



CRITICAL REVIEW

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Recent advancements towards the green synthesis of carbon quantum dots as an innovative and eco-friendly solution for metal ion sensing and monitoring

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In recent years, the synthesis of carbon quantum dots (CQDs) through green methods for environmental remediation has gained significant interest owing to their benefits of reducing toxic by-products and minimising the usage of hazardous chemicals. CQDs are a new type of zero-dimensional carbon nanomaterials having a size less than 10 nm. They have attracted much attention considering their outstanding optical characteristics, non-toxicity, low-cost synthesis, biocompatibility, uniform particle size, high photostability and highly tuneable photoluminescence. The synthesis of CQDs from biodegradable and renewable resources, such as biowastes and biomass, provides an eco-friendly and sustainable alternative to conventional synthesis methods. The synthesized CQDs possess unique optical and electronic properties, including a high selectivity and sensitivity, making them promising for metal ion sensing. This review highlights the recent progress in the green synthesis of CQDs, including their synthesis methods, optical properties and potential use in sensing applications for the detection of heavy metal ions, such as iron(III), copper(II), mercury(II), chromium(VI), lead(II), silver(I), arsenic(III) and gold(III), which are considered as major environmental pollutants. A comparison based on the quantum yield, sensitivity, selectivity, detection limit, linear range concentration and sensing mechanisms is also presented. In addition, the effect of heteroatom doping on CQD performance for heavy metal detection is also discussed. In conclusion, this review emphasizes the importance of employing eco-friendly and sustainable methodologies for CQD synthesis, which not only benefits the environment but also makes these materials more accessible and cost-effective for widespread use in detecting harmful pollutants.

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Sustainability spotlight

In an era of increasing environmental concerns and growing awareness towards sustainable synthesis, resource efficiency, waste reduction and minimal environmental impacts have become guiding principles in both the industry and laboratory. These principles guide researchers and industries in developing processes that make use of renewable resources. Researchers are currently exploring novel materials obtained from natural sources, such as plant biomass and agricultural residues, with the aim to replace petrochemical-based precursors. In this review paper, we have covered the green synthesis of carbon quantum dots (CQDs) using natural precursors, focusing on their vital role in the domain of heavy metal ion sensing and monitoring in water, harmonizing scientific progress with ecological responsibility.

Introduction

Carbon-based nano-materials, such as graphene, diamonds, carbon tubes and fullerenes, have attracted much attention from researchers owing to their extraordinary properties. The poor water solubility and weak fluorescence in the visible region limit the application of graphene and fullerenes. Furthermore, the synthesis and separation of nano-diamonds are challenging, thus hindering their applications.¹ Hence, the

scientific community explore design and synthesize of new materials that can replace graphene, fullerenes or nano-diamonds, and fluorescent carbon dots are one of these materials. Fluorescent carbon dots include carbon quantum dots (CQDs), carbon nanodots (CNDs) and graphene quantum dots (GQDs).² The appearance of CQDs was first ironically noticed by Xu *et al.* in 2004 during the purification of single-walled carbon nanotubes synthesised by an arc-discharge method.³ CQDs are mono-dispersed quasi-spherical shaped crystalline nano-materials having a size of <10 nm, exhibiting good water solubility, unique optical properties and highly tuneable photoluminescence (PL). CQDs with a surface as large as 60 nm have also been reported.⁴ Furthermore, their surface can be easily

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modified without altering their native characteristics. CQDs primarily consist of an amorphous sp^2/sp^3 -conjugated carbonogenic core with various oxygen/nitrogen-containing groups, such as hydroxyl, carboxyl and amine, on their surface. The composition ratio of surface groups often varies with the carbon precursor used and synthesis routes employed for their synthesis. The presence of surface functional groups on CQDs increases their water solubility, thus providing a greater range of possible applications, mainly in photoelectronic, analytical and biomedical fields.⁵ The doping of CQDs with hetero atoms, such as nitrogen, phosphorus and sulphur, can further enhance their properties to a great extent.⁶ It has been established that traditional transition metal quantum dots, such as cadmium telluride (CdTe), cadmium sulfide (CdS) and cadmium selenide (CdSe), show better optical characteristics and stability than CQDs. However their costly fabrication and low biocompatibility limit their utility in biomedicines, specifically in therapeutic applications.⁷ CQDs however show superior

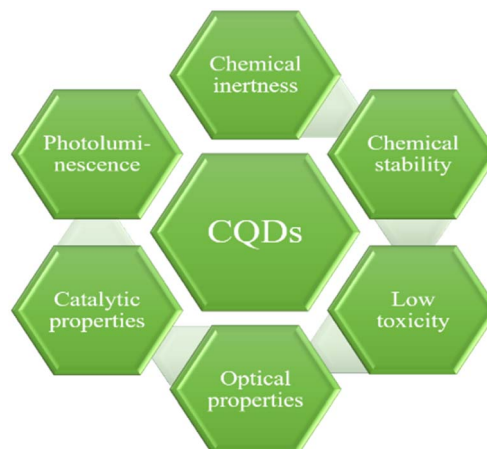


Fig. 1 Properties of CQDs.

biocompatibility, chemical stability, excellent aqueous solubility, high quantum yield (QY), and less toxicity and can be easily synthesised by eco-friendly methods. Such unique properties of CQDs make them more relevant than semiconductor quantum dots (SQDs) and organic dyes for practical applications. Such applications include sensing of metal ions, drug delivery, electrocatalysis, and photocatalysis.⁸ Various properties of CQDs are demonstrated in Fig. 1.⁹

Many efforts have been made for developing new, simple, cost-effective and efficient techniques for CQD fabrication with emphasis on non-toxic and environmentally friendly approaches. Biomass has emerged as a sustainable and non-toxic route for the synthesis of highly stable CQDs. Biomass is a large, complex, heterogeneous and biodegradable substance that can be obtained from a variety of sources such as animal



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waste, plant parts, algal waste, human sewage and industrial by-products.¹⁰ The main constituents of biomass include hydrogen, carbon, and oxygen, with trace amounts of hetero atoms such as sulphur, nitrogen, phosphorus, and heavy metals ions.¹¹ Numerous chemical reactions are feasible at biomass due to the presence of various functional groups on the chemical compounds present within them. Nanomaterials derived from biomass shows excellent biocompatibility, nontoxicity, and good water solubility. Even though the formulation of CQDs from natural bio-sources has its own set of obstacles, it is popular due to a number of benefits including pollution-free nature, sustainability, low cost and green preparation processes.¹² Such CQDs have the potential to be used in various applications. Heavy metal ion sensing is one of the most studied applications of these CQDs due to their high QY, low toxicity and good photo stability. CQDs show a strong fluorescence intensity even at very low concentrations. Excellent photostability confirms fluorescence signal stability and thus assuring accurate detection results.¹³ CQD-based sensors have shown the selective and sensitive detection of various anions, metal ions and other organic moieties depending on the affinity of different surface groups present on their surface. The limitations of CQDs include their post functionalization, complex purification and separation procedures and structural characterization with respect to their geometries, composition, and crystal shape. Such issues must be addressed before their application in biosensing, nanomedicine and bioimaging.¹⁴ The present review is thus focused on the progress in the field of CQDs with special emphasis on eco-friendly synthesis by hydrothermal, microwave-assisted and carbonisation methods. This also includes the recent development for their utilization as fluorescent probes for selective detection of different metal ions. Their importance in biomedical, pharmaceutical, and environmental fields is also included.

Synthesis method

Due to the active contribution of several research groups, many simple and cost-effective routes have been developed in order to get the CQDs of desired functionality, size and structure, for specific applications. The synthetic methods of CQDs have been divided into two approaches: "Top-down and Bottom-up". The top-down process involves the synthesis of the CQDs from macroscopic graphite-like structures by breaking them down into nano range either by physical or chemical methods. Several top-down synthesis approaches have been reported and classified into main five categories: (a) chemical oxidation;^{15–18} (b) laser ablation;¹⁹ (c) arc-discharge;³ (d) electrochemical oxidation^{20–22} and (e) ultrasonic synthesis.²³ Mono-disperse CQDs with precisely defined molecular structures and sizes are produced using these methods; however, such processes require costly precursors, complex instrumental set-ups and sophisticated facility. Furthermore, the "bottom-up" approach does not require sophisticated techniques and costly precursors, and produces CQDs from cheaper precursors using simple experimental set-ups. This approach involves the synthesis of CQDs using molecular precursors such as carbohydrates, citrate

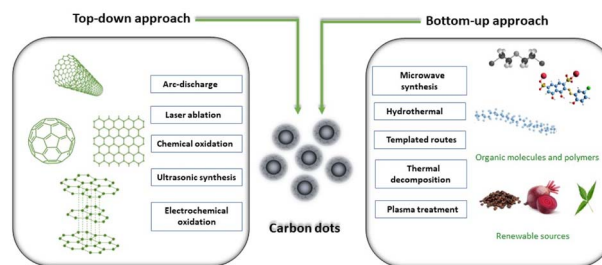


Fig. 2 Synthesis methods of CQDs and their classification.

and polymer-silica nano-composites by either microwave irradiation,²⁴ thermal decomposition,²⁵ hydrothermal treatment,²⁶ template based routes²⁷ or plasma treatment.²⁸ The first step in the bottom-up process is to select suitable carbon precursors, which directly influence the characteristics of the resulting CQDs. The second step involves the carbonisation of the selected carbon precursor followed by purification in order to remove impurities that might form during the carbonisation process. This type of CQD synthesis process involves assembling carbon atoms or molecules through chemical processes to form nanoscale carbon structures. Molecules having sufficient functional groups such as hydroxyl/carboxyl are suitable to be used as carbon precursors for this process. A schematic representation of various routes employed for CQD synthesis is summarized in Fig. 2.

The green approaches for the synthesis of CQDs have attracted the attention of scientific community due to their non-venerable nature. Such approach requires a green material as the carbon source for the synthesis of CQDs. The raw materials as well as methods used for the synthesis of CQDs strongly affect the properties including the size, crystallinity, functional groups, colloidal stability, fluorescence properties, QY and compatibility. In the subsequent sections, some representative methods for the green synthesis of CQDs from green carbon precursors are discussed. Mostly hydrothermal, microwave synthesis and carbonisation methods were reported for the fabrication of CQDs using a green carbon source as the raw material. The detailed description of each method is also given.

Microwave synthesis of CQDs

Microwave pyrolysis is considered as one of the best bottom-up techniques for the synthesis of CQDs. It involves breaking off the chemical bonds with the help of high energy microwave radiations.²⁹ This process requires less time and provides homogeneous heating, resulting in the formation of uniformly sized CQDs. Zhu *et al.* first reported the synthesis of stable luminescence CQDs using microwave.³⁰ For CQD synthesis, various concentrations of saccharide and polyethylene glycol (PEG-200) were mixed with distilled water to obtain homogeneous solutions. The solutions obtained were then heated in a 500 W microwave oven for 2–10 minutes. A change in solution colour from yellow to dark brown indicates the formation of CQDs. Liu *et al.* have reported the microwave-assisted fabrication of nitrogen-doped carbon quantum dots (N-CQDs) and



CQDs by utilising tomato as the raw carbon source. Nitrogen doping was done with “N” sources such as ethylenediamine and urea. This process generally led to the formation of CQDs along with larger C-nano/-micro particles, which could be removed by centrifugation at a higher speed (rpm) followed by dialysis of the supernatant liquid through a membrane. The solid powder of nanoparticles (NPs) was then obtained by lyophilization.³¹ These CQDs were used for the bioimaging of plant pathogenic fungi and the detection of vanillin. A waste cotton linter as the carbon source has been used by Hasan *et al.* for the synthesis of water-dispersed fluorescent CQDs in a very short time *via* a microwave-assisted hydrothermal process. The average particle size of the synthesised CQDs was found to be 10.14 nm.²⁴ This method is economic and easier than the others reported in the literature; further, the formed CQDs have been used for cancer-imaging applications. In order to check the effectiveness of CQDs in cell imaging, two different concentrations ($50 \mu\text{L mL}^{-1}$ and $100 \mu\text{L mL}^{-1}$) of the CQD colloidal solution were applied to a human mesothelioma cell line and human umbilical vein endothelial cells for different durations. However, it was found that the cotton-linter-derived CQDs were cytotoxic to cancer cells and lower their viability, while being cytotoxic to healthy human cells also at the same concentration. Various studies in the literature reported the anti-cancer properties of CQDs, and these properties are largely attributed to the synthesis protocol and carbon precursors used for their synthesis. Lotus root (LR) has also been used as a carbon material for the synthesis of fluorescent N-CQDs showing a high QY of 19%. The CQDs were spherical in shape and their average size was found to be 9.41 nm, as revealed by TEM analysis. These CQDs have been employed for selective mercuric ion (Hg^{2+}) detection and the limit of detection (LOD) was found to be 18.7 nM. The selectivity of LR-CQDs towards Hg^{2+} ions is due to the stronger affinity and quicker chelating kinetics of Hg^{2+} towards hydroxyl, carboxyl and amino groups present on the CQD surface than those of other metal ions. Additionally, the $\text{Hg}^{2+}/\text{Hg}^+$ redox potential is located between the conduction band and the valence band of LR-CQDs, which results in photoinduced electron transfer from the conduction band to the complex states of Hg^{2+} causing quenching of fluorescence intensity. The UV-vis absorption spectra of LR-CDs and LR-CQDs- Hg^{2+} were reported in order to further understand the binding between LR-CDs and Hg^{2+} ions. LR-CQDs show an absorption peak at 280 nm; however, by the addition of Hg^{2+} ions to the LR-CQD solution, the absorption peak significantly diminished, showing the binding of LR-CQDs and Hg^{2+} ions.³² Zaman *et al.* used fruit bunch biochar for the synthesis of CQDs by a microwave-assisted method. This method gives fluorescent CQDs within few minutes, which have carboxylic, hydroxyl and carbonyl groups at the surface, responsible for their good aqueous solubility. These CQDs were found suitable for the detection of Cu^{2+} ions in their concentration range of 0–400 μM . The plausible reason for fluorescence emission quenching of CQDs in the presence of Cu^{2+} ions is the interaction of CQD surface functional groups with Cu^{2+} ions. The significant fluorescence quenching effect of Cu^{2+} is due to the quick electron transfer between Cu^{2+} ions and oxygen-rich groups on the

