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Valorization of whey for green synthesis of carbon dots and their potential applications

Amrita Poonia
Department of Dairy Science and Food Technology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, India

Lizet Aguirre-Güitrón
Universidad Tecnológica de Nayarit, Xalisco, Mexico

Maricarmen Iñiguez-Moreno
Tecnologico de Monterrey, School of Engineering and Sciences, Monterrey, Mexico, and

Dushica Santa
Faculty of Agricultural Sciences and Food – Skopje, Ss. Cyril and Methodius University in Skopje, Skopje, North Macedonia

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Abstract

Purpose – This paper aims to develop carbon dots using whey as a valuable resource and to create a sustainable and biocompatible nanomaterial with potential applications in a variety of fields owing to its unique optical properties and antimicrobial capabilities, which are frequently used as sensing agents for detecting specific molecules in food, environmental and biomedical applications. Versatility of carbon dots (CDs) allows the utilization of these dots for a wide range of applications in areas such as food safety, antibacterial properties, production of composite polymers for food packaging, treatment of different diseases and detection of food-borne pathogens. Owing to their high brightness, low toxicity and excellent biocompatibility, CDs have attracted significant interest in food safety. This is also a cutting-edge technology that bids new ideas for treating various diseases.

Design/methodology/approach – Literature review related to using whey as the carbon source for synthesis of CDs was collected and studied from different sources like Google Scholar, Research Gate, online journals available at library of Banaras Hindu University, Web of Science and Scopus. A database of more than 100 scientific sources from different sources was made as per the headings and sub headings of the paper.

Findings – Whey generated as a by-product from the cheese industry contained a good amount of carbon and nitrogen that can be used for the fabrication of CDs. CDs produced using whey exhibited great photostability, high sensitivity and outstanding biocompatibility and also showed that Fe3+ ions could be quickly, sensitively and extremely selectively detected in an aqueous solution of CDs, with a revealing limit of 0.409 µM in the linear range of 0–180 µM. CDs are a promising area of study to a key component of next-generation multifunctional nanomaterials, promoting creativity, sustainability and useful solutions across a variety of industries, including health care and energy. The susceptibility of *S. typhimurium* (Gram-negative) was found to be higher than that of *L. monocytogenes* (Gram-positive) bacteria with MIC and MBC of 500 and 1000 µL/mL, respectively.

Originality/value – Whey-derived CDs are an environmentally beneficial substitute for conventional additives and their biocompatibility guarantees that they adhere to food safety regulations. In light of the future, the green volarization of dairy waste for the synthesis of CDs is consistent with the increasing worldwide focus on environmental responsibility and sustainability.

Keywords Carbon dots, Whey, Sustainability, Hydrothermal method, Active packaging, Nanomaterials

Paper type General review

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Introduction

Carbon dots (CDs) are zero-dimensional, semi-spherical nanomaterials comprising carbon, hydrogen and oxygen with a size of <10 nm. Nanoscale carbon particles known as CDs has generated a great deal of attention owing to their many uses in drug administration, bio-imaging, sensing and in packaging. By reusing a waste stream, the use of whey as a precursor for CDs not only solves environmental issues but also offers a sustainable and cost-effective substitute for conventional carbon dot synthesis techniques. The potential for revolutionary breakthrough at the crossroads of material science and environmental responsibility is highlighted by this convergence of scientific inventiveness and sustainable resource utilization. The process of creating CDs from dairy waste entails turning the organic substances found in whey into carbon-based nanoparticles. Green chemistry principles can be emphasized in this process by using techniques like microwave-assisted synthesis or hydrothermal synthesis (Moradi *et al.*, 2023). These methods have the benefit of minimizing the impact on the environment and guaranteeing the sustainability of the process because they usually use water as a solvent and do not include harmful chemicals. The resultant CDs have distinct chemical and visual characteristics that allow them to be used in a various applications, particularly in food sector.

The CDs may be incorporated into food items in different ways, with advantages including, improved food preservation and antibacterial qualities, and they can even be used as a natural and safe food colouring substitute. They are the best options for food-related applications because of their tiny size and biocompatibility, which guarantees that they fulfill safety requirements while offering innovative characteristics (Omerović *et al.*, 2021). Moreover, the circular economy idea which advocates for the valorization and repurposing of waste materials instead of their disposal in landfills is consistent with the utilization of CDs made from dairy waste. To ensure appropriate and ethical procedures in their use within the food sector, it is imperative to take into account the potential environmental and safety concerns connected with the use of nanomaterials (Mustafa and Andreescu, 2020 and Sharma *et al.*, 2021).

According to Poonia and Pandey (2023), liquid whey has attracted a lot of attention as it is easily available, reasonably priced and may have positive environmental benefits associated with using dairy wastes and by-products. Using whey as a useful resource for green value-adding has gained more attention as sustainable practices become more important (Panghal *et al.*, 2018). A potential step towards the creation of sustainable nanomaterials is the creative synthesis of CDs from whey. This approach also helps in decreasing environmental pollution and also increases the value of CDs. There is limited research and literature available about utilization of whey for synthesis of CDs. This review paper covers the green synthesis of CDs using whey that can help reduce waste and provide materials with additional value.

Synthesis of carbon dots

CDs can be synthesized using two major alternatives, top-down as well as bottom-up methods, which offer different ways to produce these nanomaterials with varying properties. Main top-down and bottom-up methods for CDs obtention is shown in Figure 1. A summary of by-product (whey) as a source of carbon for preparing CDs has been depicted in Table 1.

