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Carbon quantum dots as emerging biosensors for food safety and environmental applications: Advances and challenges

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ABSTRACT

Carbon quantum dots (CQDs) are the particles confined in all dimensions which often referred as zero dimensional nanomaterials. CQDs are becoming highly versatile nanomaterials because of their photocatalytic tunability, high biocompatibility, low cytotoxicity, and environmentally friendly synthesis pathways. This review provides a detailed overview of recent advances in the synthesis, functional properties, and application of CQDs as biosensors for food safety and environmental monitoring. Review classifies synthesis methods into top-down and bottom-up methods, with special focus on green and sustainable processes using biomass and food waste. CQDs' distinctive optical, antioxidant, and antimicrobial characteristics are discussed with respect to their applicability in food contaminant detection, heavy metal detection, pathogens, and food additive detection. In addition, their application in smart packaging and real-time indicators of spoilage is considered. Specific limitations including low fluorescence quantum yield, no reproducibility of synthesis, and a lack of long-term biosafety data have been critically assessed. Lastly, concluded by outlining future directions such as CQD-based wearable biosensor development and new functionalization strategies to further improve sensitivity and stability. This review gives an excellent insight into the use of CQDs as future-generation biosensing materials, providing a pathway towards their scale-up and secure application in food and environmental industries.

1. Introduction

Carbon quantum dots (CQDs) are fluorescent nanomaterials that have a zero-dimensional structure (Shafi et al., 2024). They provide several advantages, including excellent biocompatibility, resistance to photo-bleaching, and straightforward manufacturing processes. Carbon dots (CDs) are categorized into graphene carbon dots (GQDs), CQDs, carbon nanodots (CNDs), and carbonized polymer dots (CPDs) based on the carbon core structure, the presence of surface functional groups, and the consequent variations in characteristics (F. Wang et al., 2025). CDs have recently emerged as a viable rival to traditional heavy metal-based quantum dots, particularly due to their promise as a more environmentally friendly and compatible substitute. These nanoparticles are spherical and have a size of zero dimensions. They are soluble in water and can emit light, which can be adjusted. They are also stable when exposed to light. These nanoparticles show great potential in several fields such as sensing, photo-catalysis, and biomedicine. So far, CDs have been created utilizing many methods such as hydrothermal,

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Abbreviations: CQDs, Carbon quantum dots; CDs, Carbon dots; GQDs, Graphene carbon dots; CNDs, Carbon nanodots; CPDs, Carbonized polymer dots; CVD, Chemical vapor deposition; QY, Quantum yield; SET, Surface energy transfer; IFE, Inner filter effect; FA, Folic acid; AAP, Ascorbic acid phosphate; CMC, Carboxymethyl cellulose; BAs, Biogenic amines; DESs, Deep eutectic solvents; MTT, Methyl thiazolyl tetrazolium; PET, Photoinduced electron transfer; LUMO, Lowest unoccupied molecular orbital; HOMO, Highest occupied molecular orbital; MACDs, Malic acid carbon dots; SWCNTs, Single walled carbon nanotubes; N-CQDs, Nitrogen-doped CQDs; S-CQDs, Sulfur-doped CQDs.

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solvothermal, arc discharge, pyrolysis, laser ablation, and electrochemical carbonization techniques, using a range of chemical and natural substances as starting materials (R. Li et al., 2025; Yosri et al., 2025). Among these options, the hydrothermal strategy is an efficient one-step bottom-up method that is commonly utilized as a green approach.

In addition, significant attention is now focused on the synthesis of carbon dots from natural resources due to the advantageous ecological and sustainable properties of the starting material. These precursors are said to include significant quantities of cellulose, protein, amino acids, flavonoids, and other substances (Ghahremani et al., 2025; Shan et al., 2025). Additionally, they are touted for their low cost and easy accessibility. The optical characteristics and physiological effects of carbon dots are contingent upon the composition and can fluctuate depending on the selection of the initial substance. Various biomasses such as tomato, potato, banana, lemon, grape juice, mango leaves, coriander leaves, neem extract, pomegranate, apple juice, milk, egg, mint leaves, and algal blooms have been investigated for their potential in this extensively used approach (Kumar & Rhim, 2024; Pengsook et al., 2025).

The variety of materials suitable for synthesizing CQDs is extensive, encompassing any substance that contains carbon, including massive carbon structures (e.g., carbon targets), organic molecules, and biomass materials (Murugesan et al., 2025). Biomass materials can be obtained from several sources, such as natural biomass (such as food waste, straw, and crab shells), biomass fractions (such as cellulose and lignin), and micro-molecules generated from biomass (such as citric acid and glucose) (Ezati, Priyadarshi, et al., 2022). Currently, the generally employed techniques for preparation include hydrothermal method, microwave-assisted method, pyrolysis method, and others. The produced colloidal quantum dots typically exhibit a poor fluorescence quantum yield and possess a singular functionality (Chen et al., 2022). Enhancing the functionalization of CQDs can enhance their luminescent properties and enable them to directly or indirectly attach to other substances (Wen et al., 2023). CQDs have been employed for the identification of heavy metal ions, insecticides, and antibiotics, as well as for photocatalytic cleaning and various other applications (Deka et al., 2022). Regarding the detection of substances in food, the combination of CQDs with biology and immunology can be utilized to enhance the accuracy and sensitivity of detection (Madhu et al., 2025). CQDs can detect heavy metal ions as well as be combined with antibodies, nucleic acid aptamers, and other nanomaterials for the qualitative/quantitative detection of certain organic compounds or bacteria (M. Li et al., 2025). These characteristics make them ideal candidates for novel techniques and approaches in the field of bio-sensing, specifically for quick detection purposes. The present obstacles in the advancement of CQDs in food safety are enhancing fluorescence quantum yield, expanding the utilization of agricultural and food waste as raw materials for their production, and creating novel detection applications for food products (Naseer et al., 2025; Riahi et al., 2025). This review discusses the characteristics, methods of preparation, and ways to enhance the functionality of CQDs. The primary focus is on the application of CQDs in ensuring food safety. Additionally, the detection principles of various types of CQDs are explored, along with the factors that affect the detection and processing of toxic and hazardous substances. To tackle the greater potential of CQDs, it is important to objectively analyze the extensively documented setbacks that limit their real-world use. These range from low and unreliable fluorescence quantum yield, low reproducibility related to the varying synthesis methods, limited selectivity towards complicated food and environmental systems, and issues with long-term stability and storage. Also, regulatory ambiguities and limited biosafety information further limit their commercial translation, particularly in food applications. Despite increasing interest, most reviews are short on in-depth coverage of these practical restraints. Hence, this article not only summarizes recent developments but also includes comparative analyses and underscores information from recent reviews with the aim of providing a balanced overview. By tackling important issues like stability, selectivity, and regulatory compliance, the review offers a critical basis for future work and responsible creation of CQD-based technologies.

2. Synthesis of CQDs

Numerous investigations have been conducted on the various carbon dot production techniques. Every procedure seeks to enhance the synthesis plan and optimize the reaction conditions in order to produce carbon dots that perform better and are more economical and environmentally friendly. The two basic categories of synthesis methods are "top-down" and "bottom-up," which are based on the carbon source and the procedure utilized (Aksu & Güzdemir, 2025). Bottom-up is easier, less expensive, and more often used than top-down. Fig. 1 summarizes the most popular CQD synthesis techniques together with their benefits and drawbacks.

2.1. *Top-down method*

The synthesis pathways that use oxide reduction as a carbon source are among the top-down techniques used to create CQDs (Rani & Shanker, 2025). CQDs have been produced using a variety of carbon sources, including graphite (Nejatpour et al., 2025), candle soot (Kempahanumakkagari et al., 2025), carbon rods (Karami et al., 2025), etc. The electrochemical processes route is one of the top-down approaches for creating CQDs (Zare et al., 2025), laser ablation (Kaur et al., 2025), and high energy ball milling (Hesham et al., 2025). For example, one of the earliest methods for creating CQDs was the purifying of single sealed nanotubes made of carbon (SWCNTs) from arc-discharge soot. Nitric acid was used to oxidize the arc-discharge soot, and a NaOH solution was used to remove it. The resulting substance was separated using a gel electrophoresis implementation. which detached the suspended particles into three substance classes: sufficient-sized nanotubes that could not pass through the gel, short enough wavy structures with a sluggish band, and CQDs with luminescence features with a rapid band (Y. Wang et al., 2025). (Kaur et al., 2025) also manufactured the CQDs using laser ablation, which is likewise a top-down approach, following the previously described top-down method. Carbon nanoparticles were produced by the laser treatment of a carbon target using argon as the transport gas. Water vapor was introduced to the chemical reactions chamber at 75 kPa and 900°C. The aggregates of carbon nanoparticles were then refluxed with nitric acid for 12 hrs. The dots became photoluminescent after the product was surfaces treated with naturally derived species.

