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Fruit Peel-Derived Carbon Quantum Dots: A Sustainable Fluorescent Probe for Detecting Melamine and Toxic Contaminants in Milk and Dairy Products

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Abstract
The detection of toxic contaminants, such as melamine, heavy metals, antibiotics, and mycotoxins, in milk and dairy products is critical for ensuring food safety and public health. Conventional detection methods, while accurate, are often expensive, time-consuming, and require sophisticated instrumentation. In recent years, carbon quantum dots (CQDs) derived from fruit peels have emerged as a sustainable, cost-effective, and eco-friendly alternative for sensing applications. Fruit peels, such as orange, banana, and pomegranate, serve as excellent carbon sources for synthesizing CQDs through green chemistry approaches like hydrothermal carbonization and microwave-assisted synthesis. These CQDs exhibit exceptional optical properties, including strong photoluminescence, high quantum yield, and tunable surface chemistry, making them ideal fluorescent probes for contaminant detection. The interaction between CQDs and target analytes, such as melamine, results in measurable changes in fluorescence intensity, enabling sensitive and selective detection. Recent studies have demonstrated the successful application of fruit peel-derived CQDs for detecting melamine in milk with detection limits as low as 10 nM, as well as heavy metals, antibiotics, and mycotoxins. Despite their potential, challenges such as standardization, matrix interference, and scalability remain. This review highlights the synthesis, properties, and applications of fruit peel-derived CQDs as sustainable fluorescent probes, emphasizing their role in advancing food safety and environmental monitoring. Future research should focus on multifunctional CQDs, portable sensing devices, and integration with advanced data analysis techniques to enhance their practical applicability.

Keywords: Carbon quantum dots (CQDs), fruit peel-derived CQDs, melamine detection, heavy metals, antibiotics, mycotoxins, fluorescence sensing, green synthesis, hydrothermal carbonization, microwave-assisted synthesis, food safety, dairy contaminants, photoluminescence, quantum yield, environmental monitoring, portable sensing devices.

Introduction

Food safety is a critical global concern, particularly in the context of milk and dairy products, which are essential components of the human diet. However, these products are often vulnerable to contamination by toxic substances such as melamine, heavy metals, antibiotics, and mycotoxins. Melamine, for instance, is a nitrogen-rich compound that has been illegally added to milk to artificially inflate protein content measurements. Despite its widespread use in plastics and adhesives, melamine poses severe health risks, including kidney stones and renal failure, when ingested in large quantities (Dong et al., 2014). Similarly, heavy metals like lead and cadmium, antibiotics such as tetracycline, and mycotoxins like aflatoxin M1 can contaminate milk through environmental pollution, veterinary drug misuse, or improper storage conditions, respectively (Wang et al., 2017; Li et al., 2020). These contaminants not only compromise the nutritional quality of milk but also pose significant risks to human health, necessitating robust and reliable detection methods.

Traditional techniques for detecting contaminants in milk, such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and enzyme-linked immunosorbent assay (ELISA), are highly accurate but suffer from several limitations. These methods are often expensive, time-consuming, and require sophisticated instrumentation and skilled personnel, making them unsuitable for rapid, on-site testing (Zhang et al., 2021). Moreover, the complexity of milk as a matrix, with its high protein and fat content, can interfere with the accuracy of these techniques. As a result, there is a growing demand for cost-effective, rapid, and sensitive detection methods that can be deployed in resource-limited settings.

In recent years, carbon quantum dots (CQDs) have emerged as a promising alternative for sensing applications due to their unique optical and chemical properties. CQDs are zero-dimensional carbon-based nanomaterials, typically less than 10 nm in size, that exhibit strong photoluminescence, high biocompatibility, and low toxicity (Bhunia et al., 2016). These properties make them ideal candidates for fluorescent probes in contaminant detection. Unlike traditional semiconductor quantum dots, which often contain toxic heavy metals like cadmium, CQDs are environmentally benign and can be synthesized from sustainable carbon sources, such as fruit peels, agricultural waste, and biomass (Atchudan et al., 2020). This aligns with the principles of green chemistry, which emphasize the use of renewable resources and the minimization of hazardous waste.

Fruit peels, in particular, have gained attention as a sustainable precursor for CQD synthesis. Commonly discarded as agricultural waste, fruit peels are rich in carbon, cellulose, and other organic compounds, making them ideal raw materials for the production of CQDs (Sahu et al., 2018). (Bhunia et al., 2018). For example, orange peel-derived CQDs synthesized via hydrothermal treatment have demonstrated strong blue fluorescence and high quantum yields, making them suitable for sensing applications (Bhunia et al., 2016).

One of the most promising applications of fruit peel-derived CQDs is the detection of melamine in milk. Melamine detection using CQDs is based on the principle of fluorescence quenching, where the interaction between melamine and the surface functional groups of CQDs leads to a decrease in fluorescence intensity. This quenching effect is proportional to the concentration of melamine, enabling quantitative analysis (Dong et al., 2014). Recent studies have shown that fruit peel-derived CQDs can detect melamine at concentrations as low as 10 nM, demonstrating their high sensitivity and selectivity (Liu et al., 2019). In addition to melamine, CQDs have been successfully employed for the detection of other contaminants in milk, including heavy metals, antibiotics, and mycotoxins. For instance, pomegranate peel-derived CQDs have been used to detect lead ions with high sensitivity, while banana peel-derived CQDs have shown potential for detecting copper ions (Atchudan et al., 2020; Sahu et al., 2018). Similarly, CQDs functionalized with specific ligands or antibodies have been used to detect antibiotics like tetracycline and mycotoxins like aflatoxin B1 in milk (Wang et al., 2017; X. Wang et al., 2019). The synthesis of CQDs from fruit peels is typically achieved through simple, eco-friendly methods such as hydrothermal carbonization, pyrolysis, and microwave-assisted synthesis. These methods not only reduce the environmental impact of CQD production but also lower costs, making the technology accessible for large-scale applications