Characterization of carbon dots

To understand the mechanism associated with CDs, unique physical features, their characterization is foremost. For CDs characterization, different techniques such as spectroscopic techniques have been listed, including as ultraviolet-visible (UV-vis) spectroscopy and Fourier-Transform Infrared Spectroscopy. X-ray diffusion (XRD), Zeta

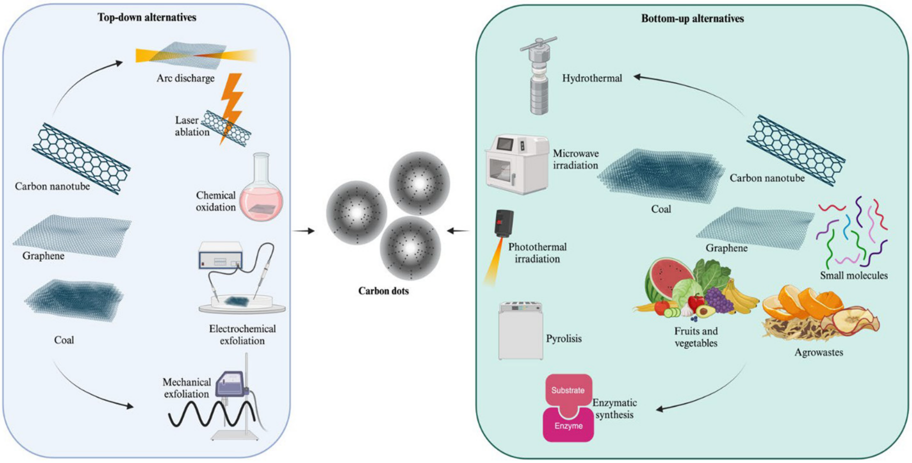

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Figure 1. Main top-down and bottom-up methods for carbon dots obtention

potential, quantum yield analysis, high-resolution electron microscopy (HRTEM), high resolution XPS, transmission electron microscopy (TEM), are also recommended to characterise isolated CDs from whey. Instrumental characterization of whey-based CDs are explained in Table 2.

Potential applications of carbon dots

Whey-derived CDs are an environmentally beneficial substitute for conventional additives and their biocompatibility guarantees that they adhere to food safety regulations. In light of the future, the green volarization of dairy waste for the synthesis of CDs is consistent with the increasing worldwide focus on environmental responsibility and sustainability (Oladzadabbasabadi *et al.*, 2023). To uncover new uses and advantages for the environment as well as the food industry, researchers and professionals from the industry are likely to investigate and improve this technique further. Antioxidant activity and cytotoxicity of whey-based CDs are listed in Table 3. A more sustainable and circular approach to food production is encouraged by the adoption of green value-adding techniques in the food sector, which also solves waste management issues (Pushparaj *et al.*, 2022). The increasing number of metabolic syndrome diseases, increasing accumulation of non-biodegradable food packaging wastes and declined health status of the consumers of processed foods have entailed scientific findings into a suitable panacea for these (Kehinde *et al.*, 2023)

Food packaging

The fluorescence properties of CDs can be harnessed to create labels that change colour or emit fluorescence when tampering or contamination occurs. These properties can be controlled to create distinctive patterns or codes that are difficult to replicate, enabling the application of CDs to prevent counterfeiting in food packaging (Jiang *et al.*, 2021 and Liu *et al.*, 2021). The authentication process can be performed by specialized devices or smartphone apps equipped with appropriate filters that can be used to verify the authenticity

Table 1. A summary of dairy industry by-product (whey) as carbon source for preparing carbon dots

Carbon source	Synthesis method	Key findings	References
Sour whey	Hydrothermal method	Carbon produced from sour whey showed important characteristics such as low cytotoxicity and antimicrobial properties The synthesized CDs have potential antimicrobial or antioxidant agents in food formulations, as well as ultra violet-blockers and nanofillers in the development of composite polymers for food packaging The susceptibility of *S. typhimurium* was found to be higher than that of *L. monocytogenes*, with a minimum inhibitory concentration and minimum bactericidal concentration of 500 and 1000 μL/mL, respectively	Koutamehr *et al.* (2023)
Sour whey	Hydrothermal method	Monodispersed and quasi-spherical carbon dots with an average size of 7.2 nm were synthesized CDs (2,500 and 5,000 mgL^{-1}) were added to the cheese through an alginate-based coating or directly to the cheese brine were more effective on *Enterobacteriaceae* as compare to *Pseudomonas* spp.	Lacivita *et al.* (2023)
Whey proteins	Single-step microwave-assisted treatment	CDs were shown to be effective for the *in vitro* scavenging of superoxides and hydroxyl radicals	Das *et al.* (2016)
Whey proteins	Microwave irradiation	Antibacterial properties of both CNDs were studied against both gram-positive and gram-negative bacterial strains, showed an increased antibacterial activity after DHFI crosslinking Whey protein carbon nanodots -DHFI has showed a stable and prominent bacteriostatic activity for 6 h for both strains of bacteria	Mukherjee *et al.* (2023)
Whey proteins	Hydrothermal decomposition	The PL spectra of carbon dots showed that the dominant excitation and emission wavelengths of carbon dots were 275 and 420 nm, respectively The Fe^{3+} ion sensing application of the carbon dots performed by mixing Fe^{3+} solution and carbon dot solution showed a 36% decrease in luminescence intensity Carbon dots derived from whey protein can be applied as the luminescent sensor for Fe^{3+} ions hemoglobin detection	Hong *et al.* (2023)