2.2. *Bottom-up method*

The bottom-up methods may be employed for large-scale CQD productions and are easier to implement. The constituent molecules and polymer may undergo dehydration and consequent carbonization in the majority of from the bottom up techniques, leading to the creation of CQDs or PDs (Zhang et al., 2025). The techniques such as solvothermal, hydrothermal, chemical vapor deposition (CVD) microwave-assisted methods, combustion, and ultrasonic-assisted methods are categorized under bottom-up approaches in the synthesis of CQDs (Mao et al., 2025; Sul et al., 2025). For instance, CQDs were created by pyrolyzing citric acid in one step at temperatures of < 200°C with branched-polyethylenimine (BPEI). This produced polyamine-functionalized CQDs with a 42.5% quantum yield (QY) (Fu et al., 2025).

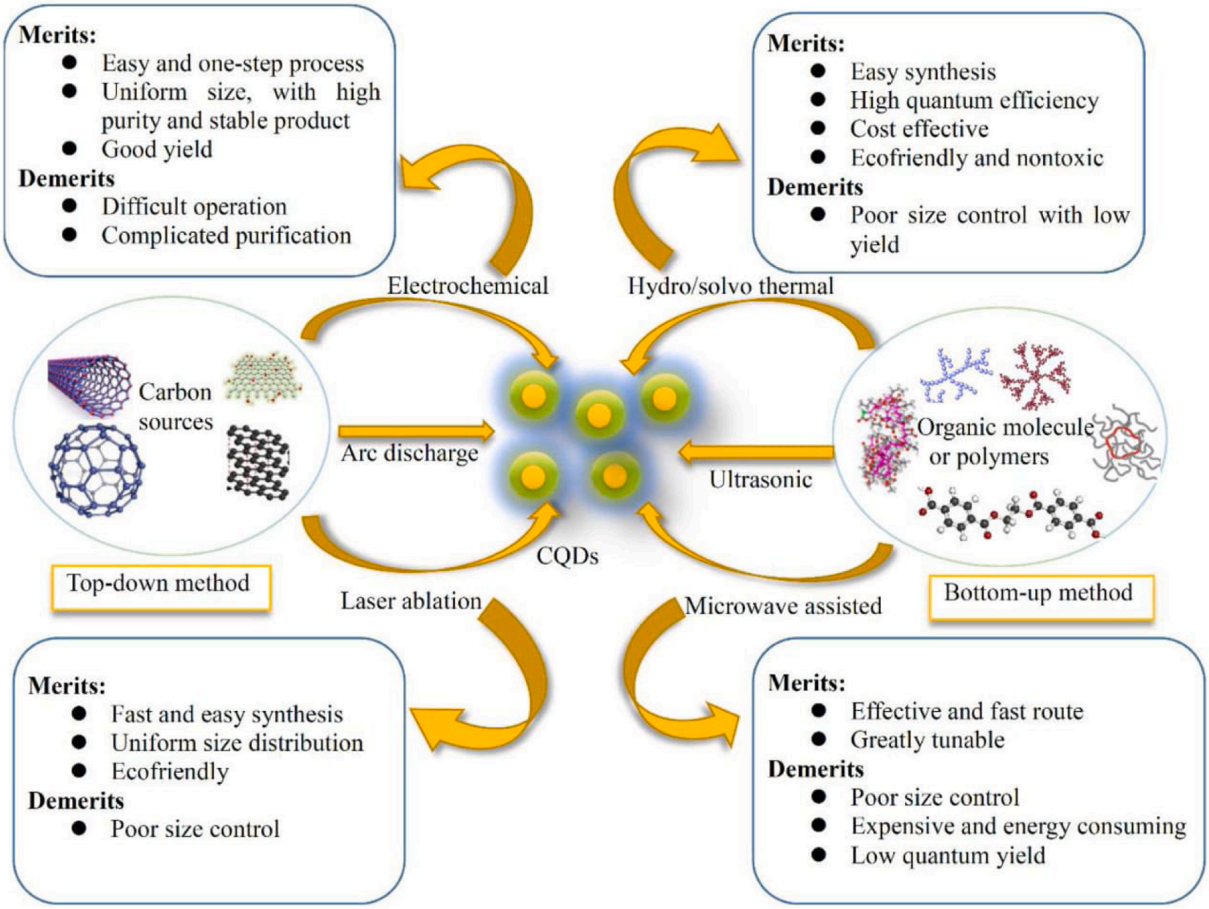

Fig. 1. Schematic diagram of various synthesis methods of CQDs and their advantages and disadvantages. Fig. 1 is adapted with permission (copyright © 2023 Elsevier Ltd., Amsterdam, the Netherlands) from (Khan et al., 2023).

3. Properties of CQDs

3.1. Light absorption

Using fruit juice from *Actinidia deliciosa* as a carbon precursor and ammonia from water as a nitrogen dopant, this article explains the environmentally friendly production of fluorescent nitrogen doped carbon dots (N-CDs). X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, fluorescence spectroscopy, UV-visible spectroscopy (UV-Vis), energy dispersive spectroscopy (EDS), Fourier transform infrared spectroscopy (FTIR), selected area electron diffraction (SAED), and high-resolution transmission electron microscopy (HR-TEM) were employed to investigate the artificially produced N-CDs (Arul & Sethuraman, 2018). The computed inter-layer distance was 0.21 nm, while the average size of the N-CDs was roughly 3.59 nm. The synthesized N-CDs' graphitic character was demonstrated by the SAED pattern and Raman spectroscopy. When excited at 315 nm, the N-CDs were observed to emanate a strong blue hue at 405 nm. FTIR, EDS, and XPS analyses verified that nitrogen was doped across the N-CDs' surface. It was discovered that the produced N-CDs had outstanding catalytic activity when Rhodamine-B was reduced with sodium borohydrate. The cytotoxicity and biocompatibility of N-CDs to L-929 and MCF-7 cells were assessed using the MTT test. According to the data, N-CDs have excellent biocompatibility and minimal cytotoxicity on both L-929 and MCF-7 cells (Arul & Sethuraman, 2018).

Researchers from a wide range of disciplines have recently focused a great deal of attention on CQDs because of their special characteristics. For the first time, a novel use of a CQD-based hybrid as a superior electrode material for supercapacitors is documented in this work. A simple chemical oxidation process is used to create the CQDs, which are then thermally reduced and further ornamented with RuO_2 to create the composites (Zhu et al., 2013). The hybrid has exceptional rate capability (88.6, 84.2, and 77.4% of capacity retention rate at 10, 20, and 50 A g^{-1} compared with 1 A g^{-1}) and a specific capacitance of 460 F g^{-1} at an ultrahigh current density of 50 A g^{-1} (41.9 weight percent Ru loading). The hybrid exhibits remarkable cycling stability, retaining 96.9% of its capacity after 5000 cycles at 5 A g^{-1}. The formation of a CQD-based hybrid network structure that can support rapid transportation of charges and ionized motion during the charge–discharge process, as well as the significantly improved utilization of RuO_2 made possible by the effective dispersion of tiny reduced CQDs, are the main causes of these outstanding electrochemical performances. Furthermore, it is determined that a critical element influencing the hybrid's performance is the contact resistance at the interface among active substances and current collection devices. The findings show how promising CQD-based hybrid materials are for creating high-performance super capacitor electrode components.

3.2. Photoluminescence

CQDs is distinguished by its graphitic core and shell layers that are packed with functional groups and hydrogen atoms. Both top-down and bottom-up methods are used to create CQDs from artificial and organic precursors. To modify their properties, CQDs can be altered chemically (surface functionalization/passivation, doping, etc.) and physically (core–shell structure, material composite mixing, etc.) (John et al., 2021). Researchers discussed the latest developments and potential uses of CQDs enhanced by physical and chemical changes to their composition and structure in optical (such as fluorescent ink sensing, and bioimaging) and catalytic (such as electrocatalysis and photocatalysis) applications (Fig. 2). A new fluorescent subclass of the carbon nanomaterial family, CDs have been seen as a flexible new platform for a wide range of applications. Photoluminescence correlative applications are at the forefront of this cutting-edge research because of CDs' excellent chemical scalability, low cost, and benign biocompatibility (Li & Dong, 2018).