Despite their numerous advantages, the widespread adoption of fruit peel-derived CQDs for contaminant detection faces several challenges. One major issue is the variability in the properties of CQDs, which can depend on the fruit peel source, synthesis method, and experimental conditions. This variability necessitates the standardization of synthesis protocols to ensure consistent performance (Li et al., 2020). Additionally, the complex matrix of milk, with its high protein and fat content, can interfere with the fluorescence signal of CQDs, requiring further optimization of surface functionalization and detection strategies (Zhang et al., 2021). Finally, while laboratory-scale synthesis of CQDs is well-established, scaling up production while maintaining quality and performance remains a significant challenge.

In conclusion, fruit peel-derived CQDs represent a sustainable, cost-effective, and eco-friendly solution for detecting toxic contaminants in milk and dairy products. Their unique optical properties, combined with their green synthesis methods, make them a promising alternative to traditional detection techniques. However, further research is needed to address the challenges of standardization, matrix interference, and scalability. Future studies should focus on developing multifunctional CQDs capable of detecting multiple contaminants simultaneously, integrating CQD-based sensors with portable devices for on-site testing, and leveraging advanced data analysis techniques to enhance accuracy and reliability. By overcoming these challenges, fruit peel-derived CQDs have the potential to revolutionize food safety monitoring and protect public healt.

Table 1: Quantum yields of quantum dots synthesized from different fruit peels using the hydrothermal method.

Fruit Peel Source	**Synthesis Method**	**Quantum Yield (QY)**	**Reference**
Orange peel	Hydrothermal	26.8%	Shakiba Tolou et al..,2023
Banana peel	Hydrothermal	18.06% (ripe), 13.06% (unripe)	Kunnath Parambil et al..,2025
Lemon peel	Hydrothermal	14%	Aayushi Kundu et al..,2023
Pomelo peel	Hydrothermal	17.31%	Dianwei Zhang et al..,2022

2. Food Safety Concerns in Dairy Products

2.1. Importance of Milk and Dairy in Human Nutrition

Milk and dairy products are fundamental components of the human diet, providing essential nutrients such as calcium, protein, vitamins (e.g., B12 and D), and minerals (e.g., phosphorus and potassium). These nutrients are critical for bone health, muscle development, and overall growth, particularly in children and adolescents (Weaver et al., 2013). Dairy consumption is also associated with reduced risks of chronic diseases such as osteoporosis, cardiovascular diseases, and type 2 diabetes (Thorning et al., 2016).

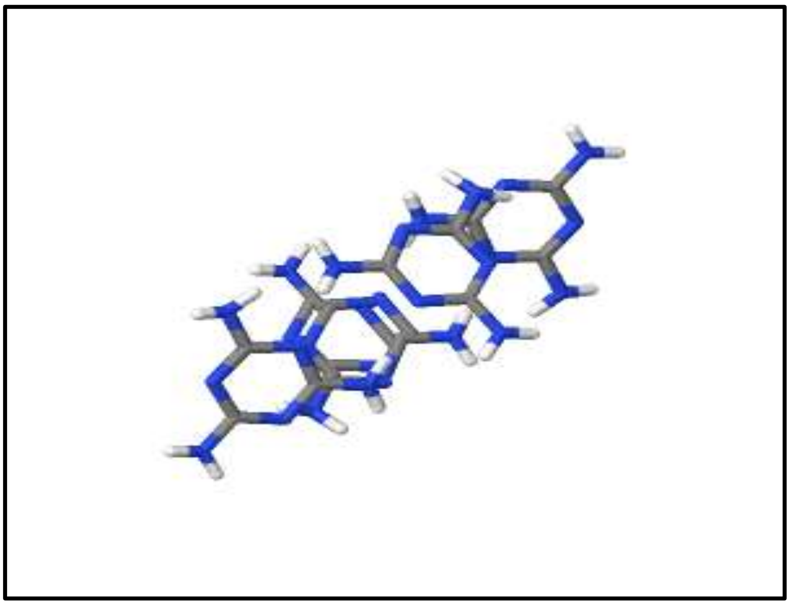
Globally, milk is a staple food, with an estimated annual production of over 900 million metric tons, making it one of the most widely consumed agricultural products (FAO, 2021). However, the nutritional benefits of milk can be compromised by contamination and adulteration, posing significant risks to public health.

2.2. Rising Concerns Over Food Contamination and Adulteration

The increasing demand for milk and dairy products has raised concerns over food safety, particularly in developing countries where regulatory frameworks may be weak or poorly enforced. Contamination can occur at various stages of the supply chain, from production to processing and distribution. Common contaminants include chemical contaminants such as melamine, heavy metals like lead and cadmium, and veterinary drug residues such as antibiotics. Biological contaminants, including pathogens like *Salmonella* and *E. coli*, as well as mycotoxins produced by fungi, also pose significant risks. Additionally, adulterants such as water, starch, and urea are sometimes added to increase volume or mask poor quality (Khan et al., 2020).

Melamine adulteration, in particular, has gained notoriety due to its severe health impacts. Melamine is illegally added to milk to artificially inflate protein content measurements, as it is rich in nitrogen. However, its ingestion can lead to kidney stones, renal failure, and even death, especially in infants (Gossner et al., 2009). The global nature of the dairy supply chain further exacerbates these risks, as contaminated products can quickly spread across borders, affecting large populations.