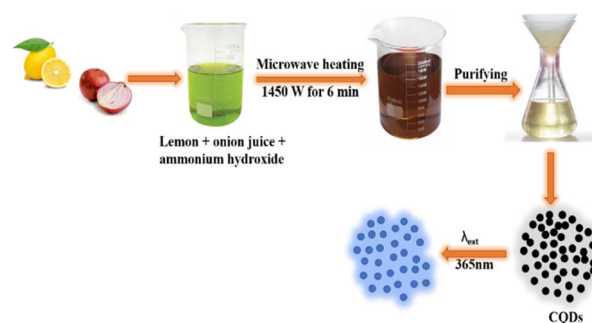


Fig. 3 Synthesis procedure of highly fluorescent CQDs from lemon and onion juices under microwave irradiation.³⁵

surface of CQD. These oxygen functional groups on CQD surfaces not only render the water-soluble property, but also exhibit strong interaction with metal ions. The high selectivity of CQDs for Cu^{2+} ions can be explained *via* strong coordination between hydroxyl functional groups on the surface of CQD and Cu^{2+} ions. This interaction enables the transfer of electrons in the excited state of CQDs to the empty 3d orbitals of Cu^{2+} ions, facilitating nonradiative electron/hole recombination that results in a significant reduction in fluorescence intensity.³³ Raw cashew gum has been utilized as the carbon source for aqueous phase synthesis of CQDs in 30–40 min using 800 W microwave radiations. The large particles were then separated by centrifugation. Freeze-drying of the filtrate resulted in a pale brown solid having an average particle size of 9 nm, as revealed by a TEM study.³⁴ Fluorescent CQDs have been synthesised using lemon and onion juice as carbon precursors (Fig. 3). The size of CQDs was found to be 6.15 nm, which were used for the determination of riboflavin in mineral/multivitamin supplements.³⁵

Hydrothermal synthesis

A hydrothermal technique has been widely used for the synthesis of CQDs using saccharides, organic acids, juices and waste peels. CQDs synthesized by the hydrothermal carbonization process are highly efficient, less expensive, non-toxic, and environmentally friendly with uniform size distribution.³⁶ The hydrothermal approach involves the heating of the precursor solution (made either in organic solvents or in water) in a hydrothermal reactor having a Teflon tube. At a relatively high temperature and pressure, the organic molecules combined together, resulting in the formation of carbon-seeding cores which further transform into CQDs.²¹ Zhu *et al.* synthesized CQDs having very a high QY (about 80%) using a hydrothermal technique.³⁷ Khan *et al.* used red lentils as the precursor for the synthesis of N-CQDs by a hydrothermal method. The prepared N-CQDs have a QY of 13.2% and exhibit bright blue fluorescence under UV light at an excitation wavelength of 365 nm. These N-CQDs have been used as nano probe sensors for the detection of Fe^{3+} in solutions.³⁸ Broccoli juice was used for the hydrothermal synthesis of CQDs at 190 °C (Fig. 4). These CQDs showed selective sensing of Ag^+ ions in aqueous solutions.³⁹



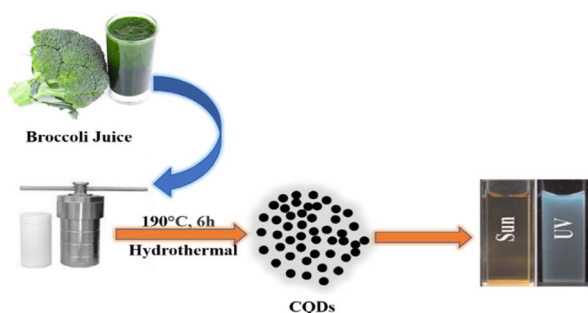


Fig. 4 Synthesis of CQDs from broccoli juice via a hydrothermal process.³⁹



Fig. 5 A schematic illustration of the synthesis of water-soluble fluorescent CQDs from watermelon peels.⁴⁶

Lu *et al.* reported the synthesis of CQDs *via* a hydrothermal route using pomelo peels as the carbon precursor at 200 °C. The resulting solutions were centrifuged to remove unreacted moieties, and the particle size was found to be 2–4 nm. These fluorescence CQDs have a QY of 6.9% and are used for sensing Hg^{2+} ions taken from a lake water sample.⁴⁰ Furthermore, banana peel waste has also been utilized as a green source for the synthesis of CQDs *via* a hydrothermal route. Unreacted organic moieties were removed *via* filtration through a mixed cellulose ester membrane. These CQDs have a QY of 20% with an average particle size of 5 nm and appeared bright blue when excited with 365 nm wavelength light. The CQDs have been used for bioimaging in nematodes due to their excellent fluorescence stability and biocompatibility.²⁶ Yang and co-workers synthesized amino-functionalized fluorescent CQDs by hydrothermal treatment of a chitosan material.⁴¹ Yu *et al.* reported the synthesis of N-CQDs with a QY of 21.9% from *Osmanthus fragrans* *via* a hydrothermal route. These N-CQDs were employed as fluorescent nano-sensors for Al^{3+} ions.⁴² Mehta *et al.* reported the synthesis of blue fluorescent CQDs having a uniform size of ~3.0 nm using sugar cane juice as the source of carbon. The mixture of sugar cane juice and ethanol was heated at 120 °C till a dark brown solution was obtained. Yadav group has reported the synthesis of CQDs using neem as the carbon source. The fluorescence CQDs have a QY of 27.2% and showed peroxidase-like activity towards the oxidation of peroxidase substrate 3,3',5,5'-tetramethylbenzidine with hydrogen peroxide.⁴³ Zhang group reported corncob residues (CRs) as carbon precursors for the synthesis of CQDs. Two types of N-CQDs were synthesized using CRs obtained after hemicelluloses pre-extraction and from enzymatically hydrolysed corncob residues (EHCRs). The main components found in CRs are cellulose and lignin, whereas the main component of EHCRs is lignin. The larger particles were removed using a cylindrical filtration membrane filter. Dialysis of the solution was carried out in distilled water using a semi-permeable membrane for 2 days. The final solution was subjected to lyophilization to obtain N-CQDs/E-N-CQDs. These CQDs (average size 9.31 nm) showed adsorption at 270–280 nm, which attributed to the π - π^* transition. The E-N-CQDs showed higher fluorescence than that of N-CQDs and are used for the selective detection of Fe^{3+} in blood with an LOD value of $0.75 \mu\text{mol L}^{-1}$. The higher fluorescence of E-N-CQDs than that of N-CQDs is due to the presence of a larger

number of aromatic rings associated with the precursor lignin.⁴⁴

Carbonization method

Carbonization is the process of heating materials in the presence/absence of air. The process requires high temperatures. Several green sources have been utilized for the synthesis of CQDs *via* the carbonization process. Highly fluorescent water-dispersible CQDs were prepared by low-temperature carbonization under a nitrogen flow using walnut shells as the carbon precursor. The average particle size was found to be 3.4 nm, as revealed by TEM. These CQDs have been used as bioimaging agents for intracellular trafficking.⁴⁵ Watermelon peels, a waste raw resource, were used to prepare CQDs *via* carbonization (Fig. 5). The carbonization process was carried out in air for 2 h at 220 °C and CQDs were obtained by sonication, filtration and centrifugation to remove larger particles. The supernatant liquid having CQDs was dialyzed against distilled water for 48 h to obtain amorphous, blue luminescent spherical shaped, and water-soluble CQDs with an average particle size of 2 nm. These CQDs were efficiently used for live cell imaging, indicating that these carbon NPs can serve as high-performance optical imaging probes.⁴⁶ Sun *et al.* described a one-step method for the large-scale synthesis of nitrogen and sulphur-co-doped CQDs (S-N-CQDs) with sulphuric acid carbonization of hair fibers at different temperatures including 40, 100, and 140 °C for 24 hours. The high reaction temperature favoured the formation of high-sulphur content S-N-CQDs of smaller size, which have longer wavelengths of PL emissions. These S-N-CQDs showed good biocompatibility, luminescence stability, low toxicity and high solubility.⁴⁷

Highly fluorescent CQDs have been synthesized by Murugan group using finger millet ragi as the carbon source by a carbonization process at 300 °C. These CQDs have been used as nano sensors for the detection of Cu^{2+} ions in real water samples with an LOD value of 10 nM.⁴⁸ Furthermore, fluorescent CQDs having a QY of 19.3% have been synthesized using sweet pepper as the source of carbon. These CQDs have been synthesized *via* a two-step process. The first step involves the low-temperature carbonization of pepper at 180 °C for 5 h and the second step involves the separation of the product. These CQDs have been used as fluorescent probes for hypochlorite



detection in tap water. The LOD value for hypochlorite has been found to be in the order of 0.05 mmol L^{-1} .⁴⁹

Optical properties of CQDs/ photoluminescence (PL) emissions in CQDs

The absorption of CQDs mainly occurs in the UV region with a tail extending into the visible region. The absorption in the UV region is attributed to the $\pi \rightarrow \pi^*$ transition of aromatic C=C and the $n \rightarrow \pi^*$ transition due to various oxygen- and nitrogen-containing groups present on the CQD surface. For example, CQD synthesis from *Lantana camara* berries shows two peaks in the UV region: one at 285 nm attributed to the $\pi \rightarrow \pi^*$ transitions of C=C and the other peak at 356 nm attributed to the $n \rightarrow \pi^*$ transition (Fig. 6). The aqueous CQD solution shows a pale yellow colour under day light and illuminates bright blue colour under UV light.⁵⁰

Fluorescence is one of the most studied properties of CQDs from both practical application and fundamental study point of view. Although the fluorescence of CQDs has attracted huge attention, the exact mechanism of fluorescence in CQDs is still a topic of discussion. Various theoretical mechanisms have been proposed for the occurrence of PL in CQDs, which lack experimental evidence. It has been suggested that the PL in such CQDs might have different excitation, which results in dependent emission, probably due to their wide size range, distinct surface defects/states, availability of different surface groups or varying degree of π -conjugation. The PL phenomenon in CQDs arises either due to their size or due to surface defects.⁵¹ Size-dependent PL emission in CQDs is one of the most fascinating properties of these materials.⁵² Smaller size of quantum dots results in a larger band gap and *vice versa*.⁵³ The synthetic procedure has a significant effect on the PL of CQDs as it controls the size and defects.⁵⁴ Kang and co-workers synthesized CQDs having blue, green, yellow, and orange emissions respectively under similar energies of excitation, which attributed to their size difference. These CQDs were treated with H_2 to

remove surface oxygen species; however, no significant change in the PL spectra was observed. Hence, it could be concluded that oxygen molecules present either on the CQD surface or in solutions are not responsible for luminescence, rather it is due to their smaller size.⁵⁵ The red shift in the emission wavelength of CQDs with the increase in size was reported by Mohapatra *et al.*⁵⁶ Nevertheless, various surface defects on the surface of CQDs can also govern the PL, which is due to the presence of various functional groups rather than their size. Thus, the PL of CQDs is affected by the size as well as the presence of surface defects. It has also been reported that the PL of CQDs might also be controlled by functional groups in a synergistic manner.³⁷ Bao *et al.* reported the synthesis of CQDs of varying sizes by an electrochemical method using carbon fibres at different potentials. It has been observed as the sizes of CQDs decreased, the emission peak shifted to a lower energy state at identical excitation wavelengths. This phenomenon is not in accordance with the "Quantum-Confinement Effect". The smaller sized CQDs were formed at higher potentials and are more oxidized, hence they bear more oxygen-containing groups on the surface. Therefore, the red shift in the emission spectra of CQDs is due to the change in surface states rather than the size effect. Similarly, the acid-treated CQDs did not show observable PL properties until their surface has been modified by amine-containing polymers. The presence of surface energy traps that become emissive upon stabilisation as a result of surface passivation may explain the PL from CQDs. A study conducted by Sun and his co-workers reported the synthesis of CQDs by laser ablation of a carbon target in the presence of water vapor with argon used as a carrier. According to electron microscopy investigations, the as-produced samples have abundance of nanoscale carbon particles arranged in clusters of varying sizes. However, no detectable PL was observed from either sample or its aqueous suspension. The sample was then further treated with a 2.6 M aqueous nitric acid solution, but still there is no significant PL. Bright luminescence emissions were found after surface passivation by attaching simple organic molecules to acid-treated carbon particles. Various organic molecules including poly(propionylethylene-imine-co-ethyleneimine) and diamine-terminated oligomeric poly(ethylene glycol) could serve as surface passivating agents. After passivation with organic moieties, the CQDs show strong PL in both solid state and solution-like suspension. The resulting emission covers a wide range of visible wavelengths that also extended into near-infrared wavelength ranges. It seems that CQDs require surface passivation to exhibit PL, and the widely accepted mechanism for the explanation of luminescence emission in CQDs is radiative recombination of excitons.¹⁹ The CQD sample with similar sizes but different degrees of surface oxidation have been reported and found to show emission from 440 to 625 nm. The plausible red shift can be explained in terms of decrease in band-gap due to the increase in the number of oxygen-containing functional groups on the CQD surfaces.⁵⁷ Deng *et al.* reported excitation wavelength-independent fluorescence emission of the CQDs, having a size range between 4 and 10 nm and identical surface-branched polyethyleneimine. The difference in the fluorescence emission is mainly attributed to the