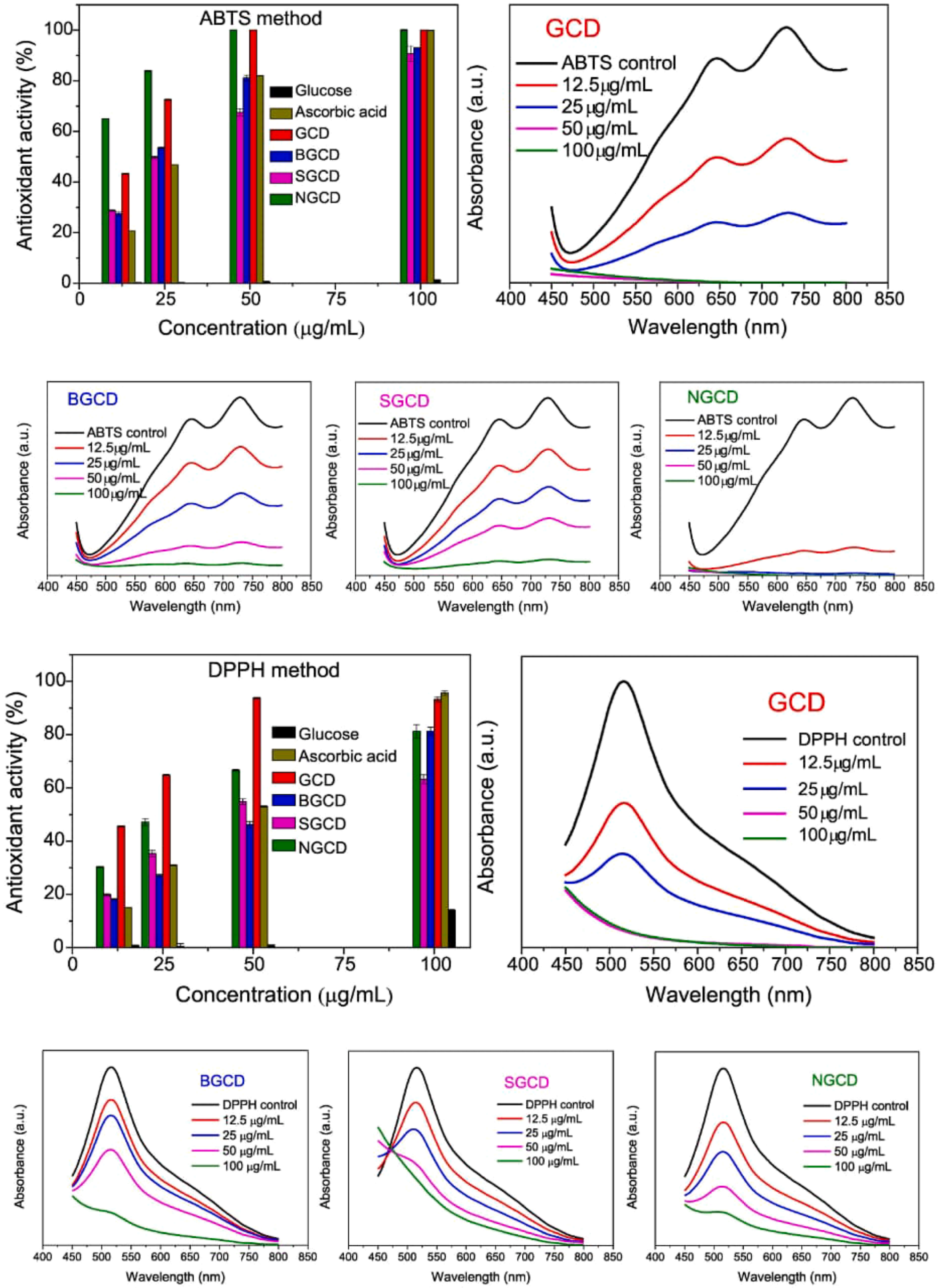

Fig. 2. Absorption spectra of DPPH and ABTS solutions with varying concentrations of GCDs, showing antioxidant activity and photoluminescence properties of CQDs as fluorescent probes. [GCD: Glucose Carbon Dot; BGCD: Boron-doped GCD; SGCD: Sulfur-doped GCD; NGCD: Nitrogen-doped GCD]. Fig. 2 is adapted with permission (copyright © 2022 Elsevier Ltd., Amsterdam, the Netherlands) from (Ezati, Rhim, Molaei, Priyadarshi, et al., 2022).

It is discovered that the photo-blinking capabilities of as-synthesised malic acid carbon dots (MACDs) are exceptional and better than those of traditional dyes. They shows in fixed and live trout gill epithelial cells that malic acid carbon dots are appropriate for super-resolution fluorescence localization imaging under various settings due to their high biocompatibility (Zhi et al., 2018). Furthermore, the so-called "excitation wavelength-dependent" emission was not detected for individual as-made malic acid carbon dots during imaging experiments. This led us to create a high-throughput, time-efficient method of separating malic acid carbon dots using C18 reversed-phase silica gel column chromatography into fractions with varying particle size distributions. They are able to ascertain how the particle size distribution affects the optical characteristics of the CD fractions of malic acid, namely the optical band gap energies and photoluminescence behaviours, thanks to this post-treatment (Zhi et al., 2018). They discovered that the bandgap energy and photoluminescence (PL) properties are affected by the MACDs' particle size. Special optical characteristics of CDs include excitation-dependent multicolour emission and PL. Analyte detection can be achieved by quenching and recovering the fluorescence of CDs. Although the static quenching mechanism of CDs was easy to verify, the process required a reaction between the CDs and the quencher, so the CDs had to be modified. This could make the operation more complex. Tartrazine, Fe^{2+}, Hg^{2+}, Fe^{3+}, glyphosate, Cu^{2+}, dopamine, and hemoglobin could all be detected via the stationary quenching system of CDs.

Quenchers can quench the fluorescence of CDs using a variety of techniques, including inner filter effect (IFE), surface energy transfer (SET), dexter energy transfer (DET), photoinduced electron transfer (PET), Fluorescence resonance energy transfer (FRET), and dynamic quenching (Zu et al., 2017). It was easy to confirm the static quenching mechanism of CDs; however, the static quenching process required some response. The process of altering the CDs was necessary because the static quenching mechanism of the CDs allows for the detection of Hg^{2+}, Fe^{3+}, Fe^{2+}, Cu^{2+}, dopamine, glyphosate, haemoglobin, and tartrazine. The procedure of confirming the FRET and PET mechanisms of CDs is complex and requires calculating the values of lowest unoccupied molecular orbital (LUMO), highest occupied molecular orbital (HOMO), energy transfer efficiency, cyandFörster distance, etc. In contrast to the static quenching mechanism of CDs, the quenchers utilized in the dynamic quenching of CDs did not need to react with CDs (Zu et al., 2017). The IFE quenching of CDs was less expensive and complex than using the IFE quenching of CDs to develop strategy because, in contrast to the other processes, it did not involve the alteration of CDs or extensive computations to validate the IFE quenching of CDs. The IFE quenching mechanism of CDs allows for the detection of Cr^{6+}, sulfide ions, ascorbic acid, fluazinam, picric acid, hemoglobin, β-glucuronidase, and alkaline phosphatase. The procedure of using the IFE quenching of CDs to build a method was simple, but it is anticipated that this technique will be applied to other fields in the future, even though all of these quenching processes are capable to small molecules, detect ions, and biomacromolecules.

3.3. Antioxidant activity

Considering its possible use in the food sector, CQD's antioxidant activity is crucial from a business perspective. Numerous research teams have presented methods and clarified the cellular level free radical scavenging capability of CQDs. For instance, utilizing electrochemical tests and UV-vis light absorption, a luminous N, S-CQD correlated with concentration free radical scavenging capacity was investigated towards Lucigenin-CL test and DPPH radicals that are free (Zhang et al., 2018). In the Lucigenin-CL experiment, which assessed the xanthine or xanthine oxidase reaction and the formation of ROS, particularly super oxide anion free radicals, they demonstrated that co-doped CQDs displayed antioxidant effects. In a different work, we used the ABTS and DPPH tests to evaluate the antioxidant capacity of CQD & heteroatom (N, S, and B) doped CQDs against ascorbic acid (Ezati, Rhim, Molaei, Priyadarshi, et al., 2022). Undoped CQDs showed 100% ABTS and DPPH activity as free radical scavengers at 50 μg/mL, whereas ascorbic acid showed 80% and 53% antioxidant activity at the same dosage. N-doped CQDs showed 65% and 30% antioxidant properties against ABTS and DPPH at a much lower dose of 12 μg/mL, whereas ascorbic acid showed about 20% scavenging capability in both free radical elimination procedures (Fig. 2). CQDs have remarkable antioxidant activity because to their high dispersibility in doping martial, surface hydroxyl groups and aqueous solution. The capacity of CQDs to scavenge free radicals is due to the generation of ROS. Through intracellular and extracellular interactions, such free radicals can be reduced and extinguished by hydrogen donation, adduct formation and electron transfer from the CQDs' hydroxyl, peroxynitrite, superoxide anion superoxide, and nitric oxide. (Roy et al., 2022). As a result, it suggests that CQD has enormous promise for a range of uses, such as biological mechanisms and food packaging, where antioxidant resistance is required.

3.4. Antimicrobial activity

Over the past ten years, there has been a lot of interest in food safety and biomedical applications due to CQD's exceptional antibacterial activity against a variety of microbial strains. Numerous studies have shown the safety of CQDs for potential future human contact applications as well as their effectiveness in biological applications such as bioimaging, medication delivery, photodynamic treatment and biolabeling (Chen et al., 2025). Apart from their water solubility and biocompatibility, CQDs have advantageous characteristics such adsorption interactions and tunable surface functional groups because of their tiny size and ability to adhere to biological surfaces for antibacterial reasons. Because of their distinct physical and chemical characteristics, CQDs are among the most promising nanomaterials. Polymers are utilized to enhance QDs' ability to adhere to bacteria, hence boosting their antimicrobial efficacy (Rajendiran et al., 2019).