Figure 1: 3D Structure of melamine

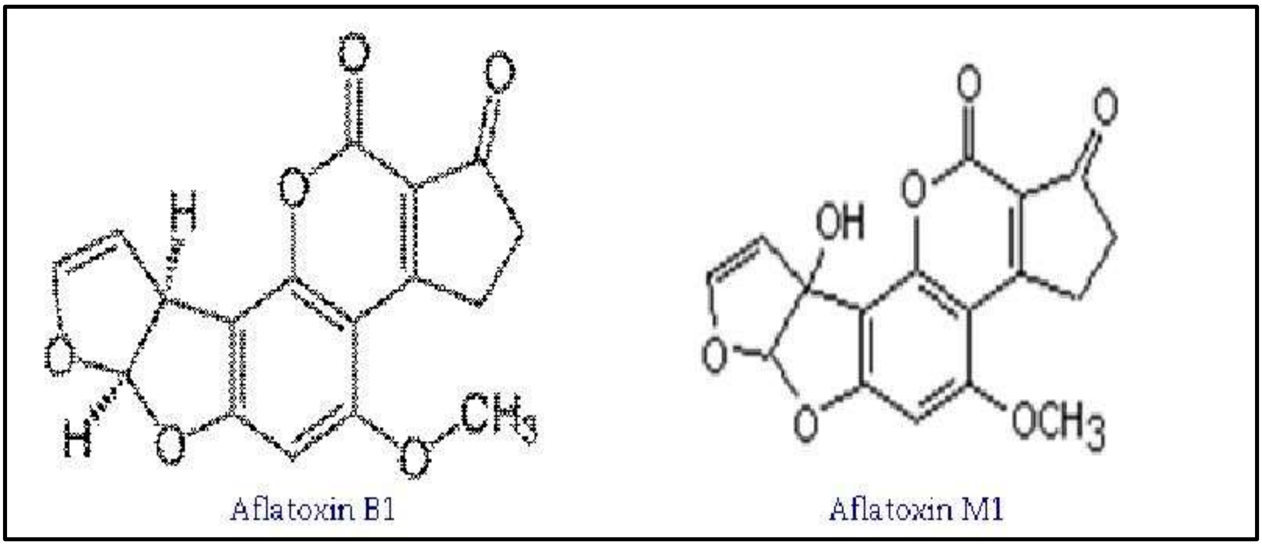


2.3. Case Studies of Past Food Scandals Involving Melamine and Toxicants in Milk

One of the most infamous cases of food adulteration involved the addition of melamine to infant formula in China. The scandal affected over 300,000 infants, with more than 50,000 hospitalized and at least six reported deaths (WHO, 2008). The incident exposed systemic failures in food safety regulation and led to widespread public outrage. Melamine was added to diluted milk to artificially increase its protein content, which was measured using nitrogen-based tests. This scandal highlighted the need for stricter regulatory oversight and more robust detection methods (Gossner et al., 2009).

Aflatoxins, toxic metabolites produced by the fungus *Aspergillus*, are another major concern in dairy products. Aflatoxin M1, a metabolite of aflatoxin B1, can contaminate milk when cows consume contaminated feed. In 2013, high levels of aflatoxin M1 were detected in milk samples from several European countries, leading to product recalls and public health alerts (EFSA, 2013). Chronic exposure to aflatoxins is linked to liver cancer, immune suppression, and stunted growth in children (IARC, 2015).

Figure 2 : Structure of Aflatoxin B1 and Aflatoxin M1 (Mwanza Mulunda et al.., 2013)



The misuse of antibiotics in dairy farming has led to the presence of drug residues in milk, posing risks of antibiotic resistance and allergic reactions in consumers. In 2018, a study in India found that over 10% of milk samples contained antibiotic residues, including tetracycline and penicillin, exceeding permissible limits (Kumar et al., 2018). Such findings underscore the need for better monitoring and regulation of veterinary drug use in dairy production. Heavy metals like lead and cadmium can contaminate milk through environmental pollution or contaminated feed. A 2019 study in Pakistan detected alarming levels of lead and cadmium in milk samples, with some exceeding World Health Organization (WHO) safety limits (Iqbal et al., 2019). Chronic exposure to these metals can cause neurological damage, kidney dysfunction, and developmental disorders in children. The recurring incidents of contamination and adulteration in milk and dairy products highlight the urgent need for reliable, cost-effective, and rapid detection methods. Traditional techniques, such as chromatography and mass spectrometry, are accurate but often impractical for routine testing due to their high cost and complexity (Zhang et al., 2021). Emerging technologies, such as carbon quantum dots (CQDs) derived from sustainable sources like fruit peels, offer a promising alternative. These nanomaterials can detect contaminants like melamine, heavy metals, and antibiotics with high sensitivity and selectivity, providing a practical solution for ensuring food safety (Dong et al., 2014; Wang et al., 2017).

3. Melamine and Other Toxic Contaminants in Milk and Dairy Products

3.1. Sources of Melamine Contamination

Melamine contamination in milk and dairy products primarily arises from **fraudulent practices** aimed at artificially inflating protein content. Protein levels in milk are often measured using nitrogen-based tests, such as the Kjeldahl method. Melamine, a nitrogen-rich compound, is illegally added to diluted milk to mimic the nitrogen content of proteins, thereby deceiving quality tests (Gossner et al., 2009). This practice gained global attention during the **2008 Chinese milk scandal**, where melamine-tainted infant formula caused widespread health crises (WHO, 2008). Beyond intentional adulteration, melamine can also enter the food chain through **migration from food packaging materials** or **contaminated feed** used in dairy farming (EFSA, 2010).