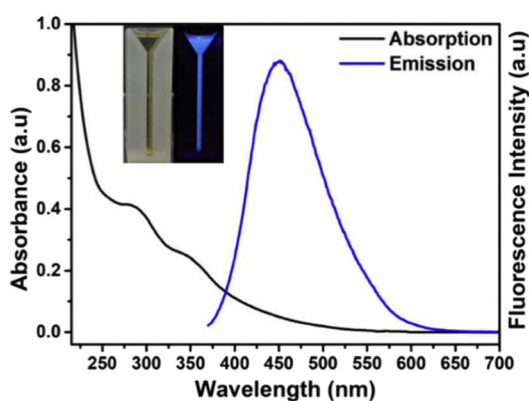


Fig. 6 UV-vis spectra of CQDs synthesized from *Lantana camara* berries. Reproduced from ref. 50 with permission by Elsevier, copyright 2023.



size of CQDs.⁵⁸ Giannelis and co-workers carried out temperature-controlled carbonisation using ethanolamine and citric acid at different temperatures for the synthesis of CQDs. The CQDs having a high QY of 50% were obtained at low temperatures and PL is mainly due to the presence of amide-containing organic fluorophores. At a higher temperature, pyrolysis results in the formation of spherical shaped particles with an average diameter of 19 nm and their QY has been decreased to 15%. The decrease in the QY is due to the fact that the pyrolysis at higher temperatures results in the utilization of organic fluorophores for the formation of carbogenic cores.⁵⁹ Recent studies have reported a new and intriguing phenomenon of fluorescence known as up-conversion fluorescence emission. It is defined as the longer excitation wavelength produces the shorter emission wavelength. Absorbing numerous infrared photons and releasing one visible photon is a typical example of this type of fluorescence. Three components have been reported to contribute to up-conversion fluorescence; (a) photon avalanche, (b) excited-state absorption and (c) energy transfer up-conversion. The measure of the excitation intensity-dependence fluorescence is a conventional method in order to differentiate up-conversion fluorescence from regular originated fluorescence.⁶⁰ The up-conversion PL of N-CQDs in the wavelength range of 750–960 nm has been reported by Sutiman.⁶¹ Lin showed that the CQDs emitted strong up-conversion fluorescence with an excitation wavelength of 800 nm, which is due to two-photon excitation.⁶² The up-conversion fluorescence can be easily observed with naked eyes.⁶³

Mechanisms of heavy metal detection using CQD-based sensors

Although several theories have been outlined to describe the mechanism of metal ion sensing by CQDs, the exact mechanism is still a subject of debate among the scientific community.⁶⁴ Some basic sensing mechanisms include fluorescence resonance energy transfer (FRET), coordination-induced aggregation, inner filter effect (IFE), FL quenching, photo-induced electron transfer (PET) and ion binding/aggregation. The optical absorption properties of CQDs are mainly responsible for their use in designing optical sensors for heavy metal detection. The optical absorption properties occur from the photo-excitation of charge carriers in CQDs and the subsequent transfer of electrons from the valence band to the conduction band. The generated electron-hole species are then used for metal ion sensing based on the particular interactions between metal ions and the surface functional groups of CQDs.⁶⁵ Most of the CQD-based sensors work on the principle of either quenching or attenuation of the CQD fluorescence emission in the presence of the analyte, which might be some other species or a metal ion itself.⁶⁶ The CQDs show maximum fluorescence in aqueous solutions, but due to the presence of a quencher in the solution, the fluorescence emission intensity gets diminished. The fluorescence emission of the CQDs has been reported to depend on the functional groups present on the

surface. The oxygen moieties or other functional group present on the CQD surface selectively coordinate with heavy metal ions causing a change in fluorophore properties such as anisotropy, fluorescence intensity and lifetime. This results in a signal than can indicate analytes with high sensitivity and selectively as a result of quantum confinement. Such changes might be attributed to the energy transfer between the probes and metal ions *via* selective interactions. All these features such as edge structures, surface functionalities, size and morphology of CQDs have an impact on selectivity.⁵¹ Some of the metal ion sensing mechanisms are given below.

Complex formation

One of the most accepted mechanisms for the detection of metal ions using CQDs is complex formation. FTIR spectroscopy is widely used for the detection of various oxygen-containing functional groups such as -COOH , -OR , C=O , and -OH on the CQD surface. Further, surface modification can also be done by doping with hetero atoms such as phosphorus, nitrogen and sulphur to add other groups such as -CN , -NO_2 , -NH_2 , $\text{-SO}_3\text{H}$ and -SH on the surface.⁶⁴ It is reported that the metal ion sensing property of CQDs gets enhanced by doping with electronegative atoms. These groups form a coordination complex with metal ions by donating their lone pair of electrons. For example, the Au^+ ion sensing has been carried out using CQDs synthesized from peach gum and jackfruit seeds. The presence of nitrogen donor functional groups on the CQD surface is responsible for their sensing properties, as revealed by spectroscopic measurements. The solution of CQDs showed a change in colour from light blue to dark blue under UV-light after the addition of Au^+ ions, and the LOD value was found to be $0.064\ \mu\text{M}$.^{67,68} The PL property of CQDs is also affected by the nature of the functional group present on the surface, as these groups govern their hydrogen bonding capacity, which, in turn, affects their optical property. CQD surface functional groups can serve as electron-withdrawing and electron-donating groups, and thus can change the CQD surface charge. This surface charge influences the CQDs' ability to establish hydrogen bonds with other molecules, which can cause changes in the energy levels of the excitons responsible for the PL effect. The CQDs synthesised by using D-glucose and sago waste have been utilised as selective fluorescence detectors for lead (Pb^{2+}) ions, and a decrease in the fluorescence emission intensity was observed due to Pb^{2+} ion complexation on the CQD surface. The interaction of metal ions with functional groups such as -OH , C=O and -COOH on the surface of these CQDs can be concluded using FTIR data.^{69,70} Bi *et al.* reported the fluorescence emission quenching of CQDs synthesized using turbot fish in the presence of Fe^{3+} ions. The IR data confirm the presence of -NH_2 and -OH groups on the CQD surface, and their interaction with Fe^{3+} ions would result in the quenching of fluorescence emissions.⁷¹ A hydrothermal method has been used to synthesize N-CQDs from red lentils and utilized for the selective detection of Fe^{3+} ions. The presence of amide and hydroxyl groups on the surface of CQDs was confirmed by FTIR analysis, which might be due to the presence of proteins and



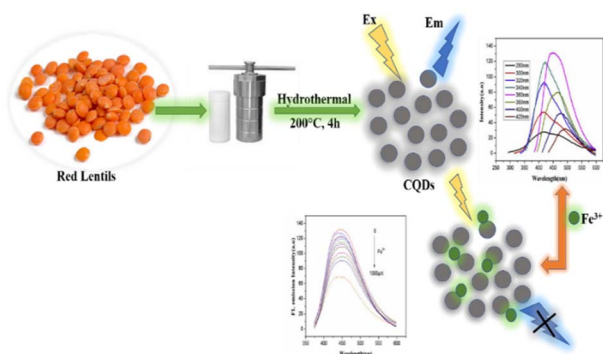


Fig. 7 Synthesis of CQDs using red lentils for Fe^{3+} ion detection.³⁸

carbohydrates in red lentils. The addition of Fe^{3+} to the solution of N-CQDs results in a reduction in fluorescence emission intensity probably due to the interaction of amide/hydroxyl functionalities with Fe^{3+} ions (Fig. 7).³⁸

N-CQDs synthesized using chitosan have also been reported as a detection probes for Hg^{2+} ions with an LOD of 80 nM. These N-CQDs showed a maximum fluorescence intensity at 440 nm, and the addition of Hg^{2+} ions resulted in a reduction in fluorescence intensity. The fluorescence decay showed a linear behaviour with a Hg^{2+} concentration within the range of 80–300 μM . The linear range of detection in case of CQD metal ion sensing involves the concentration range of metal ions in solutions that can be precisely quantified and detected by CQDs.⁷² Sachdev and co-workers reported a hydrothermal method for the synthesis of CQDs using coriander leaves and used them for the detection of Fe^{3+} ions. FTIR data showed the presence of carboxyl groups on the CQD surface, which produce carboxylate ions. These groups interact with Fe^{3+} ions, resulting in the quenching of fluorescence emissions of 400 nm, which is evident from the FTIR studies.⁷³ CQDs have been synthesized using bamboo leaves and then modified with branched polyethyleneimine. These CQDs have been utilised as sensitive and selective fluorometric sensors for Cu^{2+} ions having an LOD value of 115 nM. FTIR and XPS data conclude the formation of cupric–amine complexes responsible for fluorescence emission

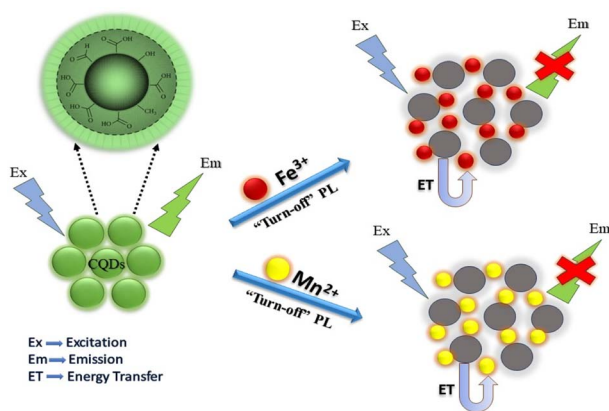


Fig. 8 Quenching mechanism of the synthesised CQDs for Mn^{2+} and Fe^{3+} ions.⁷⁵

quenching.⁷⁴ Krishnaiah *et al.* reported the green synthesis of CQDs utilising waste biomass of *Poa parentis* for Mn^{2+} and Fe^{3+} ion sensing. The possible sensing mechanism of CQDs towards these ions is due to the formation of complexes between metal cations and negatively charged surface CQDs. This complex formation results in charge transfer between CQDs and metal ions due to non-radiative recombinations, leading to a decrease in fluorescence intensity.⁷⁵ The graphical representation of the quenching mechanism is shown in Fig. 8.

Inner filter effect (IFE)

IFE is also known as apparent quenching, which is an important fluorometric non-radiative energy transfer process that occurs *via* the overlapping of quencher's absorption spectrum with the CQD excitation or emission spectra. It is not a quenching process but it is rather due to the attenuation of the excitation wavelength or absorption of emitted or excited wavelengths by an extra content of chromophoric or fluorophoric species or due to the presence of some other absorbing species in the detection medium.⁷⁶ Despite the fact that this effect leads to a reduction in intensity with no time decay, it could not be entitled as quenching. This is a process in which a second absorber declines the particle emission. The IFE effect can be still observed if the separation between re-absorber and emitter is more than ten nano meters.⁷⁷ In this process, the absorption peaks of the CQDs were not affected, suggesting that no new complexes were formed, thus the fluorescence lifetime of CQDs was not affected. To understand the IFE mechanism of CQDs, sophisticated instruments are not required, thus it is less expensive and easy to operate. The metal ion concentration does not affect the life time of fluorescence quenching in IFE. This mechanism was investigated for the detection of $\text{Cr}(\text{vi})$ using CQDs as sensors. It was found that the absorption bands of $\text{Cr}(\text{vi})$ were completely overlapped with the excitation and emission spectra of CQDs.⁷⁸ The fluorescence emission quenching of CQDs synthesised using pineapple in the presence of Fe^{3+} has also been found to follow IEF.⁷⁹

FRET mechanism

FRET is an electro dynamic phenomenon, which primarily relies on energy transfer from donors (CQDs in present case) in the excited state to the quencher (also known as acceptor) in its ground state due to the overlapping of the donor emission spectrum with the absorption spectrum of the quencher. The energy transfer efficiency (E) can be derived according to eqn (1).⁷⁷ The amount of energy transferred typically depends on four factors: (i) the extent of spectral overlap between the donor emission and the acceptor absorption, (ii) the donor unit's fluorescence QY, (iii) the relative geometric orientation of the donor and acceptor units, transition dipoles and (iv) the relative distance between the donor and acceptor molecules.⁸⁰ The sensors showing FRET mechanism generally have low LOD values and high accuracy. FRET occurs without any photon appearance due to long-range dipole–dipole interactions between CQDs and the quencher. The CQD and quencher distance should be in the range of 10–100 Å. The Förster



distance (R_0) between the quencher and CQDs and the CQD-quencher distance (r) can be calculated using eqn (2)–(4).^{81,82} CQDs-FRET-based sensors have several advantages over organic dyes and fluorescent protein FRET-based sensors. These include high molar extinction coefficients, excellent photostability, broad absorption spectra, symmetric and narrow emission spectra in the infrared to ultraviolet range, high QYs, good aqueous solubility and extended fluorescence lifetimes.⁸³ CQDs showing FRET mechanisms can sense both inorganic and organic analytes. Common examples of inorganic analytes include Co^{2+} , Cu^{2+} , $\text{Fe}^{3+/2+}$, sulfide ions, and ammonia. Shen *et al.* reported FRET in CQDs synthesized using sweet potato hydrothermally in the presence of Fe^{3+} ions with an LOD value of $0.32 \mu\text{M}$.⁸⁴

$$E = 1 - \tau/\tau_0 \quad (1)$$

$$R_0 = 0.211[\kappa^2 n^{-4} \Phi J(\lambda)]^{1/6} [\text{in } \text{\AA} \text{ unit}] \quad (2)$$

$$E = 1/\{1 + (r/R_0)^6\} [\text{in } \text{\AA} \text{ unit}] \quad (3)$$

$$\int_0^\infty F_D(\lambda) \varepsilon_A(\lambda) d\lambda \quad (4)$$

τ and τ_0 are the lifetimes in the absence and presence of quencher respectively. κ : orientation factor of CQDs and the quencher transition dipoles and taken as $2/3$. Φ : QY of the CQDs. n : refractive index of medium. $J(\lambda)$: integral of overlap values. $F_D(\lambda)$: corrected fluorescence intensity of the CQDs. $\varepsilon_A(\lambda)$: Quencher's extinction coefficient.