(*continued*)

Table 1. Continued

Carbon source	Synthesis method	Key findings	References
Whey	Hot air oven	CQDs as an effective sensor probe for selective selenite monitoring in water upon functionalization with appropriate ligand The functionalized GCQDs probe is shown to detect selenite with high sensitivity in 10–1000 ppb detection range Selective for selenite over other relevant ions (such as Cu2+, As3+, As5+, Pb2+, Ni2+, Se6+, Cl−, Br−, NO3−, NO2− and F-) and displays a sub-ppb detection limit at 1.1% SD	Devi *et al.* (2017)
Whey	Hydrothermal method	The fabricated CQDs showed a bluish-white emission under ultraviolet light with an excitation-dependent property As the pH value increased, the fluorescence activity decreased accordingly without any remarkable shift in absorption indicating the potential application of carbon quantum dots as pH sensors in various chemical and biological systems	Burak İlter *et al.* (2023)
Whey	Hydrothermal method	The produced CDs exhibited great photostability, high sensitivity and outstanding biocompatibility Results showed Fe^{3+} ions could be quickly, extremely selectively and sensitively detected in an aqueous solution of CDs, with a revealing limit of 0.409 μM in the linear range of 0–180 μM	Kayani *et al.* (2024)
Whey (liquid)	Hydrothermal method	Liquid whey CDs shows blue fluorescence with an average size of 9.04 and spherical morphology Bactericidal activity was recorded against *S. aureus*	Thakur *et al.* (2024)

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Table 2. Instrumental characterization of whey-based CDs

Name of equipment	Key findings	References
1H NMR	• Different sets of hydrogen atoms bonded to carbon species were present • Signals (1–3 ppm) is being linked to sp^3 C-H protons ($-CH_3$) • In addition, the signal at $\delta = 7.4$ ppm can be identified as an aromatic or sp^2 proton, • Strong signals at $\delta = 9.4$ ppm are in concordance with the aldehydic protons • Signals linked to sp^3 (C-H) protons, aromatic or sp^2 protons, • Strong signals in concordance with the aldehydic protons	De and Karak (2013), Kayani *et al.* (2024), Lacivita *et al.* (2023)
High-Resolution transmission electron microscopy (HRTEM)	• Uniform spherical shapes were evenly dispersed • Size distribution ranges from 1–5 nm, with a mean particle diameter of roughly 3.12 nm • CDs do not exhibit a distinct crystal lattice, implying an amorphous structural nature	Kayani *et al.* (2024)
C NMR	• The hybridized carbon atoms which correspond to aliphatic (sp^3) carbon atoms were found in the range of 10–60 ppm • The signals in the range of 60–80 ppm (e.g., signals around 63, 67, and 72 ppm) are attributed to carbon and this shows C-O-C, COOH and C-O, respectively • In δ = 100–130 ppm, C = C aromatic or sp^2 carbons can be identified and the signals at around 152, 162 and 178 ppm (due to the presence of aldehyde and carboxylic group) • Hybridized carbon atoms corresponding to aliphatic (sp^3) carbon atoms, the signals due to a carbon in the vicinity of an electronegative element • Signals related to the C = C aromatic or sp^2 carbons were identified	Arroyave *et al.* (2021), Lacivita *et al.* (2023)
High resolution XPS	• Three peaks located at 132.2, 134.1, and 135.2 eV were identified to indicate the presence of P-C, P-C/P-N • Also, 286.1, 289.7 and 290.3 eV peaks can be attributed to C-O/C-N, O-C = O bonding and CO_3^{2-}	Li *et al.* (2017), Dehvari *et al.* (2019)

(*continued*)

Table 2. Continued

Name of equipment	Key findings	References
FTIR	• The characteristic stretching vibrations of N-H/O-H bonds, C-H, C = O, and vibrations of C-O-C bonds in the CDs spectrum can be observed at 3394 cm^{-1}, 2925 cm^{-1}, 1668 cm^{-1} and 1603 cm^{-1}, respectively • Absorption corresponding to the stretching vibrations of C-O and C-N can also be observed at 1407 cm^{-1} and 1228 cm^{-1}, respectively • Also, the peaks at 1122 cm^{-1}, 1043 cm^{-1}, 781 cm^{-1} and 613 cm^{-1} can be ascribed to the stretching of P = O, P-O-C, P-O-H, and the bending mode of P-O, respectively • Stretching vibrations of O-H and N-H in the region 2900 cm^{-1} to 3400 cm^{-1} • Absorption peak at 1676 cm^{-1} corresponding to the stretching vibration of C = O • Absorption peak at 1521 cm^{-1} attributed to the stretching vibration of C = C, • Peak at 1398 cm^{-1} identified as C-N, N-H • Area of the FTIR spectrum, absorption bonds assigned to the presence of P= O, P-O-C, P-O–H, P − O, Ca = O, and O-Ca-O groups were also observed	Rodríguez-Félix *et al.* (2021), Estrella-Osuna *et al.* (2022), Rodríguez *et al.* (2022), Kayani *et al.* (2024), Lacivita *et al.* (2023)
XRD	• Diffraction peak centred at $2\theta = 23.00°$, which is linked to the diffraction plane (002) indexed for graphitic materials • The weak diffraction peaks at around $2\theta = 23.56°$ are probably due to the presence of CDs doped with P heteroatom • Moreover, other represented peaks can be attributed to crystalline moieties of some residual mineral salts such as sylvite (KCl) ($2\theta = 28.06°$, 49.91° and 40.24°), and potassium sodium calcium phosphate ($2\theta = 31.22°$, 31.41°, and 45.12° • The CDs exhibited broad 2θ patterns around 22.5 and 41°, attributed to disordered carbon atoms which confirms the dominance of C (002) and C(100) planes associated with hexagonal graphite structure of CDs particles	Lin *et al.* (2018), Kumar *et al.* (2019), Llamas-Unzueta *et al.* (2021), Kayani *et al.* (2024)

