae | Hydrothermal | 0–25 | 0.018 μM | Singh et al. (2019) |
| Shallots | Hydrothermal | 20–80 | 3.5 μM | Sakaew et al. (2020) |

Catalytic degradation of environmental pollutants

Biomass-derived carbon quantum dots can detect small organic molecules or biomolecules in addition to metal ions. Chlorophenoxyacid herbicides are widely used for crop weed control, but due to their chemical stability, resistance to biodegradation, and good water solubility, these compounds can easily enter groundwater or be washed into surface water. Due to their potential mutagenicity and toxicity, they are considered harmful to human health and are therefore listed as priority pollutants by the U.S. Environmental Protection Agency (EPA) (Sannino et al. 2015). Pesticide residues may enter the environment through farmland, water bodies, and the atmosphere, posing potential risks to ecosystems and environmental health. Detection of pesticide residues can assess the potential impact of pesticide use on the environment and help develop rational pesticide use strategies and environmental protection measures. Although the sensitivity of traditional gas chromatography and electrochemical detection of pesticide residues is high, these methods are expensive and complicated to operate, plus the unknown harm to the human body. Fluorescent carbon quantum dots are being noticed for their excellent biocompatibility, fluorescence stability, and ease of handling (Tao et al. 2022a). Methomyl is a carbamate insecticide that is widely used to treat agricultural crops. It is highly soluble in water and therefore has a high potential to contaminate ecosystems. Researchers have devised a new method to determine the concentration of methomyl in grain. The method uses green deep eutectic solvent (DES) to extract methomyl, which is subsequently analysed using an enzyme-inhibited fluorescence enhancement method. The presence of methomyl was

successfully detected using biomass CQDs synthesized from grain as a precursor as a fluorescent probe (Guo et al. 2022).

In addition to pesticide residues, biomass carbon quantum dots can also be used for other environmental pollutants. phenanthrene (Liu et al.) is one of the 16 polycyclic aromatic hydrocarbons (PAHs) listed as major pollutants by the U.S. Environmental Protection Agency (EPA), a known human skin photosensitizer and mild allergen, and is considered a toxic and carcinogenic substance that may have adverse effects on human health (Sannino et al. 2014). Tetracyclines are a widely used class of antibiotics that are used in human, animal and agricultural production; however, their use also leads to the presence and spread of tetracyclines in the environment. The presence of tetracyclines in the environment can negatively affect water bodies and soil ecosystems, leading to eutrophication of water bodies and soil contamination. Biomass-derived carbon quantum dots was fabricated using carp seeds and tobacco leaves to detect tetracycline under different detection limits of 0.0041 μM and 0.52 μM (Liang et al. 2022b; Qi et al. 2019). Besides, the biomass carbon quantum dots have been able to achieve the detection of the drug Huang Cen (Tang et al. 2022a), uric acid (Zhao et al. 2018), and mercaptans (Lu et al. 2018) fluorescence sensing of small organic molecules. The superior biocompatibility and chemical durability of biomass carbon quantum dots, in comparison to semiconductor quantum dots, make them highly suitable for utilization as analytical sensors.

The contamination of wastewater with toxic dyes is a critical environmental issue that has detrimental effects on health and sustainable development. Particularly, the widespread use of carcinogenic dyes such as methylene blue, methyl orange, and naphthol azo at both domestic and industrial levels has resulted in insufficient drinking