Ion binding

Different kinds of functional groups could arise on the surface of quantum dots depending on their synthetic protocol and precursors used. Every functional group has a specific affinity towards a particular metal ion.⁸⁵ This is why CQDs synthesized using different precursor/synthetic protocols showed selectivity towards different metal ions. For example, N-CQDs showed selective sensing ability towards Cu^{2+} ions due to the presence of nitrogen atoms on their surface. Although FT-IR and XPS data suggest the presence of $-\text{OH}$, $-\text{COOH}$, and $\text{C}=\text{O}$ groups, Cu^{2+} only binds to $-\text{NH}_2$ groups to form a copper-amine complex. The appearance of a new IR absorption band at 256 nm attributed to the formation of a copper-amine complex.⁸⁶

Aggregation

Aggregation-caused fluorescence quenching is a phenomenon in which a fluorophore molecule displays strong luminescence in dilute solutions, but in concentrated solutions or in solid state the fluorescence intensity is decreased or sometimes even disappears completely. A majority of CQDs because of their reabsorption and quenching effects at high concentrations show this phenomenon. As a result, above a certain (low) concentration, the PL intensity of CQDs decreases as the concentration increases. At high concentrations, small organic luminescent molecules are close enough, as their planar polycyclic aromatic structure enables them to orientate due to

strong intermolecular π - π stacking interactions. This superposition of organic molecules allows the photoexcited state to return back to the ground state *via* the nonradiative transition, resulting in fluorescence quenching. CQDs are also composed of similar planar aromatic ring structures, thus it can be assumed that a similar quenching process occurs as the concentration of CQDs increases. The aggregation phenomenon can be prevented *via* molecular conformation control or by incorporating bulky groups such as bulky rings.⁸⁷ The instability of CQDs followed by their interaction with the metal ions has been reported to cause precipitation or aggregations. Ansi *et al.* reported the aggregation of CQDs synthesized using table sugar with Pb^{2+} ions, which results in a visual change. The clear brown solution of CQDs becomes off-white due to aggregation after the addition of Pb^{2+} ions.⁸⁸ TEM, XRD and EDAX studies revealed the aggregation facts. Furthermore, N-CQDs synthesized using jackfruit result in aggregation after the addition of Au^+ ions, which results in the quenching of N-CQD fluorescence.⁸⁹

PET quenching mechanism of CQDs

Photo-induced electron transfer (PET) is an oxidation-reduction process involving electron transfer from one system to another. In case of CQDs, the PET can occur from CQDs to metal ions or *vice versa*, resulting in the formation of cations and anions respectively. This process involves the formation of complexes in excited state, which returns to a lower energy state without emission of a photon.⁹⁰ The emission intensity is generally quenched by the analyte *via* ion coordination. The nature of PET could be reductive or oxidative. In reductive PET, CQDs can act as electron receptors and can receive electrons from the donor molecules. Oxidative PET is the polar opposite of reductive PET. The energy gap between the LUMO of quenchers and the HOMO of CQDs governs the reductive electron transfer. In oxidative electron transfer, the energy gap between the LUMO of the CQDs and the LUMO of the quencher controls the process.^{77,91,92} CQDs can detect both inorganic and organic species, which operate through PET mechanism. CQDs having surface carboxyl groups have been reported to selectively sense Cu^{2+} ions, resulting in CQD fluorescence quenching, and follow the PET mechanism.⁹³ Song *et al.* have observed the fluorescence quenching of CQDs in the presence of Fe^{3+} ions, which is attributed to the non-radiative transfer of electrons from the excited state of sensors to the d-orbital of receptors.⁹⁴ A

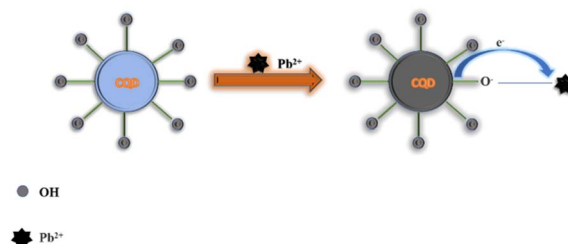


Fig. 9 Synthesis of CQDs using chocolate and their fluorescence quenching after the addition of Pb^{2+} ions following PET.⁹⁷



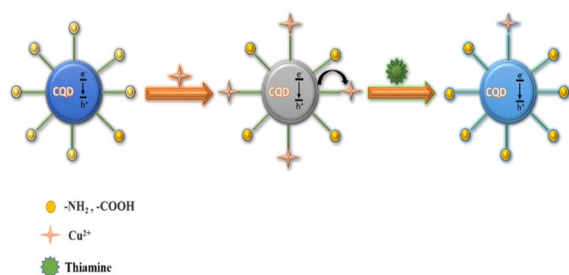


Fig. 10 Fluorescence quenching of CQDs by Cu^{2+} following the PET mechanism and the recovery of fluorescence after adding thiamine.⁹⁸

similar mechanism has been reported for CQDs (synthesized from tea) and Fe^{3+} .⁹⁵ A similar mechanism of electron transfer from the excited state of CQDs to the LUMO of Hg^{2+} has been proposed by Vandaukhuzhali *et al.* These CQDs have been hydrothermally synthesized using pineapple.⁹⁶ Liu *et al.* synthesized CQDs using chocolate by a hydrothermal method.⁹⁷ The fluorescence intensity of these CQDs has been quenched by Pb^{2+} ions, which followed the PET quenching mechanism, as given in Fig. 9. Purbia *et al.* prepared CQDs using tender coconut water *via* a microwave-assisted hydrothermal technique.⁹⁸ This CQD fluorescence intensity has been quenched in the presence of Cu^{2+} , which followed the PET quenching mechanism (Fig. 10). The fluorescence intensity of these CQDs was further recovered by the addition of thiamine. CQDs prepared from pipe tobacco exhibited a decrease in fluorescence intensity upon addition of Cu^{2+} ions with an LOD value of $0.01 \mu\text{M}$, respectively. The photo-induced transfer of electrons from the excited state of CQDs to the d-orbital of Cu^{2+} is responsible for the fluorescence quenching of these CQDs.⁹⁹

Heavy metal ion sensing using CQDs

Heavy metals including iron, chromium, copper, and aluminium are nutritionally essential elements needed by various organisms to sustain their lives. These elements have a density higher than that of water, and are the most common toxic and non-biodegradable contaminants. Their increased employment in various fields led to an increase in environment pollution. In order to identify the presence of heavy metals and to prevent their negative consequences, the development of eco-friendly, feasible and efficient sensors is required. Due to the unique physiochemical properties of SQDs and their ligand binding tendency, versatile surface chemistry and capability of attachment to various functional materials, SQDs were potentially utilised for the fabrication of sensitive fluorescence sensors during the last decade.¹⁰⁰ Nevertheless, the high fabrication cost and toxic effects of conventional SQDs make them unsuitable for their use as detection systems. However, CQDs which are generally synthesised from natural precursors possess low cytotoxicity and chemical inertness, and their surface can be easily modified due to the presence of various functional groups. Furthermore, the oxygen-containing groups present on the CQD surface are capable of interacting with metal ions and can be efficiently used as sensors. A wide range

of CQD-based sensors for the detection of toxic metal ions such as lead, chromium, iron, aluminium, arsenic, cobalt, cadmium, copper, gold, silver and mercury have been reported and will be discussed in the following sections.

Ferric ion detection

Iron is one of the most crucial metal ions in biological systems and is present mainly in two oxidation states, *i.e.*, ferric(III) and ferrous(II).¹⁰¹ Among these states, the ferric state is more toxic due to its insolubility and causes formation of hazardous radicals. The abnormal presence of Fe^{3+} can result in many serious diseases including anaemia, heart failure, mental decline, and diabetes. The maximal acceptable limit of Fe(III) in drinking water is 5.36 mM according to World Health Organization standards.¹⁰² Therefore, it becomes essential to monitor the Fe^{3+} ion concentration present in the environment and also in biological systems. CQDs have emerged as efficient materials for this purpose due to the presence of various functional groups such as hydroxyl, amino and carboxyl on their surface, which efficiently bind with Fe^{3+} and can lead to fluorescence quenching. These CQDs have been synthesised using different carbon precursors possessing different binding properties due to the different composition of surface functional groups, and thus, they exhibit different sensitivities and selectivities. For example, Architha *et al.* reported the synthesis of spherical shaped, blue-emitting CQDs from a Mexican mint extract and utilized them for Fe^{3+} ion detection. The size of these CQDs was found to be $2.43 \pm 0.02 \text{ nm}$ with an LOD value of $0.53 \mu\text{M}$ and a linear concentration range of $0\text{--}15 \mu\text{M}$. The CQD solution showed a maximum emission intensity at 447 nm , which gets decreased by the addition of different metal ions. The re-quenching of CQD fluorescence spectra was obtained by adding ascorbic acid to the CQD-metal solution. It was reported that ascorbic acid and Fe^{3+} have a high binding affinity, and the

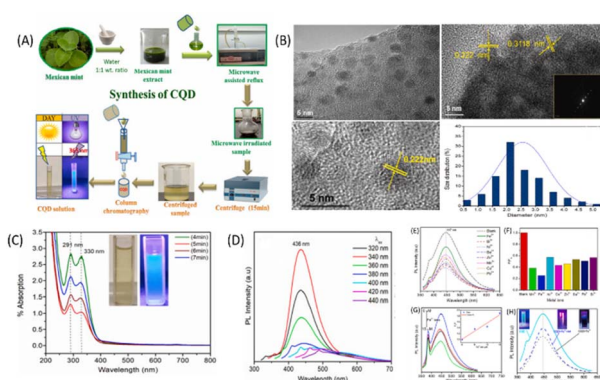


Fig. 11 (A) Synthesis of CQDs. (B) TEM spectra of the synthesized CQDs. (C) UV-vis spectra of CQDs. (D) PL spectra of blank CQDs. (E) PL spectra of CQDs in the presence of different metal ions. (F) Difference in the relative PL intensities of CQDs between the blank and solutions containing different metal ions. (G) CQD PL spectra in the presence of varying Fe^{3+} ion concentrations; the inset shows the linear relationship between F_0/F and the concentration of Fe^{3+} in the range of $0\text{--}15 \mu\text{M}$. (H) PL spectra of fluorescence quenching and re-quenching properties. Reproduced from ref. 103 with permission by Elsevier, copyright 2023.