(*continued*)

Table 2. Continued

Name of equipment	Key findings	References
TEM	• Particle size distribution analysis exhibited that size ranged from 8–20 nm with an average of 13.3 nm • Uniform distribution, monodispersed and quasi-spherical shape of carbon dots	Burak İlter *et al.* (2023), Lacivita *et al.* (2023)

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of the packaging (Liu *et al.*, 2021). On the other hand, CDs can be integrated into a polymeric matrix for the development of real-time sensors for monitoring food freshness by the detection of changes in pH, temperature or the presence of specific gases (indicative of spoilage) (Fu *et al.*, 2022; Koshy *et al.*, 2021). CDs can be engineered to exhibit temperature-sensitive fluorescence, this means that food packaging can change colour or fluorescence intensity based on temperature variations during storage and transportation (Wang *et al.*, 2023). This provides information about whether the food has been exposed to undesirable temperature conditions. Besides, temperature abuse promotes the growth of spoilage microorganisms that during their metabolism synthesize organic acids and gases, that change the pH of the food and the compositions of the atmosphere. Both changes can be identified by using CDs in the food packaging providing real-time information about the freshness conditions of the packed food. Major applications and effect of CDs on food packaging are mentioned in Figure 2.

Detection of food additives

Determining the quantity of food additive is crucial, and carbon quantum dots (CQDs) can be useful in this regard (Fan *et al.*, 2020). Liu *et al.* (2016) established a novel CQDs-MnO_2 fluorescent probe for facile, fast, and less-cost detection of ascorbic acid. This platform was effectively used in detecting various fresh fruits, commercially available fruit juices and vegetables. Ahmed *et al.* (2015) used CDs to directly measure the concentration of tannic acid in samples of white and red wine. They achieved a limit of detection (LOD) of 0.018 mg/L using this method, as tannic acid has ability to quench fluorescence. Interestingly, the researchers also observed that tartrazine, a synthetic food colourant that is not commonly used, caused a strong fluorescence quenching effect on the prepared CDs. Moreover, whey-derived CDs have the potential to be used as natural food additives (Sul *et al.*, 2023).

Detection of foodborne pathogens

Ahmadian-Fard-Fini *et al.* (2018) used a hydrothermal method to produce blue CQDs using lemon, turmeric extracts and grapes as carbon sources. Subsequently, they synthesized a novel fluorescent nanocomposite by combining CQDs with Fe_3O_4 nanoparticles, which was utilized for detection of *Escherichia coli*. The research findings demonstrated gradual quenching of the fluorescence emitted by the blue CQDs as the concentration of *E. coli* increased. Also, Choi *et al.* (2018) used fluorescent carbon quantum dots (FCQDs) functionalized with phenyl boronic acid and a diol-modified fluorescent probe (dye

Table 3. Antioxidant activity and cytotoxicity of whey-based CDs

Name of method		concentrations (mg/ml)		References
DPPH method	0.5	0.2	0.3	Koutamehr *et al.* (2023)
Carbon dots	28 ± 0.2	38 ± 1.47	263± 0.69	
ABTS method	0.5	1.0	2.0	Koutamehr *et al.* (2023)
Carbon dots	92.85 ± 0.19	93.85 ± 0.17	99.08 ± 0.22	
Viability of HCT-116 cells (%)	0.31 mg/mL	5.0 mg/mL	10 mg/mL	Koutamehr *et al.* (2023)
Exposure time: 48 h	No significant differences in comparison to control	No significant change	Cellular viability significantly decreased compared to the lower concentrations and control	Huang and Tang (2021)
Viability of TM4 cells (%)	10,000 mgL^{-1}	310–5000 mgL^{-1}		Lacivita *et al.* (2023)
Exposure time: 24 h	Dramatic effect on the cell viability	No significant changes in cell viability		

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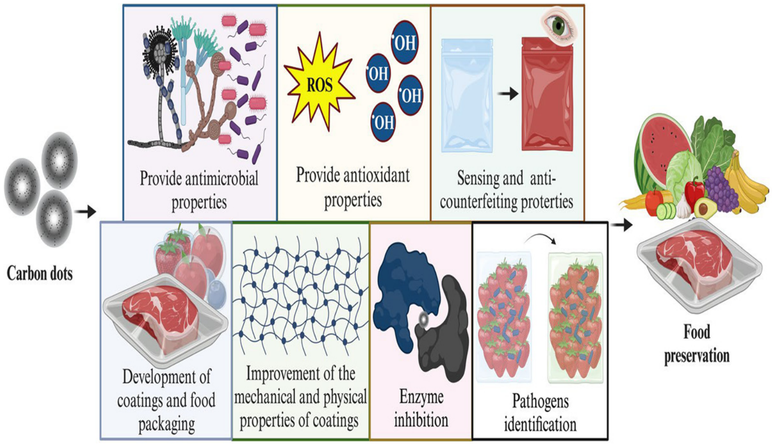

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Figure 2. Main applications and effect of carbon dots on food packaging

molecules) to create a fluorescent sensor. The FRET phenomenon may cause FCQDs to lose their fluorescence. The diol groups of polysaccharides on the bacterial cell surface would react with FCQDs with the addition of *Staphylococcus aureus* and *E. coli* to the solution of FCQDs containing dye molecules, forming new cyclic boronate ester linkages that replaced dye molecules. Following the release of the dye molecules into mixture, FCQD fluorescence was recovered. *S. aureus* and *E. coli* were detected based on the intensity of fluorescence recovery. Fluorescent sensors based on CQDs are used to identify foodborne microorganisms.