water sources and ecological complications. As a response to this problem, researchers have developed an advanced technology for degrading toxic dyes, known as photocatalytic treatment of dye-contaminated wastewater using biomass carbon quantum dots. This method offers numerous advantages, including low cost, non-toxicity, rapid reaction time, simplified procedure, and easy post-treatment steps. As a result, it presents an efficient, safe, clean, and cost-effective solution to the issue of wastewater dyeing (Han et al. 2019). A study conducted by Prasanna et al. (2013) examined the ability of biomass-derived carbon quantum dots to catalyse the degradation of organic pollutants in water using orange peel as a raw material. The researchers successfully prepared carbon quantum dots using a hydrothermal method using orange peel as a precursor, and the preparation process is shown in Fig. 10b. They compounded synthetic biomass-derived carbon quantum dots with ZnO as photocatalysts for UV degradation of blue-black naphthol azo dyes (Prasanna et al. 2013). The photocatalytic process is shown in Fig. 10c. The blue-black naphthol azo dye was almost completely degraded after 45 min of irradiation, while the degradation rate was only 84.3% with ZnO alone under similar irradiation time. By accepting or transporting electrons of oxygen-containing functional groups in the photocatalytic material, the charge generated by photoexcitation may flow more rapidly, which enhances the catalytic activity. A biomass-derived carbon quantum dot made from lemon peel was synthesized with TiO₂ nanofibres for methylene blue photocatalytic degradation. The photocatalytic activity of the composite was 2.5 times higher than the pure TiO₂ nanofibre degradation (Tyagi et al. 2016). The following mechanism could explain this. Firstly, the UV light induces excitons (hole-electron pairs) on TiO₂ nanofibres, transferring electrons to the biomass-derived carbon quantum dots surface. Secondly, the electrons on the biomass-derived carbon quantum dots surface react with oxygen to form O²⁻ and holes react with water to form hydroxyl radicals, OH⁻, and other intermediates to degrade methylene blue molecule. The larger surface area of biomass-derived carbon quantum dots also facilitates the adsorption of methylene blue on the photocatalyst surface, subsequently enhancing the photocatalytic activity.

In the realm of environmental pollutant degradation, biomass carbon quantum dots have the benefits of environmental friendliness, low toxicity, excellent photocatalytic activity, diverse functionalization alterations, and regenerability. As a result, biomass carbon quantum dots are a promising novel nanomaterial for the treatment and prevention of environmental pollution. Despite the potential applications of biomass carbon quantum dots in the field of environmental pollutant degradation, some restrictions remain. For example, after using biomass carbon quantum dots to composite with other materials, when treating environmental

pollutants, due to the limited visible light absorption capacity of biomass carbon quantum dots and the usually small particle size and surface area of biomass carbon quantum dots, the degradation efficiency is low compared to other new composite materials, for example, by preparing molybdenum disulphide nanostructures on tourmaline and using its unique properties such as spontaneous polarization and far-infrared radiation, it can achieve more efficient photocatalytic removal of organic pollutants. This is due to the excellent assembly flexibility of the material, which can provide more active sites in the structure (Hao et al. 2021).

Medicine-related Applications

Drug delivery

Biomass-derived carbon quantum dots can also act as drug carriers and functioning as a theragnostic agent. Under their biocompatibility, biomass-derived carbon quantum dots can be used as a safer drug delivery medium that can be modified; hence biomass-derived carbon quantum dots show promising applications in disease therapy with the properties of low biological toxicity, good fluorescence stability, excellent biocompatibility, and large specific surface area. Because of their small size, they can be used as carriers for biological and small molecule drugs in the biological environment via endocytosis for cell membrane transport, allowing for more creative approaches to nanomedicine. To date, carbon quantum dots can deliver and act on four types of functional molecules: general antibiotics, which can be linked to carbon quantum dots to increase cytotoxicity; photosensitizers, which can be bound to carbon quantum dots to increase the efficacy of photodynamic therapy; antifungal drugs, in which carbon quantum dots can deliver antifungal drugs to the exact site of infection in order to precisely detect and kill the fungus; and antiviral drugs and vaccines, which enhance protection against viral infections by binding to carbon quantum dots (Wang et al. 2022b).

Lenopril is a common antihypertensive drug; however, due to its narrow absorption range, only 25% of the drug is absorbed by the intestine, so it is necessary to develop an effective drug delivery medium to delay the release of lenopril in vivo. John et al. (2020) prepared wheat bran-carbon quantum dots via a hydrothermal method that can be used to deliver antimicrobial drugs and mixed with amoxicillin trihydrate solution to prepare a novel drug delivery system, namely carbon quantum dot-amoxicillin (CD-AMX). To examine the optimal drug release rate of CD-AMX as a drug delivery system, the researchers measured the drug release rate in phosphate-buffered saline of different pH, and the results showed that the CD-AMX adjuvant exhibited the maximum drug release rate under acidic conditions. It

indicates that the prepared CD-AMX adducts are pH-sensitive drug delivery systems (John et al. 2020).