The primary barrier to using CQD exceptional optical qualities is non-radiative decay. Furthermore, the passivating agent and CQD size affect their optical characteristics (Mahat et al., 2022). Several functionalization techniques have so been created to improve the optical characteristics of CQDs. In this study, size-controlled synthesis of CQDs within cetyltrimethylammonium bromide (CTAB-CQDs) of 25 nm was accomplished to stabilize their outstanding optical and antibacterial activity with a zone of inhibition of 18 mm with minimal toxicity at 86% cell viability and potent levels of 10 μg/mL. As a surface-passivating an agent, CTAB connected with bacterial cells via electrostatic attraction and reacted with CQDs via charges that were positive from amino groups ($-NH_2$). In order to improve the optical and antibacterial abilities of CQDs, CTAB enclosed them by the amide linkages and created micelles (Mahat et al., 2022). These CQDs' absorbance spectrum changed because of surface state modification and electrostatic contact processes that connected them to CTAB. The CQDs and CTAB-CQDs show excellent biocompatibility with Vero cells at their maximum effective dose of 10 μg/mL, according to a toxicity test. CQDs are a promising antibacterial agent against gram-negative bacteria, like *Escherichia coli*, which are more resistant than gram-positive bacteria, according to the antimicrobial outcome (Mahat et al., 2022). As a result, altering CQDs with CTAB changes their cytotoxicity and antibacterial properties, which may result in the creation of novel, effective instruments for biofilm and bactericides imaging at the same time.

As an eco-friendly resource, microbial biomass has garnered significant interest as a green biological material for the creation of distinctive and customized CDs. However, bacterial nanocellulose's high porosity and hydrophilic properties make it an ideal matrix for CDs with UV blocking, antimicrobial, and photoluminescent properties (Kousheh et al., 2020). For the first time, *Lactobacillus acidophilus* cell-free supernatant was used to create and characterize antimicrobial CDs using a hydrothermal process. Gram-negative *E. coli* and gram-positive *Listeria monocytogenes* were used to test the antimicrobial activity of CDs.

Additionally, the as-prepared CDs were implanted into nanocellulose using the ex-situ approach to create antibacterial and UV-protective nano-paper. High-hydroxylated groups were used to create the photoluminescent CDs, which had an average size of 2.8 nm (Kousheh et al., 2020). The CDs exhibited antibacterial action against both bacteria at a dosage of 500 mg/mL. Furthermore, in UV light, the nano-paper appeared to glow. In contrast to nanocellulose, nanocellulose exhibited the proper stretchability and flexibility with a CD loading capacity of 71.74 ± 4.13 mg/cm^2. Additionally, compared to gram-negative bacteria, the CD-incorporated nano-paper showed stronger ultraviolet-blocking properties and inhibitory effect against gram-positive bacteria. Because of their fluorescence appearance, CDs can be employed as a unique fluorescence antimicrobial/ultraviolet protection material in the nanocellulose film to create packaging that is both antibacterial and impenetrable (Kousheh et al., 2020). According to Travlou et al. (2018) manufactured nitrogen-doped CQD (N-CQD) and sulfur-doped CQD (S-CQD) and used the MIC, or minimum inhibitory concentration, quantitative and qualitative disk diffusion test to assess their ability to inhibit bacterial growth against Gram-negative (*E. coli*, CECT 831) bacteria and Gram-positive (*Bacillus subtilis subsp. subtilis* 168) (Travlou et al., 2018). With a MIC of 32 mg/mL, they discovered that N-CQD and S-CQD exhibited exceptional antibacterial efficacy against both test microorganisms. Bacterial mortality arises from an electrical connection among protons that take the form of enriched CQDs and molecule of emphasize in the microbiological cell wall.

4. Characterization of CQDs

The source typically determines the chemical structure of CQDs, which might affect the characteristics, reaction parameters, and production process. As a result, there are several ways to describe the structure of CQDs. The features and characterization process of CQDs are displayed in Fig. 3. In particular, the CQDs' morphology, aspect ratios, size distributions, and compositions are provided by TEM, EDX, and elemental mapping. For CQDs in the 1–10 nm range, TEM images often displayed a quasi-spherical form (Rezaei & Hashemi, 2021). The amount of thickness or roughness of the surface of CQDs may be measured using AFM. The crystal planes of CQDs are measured in more detail using XRD and SAED. A peak for highly crystalline carbon is seen at 23° in an XRD arrangement of CQDs, and two further peaks at 25° and 44° are linked to (002) and (100) diffraction, which show a low-graphitic carbon architecture (Yadav et al., 2023). FTIR spectroscopy is used to examine the overall structure, functional groups at the surface, and dopant collaboration with the CQDs (Shabbir et al., 2023). XPS is commonly used for surface analysis and compositional studies to determine the elemental content of CQDs and the chemical composition of heteroatoms. Carbon atoms were represented by peaks in the high-resolution spectra of C 1 s at 284.8, 286.5, and 288.2 eV (Ezati, Priyadarshi, et al., 2022). The thermal resistance of CQDs is evaluated using TGA. UV-visible radiation spectra are used to evaluate the light absorption of CQDs. Bands at 310 and 355 nm demonstrate the n-π^* conversion on the outermost layer of the CQDs, whereas the light absorbance peak at 230 nm identifies the π to π^* transition. The PL characteristic of CQDs is provided via profluorescence spectrum of emission. Following excitation at 355 nm, a PL emissions peak was seen at 450 nm (Cao et al., 2022).

To better elucidate CQDs' structure–property relationships, sophisticated characterization techniques have been utilized in addition to traditional methods. Atomic-resolution imaging by aberration-corrected transmission electron microscopy (AC-TEM) enables accurate visualization of lattice fringes and defects that are pivotal to optimizing the optical and electronic properties of CQDs (Rezaei & Hashemi, 2021). In addition to this, time-resolved photoluminescence (TRPL) spectroscopy offers indications of the fluorescence lifetime and recombination dynamics of excited carriers, which account for quantum confinement and surface passivation effects (Yadav et al., 2023). Raman spectroscopy is also commonly used to examine graphitic order and defect density via the D and G bands, providing a better understanding of structural integrity (Shabbir et al., 2023). In addition, zeta potential measurement is commonly carried out to identify the surface charge and colloidal stability of CQDs in water suspensions (Cao et al., 2022). All these supporting techniques together help to provide a more holistic assessment of the structure–function relationship in carbon quantum dots and enable their application-related optimization.

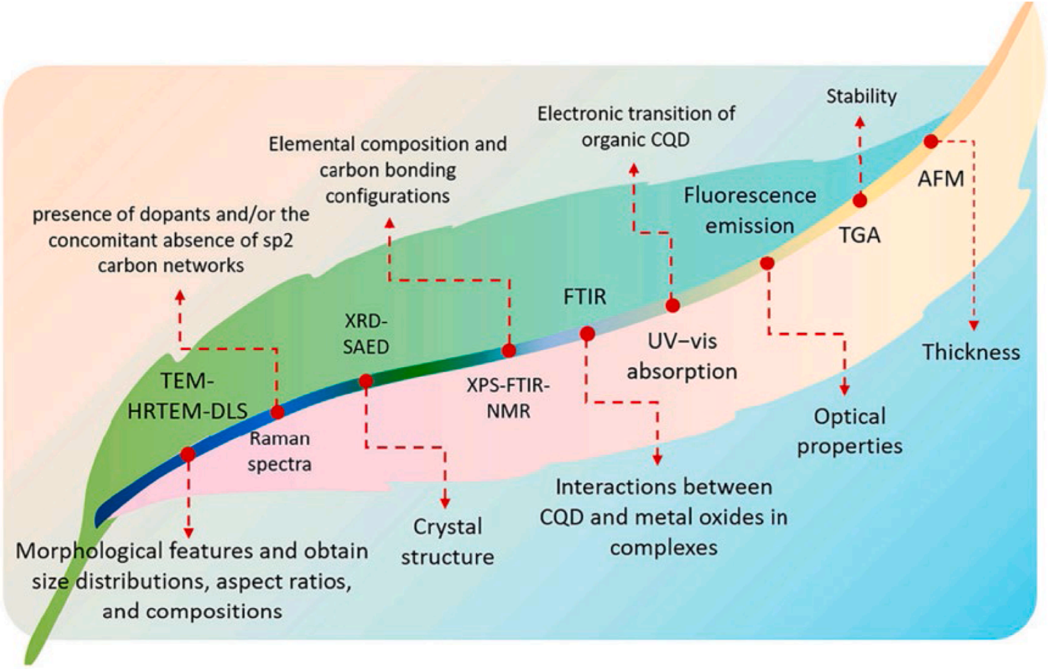

Fig. 3. Characterization methods of CQDs. Fig. 3 is adopted from (Semeniuk et al., 2019) and it is a subscription based article (Copyright © 2019 by authors) distributed under the term and condition of the Copyright Clearance Centre, Inc ("CCC").

5. Carbon dots in biosensors and biomarker

M-CDs can accurately and sensitively detect folic acid, which is a type of vitamin B9 that belongs to the group of water-soluble B group vitamins (Cui, Ning, et al., 2024). Folic acid (FA) is essential for the production of red blood cells, the development of the body, and the prevention of anemia (Cui, Fan, et al., 2024). FA, being a crucial biomolecule, is associated with various chronic disorders such as stroke, heart attack, psychosis, mental decline, neural tube disorder, and more (Hong et al., 2024). Additionally, excessive intake of FA can result in pernicious anemia. Some researchers are investigating the use of carbon dots produced from chemical precursors to track this analyte (Chen et al., 2024). (Priyadarshi et al., 2024) have documented the production of luminescent CDs to analyze FA. Citric acid and the ethylene imine polymer were used as starting materials to do this. In addition, aconitic acid and lactose were also employed for this purpose. A separate team successfully created AgInS2 quantum dots for the purpose of detecting FA. Additionally, a dual-emission fluorescence nano-probe was used to detect FA in a blood sample, successfully demonstrating the practical usage of these particles. None of them provides an acceptable explanation for the selectivity of these systems towards FA in comparison to other interfering biomolecules, despite the fact that some of them exhibit notable sensitivity. The current method demonstrates remarkable sensitivity and exceptional selectivity towards FA among a group of 16 biomolecules. 280 nM is shown to be the detectable threshold of FA. A detailed analysis of the quenching mechanism shows that the inner filter effect is responsible for the selectivity of M-CDs towards FA.