fluorescence restoration of CQDs is attributed to the release of loosely bound Fe^{3+} ions from the CQD surface by adding 15 μM ascorbic acid solution. To prove this mechanism, a turn ON–OFF assay was performed, and the logic gate operation was also studied. The graphical representation of the synthesis of CQDs and their characterisation using a Mexican mint extract is shown in Fig. 11. The maximum decrease was observed for Fe^{3+} ions and the minimum decrease for Ni^{2+} ions. Thus, this showed high selectivity for Fe^{3+} ions. The Fe^{3+} ion selectivity with CQDs is attributed to the presence of oxygen groups on the CQD surface, which binds with Fe^{3+} . The complex formation results in a change in the distribution of surface energy traps and enhancement of the non-radiative recombination of electrons and holes, which leads to fluorescence quenching.¹⁰³ Edison *et al.* reported the green synthesis of N-CQDs by hydrothermal carbonization of a *Prunus avium* fruit extract, which have a QY of 13%. The synthesized N-CQDs showed maximum fluorescence emission intensity at 411 nm, which gets quenched by adding Fe^{3+} ions due to the formation of a stable complex. The presence of phenolic hydroxyl groups was confirmed by FT-IR and XPS spectroscopy data. The sensing of Fe^{3+} ions has been carried out in water, and the LOD values were found to be 0.96 μM with a linear range from 0 to 100 μM . A wide linear range of detection indicates that the sensing system can accurately detect and quantify a wider concentration range of metal ions. The mechanism for fluorescence quenching has been reported to be non-radiative electron or energy transfer from the N-CQD surface to the metal. The facile synthesis of highly luminescent CQDs using *Prunus cerasifera* fruits has also been reported. The aqueous solution of CQDs shows bright blue fluorescence. The fluorescence intensity of CQDs was selectively quenched by Fe^{3+} ions in the concentration range of 0–0.5 mM.¹⁰⁴ Recent studies have reported that doping of CQDs with hetero-atoms other than nitrogen results in improved sensitivity and selectivity towards Fe^{3+} ions. Wu *et al.* reported a straight forward hydrothermal strategy for the fabrication of blue-emissive sulfur-doped CQDs with an average size of 3.2 nm and a QY of 4.4% using Vitamin B1 in the presence of ethylenediamine. These CQDs have been used as novel fluorescent sensors for the sensitive and selective detection of Fe^{3+} . The LOD value obtained for Fe^{3+} was 177 nM.¹⁰⁵ Aslandaş *et al.* reported the green synthesis of CQDs by sonication of blueberries and used them as sensors for Fe^{3+} detection in the concentration range of 12.5–100 μM . The sensitivity of the CQDs was examined by screening various metal ions such as Pb^{2+} , Hg^{2+} , Mn^{2+} , Ag^{+} , Zn^{2+} , Cd^{2+} , Cr^{3+} , Cu^{2+} , Fe^{3+} , Na^{+} and Pb^{2+} . It has been observed that the fluorescence intensity of these CQDs gets maximum quenched in the presence of Fe^{3+} ions, while other metal ions show a small decrease in fluorescence intensity. The formation of CQD– Fe^{3+} complexes seems to prevent the radiative recombination of excitons and promotes charge transfer, thus resulting in fluorescence quenching. The temperature-dependent fluorescence and absorption measurements were also studied and it was found that there are very less changes in the absorption spectrum by increasing the temperature. Furthermore, the fluorescence intensity decreases gradually with the increase in temperature as the non-radiative

transitions get enhanced with the temperature.¹⁰⁶ Lu *et al.* reported the synthesis of N-CQDs *via* hydrothermal carbonization of watermelon juice and CQDs have a QY of 10.6%. The fluorescence emission of N-CQDs was potentially quenched by Fe^{3+} ions, while other metal ions show negligible fluorescence quenching. The high selectivity towards Fe^{3+} ions was attributed to the interaction between surface functional groups, *i.e.*, carboxyl hydroxyl and amine groups of N-CQDs with Fe^{3+} ions. The LOD value was found to be 0.16 μM .¹⁰⁷ Liu *et al.* reported a simple, green, and low-cost method for CQD synthesis *via* hydrothermal treatment of rose-heart radish. These CQDs have a fluorescent QY of 13.6% and utilised for the facile detection of Fe^{3+} in the linear range from 0.02 to 40 M with an LOD value of 0.13 M.¹⁰⁸ Yang *et al.* reported the fabrication of CQDs using mangosteen pulp by a calcination method. These CQDs showed strong blue fluorescence under ultraviolet illumination. The fluorescence has been quenched in the presence of Fe^{3+} ions, resulting in the formation of CQDs/ Fe^{3+} complexes. The LOD value was found to be 52 nM.¹⁰⁹ Venkatesan *et al.* used the *Boswellia ovalifoliolata* bark extract for the synthesis of water-soluble CQDs with size 4.16 ± 0.22 nm and used them for Fe^{3+} detection. These CQDs showed strong green emissions under UV light and have a QY of 10.2%. They have been used as sensitive and selective probes for Fe^{3+} ions with a linear relationship up to the concentration of 500 μM and an LOD value of 0.41 μM has been observed.¹¹⁰

Copper ion detection

Copper (Cu^{2+}) ions are commonly present in human body and involved in various biological processes. However, the long-term exposure to these ions can result in a number of diseases including liver damage, urinary stone, Parkinson's and Alzheimer's diseases.¹¹¹ Similar to Fe^{3+} ion detection by CQD-based sensors, several studies have been reported for the fabrication of reusable and steady sensors with high selectivity and sensitivity for Cu^{2+} ions. Chaudhary *et al.* reported the synthesis of spherical shaped, fluorescent N,S-doped CQDs using banana juice as the carbon source by a hydrothermal method. The average size of CQDs was found to be 1.27 nm with a QY of 32%. These N,S-CQDs were further utilized as novel fluorescent probes for the detection of Cu^{2+} in the water sample with LOD values of 0.3 $\mu\text{g mL}^{-1}$. The decrease in the fluorescence intensity after the addition of Cu^{2+} ions has been observed and found to be linear from 1 to 800 $\mu\text{g mL}^{-1}$. The reason for this quenching is the formation of complexes between functional groups present on the CQD surface and Cu^{2+} ions along with charge transfer between N,S-CQDs and Cu^{2+} , which showed non-radiative recombination.¹¹² In another study, Murugan and co-workers used finger millet ragi for the synthesis of fluorescent CQDs having a size in the range from 3 to 8 nm. These CQDs sense Cu^{2+} ions in real water samples at a very low Cu^{2+} ion concentration of 10 nM. A linear correlation has been observed between the quenching efficiency and the concentration of Cu^{2+} ions in the range from 0 to 100 μM .⁴⁸ Tai reported the synthesis of fluorescent CQDs from human fingernails having an average size of 1.72–5.85 nm and used them for Cu^{2+}



detection. These CQDs selectively detect Cu^{2+} at a much low concentration of 1 nM. XPS and FTIR studies suggest the complex formation with Cu^{2+} and carboxylate/amino groups present on the CQD surface. A linear correlation was obtained between the quenching intensity and the concentration of Cu^{2+} ions in the linear range of 0–1 nM.¹¹³ Qu and co-worker reported the conjugation of *N*-(2-aminoethyl)-*N,N,N'*-tris(pyridin-2-ylmethyl)ethane-1,2-diamine (AE-TPEA) on the CQD surface to form a recognition unit, which showed high sensitivity and selectivity toward Cu^{2+} over other metal ions.¹¹⁴ Gedda *et al.* reported the use of prawn shell biomass for the synthesis of CQDs, which were further used as selective sensors for Cu^{2+} ions with an LOD value of 5 nM. The high selectivity of CQDs towards Cu^{2+} compared to other metal ions was due to the high affinity of Cu^{2+} ions towards the amine groups present on the surface of CQDs.¹¹⁵

Mercury ion detection

Mercury ions are one of the major contaminants due to their high toxic nature, and are responsible for various human disorders including mitosis impairment, DNA damage, kidney toxicity and sometimes permanent damage to endocrine and nervous systems.¹¹⁶ Even after the removal of the pollutant source, the Hg^{2+} ions tend to remain in the system for a larger time and lead to poisoning.¹¹⁷ The maximum allowable level of Hg^{2+} in drinking water is 10 nM. It is thus essential to develop sensitive and selective sensors. Which can detect mercury ions at a very low concentration. Several CQDs synthesized using green carbon sources have been reported for Hg^{2+} ion detection and their addition to CQDs resulted in their fluorescence quenching. Wenbo Lu *et al.* reported the synthesis of CQDs using pomelo peel and utilized them as sensors for Hg^{2+} ions in water samples. The electron transfer process among CQDs and metal ions was proposed as a probable fluorescence quenching mechanism, which was further proven by eliminating Hg^{2+} from the CQD surface *via* a chelator.⁴⁰ Qin, *et al.*, reported the synthesis of CQDs of 1–4 nm size using flour as the carbon precursor having a QY of 5.4%. The prepared CQDs were used as fluorescent sensing probes for the detection of Hg^{2+} ions with an LOD value of 0.5 nM in the linear range of 0.0005–0.01 M. The high selectivity and sensitivity of these CQDs towards Hg^{2+} ions attributed to strong affinity between Hg^{2+} ions and carboxylic groups on the CQD surface. It was found that the PL intensity of these CQDs is pH sensitive and increases with the increase in pH values. In an acidic medium, the CQDs showed low quenching efficiency due to the breaking of CQD– Hg^{2+} complexes *via* protonation of the surface-binding carboxyl groups. However, deprotonation occurs at high pH and carboxylate groups present on CQDs strengthen the interaction between CQDs and Hg^{2+} ions.¹¹⁸ Gu, *et al.* reported the synthesis of fluorescent N-CQDs using lotus root as the carbon source having a nitrogen content of 5.23%. These N-doped CQDs have a diameter of 9.41 nm and used as a sensor for the detection of Hg^{2+} ions and cell imaging. The N-CQDs efficiently detect Hg^{2+} ions in a linear range from 0.1 to 60.0 μM with an LOD value of 18.7 nM.³² The graphical representation of CQD syntheses and their characterisation using lotus root is shown in Fig. 12.

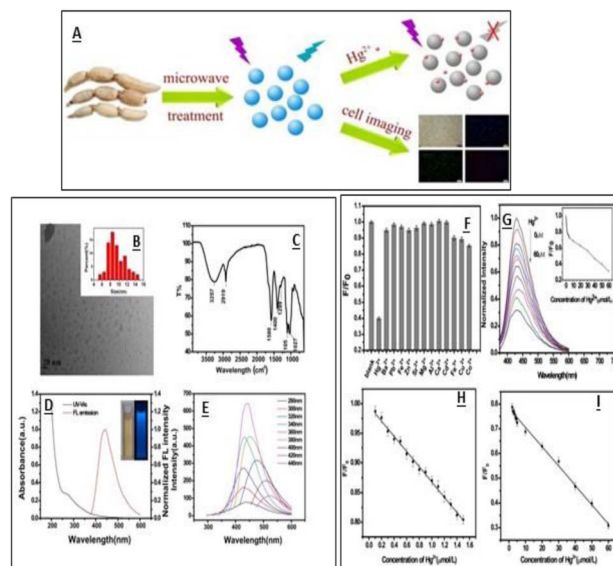


Fig. 12 (A) Synthesis of CQDs. (B) TEM spectra of the synthesised CQDs. (C) FTIR spectra of CQDs. (D) UV-vis and fluorescence emission spectra of CQDs. (E) Emission spectra of CQDs at different excitation wavelengths. (F) Fluorescence response of CQDs towards different metal ions. (G) Fluorescence spectra of CQDs at different Hg^{2+} concentrations. (H). (I) Relationship between the F/F_0 and Hg^{2+} concentrations. Reproduced from ref. 32 with permission from Elsevier, copyright 2023.

Yadian *et al.*, reported a green method for the synthesis of water-soluble N-CQDs using ethane diamine as the nitrogen source and barley as the carbon source with a QY of 14.4%. These blue fluorescent N-CQDs showed selective detection of Hg^{2+} ions in the range of 10–160 μM with an LOD value of 0.48 μM . The quenching of fluorescence is attributed to the interaction between Hg^{2+} and carboxylic group present on the N-CQD surface.¹¹⁹ Li *et al.* used Hongcaltai as the carbon source for the synthesis of CQDs using hydrothermal treatment. These CQDs showed the selective detection of ClO^- and Hg^{2+} ions.¹²⁰ Hasan and co-worker reported the synthesis of CQDs using *Tamarindus indica* leaves having a QY of 46.6%. These CQDs were used as selective nano-probes for the turn-off sensing of Hg^{2+} with an LOD value of 6 nM in the dynamic range of 0–0.1 μM .¹²¹

Lead ion detection

Lead is considered as a hazardous metal causing many disorders in the human body and posing a threat to the environment. It occurs mainly in three oxidation states, *i.e.*, Pb(0), Pb(II) and Pb(IV). The main source of lead ions in drinking water is the use of service pipes containing lead and other relevant accessories, which corrode in the presence of acidic water. The lead uptake