Shao et al. (2020) used carbon quantum dots to load the anticancer drug lycopodium and determined the cytotoxicity of HepG2 cells after incubation in lycopodium-biomass-derived carbon quantum dots solution and lycopodium solution using the 3-[4,5-dimethylthiazol-2-yl]-2,5 diphenyl tetrazolium bromide method (Shao et al. 2020). There was no dose-dependent effect of lithophane-biomass-derived carbon quantum dots solution and lithophane-biomass-derived carbon quantum dots solution on LX-2 cells (normal human cells), while the mortality of HepG2 incubated in lithophane-biomass-derived carbon quantum dots solution was significantly increased, indicating better antitumor properties of lithophane-biomass-derived carbon quantum dots. Lycopodium is loaded on carbon quantum dots through hydrogen bonds formed between functional groups on the surface of the carbon quantum dots (Kayal and Ramanujan 2010). Subsequent endocytosis allows faster uptake into cancer cells, producing better anticancer activity. For the first time, green luminescent carbon quantum dots with carboxyl-rich surfaces can be used as trackable drug delivery agents for local cancer treatment in mouse models (Jaleel and Pramod 2018). The carboxyl groups of carbon quantum dots can form a pH-sensitive linkage with doxorubicin via amino groups. When the carbon quantum dots–drug linkages break in the tumour microenvironment, tumour-specific drug release occurs. Anticancer studies *in vivo* and *in vitro* revealed that the cytotoxic effects are derived from anticancer drugs rather than bioimaging agents or vectors. During delivery into the nucleus, the carbon quantum dots in the cytoplasm fluoresced as the doxorubicin was released from hollow carbon quantum dots in a pH-controlled manner (Fig. 11c).

Finally, carbon quantum dots derived from biomass waste can significantly impact drug delivery, providing fewer side effects and smarter therapeutic approaches to cancer treatment. However, carbon quantum dots face some challenges as nano-drug delivery vehicles. More attention from researchers and more research examples are required to validate and develop them for antifungal and antiviral applications. Many carbon quantum dots have short emission wavelengths unsuitable for *in vivo* signal tracking, so there is an urgent need to develop more red light-emitting or even near-infrared carbon quantum dots for antimicrobial applications (Wang et al. 2022b).

Biosensing

In recent years, the development of various nanomaterial-based biosensors has presented new functionalities. In particular, zero-dimensional nanostructures are very attractive in many biosensing applications (Brindha et al. 2018; Iravani

and Varma 2020). Zero-dimensional nanostructures of carbon quantum dots with less than 8 nm size have good excitation wavelength-dependent photoluminescence properties with good optical stability, electrical conductivity, and surface area. Carbon quantum dot biosensors based on biomass waste as precursors have been rapidly developed and are expected to become an important field shortly (Thangaraj et al. 2019). Biosensor devices consist of three major parts (Fig. 11a). (i) a detector, which recognizes the stimulus, (ii) a signal transducer, which converts the stimulus to output, and (iii) a reader device, which amplifies and displays the output in an understandable format. As an analytical device, a biosensor converts a biological response into an electrical signal. In medicine, the use of biosensors is receiving momentum where it can detect tumours, DNA, and elevated blood glucose levels accurately and precisely (Mokhtar et al. 2022).

Molecular recognition of specific molecules by functional carbon quantum dots can discriminate cancer cells from normal cells. Folic acid was used to functionalize carbon quantum dots to target cancer cells as a nanoprobe. A high affinity between the folic acid portion of the nanoprobe and cancer cells receptor (e.g., HeLa cells) may explain its working mechanism. Cancer cells could be successfully identified using these specificities (Feng and Qian 2018). A gold nanoparticle is a class of precious metal nanomaterials with a wide range of applications. A similar principle was adopted for the ultra-sensitive detection of HIV. In the experiment (Fig. 11b), the carbon quantum dots with the ssDNA probe were attached to the surface fluorescence resonance energy transfer with the gold nanoparticle, resulting in a burst of fluorescence. When the target ssDNA is added, the gold nanoparticle is separated from the probe ssDNA, the gold nanoparticle is then exposed, and the fluorescence is restored (Qaddare and Salimi 2017).