6. CQDs for detection of food contamination

CQDs have been widely used as fluorescent alternatives to act as probes that are fluorescent in food detection applications. CQDs have extensive surfaces with functional groups that allow them to interact with a wide range of materials and alter their optical properties. Table 1 lists the sensing applications of CQD-based sensors created from chemical compounds in the food business. These uses include the detection of pesticides, nutritional materials, microbial toxins, pathogenic bacteria, and restricted or forbidden additions.

6.1. Food additives

Humans may have major health issues if they consume limited or prohibited nutrients and dietary additives. Glutathione, tannic acid, Ascorbic acid, carmine, nitrite, tartrazine, and sunset yellow are among the nutrients and food additives that have been shown to provide serious health hazards when identified by CQDs. An important environmental issue is residual glyphosate, a dangerous herbicide. According to Khan et al. (2023) created glyphosate antibody-CQDs that could identify glyphosate in the environment, and they demonstrated that the glyphosate threshold for detection was 8 ng/mL (Khan et al., 2023). The PL spectra of the resulting CQDs showed a linear relationship with the increase in glyphosate concentration from 0.01 to 80 ng/mL. CQDs were used to detect glyphosate in bacteria, with reasonable recoveries (87.4–103.7%). (Li et al., 2016) employed N and S co-doped CQDS to analyze ultrasensitive pesticides at the trace level. To assess residual pesticides with a threshold for detection of 5 ppb, they developed a straightforward, sensitive, and effective CQD sensor. In actual food trials, the remarkable sensitivity of co-doped CQDs for recognizing pesticides has been tested and proven. In another work, dried lemon peel was hydrothermally prepared at 200°C to create CQDs with an 11% quantum yield. Under the wavelength of 505 nm, the produced CQDs showed strong emission and an 11% quantum yield. Carmine could selectively extinguish the fluorescence of CQDs with greatest absorption at a wavelength of 508 nm. With an upper limit of detection of 0.16 mg/L, the produced CQDs were employed as fluorescent probes for the sensitive measurement of carmine in beverages (Su et al., 2018). Because of

Table 1
CQDs-based sensors in food applications.

Food types	Synthesis method	Carbon sources	Method	Analyte	Detection of limit	References
Tea	Hydrothermal	Citric acid	Immune reaction	Glyphosate	8 ng/mL	(Wang et al., 2023)
Red wine	Hydrothermal	H_2SO_4 and HNO_3	Tuning aggregation/ disaggregation	Ochratoxin A (OTA)	13 pg/mL	(Wang et al., 2017)
Corn and peanut	Hydrothermal	Pancreatin	Fluorescence recovery	Aflatoxin B_1 (AFB_1)	5 pg/mL	(Wang et al., 2016)
Water	Conventional solvothermal	Citric acid	Fluorescence based	Hg^{2+}	26.7 nM	(Guo et al., 2022)
Milk	Hydrothermal	Histidine	Fluorescence quenching	Melamine	36 nM	(Dai et al., 2014)
Dairy products	Hydrothermal	Citric acid and urea	Fluorescence	Melamine	0.47 ppm	(Phimmasone et al., 2023)
White wine	Microwave assisted	Xylan and branched polyethyleneimine (BPEI)	Fluorescence	Tannic acid	44.9 nM	(Yang et al., 2019)
Various food samples	Hydrothermal	Citric and phosphoric acid	Fluorescence	Coccine	24.8 and 9.4 nM	(Liu et al., 2022)
Fruit and vegetable juices	Hydrothermal	Sodium citrate	Fluorescence recovery	Ascorbic acid	42 nM	(Shi et al., 2021)
Shrimp	Ultrasonic treatment	Citric acid and urea	Fluorescence	pH change	-	(Zhang et al., 2020)
Various food samples	Hydrothermal	Ethylene glycol	Fluorometric assay	Formalin	1.5 mg/L	(Naksen et al., 2022)
Jujube fruit	Carbonization/ dehydration	Melamine and citric acid	Fluorescence based	Fe^{3+}	0.5 to 10 μM	(Liu et al., 2021)
Watermelon juice, soymilk, apple juice	Commercial	H_2SO_4 and HNO_3	ELISA	SEB	10 pg/mL	(Tang et al., 2010)
Green tea and black tea	Hydrothermal	Polyethylenimine and citric acid	Fluorescence based	Tannic acid	0.6 nmol/L	(Sistani & Shekarchizadeh, 2021)
Shellfish	Hydrothermal	Urea and citric acid	Fluorescence	Domoic acid	0.05-5 μM	(Wang et al., 2022)
Pickled olives	Hydrothermal	*Caelsalpinia pulcherrima* seed	Fluorescence	Various food additives	252 ng/mL	(Carneiro et al., 2021)
Eggshell and tap water	Hydrothermal	Citric acid	Fluorescence recovery	*Salmonella typhimurium*	50 CFU/mL	(Wang et al., 2015)
Honey and milk	Hydrothermal	Glutathione and citric acid	Fluorescence	Tetracycline	0.56 μmol/L	(Fan et al., 2023)
Dietary food samples	Hydrothermal	Citric acid	Fluorescence	Curcumin	28.7 nM	(Liu et al., 2020)

ELISA: Enzyme linked immunosorbent assay; SEB: Staphylococcal enterotoxin B its negative health effects, tartrazine is one of the most contentious food additives (Amchova et al., 2024). In one investigation, using lemon peels as a synthetic substance, researchers used CQDs to detect the concentration of tartrazine. The outcome showed that the PL intensity dramatically decreased when the tartrazine level was increased to 80 μM. Food (juice, ice cream, and energy drinks) was analyzed and recovered using this technology, confirming the method's feasibility (Chatzimitakos et al., 2017).

6.2. Nutrients

Numerous substances can chelate metals, and some metal ions may react with CQDs to quench their fluorescence. These metal ions can be added to the CQD solution to restore the fluorescence of CQDs. This idea could eventually lead to the development of fluorescence-enhanced sensors for food nutrient identification. Using polyethyleneimine and glucose as raw material components, Zhang et al. (2019) created branched polyethyleneimine functionalized CQDs (PEI-CQDs) by a hydrothermal procedure. Cu^{2+} could effectively extinguish the PEI-CDs' fluorescence, which some biothiols may then recover. Based on this, a PEI-CDs-Cu^{2+} system-based "turn-on" fluorescent probe for GSH detection has been created. One major benefit of the PEI-CDs-Cu^{2+} system over conventional GSH detection probes is its ability to detect GSH at both low and high concentrations using various PEI-CDs and Cu^{2+} concentration combinations. This had respective quantum yields of 9.6% and 4.2%. Additionally, the PEI-CDs-Cu^{2+} exhibits exceptional biocompatibility and outstanding optical stability. Furthermore, it is noteworthy that the proposed probe has effectively visualized the presence of GSH in MGC-803 cells (Zhang et al., 2019).

Ma et al. (2019) developed yellow CDQs. The fluorescence recovery of CDs occurred when AA is introduced to the CDs + Cu^{2+} solution, reducing Cu^{2+} to Cu^{+}. In the range of 100–2800 μM, the fluorescence intensity has a linear correlation with the AA concentration, with a limit of detection of 60 μM. Findings indicated that, the probe may be used to detect AA in actual samples such fresh oranges, orange juice, and VC pills. Additionally, ACP, which hydrolyses ascorbic acid-phosphate (AAP) enzymatically to create AA, can be indirectly detected by the probe. The work offers a simple fluorescent probe for AA detection in actual samples and broadens the use of CDs in multi-component detection (Ma et al., 2019).

6.3. Food pathogens

Food safety and quality are important public health issues that affect people all around the world. The detection and monitoring of food safety and quality has made extensive use of several fluorescence detection methods in recent years. QD-based fluorescent nano-sensors have become the go-to option for food quality and safety analysis because of its many benefits, including high sensitivity, excellent specificity, convenient and quick detection, and a wide sensing range (Aksu & Güzdemir, 2025). The latest developments in QD-based fluorescent nano-sensors for the detection and tracking of food additives, heavy metal ions, pesticide residues, other chemical components, veterinary drug residues, mycotoxins, temperature, foodborne pathogens, humidity, and volatile components at the trace level are also getting significancy in food and biotechnology sectors (Jia et al., 2023).