Antimicrobial properties

The antibacterial activity of CDs is highly correlated with both their surface charges and N content. To guarantee the creation of CDs containing cationic groups on the CD surface, amines or quaternary ammonium salts are frequently used as a starting materials for production of these carbon-based probes in reported antimicrobial CDs (Ghirardello *et al.*, 2021). Koutamehr *et al.* (2023) discussed the use of CDs, for preservation of food owing to their antioxidant and antimicrobial properties. CDs, derived from sustainable and eco-friendly sour whey, showed major characteristics for potential use in food formulations, like low cytotoxicity and antimicrobial properties. This study reported the antimicrobial, cytotoxic and antioxidant properties of the synthesized CDs, revealing low toxicity and higher susceptibility of *Salmonella typhimurium* compared to *Listeria monocytogenes*. Lacivita *et al.* (2023) synthesized monodispersed CDs using sour whey for cheese packaging, with an average size of 7.2 nm. CDs, especially in coated cheese, demonstrated a substantial preserving effect, doubling shelf -life in comparison to control. Adding CDs to the brine at 5,000 mg/L extended cheese shelf life by over 10 days, showcasing potential for sustainable applications in the food industry. Kousheh *et al.* (2020) produced and characterized antibacterial CDs using a hydrothermal technique from *Lactobacillus acidophilus* cell-free supernatant for the first time. *E. coli* and *L. monocytogenes* were used to test the antimicrobial efficacy of CDs. Owing to their fluorescence appearance, CDs may be used as new fluorescence antimicrobial and ultraviolet protective material to prepare an antimicrobial and counterfeiting-proof packaging.

Also, Riahi *et al.* (2022) used a hydrothermal technique to create chitosan-based CQDs with multifunctional characteristics. High antibacterial and antifungal activity against *Penicillium chrysogenum* and *Aspergillus niger* were showed by the CQD against *L. monocytogenes* and *E. coli*.

The generation of reactive oxygen species (ROS), cytoplasmic leakage, cell structure disintegration, disruption of the electron transport chain, protein denaturation, lipid peroxidation and genomic DNA fragmentation are some of the mechanisms of whey derived CDs that provides CDs their antibacterial properties. The size, shape, surface charge and functional groups of CDs are all strongly associated with their antibacterial qualities (Dong *et al.*, 2020). Comparable outcomes were reported by Han *et al.* (2015) used poly methyl methacrylate, silver nanoparticles, and CDs made from cow milk to create a polymer film. The membrane demonstrated a strong bactericidal impact o*n E.coli* and *S.aureus*. The nano-composite antibacterial film was believed to provide numerous application opportunities in the areas of food packaging, drinking water and sanitation disinfection due to its superior antibacterial activity, light transmission and flexibility.

Comparative analysis of whey derived carbon dots with other carbon dots

Whey can be used as a precursor for CDs synthesis, which will help the food industry to minimize waste, protect the environment, and promote the circular economy (Shahraki *et al.*, 2023). Owing to their incredibly low toxicity, high fluorescence and exceptional biocompatibility whey-derived CDs are intriguing options for usage as bioimaging agents, UV-blockers and nanofillers in the creation of composite polymers for food applications. The use of whey by-products as a CDs source not only minimizes waste but also provides a sustainable alternative to old/traditional methods that rely on non-renewable carbon sources. CDs produced using whey are inexpensive, sustainable and eco-friendly source, and also demonstrated important characteristics such as low cytotoxicity, antioxidant agents and antimicrobial activities. Whey-derived CDs show promise for food preservation due to their antimicrobial activity and stability. CDs made from whey provide an environmentally friendly and industrially viable alternative.

Moreover, whey-derived CDs have the potential to be used as natural food additives (Sul *et al.*, 2023). In response to customer concerns regarding the use of artificial ingredients in food products, these CDs have the potential to replace artificial colourants and preservatives. Whey-derived CDs are an environmentally beneficial substitute for conventional additives and their biocompatibility guarantees that they adhere to food safety regulations. In light of the future, the green volarization of dairy waste for the synthesis of CDs is consistent with the increasing worldwide focus on environmental responsibility and sustainability (Oladzadabbasabadi *et al.*, 2023). The use of whey-derived CDs could become a distinguishing feature of sustainable food production as customers seek more environmentally friendly and open methods from the food industry. To uncover new uses and advantages for the environment as well as the food industry, researchers and professionals from the industry are likely to investigate and improve this technique further. A more sustainable and circular approach to food production is encouraged by the adoption of green value-adding techniques in the food sector, which also solves waste management issues (Pushparaj *et al.*, 2022).