The sensors described above are just a few of the many applications for biomass carbon points. Efficient sensors can improve the physical and environmental lives of people. More precise detection methods can detect problems earlier and more easily, resulting in more efficient solutions. As a result, this will have a greater positive impact on the economy, life, and the environment.

Bioimaging

As mentioned above, biomass waste carbon quantum dots have many advantages over semiconductor or ordinary carbon quantum dots, including non-inferior fluorescence intensity and fluorescence stability, a wide source of inexpensive raw materials, and excellent biocompatibility for bioimaging.

Sahoo et al. (2020) used lychee peel as a carbon source to produce carbon quantum dots by a solvothermal method

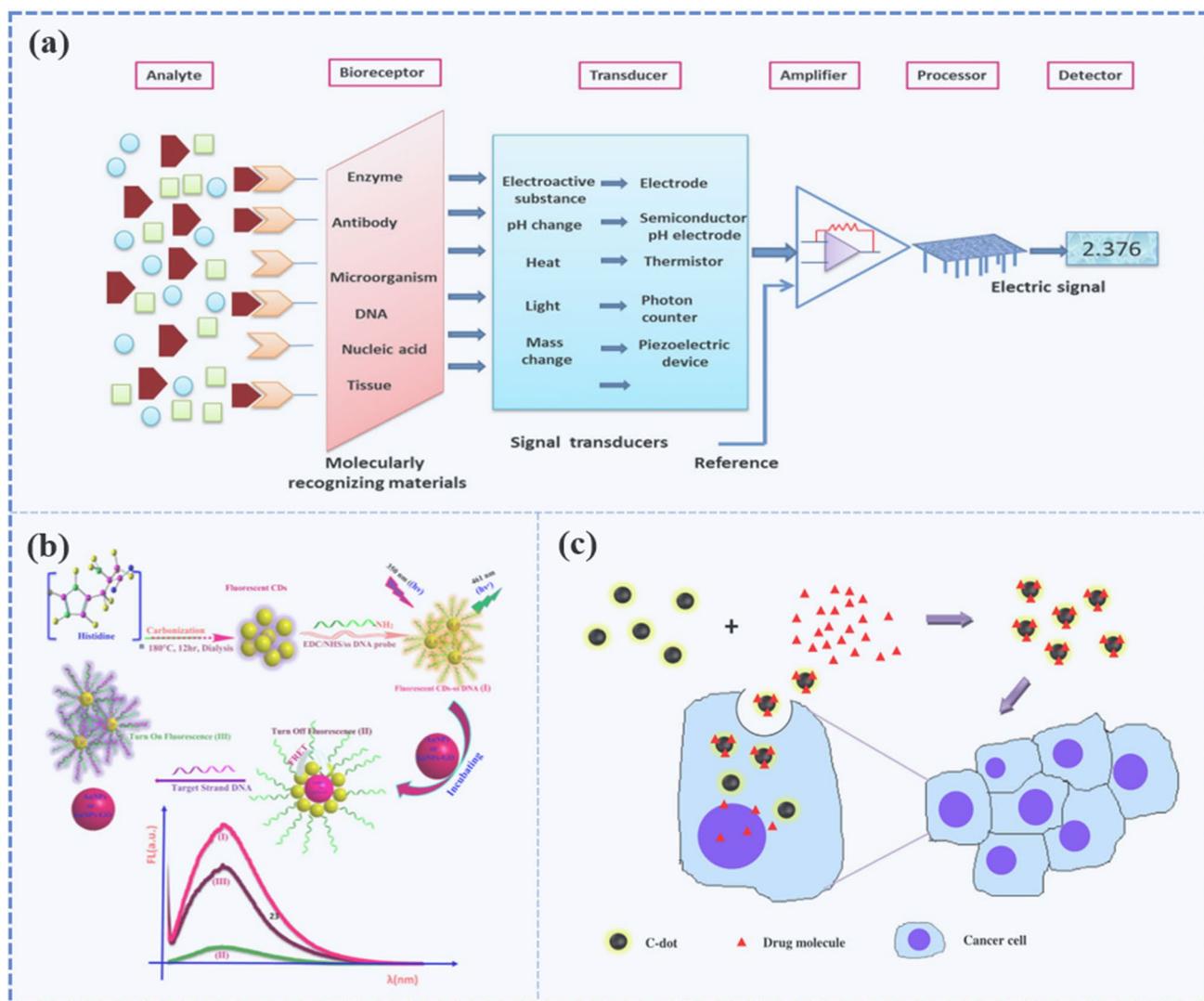


Fig.11 a A biosensor device. Reproduced with permission from Thangaraj et al. (2019); **b** The mechanism for the FRET-based detection system: in the first part, the fluorescence of DNA-carbon quantum dots was quenched by gold nanoparticle/gold nanoparticle-graphene oxide through FRET; and then the fluorescence of carbon quantum dot was recovered in the presence of target DNA. Repro-

duced with permission from Qaddare and Salimi (2017); **c** Drug-loaded carbon quantum dots, releasing the 4-Substituted-2,5-dimethoxyamphetamines into the nucleus and emitting the fluorescence in the cytoplasm. Reproduced with permission from Jaleel and Pramod (2018)

and evaluated their potential use in cellular imaging of A375 cells. First, the killing effect on A375 cells was explored by the MTT method. A375 cells were subjected to an MTT assay in the presence of carbon quantum dots. The results showed that the cell survival rate of A375 exceeded 89% despite the addition of large concentrations of carbon quantum dots. The researchers then used A375 cells to explore multicolour cell imaging by ingesting microscopic images of A375 (Fig. 12b). Various wavelengths of 405, 488, and 543 nm were used for 12 h to photograph A375 cells in the bright field. The fluorescence intensity was reduced by adding different concentrations of Fe^{3+} , including 1.6 μM (b series) and 22 μM (c series). Therefore, the researchers

propose that the carbon quantum dots made from lychee peel as a carbon source can be applied in multicolour cell imaging in the presence and absence of Fe^{3+} ions (Sahoo et al.).

Biological cells emit autofluorescence mainly blue and green, which produces certain background interference when the fluorescence of carbon quantum dots emits short wavelengths of blue light, so controlling the colour of the light emitted by carbon quantum dots has become an urgent problem. Carbon quantum dots depend on excitation light wavelength, thus allowing to observe red and green fluorescence imaging in HepG2 cells by varying the wavelength of excitation light (Fig. 12d) (Xue et al. 2016).