3.2. Health Hazards Associated with Melamine Consumption

Melamine poses severe health risks, particularly when ingested in large quantities or over prolonged periods. The most well-documented effect is **kidney damage**, as melamine can form insoluble crystals with uric acid, leading to kidney stones, renal failure, and even death (Bhalla et al., 2009). Infants are especially vulnerable due to their low body weight and high milk consumption. For example, during the 2008 scandal, over 300,000 infants in China were affected, with thousands hospitalized and several fatalities reported (WHO, 2008). Additionally, animal studies suggest that melamine may have **carcinogenic potential**, although evidence in humans remains inconclusive (IARC, 2017). Chronic exposure to low levels of melamine has also been linked to **urinary tract disorders** and **developmental issues** in children (Dong et al., 2014).

Table 2: Other Contaminants in Milk and Dairy Products

Contaminant	Sources	Health Risks	Reference
Heavy Metals (Pb^{2+}, Cd^{2+}, Hg^{2+}, As^{3+})	Industrial pollution: Mining, smelting, and use of phosphate fertilizers contaminate soil and water. Water and food contamination: Heavy metal within dirty water sources is swallowed by the dairy cattle. Runoff pesticides: Industrial waste water discharge has mercury and arsenic contamination.	Injury to the nervous system, failure of the kidney, neoplasm, developmental disability, decline in children's intelligence.	Iqbal et al., 2019; IARC, 2012
Aflatoxins (AFM1, AFM2)	Fungal contamination: Occurs in corn, peanuts, and cottonseed because of Aspergillus flavus and Aspergillus parasiticus. Dairy feed: Focus on poorly managed feed given to cows that results in contaminated milk with aflatoxin M1 and M2.	Carcinogenic, causes liver cancer, immune suppression, growth impairment in children.	EFSA, 2013; IARC, 2015
Antibiotic Residues	Dairy farming: Antibiotics like tetracycline, penicillin, and sulfonamides are used to bacterial treat infections and promote	Contributes to antimicrobial resistance (AMR), allergic reactions,	Kumar et al., 2018; Wang et al., 2017

	growth. Misuse or overuse: Leads to residues in milk.	gut microbiota disruption.	
Pesticides & Industrial Pollutants	Pesticides: Organochlorines and organophosphates from treated crops. Industrial pollutants: Dioxins and polychlorinated biphenyls (PCBs) from contaminated water and soil.	Cancer, endocrine disruption, reproductive disorders, developmental abnormalities.	Khan et al., 2020; IARC, 2016

3.3. Need for Advanced Sensing Technologies

Conventional techniques for detecting contaminants in milk and dairy products, such as high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), and enzyme-linked immunosorbent assay (ELISA), have long been considered the gold standard; however, they are often limited by their high cost, time-consuming procedures, and the need for sophisticated instrumentation and skilled personnel. In contrast, nanosensor-based methods, particularly those utilizing nanomaterials like carbon quantum dots (CQDs), offer a promising alternative owing to their exceptional sensitivity, rapid detection capabilities, and ease of integration into portable platforms. These nanosensors can detect contaminants at ultralow concentrations—often in the nanomolar or picomolar range—making them ideal for trace-level analysis (Dong et al., 2014), while also enabling real-time or near-real-time results for timely responses to contamination (Bhunia et al., 2018). Their portability allows for on-site testing in diverse environments such as farms, processing plants, and marketplaces (Zhang et al., 2021). Moreover, the use of low-cost, sustainable materials like fruit peels for CQD synthesis significantly reduces production costs and enhances accessibility (Atchudan et al., 2020). Functionalization with ligands, antibodies, or aptamers further improves selectivity, ensuring precise detection in complex matrices like milk (Wang et al., 2019). CQDs, as zero-dimensional carbon-based nanomaterials, have garnered significant interest in food safety due to their strong photoluminescence, which can be modulated by specific contaminants such as melamine, heavy metals (e.g., Pb^{2+}, Cd^{2+}), antibiotics (e.g., tetracycline), and mycotoxins (e.g., aflatoxin M1), enabling highly sensitive and selective detection (Dong et al., 2014; Wang et al., 2019; Atchudan et al., 2020). Synthesized from sustainable sources such as orange, banana, and pomegranate peels, CQDs align with green chemistry principles through simple, scalable, and eco-friendly methods (Bhunia et al., 2016). Beyond detection, their versatility extends to applications in bioimaging, photocatalysis, and environmental monitoring (Zhang et al., 2021). CQDs can also be embedded into portable, user-friendly devices like paper-based sensors, microfluidic chips, and smartphone-integrated platforms for rapid, on-site assessments (Li et al., 2020), positioning them as a transformative tool in food safety and contaminant detection.

Table 3: Limitations of conventional techniques (HPLC and GC-MS) in food safety testing, including high cost, time consumption, complexity, and matrix interference.