Analytical applications

As a result of their excellent water solubility and photostability, CDs are applicable to fields such as medicine and food safety (Manzoor *et al.*, 2023). CDs have found extensive utilization in environmental, pharmaceutical, clinical and food analysis. Their benefits, such as low dosage requirements, low limits of detection, ease of operation, wide linear range, rapid response and dependable results, make them highly advantageous in these field (Yang *et al.*, 2023). Beyond food safety applications, CDs exhibit promise as photosensitizers, facilitating localized apoptosis in cancer cells and aiding in drug delivery and genetic diagnosis through nanometer complex compounds (Chai *et al.*, 2022). Their broad utility spans, various domains, including biochemical sensors, imaging tools, photocatalytic technology, drug carriers, light-emitting devices and energy conversion/storage systems.

Pesticides detection in food

Due to the sensitive changes of fluorescence in the presence of pesticides, the fluorescence technology based on CDs is drawing attention of the researchers in detection of pesticides in food. Enzyme-based fluorescence techniques for pesticide detection were developed because pesticides have an inhibitory influence on enzyme activity (Shi *et al.*, 2019). Fluorescence-based CDs have garnered significant interest among researchers for their applications in these areas. This is attributed to their exceptional optical properties, excellent water solubility, low toxicity, as well as their ability to selectively and sensitively respond to changes in fluorescence when exposed to pesticides. Kailasa and Hussain reviewed the use of CD-based fluorescent sensors for the analysis of pesticides in different food products. The sensors have been applied to a wide variety of foods such as rice, fruits (apple and strawberry), vegetables (tomato, lettuce and cucumber), honey, cereals, grape juice, soya and even human urine. A broad range of pesticides are detected by these sensors, including common ones such as glyphosate, methyl parathion and chlorpyrifos, as well as others such as thiamethoxam, dinotefuran and aldicarb.

Detection of veterinary drugs in food

Tetracyclines as an effective antibiotics, have been mainly used in treatment of infections in animals as well as human beings caused by Gram-positive bacteria. Hou *et al.* (2015) in their study introduce a fluorescent sensor for methyl parathion, using L-tyrosine methyl ester functionalized CDs (Tyr-CDs) and the tyrosinase system. These CDs are produced via hydrothermal reaction using methyl ester of L-tyrosine and citric acid. The sensor functions by fluorescence quenching due to the oxidation of tyrosine methyl ester on the dot’s surface when interacting with tyrosinase. Jalili *et al.* (2020) addressed the challenge of detecting antibiotic residues in milk products with focus on penicillin-G. Their innovative approach involved the development of a ratiometric fluorescent sensor, comprising varied coloured CDs and a mesoporous structured molecularly imprinted polymer (B/YCDs@mMIP). This sensor demonstrated a linear response between 1 and 32 nM with detection limit of 0.34 nM for PNG, exhibiting very good specificity for PNG over its analogs. Notably, the sensor’s unique feature was the discernible change in fluorescence colour, from yellow into blue, upon PNG addition, which allowed visual detection. By encapsulating yellow-emissive CDs and blue emissive CDs into the mesoporous molecularly imprinted polymer, this “green” approach offered a reliable and sensitive means of directly detecting penicillin-G residue in milk. Hao *et al.* (2021) developed a smartphone-integrated dual-emission ratiometric fluorescence probe for cephalexin detection in milk. They used blue-emitting CDs and red-emitting CdTe quantum dots with a cephalexin antibody for selectivity. The method exhibited a linear range of 1–500 µM and a 0.7 µM detection limit. Using a smartphone app, colour changes under UV light were captured for visual detection in milk samples (94.1%–102.2% recovery). This approach offers a simple and cost-effective solution for monitoring antibiotic residues in milk and other dairy products.

Detection of heavy metal ions

C-dots commonly possess oxygen-based surface functional groups like hydroxyl and carboxylic groups, fostering a hydrophilic character and increasing surface active sites. Consequently, C-dots can effectively engage with metal ions through surface bonding, thereby altering the properties of CDs. Furthermore, techniques such as element doping and/or surface modification have been identified as potential methods to enhance the capability of C-dots in detecting pollutants. Wang *et al.* (2021) investigated mercury ions and thiophanate methyl (TM) as environmental contaminants with health risks. They developed a fluorescence-based method using thioctic acid CDs to detect Hg2+ and TM. These SCDs were effective even in the presence of other substances and showed detection limits of 33.3 nmol/L for Hg2+ and 7.6 nmol/L for TM. The study demonstrated the potential of SCDs for accurate detection in real water samples like grape juice, tap water Citri Reticulatae Pericarpium water, suggesting their promising use in environmental monitoring and food safety control. Xie *et al.* (2018), developed a novel dual-emission CDs-AuNCs nanohybrid for highly sensitive ratiometric detection of Hg^{2+} in the environment. This nanohybrid exhibited strong emissions at 440 and 655 nm under 360 nm excitation. Upon encountering aqueous $Hg^{2+,}$ the 655 nm emission decreased significantly, enabling accurate ratiometric detection and quantification of $Hg^{2+.}$ The nanohybrid detected Hg^{2+} at ultra-low concentrations of 0.73 nM and showed remarkable selectivity even in real-world samples such as tap water.

Hazards detection in food processing

During food processing, various hazards arise from external conditions and processing methods. These hazards typically include heterocyclic and biogenic amines, aflatoxins and another components. It is essential to identify and assess these hazards in the food industry. CDs are promising materials for this purpose. Liang *et al.* (2018) introduced a sensitive method for the detection of aflatoxin B1 in peanut samples using CDs coated dummy molecularly imprinted polymer monolithic column in combination with HPLC detection. The CDs-DMIP monolithic column was synthesized using 5,7-dimethoxycoumarin as a dummy template molecule, allowing accurate AFB1 determination by HPLC-FLD. The method showed excellent linearity of 0.5–2000 ng/mL with a high correlation coefficient (0.9999) and recoveries ranging from 79.5% to 91.2%. Detection limits were 0.118 ng mL-1 ($S/n = 3$) and 0.393 ng mL-1 ($S/n = 10$) and the enrichment factor was greater than 71-fold.