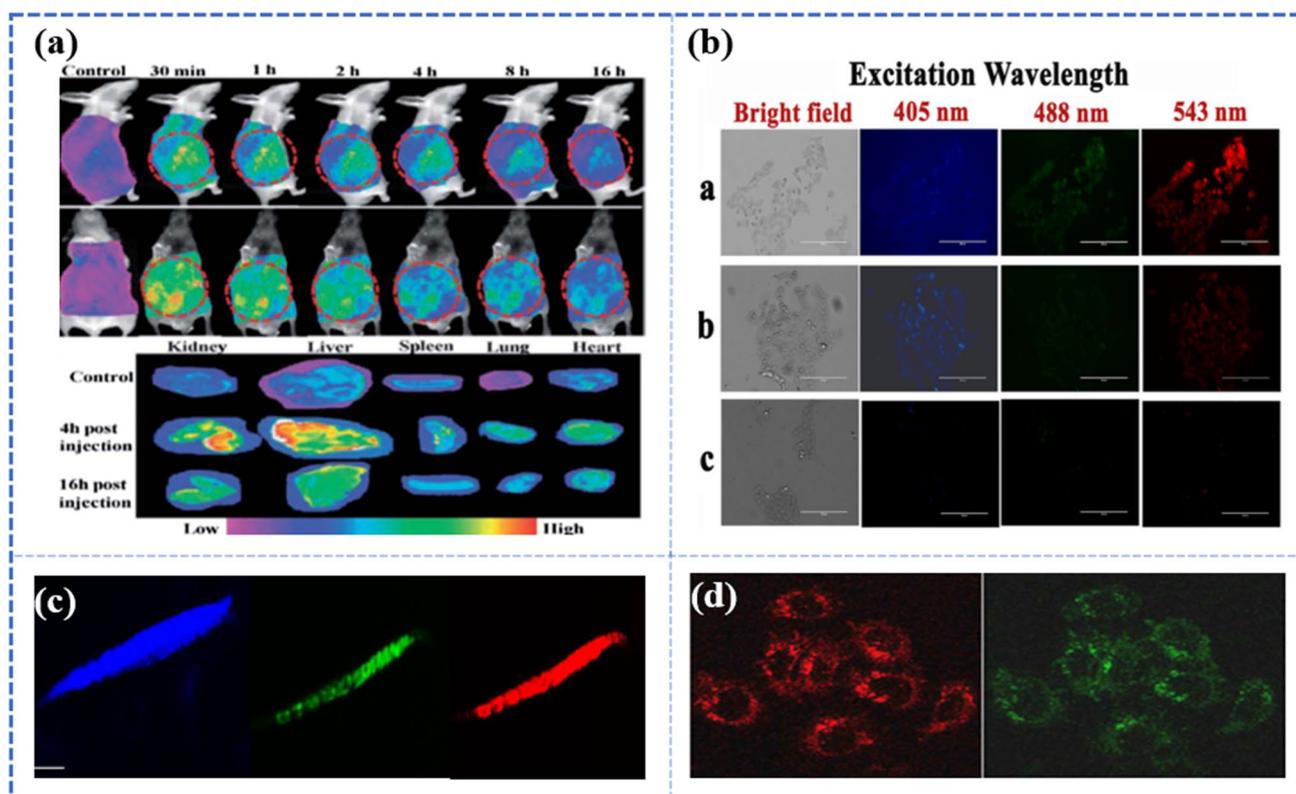


Fig. 12 **a** Lateral and frontal views of mice after intravenous injection of graphene quantum dots and ex vivo images of anatomical organs. Reproduced with permission from Khatun et al. (2015); **b** Microscopic cell images of A375 cells at the bright field, 405 nm, 488 nm, 543 nm. Reproduced with permission from Sahoo et al. (xxx); **c**

Imaging of HeLa cells under different filters. Reproduced with permission from Atchudan et al. (2019); **d** Multicolour imaging of nematode hatching in an in vivo model of carbon quantum dots at different excitation wavelengths. Reproduced with permission from Atchudan et al. (2021)

The prepared fluorescent carbon nanodots were used for in vivo imaging (Khatun et al. 2015). The nanoparticles were injected into mice by intravenous injection. As shown in Fig. 12a, fluorescence emission was visible throughout the body of the mice 30 min after injection. The fluorescence intensity was maintained for about 8 h and then decreased slowly. After 16 h, the fluorescence intensity became very faint. The imaging results clearly show the accumulation of nanoparticles in the liver, kidney, and spleen 4 h after exposure. Faint signals were also detected in the heart and lungs. The accumulation level decreased significantly 16 h after exposure (Luo et al. 2014). Atchudan et al. (2021) used banana peel waste to yield carbon quantum dots with good biocompatibility and fluorescence stability, which showed great potential for cell imaging. The carbon quantum dots were internalized into nematodes (Fig. 12c) and labelled the cell membrane and the whole body of the nematode, emitting blue, green, and red fluorescence at 400, 470, and 550 nm excitation, respectively (Atchudan et al. 2021).

A close relationship exists between the properties and the applications of carbon quantum dots, and therefore an in-depth understanding of their properties and structural

relationships is required for the effective use of carbon quantum dots in biology and biomedicine. The carbon quantum dots surface are often modified and functionalized to enhance their targeting selectivity. Nevertheless, some molecules in the biological environment may interact with the functional groups on carbon quantum dots which would have led to mis-signalling. Thus, the surface functional groups must be carefully selected to fit the specific applications of carbon quantum dots. Moreover, because carbon quantum dots have difficulty entering the nucleus, most studies on the cytotoxicity of carbon quantum dots have focused on the cytoplasmic level. It may not be possible to replicate the environment complexity accurately in humans using commonly used animal models for in vivo toxicity. Hence, there is a need to perform toxicity studies on primates to reveal their potential clinical translational value.