Recently, CQDs have gained interest in a number of disciplines because of their exceptional qualities, which include fluorescence, photocatalysis, low toxicity, water solubility, and biocompatibility. Specifically, CQDs are likely to be employed for food packaging and preservation because of their functional qualities, which include antioxidant, antibacterial, and UV protection. Furthermore, the introduction of CQDs, a quick, sensitive, and affordable method for evaluating food safety for the measurement of many pollutants, such as heavy metals, pesticides, and pathogens, has made sophisticated analytical paths feasible (Chelladurai et al., 2024). The most popular biopolymers for creating CQD-doped films are cellulose, starch, pectin, carrageenan, gelatin, chitosan, and carboxymethyl cellulose.

A sensitive and selective test of *E. coli* O157: H7 was conducted using CQDs made using a green one-step method. via orange peel as a carbon source, CQDs were created via a microwave-assisted process. When excited at 420 nm, the CQDs showed a bright green fluorescence. Aaptamer-CQDs and magnetic nanoparticles tagged with DNA that is complementary (cDNA-MNPs) were used to create a fluorescent probe (CQDs-MNPs) for *E. coli*. When *E. coli* was added, the CQDs-MNPs' fluorescence intensity dropped. To create a fluorescence method with a detection range of 500–106 CFU/mL and a detection limit of 487 CFU/mL, the linearity between fluorescent intensity and *E. coli* concentration was utilized. This method was used to analyse *E. coli*-contaminated milk samples, and the results were consistent with those obtained using plate-counting techniques. There is a lot of promise for ensuring food safety and quality with this luminous probe (Hu et al., 2021).

Apart from food uses, CQDs have also been found to be potential nanocarriers for biomedical applications, especially for DNA, RNA, and vaccine delivery (Chelladurai et al., 2024). Their surface chemistry can be tuned, they are highly water-soluble, cytotoxicity is low, and they can permeate biological barriers, allowing for high efficiency nucleic acid loading, enzymatic degradation protection, and targeted delivery (Jia et al., 2023). Recent research has shown the applications of surface-functionalized CQDs in gene transfection and mRNA delivery, highlighting their promise in immunotherapy and precision medicine. Thus, the use of CQDs as nucleic acid and vaccine carriers is an area of interest that should be explored deeper, particularly with respect to evolving multifunctional platforms that integrate diagnostics, delivery, and imaging into a single nanosystem (R. Li et al., 2025).

6.4. Detection of heavy metals

Quantum dots are a great option for heavy metal detection because of recent research. Amongst these CQDs, QDs, are interesting because of their high level of biological activity, safety, and biological compatibility. A CQDs sensor was employed by Athika et al. (2019) to detect Cr^{6+} ions. The CQDs sensor demonstrated a linear detection ability based on the amount of Cr^{6+} ions and a limit of detection of 14 μM for Cr^{6+} ions (Athika et al., 2019). Mei et al. (2024) described a simple pyrolytic synthesis technique that uses doping heteroatoms to create extremely crystalline N-CQDs from tartaric acid and chitosan as precursors. Fe^{3+} ions were able to effectively extinguish the fluorescence of CQDs because of the chelation between their surface functional groups and Fe^{3+}. However, the addition of L-ascorbic acid recovered the luminescence of CQDs. When AA is added, fewer Fe^{3+} ions are accessible for ascorbic acid detection. Consequently, a weak detection limit of 0.02 M was achieved (Mei et al., 2024). Thus, this method can also be used to detect ascorbic acid in juices made from vegetables and fruits.

7. CQDs for food quality monitoring

7.1. Food packaging applications

In packaging, carbon dots are the most important component and have a wide range of possible uses. They can contribute to the creation of novel biodegradable, anti-ultraviolet, antibacterial, antioxidation and biocompatible films for food packaging in order to maintain the food's freshness and quality increase its shelf-life (Table 2). The possible application of CQDs as operational fillers in the creation of active packaging films was examined by (Ezati, Rhim, Molaei, & Rezaei, 2022). Glucose served as the carbon source for the single-pot hydrothermal process used to manufacture CQDs. Chitosan and gelatin composite films were made using CQDs without significantly altering the films' mechanical properties, WVP, or WCA. The UV-blocking ability of the film rose by 99% with the addition of CQDs. High antioxidant activity was also demonstrated by the CQD-doped composite material.

Table 2
Application of CQDs in food packaging films.

CQD sources	Polymer matrix	Average size (nm)	Characteristics	Food applications	References
Glucose	Gelatin (Gel)/ chitosan (CH)	-	Antioxidant, UV barrier, antimicrobial activity against *L. monocytogenes, E. coli*, and *Aspergillus flavus*	Avocado	(Ezati, Rhim, Molaei, & Rezaei, 2022)
Banana	CH solution	<1	Antimicrobial activity and shelf-life extension	Soy milk	(Zhao et al., 2020)
Tea residue	Polyvinyl alcohol (PVA)	8–10	UV barrier	Grape	(Patil et al., 2020)
Kelp	CH coating	0.54–0.83	Antioxidant activity and antimicrobial activity against *E. coli* and *S. aureus*	Fresh-cut cucumber	(Fan et al., 2019)
Urea and glucose	CNF	-	Antimicrobial activity against *E. coli* and *L. monocytogenes*, antioxidant, and UV barrier	Tangerine and strawberry	(Singh et al., 2024)
Lemon	Carboxymethyl cellulose (CMC)	-	Antifungal efficacy against *Aspergillus niger* and *Penicillium chrysogenum*, strong antibacterial activity against *E. coli* and *L. monocytogenes*, and antioxidant activity	Lemon fruits	(Riahi et al., 2022)
Agricultural waste fibres (jute, banana, and water hyacinth)	PVA	-	Antimicrobial activity against *Bacillus cereus* and *Salmonella typhi*	Coconut	(Murali & Daniel, 2025)
Grape leaves	Persian gum (PG)/ Gel	-	Antibacterial activity against *E. coli* and *Staphylococcus aureus*	Grape	(Khoshkalampour et al., 2023)
Coffee ground	Gel/PVA	6.2–8.4	UV barrier and antioxidant activity	Active film component to enhance the shelf-life of pork.	(Min et al., 2023)
Tangerine peel	CH/pullulan	8.4–9.2	Antimicrobial efficacy against diverse bacteria, non-toxicity, biocompatibility, and degradability	Bread packaging with active packaging film.	(Sul et al., 2025)
Blueberry pomace	CH	3.1	UV barrier and antioxidant activity	An intelligent and active film component to prolong the shelf life of prawns, fish and pork.	(Wang et al., 2024)
Coconut husk	Carrageenan (CAR)	3.3	UV blocking, antioxidant, antibacterial and gas barrier	Halochromic film sensor to track the deterioration of milk.	(Sangeetha et al., 2024)
Rose petal residues	CAR	2.3–4.1	Water vapor permeability and UV-blocking	Using an intelligent film component to prolong the shelf-life of prawns and pork.	(Wagh et al., 2024)
Eggplant peel	CMC/Gel	2.4-6.3	Antimicrobial activity against *E. coli* and *L. monocytogenes*, antioxidant, and UV barrier	Active food packaging that contains an antimicrobial agent.	(Khan et al., 2024)

L. monocytogenes and *E. coli*, which similarly generate ROS and have antibacterial properties against dangerous microbes, were eliminated by the composite film. When lemon fruit is edible and coated with a carboxymethyl cellulose-based CQD (CMC/CQD) film, mold growth is greatly reduced, and the fruit's shelf life is increased (Riahi et al., 2022). The CQD-added CMC film demonstrated enhanced water and physical

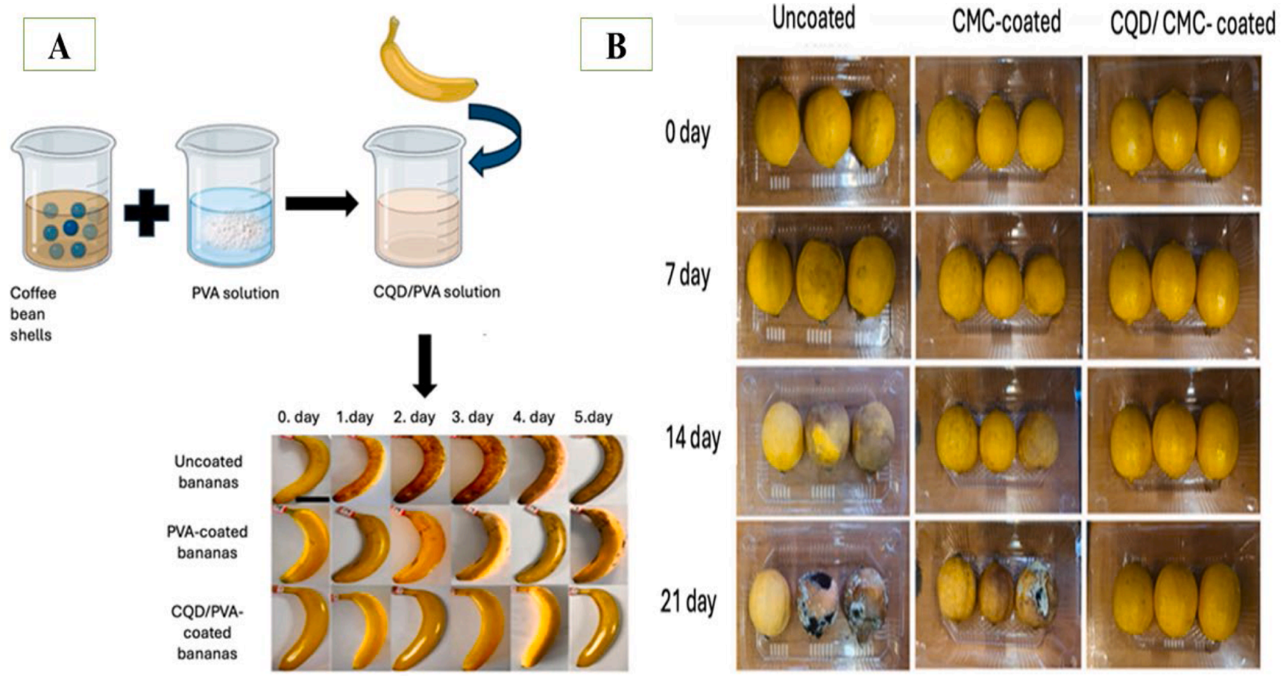

Fig. 4. (A) CQD/PVA coating solution and pictures of coated and uncoated bananas on various days; (B) uncoated lemons (control), coated lemons with CMC, and coated lemons with CQD/CMC edible coating over the course of 21 days of storage. Fig. 4 is adopted from (Aksu & Güzdemir, 2025) and it is a subscription based article (Copyright © 2025 by authors) distributed under the term and condition of the Copyright Clearance Centre, Inc ("CCC").