Yan *et al.* (2022) presented new dual-emission ratiometric fluorescence sensor for biogenic amines using blue fluorescent CDs and yellow fluorescent CdTe quantum dots. The sensor quantitatively detected 8 biogenic amines with rapid response (30 s) and lower limits of detection (1.259–5.428 μM). In a study by Shi *et al.* (2019), a novel method for sensitive histamine detection was developed using CQDs and synthetic peptides. These peptides, selected through biopanning, had a high affinity for histamine. CQDs' fluorescence was quenched by these peptides, and in presence of histamine, fluorescence was restored due to a stronger interaction. One specific peptide, Hisp3 (DIDRAGKASHWP), and its dipeptide derivative (Hisp3-2-C) showed promise as histamine receptors. This system demonstrated high sensitivity and selectivity, detecting histamine at low concentrations. It quantified histamine varies from 0.1–100 ppm, with limit of detection of 13.0 ppb.

Treatment of various diseases

Cancer therapy

The diversity of CDs in cancer therapy is demonstrated by a number of studies that have explored their application in early tumour detection, accurate characterization and enhancement of treatment efficacy. Wang *et al.* (2023) report on food-derived CDs, which show promise in these areas due to their inherent therapeutic properties, including drug delivery, anti-angiogenic effects and promotion of apoptosis. These properties, together with the induction of cellular reactive oxygen species and the enhancement of immune responses, contribute to the anticancer potential of food-based CDs. Advances in carbon-based quantum dots (CQDs) for tumour diagnosis are comprehensively reviewed by Wang *et al.* (2020), who highlight the potential of CQDs to improve tumour tissue imaging and biomarker detection. The collective results of these studies suggest a promising future for CDs in cancer therapy, where their multifunctional nature enables them not only to aid in diagnosis through bioimaging, but also to actively participate in treatment by inhibiting cancer cell growth and inducing apoptosis.

Treatment of inflammatory disease

CDs have attracted considerable attention for their potential as therapeutic agents in the treatment of inflammatory diseases. Sharma *et al.* (2020) provide a critical examination of the current landscape and summarize the multiple roles that CDs can play, supported by evidence from both *in-vitro* and *in-vivo* studies. The potential of CDs stems from their unique physicochemical properties, biocompatibility and bioactivity, which are being exploited to develop innovative therapeutic interventions. Gudimella *et al.* (2022) contribute to this promising field with their green synthesis of fluorescent CDs derived from *Carica papaya* leaves. Hu *et al.* (2016) investigated the therapeutic effects of Radix Sophorae Flavescentis carbonisata-based CDs on ethanol-induced acute gastric ulcers in rats. Their research indicates the protective effects of these CDs against both inflammation and oxidative stress, suggesting a viable pathway for their clinical application. Similarly, Wang *et al.* (2020) developed CDs from the carbonisata cocoon of the mulberry silkworm and demonstrated significant anti-inflammatory effects, particularly in the inhibition of inflammatory markers, suggesting a new avenue for therapeutic development.

Toxicity of carbon dots

Although CDs have demonstrated significant advantages in applications connected to food, questions have been raised about their toxicity. A number of variables, including dose, surface functionalization and size, can affect how harmful CDs are (Ngafwan *et al.*, 2021). Since CDs can pass through biological barriers due to their small size, there are concerns regarding how using those in food-related applications can affect human health. The absence of regulated rules and established testing protocols specifically for nanomaterials used in the food business poses a significant obstacle to determining the toxicity of CDs. Through *in-vitro* and *in-vivo* experiments, researchers are trying to understand possible negative impacts of CDs. The evaluation of carbon dot's effects on organ systems, cellular construction and general physiological processes is the goal of these investigations. The alteration of the outer layer of CDs, known as surface functionalization, is a critical factor in determining their toxicity (Alas *et al.*, 2020). The interaction of CDs with biological systems can be influenced by the addition of functional groups to their surface. According to some research, carbon dot's surface chemistry can be modified to improve their biocompatibility and lower any possible toxicity. Although some research suggest that certain CDs are not dangerous, thorough and consistent toxicity tests are still required. Furthermore, there is still much to learn about the long-term impacts of carbon dot exposure in relation to food applications (Wang *et al.*, 2020).

It is crucial to remember that even while some research suggests that some CDs are not harmful, thorough and consistent toxicity evaluations are still required. Furthermore, research on the long-term impacts of carbon dot exposure in relation to food applications is also ongoing. To sum up, the subject of carbon dot's toxicity in the food sector is intricate and constantly changing. Although CDs have potential uses in the food industry, it is imperative to fully comprehend both the hazards and benefits of using them before implementing them on a large scale. CDs must be safely integrated into food-related applications by ongoing research, regulatory efforts, and testing methodology developments.

Challenges and limitations with their possible improvement strategies

Lack of standardization methods and knowledge of formation mechanisms

The precursors, synthesis conditions and post-synthesis treatments used in the various methods of green synthesis, now used for CDs differ significantly. The physico-chemical characteristics of CDs become inconsistent as a result of this unpredictability, which limits scalability for industrial applications and also affects the reproducibility of results. There is a lack of comprehensive knowledge and comprehension of the mechanisms controlling CDs development and nucleation using green synthesis techniques. It is quite challenging to adjust and regulate the characteristics of CDs for various applications without a thorough understanding of these principles. Furthermore, the synthesis parameters influencing the optical and structural characteristics of CDs should be the main focus of future studies.