Fig. 13 Synthesis of CQDs using lemon peels *via* a hydrothermal treatment.¹²⁵



Table 1 Metal ion sensing by CQDs

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|-------------------------------|--|-----------------------------|-------------------|--------------------------------------|---------------------------|-------------------------|------------|
| 1 | Lotus root | Microwave | 9.41 Blue | 19.0 | Hg ²⁺ | 0.1–60 µM | 18.7 nM | 32 |
| 2 | Broccoli | Hydrothermal | 2–6 Blue | NA | Ag ⁺ | 0–600 µM | 0.5 µM | 39 |
| 3 | Pomelo peel | Hydrothermal | 2–4 Blue | 6.9 | Hg ²⁺ | NA | 0.23 nM | 40 |
| 4 | Finger millet ragi | Pyrolysis | 3–8 Blue | NA | Cu ²⁺ | 0–100 µM | 10 nM | 48 |
| 5 | Lantana camara berries | Hydrothermal | 5 ± 3 Blue | 33.1 | Pb ²⁺ | 0–200 µM | 9.64 nM | 50 |
| 6 | Peach gum polysaccharides | Hydrothermal carbonization | 2–5 Blue | 28.46 | Au ³⁺ | 0–50 µM | 0.64 µM | 67 |
| 7 | Sago waste | Thermal pyrolysis | 6–17 Blue | NA | Pb ²⁺ Cu ²⁺ | NA | 7.49 µM 7.78 µM | 69 |
| 9 | D-Glucose | Simple heating method | >20 Green | NA | Pb ²⁺ | 0.010–0.030 µM | 0.014 µM | 70 |
| 10 | Grilled turbot fish | Microwave heating | 3–5 Blue | 1.67 | Fe ³⁺ | 20–110 µM | 3.96 µM | 71 |
| 11 | Coriander leaves | Hydrothermal | 2.38 Blue | 6.48 | Fe ³⁺ | 0–60 µM | 0.4 µM | 73 |
| 12 | Bamboo leaves | Hydrothermal | 3.6 Blue | 7.1 | Cu ²⁺ | 0–66 µM | 0.115 µM | 74 |
| 13 | Sweet potato | Hydrothermal | 3.39 Blue | 8.64 | Fe ³⁺ | 1–100 µM | 0.32 µM | 84 |
| 14 | Table sugar | Microwave | 3.5 Blue | 2.5 | Pb ²⁺ | NA | 67 µM | 88 |
| 15 | Jackfruit seeds | Microwave | 3–7 Blue | 17.91 | Au ³⁺ | 0–100 µM | 239 nM | 89 |
| 16 | Waste tea | Hydrothermal | 10 Blue | 7.1 | Fe ³⁺ | 53.5–267.5 µM | 0.15 µM | 95 |
| 17 | Pineapple peel | Hydrothermal | 2–3 Blue | 42.0 | Hg ²⁺ | 0.1–100 µM | 4.5 nM | 96 |
| 18 | Chocolate | Hydrothermal | 6.41 Blue | NA | Pb ²⁺ | 0.033–1.67 µM | 12.7 nM | 97 |
| 19 | Coconut water | Microwave-assisted hydrothermal method | 1–6 Blue and green | 2.8 | Cu ²⁺ | 10–50 µM | 0.280 µM | 98 |
| 20 | Pipe tobacco | Hydrothermal | 5 Blue | 3.2 | Cu ²⁺ | 0–40 mM | 0.01 µM | 99 |
| 21 | Mexican mint | Microwave-assisted reflux method | 2.43 ± 0.02 Blue | 17 | Fe ³⁺ | 0–15 µM | 0.53 µM | 103 |
| 22 | Prunus cerasifera | Hydrothermal | 3–5 Blue | NA | Fe ³⁺ | 0–0.5 mM | NA | 104 |
| 23 | Vitamin B1 | Hydrothermal | 3.2 Blue | 4.4 | Fe ³⁺ | 0.1–1.00 mM | 177 nM | 105 |
| 24 | Blueberry | Liquid N ₂ treatment and centrifuge processes | NA | NA | Fe ³⁺ | 12.5–100 µM | 9.97 µM | 106 |
| 25 | Watermelon juice | Hydrothermal carbonization | 3–7 Blue | 10.6 | Fe ³⁺ | 0–300 µM | 0.16 µM | 107 |
| 26 | Rose-heart radish | Hydrothermal treatment | 1.2–6 Blue | 13.6 | Fe ³⁺ | 0.02–40 µM | 0.13 µM | 108 |
| 27 | Mangosteen pulp | Hydrothermal | 5 Blue | 2.8 | Fe ³⁺ | 0–0.18 mM | 52 nM | 109 |
| 28 | Boswellia ovalifoliolata bark | Hydrothermal-carbonization | 4.16 ± 0.22 Green | 10.2 | Fe ³⁺ | 0–500 µM | 0.41 µM | 110 |
| 29 | Banana juice | Hydrothermal | 1.27 Blue | 32 | Cu ²⁺ | 1–800 µg mL ⁻¹ | 0.3 µg mL ⁻¹ | 112 |
| 30 | Prawn shell | Hydrothermal | 4 Blue | 9 | Cu ²⁺ | 0.1–5 µM | 5 nM | 115 |
| 31 | Flour | Microwave | 1–4 Blue | 0.5 | Hg ²⁺ | 0.0005–0.01 µM | 0.5 nM | 118 |



Table 1 (Contd.)

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|----------------------------------|--------------------|------------------------------------|-------------------|--------------------------------------|--|--|------------|
| 32 | Highland barley | Hydrothermal | 5.8 Blue | 14.4 | Hg ²⁺ | 10–160 µM | 0.48 nM | 119 |
| 33 | Hongcaitai | Hydrothermal | 1.6–2.3 Blue | 12.1 | Hg ²⁺ | 0.2–15 µM | 60 nM | 120 |
| 34 | <i>Tamarindus indica</i> leaves | Hydrothermal | 3.4 ± 0.5 Blue | 46.6 | Hg ²⁺ | 0–0.1 µM | 6 nM | 121 |
| 35 | Potato-dextrose agar | Microwave | 4.3 Blue | 9.0 | Pb ²⁺ | 0–20 µM | 0.11 nM | 122 |
| 36 | Ocimum sanctum leaves | Hydrothermal | 3.0 Green | 9.3 | Pb ²⁺ | 10–1000 µM | 0.59 nM | 123 |
| 37 | Bamboo leaves | Solvothermal | 3–7 Red | 4.7 | Pb ²⁺ Hg ²⁺ | 0.6–800 nM 1–1000 nM | 0.14 nM 0.22 nM | 124 |
| 38 | Lemon peel waste | Hydrothermal | 1–3 Blue | 14 | Cr ⁴⁺ | 2.5–50 µM | 73 × 10 ^{−3} µM | 125 |
| 39 | Quince fruit | Microwave | 4.85 ± 0.07 Blue | 8.55 | As ³⁺ | 0.5–10 µM | 0.01 µM | 126 |
| 40 | Edible prickly pear cactus | Hydrothermal | 5.6 Blue | 12.7 | As ³⁺ | 2–12 × 10 ^{−3} µM | 2.3 × 10 ^{−3} µM | 127 |
| 41 | <i>Nerium Oleander</i> L. Petals | Hydrothermal | 1–9 | 3.5 | Co ²⁺ | 6.45 × 10 ^{−3} µM | 0–40 µM | 128 |
| 42 | Kelp | Microwave | 3.7 Blue | 23.5 | Co ²⁺ | 1–200 µmol L ^{−1} | 0.39 µmol L ^{−1} | 129 |
| 43 | <i>Pyrus pyrifolia</i> fruit | Hydrothermal | 2.0 ± 1.0 Blue | 10.80 | Al ³⁺ | 0.005–50 µM | 0.0025 µM | 130 |
| 44 | Honey | Solvothermal | 2 Blue | 19.8 | Fe ³⁺ | 5.0 × 10 ^{−9} to 1 × 10 ^{−4} mol L ^{−1} | 1.7 × 10 ^{−9} mol L ^{−1} | 131 |
| 45 | Pseudostem of banana | Hydrothermal | 2.5 Blue | 48 | Fe ³⁺ | 0–100 µM | 6.4 × 10 ^{−3} µM | 132 |
| 46 | Sugarcane molasses | Hydrothermal | 1.9 Blue | 5.8 | Fe ³⁺ | 0–20 µM | 1.46 µM | 133 |
| 47 | Onion waste | Autoclave | 15 Blue | 28 | Fe ³⁺ | 0–20 µM | 0.31 µM | 134 |
| 48 | Coffee beans | Hydrothermal | 4.6 Blue | 9.8 | Fe ³⁺ | 0–0.10 mM | 15.4–16.3 nM | 135 |
| 49 | Tomato | Chemical oxidation | 5.0–10.0 Blue, green and yellow | 12.70 | Fe ³⁺ | 0.1–2.0 µM | 0.016 µM | 136 |
| 50 | Soybeans | Ultrasonic | 2.4 Blue | 16.7 | Fe ³⁺ | 0–30 µM | 2.9 µM | 137 |
| 51 | <i>Magnifera indica</i> leaves | Pyrolysis | 2–10 Blue | 18.2 | Fe ³⁺ | NA | 3.12 µM | 138 |
| 52 | Ripe banana peels | Hydrothermal | 6.9 Blue | 27 | Fe ³⁺ | 121 × 10 ^{−6} µM | 10–200 × 10 ^{−6} µM | 139 |
| 53 | Dried rose petals | Hydrothermal | 6–9 Green | 28 | Cr ⁴⁺ | 10–200 × 10 ^{−6} µM | 81 × 10 ^{−6} µM | 139 |
| 54 | Curaua fibers | Hydrothermal | 2.4 Blue | NA | Fe ³⁺ | 0.77 µM | 0–30 µM | 140 |
| 55 | Lycii fructus | Hydrothermal | 2–5 Blue | 17.2 | Fe ³⁺ | 0–30 µM | 21 × 10 ^{−3} µM | 141 |
| 56 | Dwarf banana peel | Hydrothermal | 4 Blue | 23.0 | Fe ³⁺ | 5–25 µM | 0.66 µM | 142 |
| 57 | <i>Bombyx mori</i> silk | Hydrothermal | 5.6 Blue | 61.1 | Fe ³⁺ | 0.5–4 µM | 0.38 µM | 143 |
| 58 | Syringa oblata lindl | Hydrothermal | 1.0–5.0 Blue | 12.4 | Fe ³⁺ | 0.5–80 µM | 0.11 µM | 144 |
| 59 | Rice residue | Hydrothermal | 2.70 Blue | 23.48 | Fe ³⁺ | 3.3–32.2 µM | 0.7462 µM | 145 |
| 60 | Lemon juice | Hydrothermal | 20 Blue | 38 | Fe ³⁺ | 1–90 µM | 2.5 µM | 146 |



Table 1 (Contd.)

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|-----------------------------------|----------------------------------|-----------------------------|-------------------|--|-------------------------------|---|------------|
| 61 | Kiwi fruit peels | Hydrothermal | 5.6 Blue | 14 | Fe ³⁺ | 5–25 µM | 0.95 and 0.85 µM | 147 |
| 62 | Betel leaves | Hydrothermal | 4 Blue | 4.21 | Fe ³⁺ | 0.3–3.3 µM | 0.135 µM | 148 |
| 63 | <i>Prunus avium</i> fruit | Hydrothermal | 7 Blue | 13 | Fe ³⁺ | 0–100 µM | 0.96 µM | 149 |
| 64 | <i>Magnolia liliiflora</i> flower | Hydrothermal | 4 ± 1 Blue | 11 | Fe ³⁺ | 0–25 µM | 1.2 µM | 150 |
| 65 | Coconut water | Stirrer-assisted route | 5 Blue | 14.34 | Fe ³⁺ | 0–700 µM | 0.30 µM | 151 |
| 66 | Pinewood | Hydrothermal | 3.56 Blue | 4.69 | Fe ³⁺ | 0–2000 mmol L ⁻¹ | 355.4 nmol L ⁻¹ | 152 |
| 67 | Lychee waste | Solvothermal | 3.13 Blue | 23.5 | Fe ³⁺ | 0–22 µM | 23.6 nM | 153 |
| 68 | Betel leaf | Hydrothermal | 3.7 Blue | 4.21 | Fe ³⁺ | 0.3–3.3 µM | 0.135 µM | 154 |
| 69 | Papaya powder | Hydrothermal | 3.4–10.8 | 18.98 | Fe ³⁺ | 1–10 µmol L ⁻¹ | 0.48 µmol L ⁻¹ , 0.29 µmol L ⁻¹ | 155 |
| | W-CQDs | | Blue | 18.39 | | 1–8 µmol L ⁻¹ | | |
| 70 | E-CQDs | | | | | | | |
| 70 | Brewer's spent grain | Microwave synthesis | 5.3 ± 2.4 Blue | 14 | Fe ³⁺ | NA | 0.05 µM | 156 |
| 71 | Poa pratensis | Hydrothermal | 9 Blue | 7 | Fe ³⁺ , Mn ²⁺ | 5.0–25 µM | 1.4–1.2 µM | 75 |
| 72 | Cranberry beans | Hydrothermal | 1.23–6.63 Blue | 10.85 | Fe ³⁺ | 30–600 µM | 9.55 µM | 157 |
| 73 | <i>Catharanthus roseus</i> | Hydrothermal carbonization | 5 Blue | 28.2 | Fe ³⁺ | 0–6 µM | 0.3 µM L ⁻¹ | 158 |
| 74 | Cat feed stock | Hydrothermal carbonization | NA | NA | Fe ³⁺ | 12.5–100 µM | 32 µM | 159 |
| 75 | Mango-peel | Pyrolyzation with oxygenolysis | 2–6 Blue | 8.5 ± 0.2 | Fe ³⁺ | 4–16 µM | 1.2 µM | 160 |
| 76 | Fuel waste | Oxidative acid treatment | 5 | 3 | Fe ³⁺ | NA | 0.65 µM | 161 |
| 77 | Waste kitchen chimney oil | Ultrasonication | 1–4 Blue | 7.5 | Fe ³⁺ | 0.001–600 µM | 0.00018 µM | 162 |
| 78 | Black tea | Hydrothermal | 4.6 Blue | NA | Fe ³⁺ | 0.25–60 µM | 0.25 µM | 163 |
| 79 | Goose feather | Microwave-hydrothermal treatment | 21.5 Blue | 17.1 | Fe ³⁺ | 1–14 µM | 0.196 µM | 164 |
| 80 | <i>Fusobacterium nucleatum</i> | Hydrothermal carbonization | 4.06 Blue | 9.99 | Fe ³⁺ | 20–180 mM | 0.82 µM | 165 |
| 81 | Corn bract leaves | Solvothermal | 2.6 Blue | 6.90 | Hg ²⁺ | 0–40 µM | 9 nM | 166 |
| 82 | <i>Prosopis juliflora</i> leaves | Carbonization | 5.8 Blue | 5.0 | Hg ²⁺ | 5–500 ng mL ⁻¹ | 1.26 ng mL ⁻¹ | 167 |
| 83 | Strawberry juice | Hydrothermal | 5.2 Blue | 6.3 | Hg ²⁺ | 0.001–50 µM | 3 nM | 168 |
| 84 | China grass carp scales | Microwave supported hydrothermal | 2.6 ± 0.8 Blue | 19.9 | Hg ²⁺ | 0.014–30 µmol L ⁻¹ | 0.014 µmol L ⁻¹ | 169 |
| 85 | Honey | Hydrothermal | 2–4 | NA | Hg ²⁺ | 0–10 × 10 ⁻³ µM | 1.02 nM | 170 |
| 86 | Jinhua bergamot | Hydrothermal | 10 Blue | 50.7 | Hg ²⁺ | 0.01–100 µM | 5.5 nM | 171 |
| 87 | Coconut milk | Thermal pyrolysis | 20–50 Blue | NA | Hg ²⁺ | 30.5 × 10 ⁻³ µM | 16.5 nM | 172 |
| 88 | Cucumber juice | Hydrothermal | 2.8–4.0 Blue | 3.5 | Hg ²⁺ | 1–70 µM | 180 nM | 173 |



Table 1 (Contd.)