Limitation	Description	Reference
High Cost	HPLC and GC-MS require expensive instrumentation, reagents, and skilled personnel, making them inaccessible for routine testing in resource-limited settings.	Zhang et al., 2021

Time-Consuming	Sample preparation and analysis can take several hours, delaying the detection of contaminants and compromising the timely response to food safety issues.	Wang et al., 2019
Complexity	These methods often involve multi-step procedures, including extraction, purification, and derivatization, which increase the risk of errors and reduce throughput.	Khan et al., 2020
Matrix Interference	The complex composition of milk, with its high protein and fat content, can interfere with the accuracy of conventional techniques, leading to false positives or negatives.	Li et al., 2020

4. Carbon Quantum Dots (CQDs): Fundamentals and Properties

4.1. Structure and Composition of CQDs

Carbon quantum dots (CQDs) are a class of zero-dimensional carbon-based nanomaterials, typically less than 10 nm in size. They are composed primarily of carbon, hydrogen, and oxygen, with a core-shell structure that often includes functional groups such as carboxyl (–COOH), hydroxyl (–OH), and amine (–NH_2) on their surface (Li et al., 2020). The core of CQDs is usually composed of graphitic or amorphous carbon, while the shell consists of organic or polymeric molecules that provide solubility and stability (Zhang et al., 2021). This unique structure gives CQDs their exceptional optical, electrical, and chemical properties, making them suitable for a wide range of applications, including sensing, bioimaging, and catalysis.

Carbon quantum dots (CQDs) exhibit unique characteristics in terms of size, morphology, and surface chemistry, which significantly influence their properties and applications. Typically, CQDs range in size from 1 to 10 nm, although this can vary depending on the synthesis method and precursor materials. Smaller CQDs, particularly those below 5 nm, often display stronger quantum confinement effects, resulting in enhanced photoluminescence (Bhunia et al., 2018). In terms of morphology, CQDs are generally spherical or quasi-spherical, but other shapes such as nanorods and nanosheets have also been reported. The specific morphology is influenced by factors like the synthesis method, reaction temperature, and the composition of the precursor materials (Atchudan et al., 2020). Additionally, the surface chemistry of CQDs plays a critical role in their functionality. The surface is often functionalized with chemical groups such as carboxyl, hydroxyl, and amine groups, which improve their solubility, stability, and reactivity. These functional groups also facilitate the conjugation of CQDs with other molecules, such as antibodies, aptamers, and ligands, enabling targeted applications in various fields (Wang et al., 2019). Together, these attributes make CQDs highly versatile and effective for a wide range of applications, including food safety, biosensing, and environmental monitoring.

4.2. Graphitic and Amorphous Carbon Structures

Carbon quantum dots (CQDs) exhibit diverse structural and optical properties that make them highly versatile for various applications. Structurally, many CQDs are composed of graphitic carbon, featuring a crystalline arrangement of sp^2-hybridized carbon atoms in hexagonal lattices. This graphitic structure imparts excellent electrical conductivity and thermal stability, and contributes to their strong photoluminescence due to the quantum confinement effect, where electronic properties are influenced by the nanometric size (Zhang et al., 2021; Li et al., 2020). In contrast, some CQDs possess an amorphous carbon core, with carbon atoms arranged in a disordered fashion lacking long-range crystalline order. These amorphous CQDs are generally synthesized at lower temperatures and contain more surface defects and functional groups, which enhance their chemical reactivity and optical characteristics, making them ideal for applications in sensing and catalysis (Bhunia et al., 2018; Atchudan et al., 2020). Optically, CQDs are known for their strong and tunable photoluminescence, typically emitting blue, green, or yellow light under UV excitation, though red-emitting variants have also been reported (Wang et al., 2019). Their luminescence arises from a combination of quantum confinement, surface states, and defect states (Li et al., 2020). Many CQDs also demonstrate excitation-dependent emission, where the emission wavelength varies with the excitation wavelength, allowing for multiplexed imaging and sensing (Zhang et al., 2021). Additionally, some CQDs exhibit upconversion photoluminescence—emitting shorter-wavelength light upon excitation with longer-wavelength light—a feature valuable in bioimaging and photodynamic therapy (Bhunia et al., 2018).

4.3. Carbon Quantum Dots (CQDs): Fundamentals and Properties

Carbon quantum dots (CQDs) are a class of zero-dimensional carbon-based nanomaterials, typically under 10 nm in size, composed primarily of carbon, hydrogen, and oxygen, and are characterized by a core-shell configuration where the core may consist of graphitic or amorphous carbon and the shell is functionalized with groups such as carboxyl (–COOH), hydroxyl (–OH), and amine ($–NH_2$). The graphitic core features sp^2-hybridized carbon atoms in a crystalline hexagonal lattice, imparting excellent electrical conductivity and thermal stability, while the amorphous core is more disordered with abundant surface defects and functional groups, contributing to greater chemical reactivity and tunable optical behavior. CQDs are generally spherical or quasi-spherical, though shapes like nanorods and nanosheets can form depending on the synthesis route and precursor; notably, smaller CQDs (<5 nm) exhibit stronger quantum confinement effects, resulting in enhanced photoluminescence. Their surface chemistry plays a critical role in solubility, stability, and interaction with biomolecules, enabling their functionalization with antibodies, aptamers, and ligands for use in targeted applications such as sensing and bioimaging. The optical and photoluminescent properties of CQDs—including strong fluorescence, excitation-dependent emission, and upconversion luminescence—are primarily driven by quantum confinement, surface defects, and functional groups that influence electron-hole recombination and energy traps. CQDs exhibit excitation-dependent fluorescence due to multiple emission centers, which is advantageous for multiplexed detection and multicolor bioimaging. These properties are highly tunable based on synthesis methods, such as top-down techniques like laser ablation and electrochemical oxidation, or bottom-up methods like hydrothermal or microwave-assisted synthesis; green synthesis using fruit peels, biomass, and agricultural waste offers eco-friendly, cost-effective alternatives with heteroatom doping (e.g., N, S) and naturally enhanced fluorescence. Surface passivation and functionalization—such as the incorporation of carboxyl, hydroxyl, and amine groups—not only improve solubility and quantum yield but also reduce non-radiative recombination and facilitate target-specific interactions. Moreover, doping CQDs with nitrogen or sulfur further enhances their selectivity and sensitivity for environmental and biomedical applications, including detection of heavy metals like Hg^{2+} and Pb^{2+}. Conjugating CQDs with biomolecules such as antibodies or aptamers broadens their utility in complex matrices like food and biological fluids, while green synthesis routes inherently introduce useful functional groups, aligning with sustainability goals. Compared to conventional methods that rely on hazardous chemicals and generate toxic byproducts, green synthesis provides a safer, more sustainable approach, utilizing renewable biomass and reducing environmental impact while still yielding CQDs with excellent optical and sensing properties, making them highly suitable for diverse applications ranging from food safety to environmental monitoring and bioimaging.