Possible improvement strategies

To stop CDs from aggregating, use surface functionalization to create repulsive forces between them. Use of chemical grafting, high-shear mixing or ultrasonication to guarantee uniform carbon dot dispersion throughout the host matrix. Creation of scalable synthesis techniques, like continuous flow procedures, and enhanced reaction conditions to produce CDs on a large scale without sacrificing quality.

Lack of understanding of interaction among carbon dots and host matrix

Despite the fact that CDs are still used in many different disciplines, the relationship between CDs and the host matrix has not been well examined, as is clear from earlier studies (Varadharajan *et al.*, 2024). This knowledge is essential for maximizing CDs performance in a variety of applications, including biomedicine, energy storage and environmental clean-up.

Possible improvement strategies

Strong covalent connections between CDs and the host material can be created by either chemical grafting or *in situ* growth procedures. Use of chemical grafting, high-shear mixing, or ultrasonication to guarantee uniform CDs dispersion throughout the host matrix.

Synergistic effects between carbon dots and matrix materials

Development of effective pollution control measures requires a thorough understanding of how CDs affect the catalytic characteristics of composites. The medicinal and biocompatibility efficacy of CDs can be enhanced by a thorough comprehension of these effects.

Possible improvement strategies

Creation of nanocomposites with certain characteristics that will work with current systems and working together with industry participants to ensure a smooth integration.

Limited stability, durability and environmental impact

The long-term stability of CDs, particularly in mass applications, has not yet been investigated. Not enough research has been done on the possible degradation of nanocomposites and their effects on the environment. The creation of stable and long-lasting CDs should be a higher emphasis in future CDs research fields. To ascertain the long-term impacts, a life cycle evaluation of CDs should be conducted. It is unclear how the manufacture and disposal of carbon dot nanocomposites may affect the environment (Varadharajan *et al.*, 2024).

Improvement strategies

Developing ecologically acceptable synthesis and disposal techniques and carry out life cycle assessments. Encouraging the use of non-toxic and sustainable resources for the development of CDs. Examination of toxicity and biodegradability of CDs and the by-products of their breakdown with major objective of designing nanocomposites that are both high-performing and environmentally benign.

Production cost

The extensive use of carbon dot nanocomposites across a range of industries may be constrained by high production costs.

Improvement strategies

Optimizing the synthesis routes to use energy-efficient procedures and reasonably priced raw materials. Investigating material reuse and recycling to lower total expenses of creation of CDs.

Economic feasibility

Over 160 million tonnes of whey is produced annually during the manufacturing of cheese and paneer. Water, proteins, lactic acid, lactose, fat and minerals are the main constituents of whey. Because the precursors already include a diverse range of components, including proteins, carbohydrates, underused resources, lipids and other vitamins, substantial surface doping is frequently not required in the context of green synthesis of CDs. However, it has gained attention due to the abundance and low cost of whey by-products, as well as the potential environmental benefits of using waste materials. This strategy increases the value of CDs while simultaneously lowering environmental pollutants. As a result, researchers prioritize using clean, environmentally friendly and non-toxic precursors such inexpensive biomass such as whey. For industries like automotive, aerospace and materials research that must satisfy green production targets, the creation of CDs from biomass (food waste and agricultural by-products) offers an environmentally friendly option. Large-scale biomass conversion to CDs might be automated by engineers, which would save overall expenses.

Conclusions

With significant implications for the food industry, the green valorization of dairy by-products especially whey for the development of CDs is a viable and sustainable strategy. In addition to addressing the environmental issues surrounding the disposal of dairy wastes, this novel approach maximizes the value of these materials by turning them into CDs, a nanomaterial with a wide range of uses in food technology. The circular economy and waste valorization concepts are in line with the use of whey as a precursor for CDs. Whey is turned into CDs, which not only lessens the environmental effect of its disposal but also makes it a useful resource for the food sector. This strategy supports resource efficiency and waste reduction, both of which are in line with sustainability objectives. Whey-derived CDs provide special benefits for the food sector, especially in areas like sensing, packaging and food safety. The antibacterial characteristics of these CDs can be used as innovative nanomaterials to improve food safety and quality by preventing the growth of harmful microbes.

Furthermore, by monitoring and signaling freshness or spoiling, their use in intelligent packaging might help to enhance the storage period of food products. Organizations that use such cutting-edge and eco-friendly strategies not only lessen their environmental impact but also improve their brand's perception among consumers who care about the environment. As a result, this strategy meets not only environmental and economic objectives but also the changing expectations of society for ethical and sustainable corporate operations.

Further investigations should be done to find the potential migratory patterns of CDs from sensing or packaging films into different food systems and also to create strategies for regulating the release of CDs. More research is also required to determine how these CDs affect the GI system and sensory attributes as well as how toxicologically they are assessed using *in vitro* and *in vivo* models. Nonetheless, industry-academia collaboration is making it easier for these innovations to go from the research lab to commercial manufacturing, allowing them to work effectively in practical applications. Future research should focus on conclusive mechanism elucidation using *in situ* spectroscopy and high-resolution advanced analysis of synthesis.

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Corresponding author
Amrita Poonia can be contacted at: dramritapoonia@gmail.com