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|---------------------------------------|--|--|-------------------|--------------------------------------|---|------------------------------|------------|
| 89 | Muskmelon | Acid oxidation | 2–5 Blue 3.5–6 Green 4.5–7 Yellow | 26.9 | Hg ²⁺ | 1.0–25 µM | 330 nM | 174 |
| 90 | <i>Dunaliella Salina</i> | Hydrothermal | 4.7 Blue | 8 | Hg ²⁺ | 0.03–0.20 µM | 18 nM | 175 |
| 91 | Chinese yam | Hydrothermal | 2.7 ± 1.4 Blue | 9.3 | Hg ²⁺ | 10–30 × 10 ^{−3} µM | 1.26 nM | 176 |
| 92 | Lemon juice | Hydrothermal | Blue | 2.4 | Hg ²⁺ | 0–1.82 × 10 ³ µM | 36 × 10 ³ nM | 177 |
| 93 | Corn flour | Hydrothermal | 3.5 Blue | 7.7 | Cu ²⁺ | NA | 0.001 µM | 178 |
| 94 | Human urine | Thermal treatment | 10–30 Blue | 5.3 | Cu ²⁺ Hg ²⁺ | NA | 3.4 µM 2.7 µM | 179 |
| 95 | Peanut shells | Pyrolysis | 1.8–4.2 Blue | 10.58 | Cu ²⁺ | 0–5 µM | 4.8 µM | 180 |
| 96 | Lemon juice | Thermal coupling | 3.5 Blue | 7.7 | Cu ²⁺ | 0–15 µM | 0.047 µM | 181 |
| 97 | Kelp | Hydrothermal | 4.5 Blue to deep-green | 12.3 | Cu ²⁺ | 1–12.5 µM | 7 × 10 ^{−3} µM | 182 |
| 98 | Grass | Hydrothermal | 3–5 Blue | 4.2 | Cu ²⁺ | 0–50 µM | 1 × 10 ^{−3} µM | 183 |
| 99 | Pu-erh tea | Brewing method | NA Blue | NA | Cu ²⁺ | 0–22 µM | 51 × 10 ^{−3} µM | 184 |
| 100 | <i>Petroleum coke</i> | Ultrasonic-assisted chemical oxidation | 2.0–4.5 NA | 9.8 | Cu ²⁺ | 0.25–10 µM | 0.0295 µM | 185 |
| 101 | Celery stalk | Hydrothermal | 3.7 ± 1.1 Blue | NA | Cu ²⁺ | 0–100 µM | 0.132 µM | 186 |
| 102 | Pear juice | Hydrothermal | 10 Blue | NA | Cu ²⁺ | 0.1 mg L ^{−1} to 50.0 mg L ^{−1} | 0.1 mg L ^{−1} | 187 |
| 103 | Pineapple juice | Hydrothermal | NA Blue | 10.06 | Cr ⁴⁺ | 0–18 µM | 0.052 µM | 188 |
| 104 | Papaya waste (<i>Carica papaya</i>) | Pyrolysis | 7 Blue | 23.7 | Cr ³⁺ Cr ⁴⁺ | 0.028–2.86 µM | 2 × 10 ^{−3} µM | 189 |
| 105 | Tulsi leaves | Hydrothermal | 5 Blue | 3.06 | Cr ⁴⁺ | 1.6–50 µM | 0.015 µM | 190 |
| 106 | Kelp | Hydrothermal | 2–4 Blue | 20.5 | Cr ⁴⁺ | 0.01–50 µM | 0.52 µM | 191 |
| 107 | Denatured milk | Hydrothermal | 2 Blue | NA | Cr ³⁺ | NA | 14 µM | 192 |
| 108 | Black particulates of petrol soot | Oxidation | 1.5 green | NA | Cr ⁴⁺ | 0–20 × 10 ³ µM | 0.51 µM | 193 |
| 109 | Groundnut | Hydrothermal | 2.5 | 17.6 | Cr ³⁺ | 2–8 µM | 1.9 µM | 194 |
| 110 | Edible seeds | Pyrolysis route | 5–10 | 41.8 | Cr ³⁺ | 1–14 µM | 1.3 µM | 195 |
| 111 | Biomass | Hydrothermal | ~2.4 Blue | 22.6 | Pb ²⁺ | 1.3–106.7 µM | NA | 196 |
| 112 | Ginkgo biloba leaves | Hydrothermal | 4.18 ± 1.14 Blue | 16.1 | Pb ²⁺ | 0.1–20.0 × 10 ^{−3} µM | 0.055 nM | 197 |
| 113 | Black tea | Hydrothermal | 1.0–3.0 nm | NA | Pb ²⁺ | NA | 13.3 nmol L ^{−1} | 198 |
| 114 | Pomegranate juice | Hydrothermal | 2–5 Blue | NA | Ag ⁺ | 8.3 × 10 ^{−4} µM | 38 × 10 ^{−3} µM | 199 |
| 115 | Neem leaves | Pyrolysis and hydrothermal | 5–6 Green and blue | 54 | Ag ⁺ | NA | 0.2–0.6 × 10 ³ µM | 200 |
| 116 | Gum tragacanth | Hydrothermal | 1–1.5 Blue and green | 66.74 | Au ³⁺ | 0–100 µM | 2.69 µM | 201 |



Table 1 (Contd.)

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|---|--------------------------------------|-----------------------------|-------------------|---------------------------------------|---|--|------------|
| 117 | <i>Syzygium cumini</i> | Hydrothermal | 2.1 ± 0.7 | 6.1 | Mn ²⁺ | 0.0075–0.1 mM | 2.1 µM | 202 |
| 118 | Durian shell waste | Hydrothermal carbonisation | 10 | 28.7 | Mn ⁷⁺ | 0–100 µM | 46.8 nM | 203 |
| 119 | <i>Osmanthus fragrans</i> | Hydrothermal | NA | 21.9 | Al ³⁺ | 0.1–100 µM | 26 nM | 204 |
| 120 | Potato starch | Acid-assisted ultrasonic route | 3–5 | 10.0 | Zn ²⁺ | 0–20 µM | 1 nM | 205 |
| 121 | Linters extract | Hydrothermal | 1.15 ± 0.30 | 6.21 | Zn ²⁺ | NA | 6.4 µM | 206 |
| 122 | Whey (major dairy waste) | Pyrolysis | 4 | ~11.4 | Se ⁴⁺ | 10–50 µg L ⁻¹ | 8.48 × 10 ⁵ M ⁻¹ | 207 |
| 123 | Lemon juice | Hydrothermal | 4–5 | 21.0 | V ⁵⁺ | 0–8 ppm | 3.2 ppm | 208 |
| 124 | Roasted chickpeas | Microwave | 4.5–10.3 | 1.8 | Fe ³⁺ | 11.25–37.50 µM | 2.74–8.22 µM | 209 |
| 125 | Gelatin | Hydrothermal | 0.5–5 | 22.7 | Fe ³⁺ | 0–50 µM | 0.2 µM | 210 |
| 126 | Rice husks | Hydrothermal | 1.5–3 | NA | Cd ²⁺ | NA | NA | 211 |
| 127 | Cabbage | Hydrothermal | 2–4 | NA | Fe ³⁺ | NA | NA | 212 |
| 128 | Eggshell membrane | Hydrothermal | 8 | 9.6 | Hg ²⁺ | 10–100 µM | 2.6 µM | 213 |
| 129 | Oyster mushroom (pleurotus species) | Hydrothermal carbonization | 8 | NA | Pb ²⁺ | 10–200 µM | 58.63 µM and 177.69 µM | 214 |
| 130 | Seville orange | Hydrothermal | 4.8 | 13.3 | Fe ³⁺ | 0.033–0.133 mM | 0.53 µM | 215 |
| 131 | Shrimp shells | Calcination | 3–5 | 20 | Cr ⁶⁺ | 0–70 mM | 0.1 µM | 216 |
| 132 | Luffa sponge based activated carbon fibre | Chemical oxidation | 6.8 | 2.1 | Cr ⁶⁺ | NA | NA | 217 |
| 133 | <i>Murrayakoenigii</i> leaves | Hydrothermal | 2–8 | 5.4 | Cd ²⁺ | 0.01–8 µM | 0.29 nM | 218 |
| 134 | Coconut sap | Hydrothermal | 1–7 | NA | Ag ⁺ | 1–70 µM | 0.26 µM | 219 |
| 135 | White wasted foam | Hydrothermal | 6–8 | NA | Cr ³⁺ | NA | 6 µM | 220 |
| 136 | Crown daisy leaves | Hydrothermal | 5.0–10.0 | NA | Cu ²⁺ | 10.0–120.0 nM | 1.0 nM | 221 |
| 137 | Red beetroot | Hydrothermal | 5–7 | 27.6 | Pd ²⁺ | 3–43 µM | 33 nM | 222 |
| 138 | Rice starch | Hydrothermal | 11 | 3.2 | Hg ²⁺ | 3.3 × 10 ⁻⁷ to 50.0 × 10 ⁻⁶ mol L ⁻¹ | 1.8 × 10 ⁻⁷ mol L ⁻¹ | 223 |
| 139 | Kumquat | Hydrothermal | 1.5–4 | 0.08 | Fe ³⁺ | 0–40 µM | 0.70 µM | 224 |
| 140 | Rambutan and Pandan leaves | Hydrothermal and microwave treatment | NA | 2.46 and 2.70 | Cu ²⁺ | NA | 123 µM | 225 |
| 141 | Flax straw | Hydrothermal | 2.2 | 20.7 | Co ²⁺ and Cr ⁶⁺ | 0–500, 0.5–80 µM | 0.38, 0.19 µM | 226 |
| 142 | <i>Tagetes erecta</i> | Hydrothermal | 4–6 | NA | Fe ³⁺ | 0–90 µM | 0.36 µM | 227 |
| 143 | <i>Volvariella volvacea</i> mushroom | Hydrothermal | 5.8 | 11.5 | Fe ³⁺ and Pb ²⁺ | 1–100 µM | 12 and 16 nM | 228 |
| 144 | Quinoa saponin | Hydrothermal | 2.25 | 22.2 | Co ²⁺ | 20–150 µM | 0.49 µM | 229 |
| 145 | Betel leaves (<i>Piper betle</i>) | Hydrothermal | 3–7 | NA | Fe ³⁺ | 0–150 nM | 50 nM | 230 |
| 146 | Grape seeds | Hydrothermal | 8.9 | 27.5 | Cu ²⁺ | 150–500 µg mL ⁻¹ | 0.048 mg L ⁻¹ | 231 |



Table 1 (Contd.)