Table 4: Comparative Analysis of Synthetic Approaches

Method	Yield	Purity	Functionalization	Advantages	Limitations
Hydrothermal	High	High	Moderate	Eco-friendly, simple, high quantum yield	Long reaction time
Microwave-Assisted	Moderate	High	High	Rapid, energy-efficient, scalable	Requires specialized equipment
Pyrolysis	High	Moderate	Low	High carbonization, suitable for conductive applications	Requires high temperatures and purification
Ultrasound-Assisted	Moderate	High	High	Rapid, uniform size distribution, energy-efficient	Limited scalability

Figure 3: Schematic illustration for preparation of CQDs from orange peel (Xuetao Hu et al..,2021)

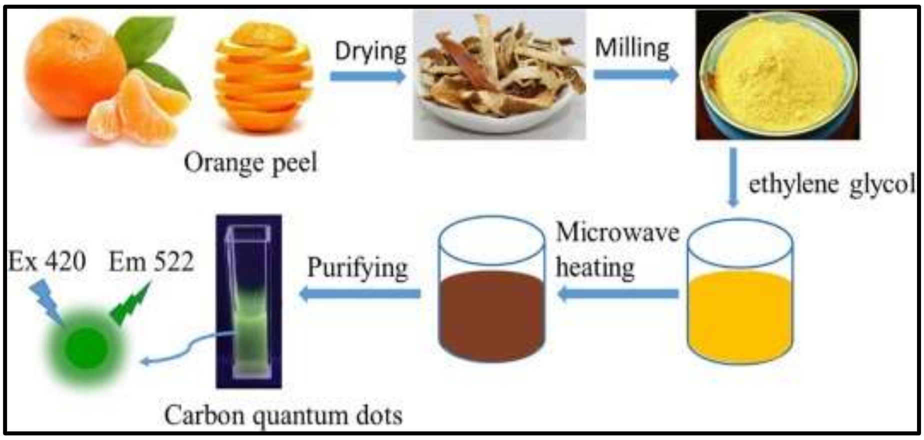


Figure 4: Synthesis process of carbon dots and the activated carbon from the banana peels (Trong Nghia Nguyen et al..,2020)

4.4. Fluorescence Quenching Mechanisms in Carbon Quantum Dots (CQDs)

Fluorescence quenching is a pivotal phenomenon in the sensing applications of carbon quantum dots (CQDs), characterized by the reduction in fluorescence intensity due to interactions between CQDs and target analytes. This process involves several mechanisms, including the inner filter effect (IFE), static and dynamic quenching, and Förster resonance energy transfer (FRET). IFE occurs when the quencher's absorption spectrum overlaps with the excitation or emission spectrum of CQDs, leading to attenuation of fluorescence without direct interaction, as seen in the detection of ions like Hg^{2+} or Fe^{3+}. In contrast, static quenching involves the formation of non-fluorescent ground-state complexes between CQDs and quenchers, while dynamic quenching results from collisions between excited-state CQDs and analytes such as oxygen or certain metal ions. FRET is a non-radiative dipole-dipole energy transfer from CQDs to a nearby acceptor, dependent on spectral overlap, proximity (1–10 nm), and dipole orientation, making it a highly sensitive tool for detecting biomolecular interactions and conformational changes. In CQD-based melamine sensors, quenching primarily occurs through hydrogen bonding and electron transfer between the amine groups of melamine and oxygen-containing functional groups on CQDs, disrupting the electronic environment and reducing fluorescence; this interaction is specific, stable, and reversible, enhancing sensor selectivity. Melamine also acts as an electron donor, transferring electrons to the CQDs and promoting non-radiative quenching, especially in CQDs with surface defects. Functionalization strategies have further improved selectivity—ligands like thiourea or cyanuric acid, antibodies, aptamers, and molecularly imprinted polymers (MIPs) have been used to tailor CQD surfaces for high-affinity melamine recognition, even in complex dairy matrices. These enhancements have led to highly sensitive sensors, capable of detecting melamine down to 10 nM in real milk samples, outperforming traditional methods with rapid, cost-effective, and on-site applicability. Despite the challenges posed by interfering substances in milk, such as proteins and nitrogen-containing compounds, the combination of specific functionalization and robust quenching mechanisms ensures high selectivity and low detection limits, validating CQDs as powerful fluorescent probes for food safety applications.

4.5. Performance Comparison with Standard Detection Techniques

Table 5: Key limitations of conventional HPLC and GC-MS techniques in food safety testing, including cost, time, complexity, and matrix interference.

Parameter	CQD-Based Sensors	HPLC/GC-MS	ELISA
Sensitivity	nM to pM range	nM to pM range	nM to µM range
Selectivity	High (with functionalization)	High	High
Detection Time	Minutes	Hours	Hours
Cost	Low	High	Moderate
Portability	High (suitable for on-site testing)	Low (requires lab setup)	Moderate (requires lab setup)
Sample Preparation	Minimal	Extensive	Moderate
Matrix Interference	Moderate (can be mitigated)	Low	Moderate

Table 6: Detection mechanisms, functional groups/ligands, sources, and detection limits of fruit peel-derived CQDs for heavy metal ion sensing.