Potential applications of carbon quantum dots

Human body imaging

Biomass waste-derived carbon quantum dots are increasingly being studied for intracellular imaging in plants and *in vivo* imaging in animals, but their application in humans is still lacking. It is currently difficult to image many parts of the human body because the human tissues absorb or scatter light before it can be detected. Therefore, advanced studies on long-term bioimaging are needed to improve intracellular photostability in deep tissue imaging by tuning biomass-derived carbon quantum dots and better fluorescence imaging detection methods and techniques. There is a need for more research and closer collaboration between engineers and natural scientists to advance the application of fluorescence imaging techniques in bioimaging. Due to advances in this technology, it may be possible to treat cancer and other diseases through photodynamic and photothermal therapies. It would be beneficial if further research were conducted into the potential applications of biomass-derived carbon quantum dots as sensors, such as in radiation prevention, global security, utility safety, and early disease detection. A study of point selectivity is necessary to improve the sensing properties of carbon quantum dots derived from biomass (Wareing et al. 2021).

Electrocatalysis

A final research area that needs more attention is electrocatalysis. In addition to their use as photocatalysts, BCDs can improve the oxygen reduction reaction in fuel cells (Sharifi et al. 2012). The slow reaction kinetics of ORR has limited the cell field, and the costly and toxic platinum-based catalysts currently used have prompted researchers to look for greener, cheaper catalysts. Han et al. (2019) have synthesized a nitrogen-doped layered porous composite (BMNC) consisting of carbon quantum dots and carbon flakes using a solvothermal method with carbonization at 900 °C, chemical activation, and nitrogen doping at 650 °C (Han et al. 2019). The catalytic activity of BMNC under an alkaline environment was investigated by linear scanning voltammetry. The onset potential of BMNC was 0.91 V, which was only 90 mV lower than commercial platinum on carbon. It was shown that BMNC electrocatalytic performance for oxygen reduction reaction was as good as commercial platinum-based electrocatalysts with the same half-wave potential and limiting current. By utilizing biomass feedstock in the electrocatalytic direction, one can provide an idea of the possibility of utilizing biomass feedstock in the electrocatalytic direction, providing an opportunity for biomass feedstock to be used in a high-value application (Kaur et al. 2021).

Although biomass carbon quantum dots have many advantages and potential applications in electrocatalysis, there are some practical limitations, and the catalytic activity of biomass carbon quantum dots in electrocatalytic reactions is limited when compared to traditional metal-based catalysts. Cobalt-based catalysts, for example, have strong catalytic activity and low catalytic reaction conditions needs (Piao et al. 2020). They also have a long lifespan and are commonly used. Metal-based catalysts, on the other hand, have several drawbacks, such as higher cost and toxicity. To get better economic and environmental benefits, it is vital to ensure that the efficiency of catalysts outweighs their shortcomings in real applications (Wang et al. 2021). And, while the preparation methods of biomass carbon quantum dots still have certain complexity and low yield problems, they also require additional research and improvement, but with the continuous progress and optimization of technology, the application prospects of biomass carbon quantum dots in the field of catalysts are still broad, and can be improved through synthetic methods, surface modification, nanostructure design, and other means to improve its performance and overcome these challenges.

Perspective

Although biomass waste carbon quantum dots with excellent optical properties, low biotoxicity, and good biocompatibility have been widely studied and applied in energy, medicine, environment, and other fields, it still needs further investigation and development. At present, the limitations can be summarized as the follows.