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|-------------------------------------|----------------------------|-----------------------------|-------------------|---------------------------------------|--|--------------------------------|------------|
| 147 | Maple tree leaves | Hydrothermal | 2–10 Blue | NA | Cs ⁺ | 100–100 nM | 160 nM | 232 |
| 148 | Sugarcane waste | Hydrothermal | 2–6 Blue | 3.34 | Hg ²⁺ | 0–300 µM | 0.1 µM | 233 |
| 149 | Borassus flabellifer | Hydrothermal | 2–7 Blue | 19.4 | Fe ³⁺ | 10–100 µM | 2.01 µM | 234 |
| 150 | Wolfberry | Hydrothermal | 1.55 ± 1 Blue | 22 | Fe ³⁺ | 3 and 100 µmol L ⁻¹ | 3 µmol L ⁻¹ | 235 |
| 151 | Wool keratin | Hydrothermal | 2–6 Blue | NA | Cr ⁶⁺ and Fe ³⁺ | 2.5–50 µM | 14.16 nM | 236 |
| 152 | Water hyacinth | Hydrothermal | 1.2–4.2 Blue | 3.3 | Fe ³⁺ | 0.25–125 µM | 113 nM | 237 |
| 153 | Manihot esculenta | Hydrothermal | 3–5 Blue | NA | Fe ³⁺ | 0–330 µM | 0.084 µM | 238 |
| 154 | Crab-shell | Hydrothermal | 10 Green | NA | Cd ²⁺ | 10–100 µM | 13.65 µM | 239 |
| 155 | Lignocellulosic agro-forest biomass | Hydrothermal | 2–6 Blue | 1.66 | Fe ³⁺ | 50–250 µM | — | 239 |
| 156 | Poria cocos | Hydrothermal | 4.61 Blue | 4.82 | Cr ⁶⁺ | 15.6–62.5 µM | 0.91 µM | 240 |
| 157 | Pig bones | Hydrothermal | 1–4 Blue | 26.4 | Co ²⁺ | 1–100 µM | 0.25 µM | 241 |
| 158 | Corn straw | Hydrothermal | 5 nm | 4.64 | Cu ²⁺ | 0–15 µg mL ⁻¹ and 30–80 µg mL ⁻¹ | 20 µg L ⁻¹ | 242 |
| 159 | Canon ball fruit | Hydrothermal | 11.2 Blue | 7.01 | Fe ³⁺ | 1–20 mg L ⁻¹ and 20–500 mg L ⁻¹ | 4.26 mg L ⁻¹ | 243 |
| 160 | Magnolia grandiflora | Hydrothermal | 12 Blue | NA | Ni ²⁺ | 0.6–3.3 µM | 0.071 µM | 244 |
| 161 | Avocado seeds | Carbonisation | 4.6–3.2 Blue | 9.2 | Cu ²⁺ /Cr ⁶⁺ | 1–10 µM | 0.9 µM | 245 |
| 162 | Tea leaves | Hydrothermal | 2.0–2.5 Blue | NA | Fe ³⁺ | 1.5–4 µM | 0.09 nM | 246 |
| 163 | Morus nigra fruit | Hydrothermal | 3–6 Blue | 24 | Fe ³⁺ | 30–200 µM | 0.04 nM | 247 |
| 164 | Grapefruit juice | Hydrothermal | 3.8 Blue | 84.93 | Cr ⁴⁺ | 0.1–400 µM | 0.079 µM | 248 |
| 165 | Lycium ruthenicum | Hydrothermal | 3.0–6.5 | 21.8 | Ag ⁺ | 5–30 µm | 0.47 µM | 249 |
| 166 | Grass | Reflux method | 20 NA | NA | Cu ²⁺ | 0–400 µM | 0.155 µM | 250 |
| 167 | Myrica rubra | Hydrothermal | 1.72–4.58 nm Blue | 54 | Fe ³⁺ | 0.7–36 µM | 59 nM | 251 |
| 168 | Pseudomonas aeruginosa | Hydrothermal carbonization | 2–6 Blue | 10.2 | Cr ⁶⁺ | 1–20 µM | 0.89 µM | 252 |
| 169 | Curcuma amada | Hydrothermal | 7 Blue | NA | Hg ²⁺ | 1–1000 mM | 0.3 µM | 253 |
| 170 | Gum ghatti | Microwave pyrolysis | 1–7 Blue | 23 | Hg ²⁺ | 0–9 µM | 0.23 nmol L ⁻¹ (nM) | 254 |
| 171 | Neem seed | Microwave heating | ~2 nm Blue | ~12.5 | Au ³⁺ | 1–10 nM | 0.2 nM | 255 |
| 172 | Maize starch | Solvothermal | NA Blue | 6.2 | Cr ⁴⁺ | 0–30 µM | 4.6 nM | 256 |
| 173 | Tinospora cordifolia leaves | Hydrothermal carbonization | 5.47 Blue | 3.7 | Fe ³⁺ | 0–25 µmol L ⁻¹ | 0.34 µmol L ⁻¹ | 257 |
| 174 | Canistel (Pouteria campechiana) | Hydrothermal | ~8.1 Blue | 1.24 | Fe ³⁺ | 0.237–0.67 mg mL ⁻¹ | 0.414 µM | 258 |
| 175 | Wheat straw | Carbonization | 1.73 Blue | NA | Cu ²⁺ | 27–2700 µM | 19.0 µM | 259 |



Table 1 (Contd.)

| Entry no. | Carbon source | Synthesis method | Average size (nm) and color | Quantum yield (%) | Metal ion | Linear range | LOD values | References |
|-----------|--------------------------------------|-----------------------------------|-----------------------------|-------------------|------------------|-----------------------------|--------------------------|------------|
| 176 | Natural rubber | Pyrolysis and hydrothermal method | 2.4 Blue | 0.6 | Mg ²⁺ | 0–250 μM | 4.3 μM | 261 |
| 177 | Elm seeds | Hydrothermal | 3.83 Blue | 6.15 | Fe ³⁺ | 0–500 μM | 3.18 μM | 262 |
| 178 | <i>Crescentia cujete</i> fruit waste | Hydrothermal | 4.36 Blue | 1.57 | Fe ³⁺ | 0–25 μM | 0.257 μM | 263 |
| 179 | <i>Polyalthia longifolia</i> | Hydrothermal | 3.33 Red | 22 | Cd ²⁺ | 2.4 nM | 7.3 nM to 12 μM | 264 |
| 180 | <i>Vitex negundo</i> leaves | Hydrothermal | 6.5 Blue | 12.2 | Mn ²⁺ | 1.25 nM | 10.0–50.0 nM | 265 |
| 181 | Spent coffee grounds | Ball milling | 1.64 ± 0.04 Blue | 3.95 | Fe ³⁺ | 2.25 μM | (0–2 mM) | 266 |
| 182 | Chebulic myrobalan | Hydrothermal carbonization | 2.5 ± 0.5 Blue | 15 | Fe ³⁺ | 0.86 μM | 5–25 μM | 267 |
| 183 | <i>Annona reticulata</i> leaves | Hydrothermal | 6 Green | 12 | Cr ³⁺ | 2 μM | 0 to 40 μM | 268 |
| 184 | Pine needles | Hydrothermal | 3.56 ± 0.85 Blue | 7.65 | Fe ³⁺ | 0.02 μM | 0.1–540 μM | 269 |
| 185 | Cow milk | Hydrothermal | 1–2 Blue | 59.47 | Fe ³⁺ | 0.1–20 μmol L ⁻¹ | 0.6 μmol L ⁻¹ | 270 |
| 186 | Prickly pear | Microwave-assisted | 2.0 ± 0.5 Blue | 14.8 | Cr ⁴⁺ | 0–150 μM | 0.04 μM | 271 |
| 187 | <i>Delonix regia</i> leaves | Hydrothermal | 6.75 ± 2.5 Red | 7 | Pb ²⁺ | 10–180 μM | 3.3 nM | 272 |

limit in drinking water has been reported to be ~15.0 ppb.¹²² Several inorganic nanomaterials such as ZnS, gold, CdS, polymer dots, and enzyme-based sensors have been utilized as fluorescent probes for the detection of Pb²⁺ ions. However, such methods have drawbacks of high cost. Thus, the development of low-cost and eco-friendly materials for the sensing of Pb²⁺ continues to be an active area of research. CQD-based sensors have attracted considerable attention due to their eco-friendly synthetic approaches. Kumar *et al.* reported the CQDs synthesized using *Ocimum sanctum* and used them for the detection of Pb²⁺ in real water samples. The quenching of fluorescence emission intensity was observed in the presence of Pb²⁺ ions with an LOD value of 0.59 nM and a QY of 9.3%. The decrease in the fluorescence intensity of CQDs attributed to the electron-hole recombination, which occurs due to the high binding affinity between the empty d-orbital of Pb²⁺ ions and the amine group present on the CQD surface.¹²³ N-CQDs have been prepared using *Lantana camara* berries thoroughly studied for FL quenching mechanism for both dynamic and static processes. The results of Stern-Volmer plots obtained at three different temperatures confirm the direct relation between the quenching constant and temperature. These N-CQDs efficiently sense Pb²⁺ ions in human urine and serum as well as in water samples. With the increase in Pb²⁺ concentration, a decrease in the fluorescence intensity at 450 nm was observed, confirming the selectivity of CQDs towards Pb²⁺.⁵⁰ CQDs having an average size of 3.5 nm have been synthesized using sugar for the sensing

of Pb²⁺ ions. Carboxylate group-induced aggregation process has been responsible for fluorescence quenching, which was confirmed by FTIR and XRD data. These CQDs have also been used for the detection of Pb²⁺ ions in real water samples.⁸⁸ Furthermore, fluorescent CQDs synthesized with bamboo leaves have been used for the selective detection of Pb²⁺ ions in river water and further employed for environmental monitoring for water safety and waste management.¹²⁴

Other cation detection

CQD-based fluorescent sensors have been reported for other heavy metal ions besides those discussed above. Several mechanisms have been reported for the detection of different metal ions using CQD-based sensors, which might be due to the presence of different functional groups on CQDs since they have been synthesized using different carbon precursors. Tyagi *et al.* reported the synthesis of spherical shaped water-soluble CQDs of 1–3 nm size using lemon peel waste as the carbon source with a QY of 14%. These CQDs showed good water solubility due to the presence of oxygen-containing groups on their surface. Further, these CQDs were used as “turn off” fluorescent probes for the detection of Cr⁶⁺ ions in aqueous solutions with an LOD value of ~73 nM. The higher selectivity of CQDs towards Cr⁶⁺ ions is due to a higher thermodynamic affinity in the concentration range of 2.5–50 μM with a linear response.¹²⁵ The schematic representation of CQDs synthesis using lemon peel waste is shown in Fig. 13.



Arumugam *et al.* reported the selective detection of Ag^+ ions using water-soluble fluorescent CQDs synthesised from broccoli. These CQDs exhibit bright blue luminescence with an LOD value of $0.5 \mu\text{M}$ for Ag^+ ions.³⁹ Yu *et al.* reported the synthesis of N-CQD from *Osmanthus fragrans* with a QY of 21.9%. Further, these N-CQDs were used as fluorescent nano sensors for Al^{3+} ions. The sensing ability was found to be in the range of $0.1\text{--}100 \mu\text{mol L}^{-1}$ towards Al^{3+} ions with an LOD value of 26 nmol L^{-1} .⁴² Quince fruit has been utilized for the synthesis of CQDs, and the influence of various anions and cations on the PL quenching of prepared CQDs was investigated. It was found that MnO_4^- and Fe^{3+} exhibit intense effects on the PL properties. Oxidising agents such as KMnO_4 are capable of introducing holes into CQDs, which further leads to an increased population of holes in CQDs and speeds up electron-hole annihilation, resulting in energy release in the form of chemiluminescence emission while simultaneously decreasing the fluorescence intensity of CQDs at the maximum emission wavelength. Additionally, it has been found that at varying pH levels, permanganate can also oxidise As^{3+} . Considering these phenomena, the potential application of synthesised CQDs for As^{3+} ions was evaluated.¹²⁶ Radhakrishnan *et al.* reported the sensing of As^{3+} ions by CQDs synthesized using prickly pear cactus fruit passivated with glutathione. The quenching mechanism was investigated to be static in nature.¹²⁷ Dutta *et al.* synthesised N-CQDs using ethylene diamine (as nitrogen source) and *Nerium Oleander* L. Petals (as carbon source). The emission intensity of Rhodamine 6G and N-CQD systems gets quenched after the addition of Co^{2+} ions, most probably due to the hindrance of the FRET mechanism.¹²⁸ Further, Zhao *et al.* reported N-CQDs synthesized using kelp and ethylenediamine for the detection of Co^{2+} ions in real water samples. IFE was reported as a plausible fluorescence quenching mechanism, which was confirmed through the overlapping of absorption and emission signals and lifetime measurements.¹²⁹ Hydrothermally synthesised CQDs using pear fruit were utilised as “turn-on” sensors for the detection of Al^{3+} ions in real water samples and found to follow chelation-enhanced fluorescence emission mechanism (CHEF). The interactions of carboxylic and amine groups on CQDs with Al^{3+} ions have been used to explain the CHEF process. Au^{3+} ion sensing in real river water has been reported using N-CQDs synthesized from natural peach gum polysaccharide and ethylenediamine.¹³⁰ Several different metal ions detected using green CQD-based sensors are summarised in Table 1.

Conclusions and future perspective

The studies reported in the literature revealed that the CQDs are one of the fascinating materials of the 20th century due to their inherent physical and chemical properties. Their easy synthetic procedure and low cost of synthesis are the additional advantages. This review presented the recent progress in green synthesis of CQDs and their applications for heavy metal ion sensing. The functional groups present on the surface of CQDs have been found to be dependent on the green precursor used for their synthesis. The major factors influencing the synthesis of CDs

include molecular state, surface state, as well as the quantum confinement effects, and these factors can be easily controlled by altering the strategies for CD synthesis. During the synthesis of CDs, several functional groups such as amine, epoxy, ether, carbonyl, carboxyl, and hydroxyl can be incorporated. Besides, the surface of CDs can be easily functionalized by doping them with heteroatoms such as N, P, S, and B using various biological, polymeric, and organic materials. Henceforth, the properties of CDs can be regulated by varying the size and extent of the surface functional groups by either adapting different synthesis techniques or using other precursors. The modification of CDs is crucial for achieving the considerable surface attributes for solvency as well as their favourable applications.

Due to the presence of different surface functionalities, these CQDs have been found to show different photo-luminescence behaviors. It has been observed that the different surface functional groups can interact with different sets of metal ions, and hence, the CQDs synthesized using different carbon sources can sense different metal ions. Thus, CQDs are the potential candidates for the detection of metal ions including environmental toxins such as mercury and lead. These chemosensors have showed low LOD values, which indicate their higher efficiencies. However, several challenges associated with CQDs are mainly their large-scale synthesis, isolation and purification. Several research groups are working near these lines for sustainable and viable use of CQDs.

Researchers are looking into a variety of carbon sources including agricultural by-products, biomass and food waste in order to establish environmentally friendly and low-cost routes to produce CQDs. These carbon sources are plentiful, renewable, and less expensive, which make them appealing alternatives to traditional sources. CQDs have the potential to be used in a variety of fields including bioimaging, optoelectronics and sensing. Undoubtedly, there will be challenges in improving the luminescence, quantum yield and electrochemical performance, and there is limited information on the mechanism of CQD synthesis, which researchers should consider further. In addition, the utilisation of green carbon sources for CQD synthesis is predicted to be beneficial for the development of sustainable technology.

Conflicts of interest

There are no conflicts to declare.

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