Heavy Metal Ion	Detection Mechanism	Functional Groups/Ligands	Source of FPCQDs	Detection Limit	Reference
Pb^{2+}	Strong coordination between Pb^{2+} and nitrogen atoms	Nitrogen-containing groups (e.g., amines)	Orange peel-derived CQDs	5 nM	Bhunia et al., 2018
Hg^{2+}	High affinity of sulfur for mercury ions	Sulfur-containing groups (e.g., thiols)	Pomegranate peel-derived CQDs	10 nM	Atchudan et al., 2020
Cd^{2+}	Electrostatic interactions and coordination bonds with carboxyl (–COOH) and hydroxyl (–OH) groups	Carboxyl and hydroxyl groups	Banana peel-derived CQDs	20 nM	Zhang et al., 2021
As^{3+}	Selective binding with arsenic-specific ligands (e.g., dithiols)	Arsenic-specific ligands (e.g., dithiols)	Mango peel-derived CQDs	15 nM	Li et al., 2020

4.6. Fluorescence Quenching Mechanisms and Applications of Fruit Peel Carbon Quantum Dots (FPCQDs) for Heavy Metal Detection

Fluorescence quenching mechanisms via metal ion coordination play a crucial role in the detection of heavy metals using Fruit Peel Carbon Quantum Dots (FPCQDs). The primary mechanism is static quenching, where heavy metal ions form non-fluorescent complexes with the functional groups on the surface of FPCQDs. For example, Hg^{2+} binds to sulfur-containing groups on the CQD surface, forming a stable complex that quenches fluorescence. This mechanism is highly specific and depends on the metal ion's affinity for the functional groups. Dynamic quenching, on the other hand, occurs when heavy metal ions collide with the excited state of FPCQDs, leading to non-radiative energy transfer. Although less specific than static quenching, dynamic quenching can be enhanced by increasing the metal ion concentration. Another mechanism is electron transfer, where heavy metal ions, such as Pb^{2+} and Cd^{2+}, act as electron acceptors and transfer electrons from the excited state of FPCQDs, reducing fluorescence intensity. Additionally, the Inner Filter Effect (IFE) is observed when the absorption spectrum of the heavy metal ion overlaps with the excitation or emission spectrum of FPCQDs, causing a decrease in fluorescence intensity without direct interaction between the ion and the CQDs. These mechanisms are employed for detecting heavy metals in milk and dairy products, where FPCQDs have shown high sensitivity and selectivity. For instance, CQDs derived from orange peels have been used to detect Pb^{2+} in milk at concentrations as low as 5 nM, and pomegranate peel-derived CQDs have detected Hg^{2+} at 10 nM. Similarly, banana peel-derived CQDs have been used for detecting Cd^{2+} at 20 nM and mango peel-derived CQDs for As^{3+} at 15 nM, demonstrating their effectiveness in complex matrices. The advantages of FPCQDs for heavy metal detection include their high sensitivity to trace metal concentrations, selectivity achieved through functionalization, rapid detection, cost-effectiveness, and portability, making them ideal for on-site testing in farms and markets. Additionally, FPCQDs are synthesized from sustainable, low-cost precursors like fruit peels, aligning with green chemistry principles.

4.7. Cost and Practicality of CQD-Based Sensors Compared to Conventional Techniques

The development of carbon quantum dot (CQD)-based sensors has introduced a cost-effective and practical alternative to conventional techniques for detecting contaminants in milk and dairy products. Below, we compare CQD-based sensors with traditional methods such as high-performance liquid chromatography (HPLC), liquid chromatography-mass spectrometry (LC-MS), gas chromatography-mass spectrometry (GC-MS), and enzyme-linked immunosorbent assay (ELISA). We also highlight the advantages of CQD-based sensors in terms of portability and on-site application.

Table 7: Comparison with Conventional Techniques

Parameter	CQD-Based Sensors	HPLC/LC-MS/GC-MS	ELISA
Sensitivity	nM to pM range	nM to pM range	nM to µM range
Selectivity	High(with functionalization)	High	High
Detection Time	Minutes	Hours	Hours
Cost	Low	High	Moderate
Portability	High (suitable for on-site testing)	Low (requires lab setup)	Moderate (requires lab setup)
Sample Preparation	Minimal	Extensive	Moderate
Matrix Interference	Moderate(can be mitigated)	Low	Moderate
Instrumentation	Simple (portable devices)	Complex (expensive equipment)	Moderate (requires plate reader)