Many studies have discussed the luminescence mechanism of carbon quantum dots, namely delocalized π -structure band transitions (Dai et al. 2022), quantum confinement effects (Zhu et al. 2015), and hole recombination behaviour (Lim et al. 2015); there are still great controversies. The various precursors, synthesis methods, and complex surface functional groups of biomass waste carbon quantum dots pose great challenges to the mechanistic study. Recent studies report that the luminescence of carbon quantum dots is not caused by one single mechanism (Wang et al. 2022a; Yu et al. 2021). Therefore, the detection and characterization methods for carbon quantum dots needs to be further improved to a deeper understanding of the skeleton and functional groups of these dots. In the light of this, a comprehensive understanding of the luminescence mechanism can be gained, and this will provide a solid foundation for basic research and practical applications of carbon quantum dots in the future.

The emission and excitation light of carbon quantum dots from biomass waste are mainly in the UV-visible range. However, the damage caused by UV light to DNA

and protein cannot be ignored, and visible emission light not only cannot penetrate the deep biological tissue for imaging but also interferes with the autofluorescence of the cells (Iravani and Varma 2020; Miao et al. 2018). This greatly limits their application in *in vivo* imaging.

Due to the superior biocompatibility of biomass-derived carbon quantum dots, many studies have applied them in the medical field, but research on their long-term effects on the human body and the ecological environment is still very limited. Biomass-derived carbon quantum dots significantly affect cancer cell targeted therapy under experimental conditions, but the short-term contact toxicity to the human body, the immune system rejection, and transcriptomic alteration effects are unknown. Further observations are needed to document the short and long-term impacts of biomass-derived carbon quantum dots on organisms such as animals, plants, and algae. Moreover, additional works are required to understand the biodegradability of biomass-derived carbon quantum dots in different environments and comprehensively evaluate the application prospects of biomass-derived carbon quantum dots in different ecosystems.

Hitherto, although the practical application of carbon quantum dots still has a long way to go, with the rapid development of carbon quantum dots in the field of materials science, the practical application of carbon quantum dots will be possible. We provide important guidelines for this promising area:

1. Being not yet available for large-scale commercial application means the performance and cost of carbon quantum dots needs to be further improved. For instance, the quantum yield of biomass waste carbon quantum dots is lower than that of commercial semiconductor. It is necessary to broaden the research scope further to the precursor selection of other high quantum yield biomass waste and to optimize experiment parameter. Moreover, the collection, transport, and storage of biomass waste need to be better planned to reduce costs.
2. Biomass carbon quantum dots face some practical limitations in electrocatalytic reactions due to their narrow light absorption range, and their research is relatively scarce when it comes to applications in photoanodes, compared to photocathodes. This restricts their potential applications in the field of photocatalytic hydrogen production. However, studies have already revealed their promising potential in photochemical reactions. Future research can further explore their mechanisms and performance in photocatalytic reactions, as well as explore a wider range of applications.
3. Although bioderived carbon quantum dots have many advantages and potential applications in electrocatalytic reactions, there are practical limitations in their actual use. Therefore, future research should continue

to explore how to overcome the limitations of bioderived carbon quantum dots in catalytic activity and focus on developing alternative materials with higher catalytic activity and lower cost. This will lead to better economic and environmental benefits and promote the widespread adoption of catalysts in practical applications.

Conclusion

As a natural renewable resource, biomass materials have a broad application prospect. With the current energy crisis becoming increasingly severe, biomass can be converted into chemicals or energy, especially biomass waste, which can effectively alleviate energy issues. This paper reviews synthesis methods, main factors affecting the performance of carbon quantum dots, the properties of biomass waste-derived carbon quantum dots, and their utilization in energy, medicine, and the environment. We systematically discussed the effects of different synthesis methods on the properties of biomass waste-derived carbon quantum dots, in which the type of biomass waste precursor, synthesis time, and temperature are the core parameters. Biomass carbon quantum dots are important for environmental applications. They play a significant role in the detection of heavy metal ions and the catalytic degradation of environmental pollutants. In addition, they provide an efficient, safe, clean and cost-effective method to treat dye-contaminated wastewater. Although their optical and electronic properties are still not thoroughly understood, there is no doubt that biomass waste carbon quantum dots with the low toxicity, fluorescence stability, and ease of functionalization properties will play a huge role in the fields of *in vivo* imaging, catalysis, sensing, and anticounterfeiting in the future.

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