barrier qualities, excellent UV protection and high transparency. Additionally, the CQD-added films showed strong antibacterial activity against *L. monocytogenes* and *E. coli*, as well as considerable antioxidant and dependable antibacterial and antifungal action against *A. niger* and *P. chrysogenum*. The lemon coated with CMC/CQD film did not grow any mold and kept its exceptional appearance even after 21 days of storage. The CQD/CMC coated film's remarkable functional properties open up a wide range of options for active packaging of foods. During storage, oxidative enzymes such as polyphenol oxidase cause banana peels to turn brown. As seen in Fig. 4(A), Aksu and Güzdemir (2025) created a coating by mixing poly vinyl alcohol (PVA) with CQDs made from coffee bean hulls in order to slow down the rate of browning. When compared to untreated or PVA-only coated bananas, bananas treated with this PVA-CQD solution and kept at 23°C for 5 days showed noticeably reduced enzymatic browning. The antioxidant qualities of the CQDs, which are abundant in polyphenolic chemicals including caffeic acid, chlorogenic acid, and ferulic acid found in coffee bean hulls, are responsible for this decrease in browning (Aksu & Güzdemir, 2025).

Citrus fruits, which are prone to fungal contamination and deterioration, have also been treated using formulations based on CQD. Chitosan functioned as a source of nitrogen and a carbon precursor, allowing CQDs to be functionalised with nitrogen (Riahi et al., 2022). The carboxymethylcellulose (CMC) matrix was then supplemented with CQDs to create a coating solution. The CMC + CQD solution and the CMC solution alone were applied to fresh lemons that were kept at 25°C and 50% relative humidity in order to determine the impact of CQDs. The control samples were left uncovered. Uncoated lemons developed mould within 7 days, and after 21 days, they were totally rotted (Fig. 4B). In contrast, CMC + CQD coated lemons showed no signs of mould formation or decay throughout the same time frame. These findings show that nitrogen-functionalized CQDs can prevent fungal contamination. Citrus fruits' shelf-life was more than tripled when CQD was present in the coating. These experiments demonstrate how CQD-infused biopolymer coatings can prolong the shelf-life and improve the quality of perishable fruits by reducing the rate of microbiological spoiling and oxidative browning.

7.2. *Real-time food spoiling detection using biosensors*

Biogenic amines (BAs) may now be reliably and quickly identified in an instant by the naked eye because of pH-responsive CDs. As the pH level was increased, freshly tangerine peel/resazurin carbon dots (Tan/Res CDs) showed a pH-responsive color change from yellow to orange. With a detection limit of 0.84 μM, Res/Tan CDs demonstrated the ability to identify ammonia by decreasing the fluorescence intensity when concentrations rose from 1 to 100 μM (Ezati et al., 2023). To enable BA tracking for pH-responsive smart food assessment, CDs have been imprinted onto parchment strips. When ammonia vapor was identified, the paper-based Res/Tan CDs sensor's color changed noticeably from yellow to brown. Additionally, the indicator's color changed to show that it could detect shrimp rotting (Fig. 5). Si et al. (2022) employed cellulose nanofiber films and carbon dots generated from lignin in a different study to visually and continuously monitor the state of preservation of food. Deep eutectic solvents (DES) were used to separate lignocellulosic composites. To detect BAs formed during food spoilage, lignin-doped CQDs were created using the extracted lignin as a ratiometric fluorescent probe. Flexible films for sensing devices can be created using carbon nanofilms. They used this information to create CNF/CQD composite film, a portable, inexpensive label that can optically confirm the freshness of real items, such as pork and shrimp. This study promoted the development of sustainable technology for analysis connected to natural products and devised a plan to construct a quick,

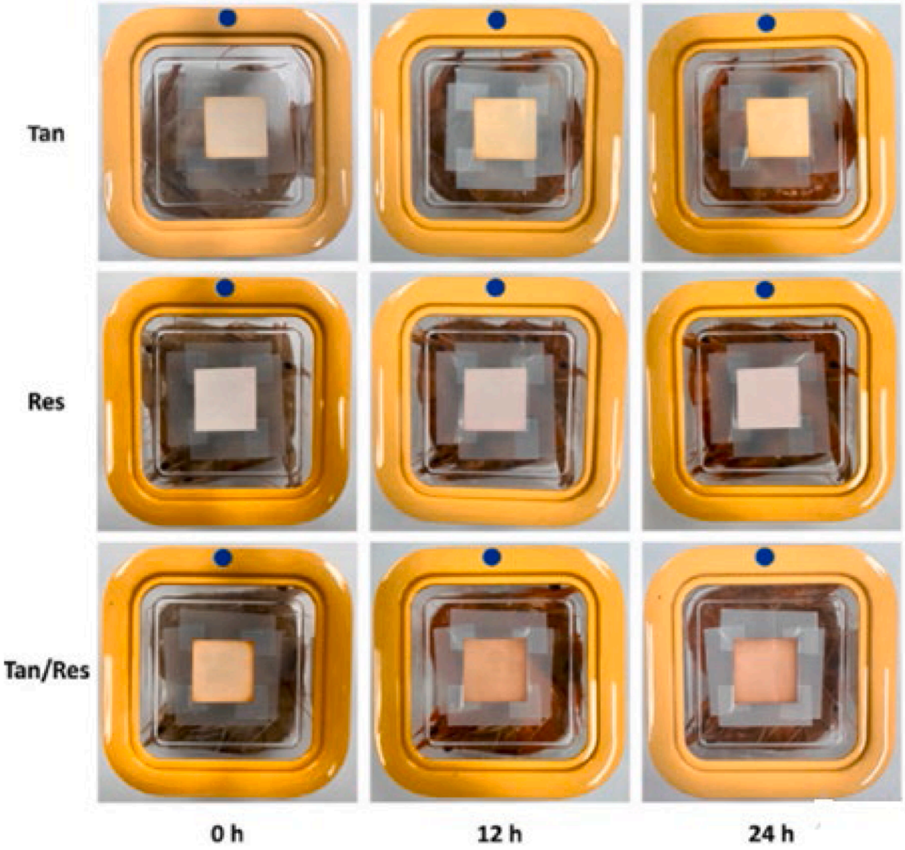

Fig. 5. An illustration of the Tan, Res, and Tan/Res CDs indices used to evaluate shrimp freshness. Fig. 4 is adapted with permission (copyright © 2023 Elsevier Ltd., Amsterdam, the Netherlands) from (Ezati et al., 2023).

instantaneously auditory food quality tracking and assessment system (Si et al., 2022).

8. Cytotoxicity of CQDs

When utilized in daily life, carbon-based products are generally low in cytotoxicity and environmentally benign. However, assessment of the cytotoxicity to the body of humans is required since nanomaterials made from carbon may enter the body through injection, gastrointestinal digestion, skin, breathing and absorption (Ezati, Rhim, Molaei, & Rezaei, 2022; Gupta et al., 2024). Determining the cytotoxicity of CQDs is therefore crucial to guaranteeing their safety in applications in medicine or food packaging. Excellent bio compatibility CQDs combine antimicrobial and antioxidant qualities, and they can be made from non-toxic starting materials using eco-friendly methods. Their strong biocompatibility makes them suitable for use in food packaging, cell imaging applications, biolabeling, and antibacterial drug administration (Fan et al., 2020; Seo & Kang, 2025). Numerous studies have examined CQDs' cytotoxicity at the level of cells. Zhao et al. (2019) investigated the *in vitro* and *in vivo* toxicity of N-CQDs. For *in vitro* investigation of the survival of cells that are mammals such as human pancreatic cancer cell line (PANC-1) and HeLa subjected to varied N-CQD concentrations utilizing methyl thiazolyl tetrazolium (MTT) assays for 24 hrs (Zhao et al., 2019). Cell viability was detected at a concentration of 0.128 mg/mL of N-CQDˆ80%, but toxicity in the two cell lines increased with concentration (Fig. 6a). Mice were used in the *in vivo* toxicity studies, which included exposing them to 5 mg/mL of N-CQDs for 7 days and using a magnifying glass to examine the morphology of the kidney, heart, liver, spleen, and lung, among other five major organs (Fig. 6b). N-CQD transformation into substances that are not toxic because of digestion is why the obtained data revealed no pathological changes in any tissue that interacted with N-CQD. The CQDs' interaction with biological components is an interconnected process. The results are determined by the cell system under inquiry as well as the cytotoxicity assay technique used. Furthermore, this interaction is influenced by other elements like as size, functional groups, surface charge, surface coating, shape, etc.

Cytotoxicity tests found that CQD dosages of 10 to 100 mg/mL produced a minor (10-20%) loss in the life of cells and were declared suitable for the preparation of food (Somasundaram et al., 2025). In cytotoxicity investigations of CQDs, the cell system under research and the testing technique employed for the cytotoxicity assay are significant. Additional parameters such as functional groups, surface charge, surface coating, size and shape influence these interactions (Khan et al., 2023).

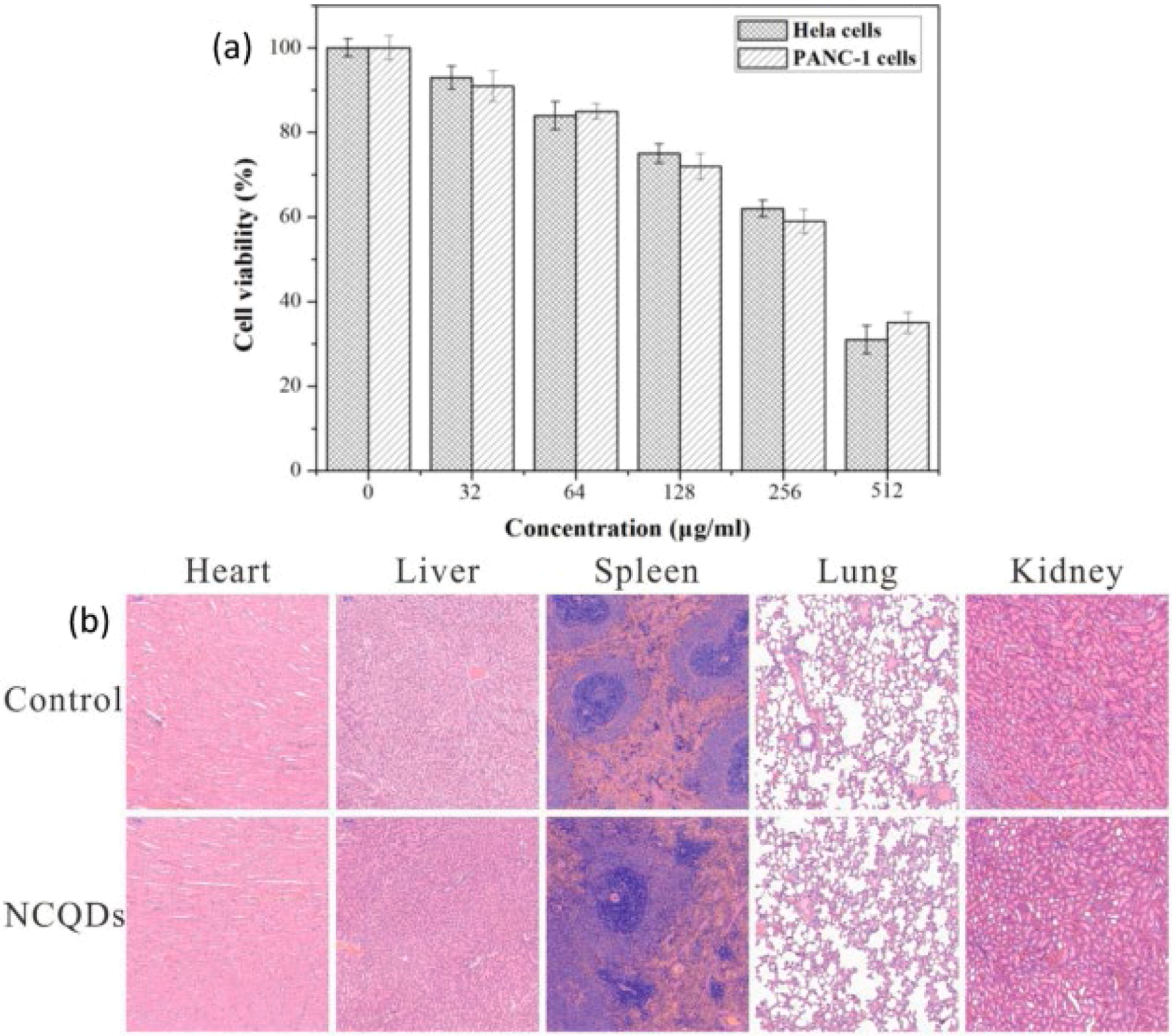

Fig. 6. (a) Relative vitality of HeLa and PANC-1 cells treated with different doses of N-CQD for 24 hours. (b) Histological sections of the heart, liver, spleen, lung, and kidney were stained with hematoxylin and eosin (H&E) after 7 days of continuous gavage administration of N-CQD and normal saline (Control). Scale bars are 200 mm [HeLA: Henrietta Lacks; PANC-1: human pancreatic cancer cell line; H&E: Hematoxylin and eosin-stain]. Fig. 6 is adapted with permission (copyright © 2019 Elsevier Ltd., Amsterdam, the Netherlands) from (Zhao et al., 2019).

Long-term biosafety studies are necessary to guarantee the overall safety of CQDs before applying them to places that are directly exposed to food or the human body, even though multiple studies have demonstrated their low cytotoxicity and stability (Keşir et al., 2025).

9. Conclusions and future prospects

Carbon quantum dots are one of the most versatile families of nanomaterials with high applicability in food safety and environmental monitoring because of their advantageous properties, including great water solubility, photoluminescence tunability, photostability, biocompatibility, and possibility of synthesis by green processes from renewable biomass resources. These properties provide unambiguous comparative benefits over traditional heavy metal-containing quantum dots, which typically trigger concerns about toxicity, environmental persistence, and legislative constraints. CQDs can be prepared by numerous top-down and bottom-up methods, and green synthesis routes, particularly hydrothermal treatment of agri-food waste, are becoming increasingly important due to their sustainability and low cost. In addition to these benefits, there are a number of limiting factors that need to be overcome for the realistic deployment of CQDs. One of the principal concerns is their relatively low and irregular fluorescence quantum yield, which in turn affects their sensitivity and stability as biosensing platforms. In addition, CQD reproducibility is normally thwarted by differences in precursor materials, synthesis conditions, and surface functionalization protocols. The selectivity of sensors based on CQDs in complex food or environmental matrices is also still a problem, in many cases demanding additional modification or incorporation with other sensing components (e.g., aptamers, enzymes). In addition, long-term stability in a variety of storage and operating conditions and the absence of universally accepted standardization procedures for synthesis and characterization are obstacles to their scalability and regulatory clearance. From a safety and regulatory viewpoint, the lack of detailed toxicological studies and biosafety testing, especially in the context of food-contact applications, represents a serious impediment to commercialization. Although numerous studies attest to the low cytotoxicity of CQDs in vitro, systematic in vivo studies, chronic exposure tests, and stability of degradation behavior in food matrices are less explored.

In the future, there are several research directions that must be taken up. Increasing the optical performance of CQDs by heteroatom doping, core–shell engineering, and sophisticated surface passivation can enhance fluorescence yield and stability. Standardization of synthesis routes and characterization methods will be essential to guarantee batch-to-batch homogeneity and quality control. Moreover, enhancing the utilization of agricultural and industrial food waste as a carbon source not only fits the principles of circular economy but also optimizes cost and environmental factors. Moreover, the creation of CQD-integrated smart packaging materials and wearable biosensors is an exciting frontier in real-time, on-site food freshness and contamination monitoring. Interfacing with future technologies like 3D printing, biodegradable polymers, and wireless sensing platforms could further expedite their path from laboratory-scale research towards commercial use. Comparative studies with available biosensing devices and interdisciplinary collaboration among researchers, industry, and regulatory agencies will be essential for establishing safety standards and realizing the complete potential of CQDs in food and environmental applications. CQDs also have enormous potential as future-generation biosensors, and their complete usefulness will depend on sustained interdisciplinary efforts aimed at removing their existing setbacks, developing regulatory guidelines, and providing functioning, scalable, and secure applications.

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Ethical approval

No animals or humans were involved in the conduction of this study.

CRediT authorship contribution statement

Puja Das: Writing – original draft, Conceptualization, Formal analysis. **Pinku Chandra Nath:** Conceptualization, Formal analysis, Writing – original draft. **Vinay Kumar Pandey:** Writing – review & editing, Writing – original draft. **Rattan Singh:** Conceptualization, Writing – review & editing. **Sarvesh Rustagi:** Writing – review & editing, Methodology. **Ayaz Mukarram Shaikh:** Writing – review & editing, Software, Investigation. **Béla Kovács:** Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

There is no conflict of interest between the authors.

Data availability

No data was used in the conduction of this review.

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