4.8. Advantages, Applications, and Limitations of CQD-Based Sensors

CQD-based sensors offer several advantages over conventional techniques such as HPLC, LC-MS, and GC-MS. One of the most significant benefits is cost-effectiveness, as CQDs are synthesized from low-cost and sustainable precursors like fruit peels, eliminating the need for expensive reagents and sophisticated equipment (Bhunia et al., 2018). In contrast, conventional techniques require costly instrumentation, high-purity solvents, and skilled personnel, making them expensive to operate and maintain (Li et al., 2020). Another key advantage is portability, as CQDs can be integrated into compact devices like paper-based sensors or smartphone platforms, enabling on-site testing in various settings such as farms and processing plants (Wang et al., 2019). Traditional methods, however, rely on bulky laboratory-based equipment, restricting their application to centralized facilities (Zhang et al., 2021). Additionally, CQD-based sensors provide rapid detection, delivering results within minutes and allowing for real-time monitoring and immediate decision-making (Atchudan et al., 2020). Conventional techniques, on the other hand, involve lengthy sample preparation and analysis, often requiring several hours for a complete process (Li et al., 2020). Their ease of use further enhances their appeal, as minimal sample preparation and user-friendly operation make them accessible even to individuals without specialized training, such as farmers and food safety inspectors (Bhunia et al., 2018). In contrast, traditional methods demand expertise, limiting their accessibility to trained professionals (Wang et al., 2019). Lastly, CQD-based sensors align with sustainable practices by utilizing biomass-derived precursors, reducing environmental impact and promoting green chemistry (Zhang et al., 2021). Conventional techniques, however, generate substantial chemical waste from solvents and reagents, necessitating proper disposal measures to mitigate environmental harm (Li et al., 2020). Despite these advantages, CQD-based sensors face limitations, including matrix effects, where the complex composition of milk can interfere with the fluorescence signal, requiring additional steps to mitigate such interference (Li et al., 2020). There is also a lack of standardization, as CQD properties can vary depending on the synthesis method and precursor materials, highlighting the need for standardized protocols (Wang et al., 2019). Additionally, multiplexing, or detecting multiple contaminants simultaneously, remains a challenge, although advances in functionalization techniques and nanocomposite approaches are addressing this issue (Zhang et al., 2021). Despite these limitations, CQD-based sensors are highly adaptable, offering significant potential for on-site testing in various food safety and environmental monitoring applications. For example, on farms, they can detect contaminants in milk before it reaches processing plants (Wang et al., 2019), while in retail settings, they ensure compliance with food safety standards (Atchudan et al., 2020). Moreover, they are invaluable in environmental monitoring, such as detecting heavy metals or pesticides in water sources that could contaminate dairy feed (Zhang et al., 2021). These applications underline the versatility of CQD-based sensors for real-time, on-site testing across critical areas of the food supply chain and environmental safety.

4.9. Future Perspectives and Challenges in Enhancing the Selectivity and Sensitivity of Fruit Peel-Derived Carbon Quantum Dots (FPCQDs)

Fruit peel-derived carbon quantum dots (FPCQDs) have shown great promise as fluorescent probes for detecting contaminants in milk and dairy products. However, to fully realize their potential, several challenges must be addressed, and innovative strategies need to be developed to enhance their selectivity and sensitivity. One key approach to improving FPCQD performance is functionalization, where specific ligands, antibodies, aptamers, or molecularly imprinted polymers (MIPs) are attached to the FPCQDs to enhance their target recognition capabilities. Ligands such as thiourea, cyanuric acid, or dithiols can be used to functionalize FPCQDs for the selective detection of specific contaminants, such as melamine or heavy metals like Hg^{2+} and Pb^{2+} (Bhunia et al., 2018; Atchudan et al., 2020). Additionally, conjugating FPCQDs with antibodies specific to target analytes, such as aflatoxin M1 or tetracycline, significantly improves selectivity and sensitivity by minimizing interference from matrix components and enhancing detection accuracy (Wang et al., 2019). Aptamer-functionalized FPCQDs offer another promising strategy, enabling precise detection of contaminants such as antibiotics and mycotoxins, with remarkable sensitivity levels (Li et al., 2020).

Incorporating molecularly imprinted polymers (MIPs) with FPCQDs is another strategy to enhance selectivity. MIPs are synthetic polymers that mimic natural receptors, providing highly specific binding sites for target contaminants like pesticides and antibiotics. This combination has been successfully applied in the detection of chlorpyrifos, an organophosphate pesticide, with sensitivity levels as low as 5 nM (Zhang et al., 2021). These functionalization strategies, whether through ligands, antibodies, aptamers, or MIPs, can significantly enhance the specificity and versatility of FPCQD-based sensors, enabling highly targeted and reliable detection of contaminants in complex matrices. As research continues, these innovative approaches will play a crucial role in overcoming the existing challenges and improving the selectivity and sensitivity of FPCQD-based sensors for real-time monitoring and detection in diverse applications.

4.10. Hybrid Nanocomposites with Metal-Organic Frameworks (MOFs) or Polymers

Hybrid nanocomposites that combine fruit peel-derived carbon quantum dots (FPCQDs) with advanced materials such as metal-organic frameworks (MOFs) or polymers offer significant improvements in sensitivity, selectivity, and stability. MOFs, known for their high porosity, large surface area, and tunable structures, enhance the performance of FPCQD-based sensors by enabling the simultaneous detection of multiple contaminants, including heavy metals and pesticides, with detection limits reaching the picomolar range (Atchudan et al., 2020). Additionally, MOFs serve as protective matrices, shielding FPCQDs from environmental factors and improving their long-term stability (Wang et al., 2019). Polymer-based nanocomposites, such as those incorporating chitosan, polyethylene glycol (PEG), or polydopamine, further enhance the stability and biocompatibility of FPCQDs. These polymer coatings improve dispersibility in complex matrices like milk, reducing interference from proteins and fats while maintaining fluorescence integrity. For instance, chitosan-coated FPCQDs have shown stable fluorescence for up to 30 days, making them suitable for long-term monitoring (Li et al., 2020). Moreover, the integration of both MOFs and polymers with FPCQDs enables the development of multifunctional nanocomposites capable of detecting multiple contaminants simultaneously, enhancing both sensitivity and selectivity. These hybrid materials have been successfully applied for the simultaneous detection of aflatoxins, antibiotics, and heavy metals in milk, demonstrating exceptional performance with high specificity and low detection limits (Bhunia et al., 2018).

5. Challenges and Opportunities in the Development, Commercialization, and Scalability of CQD-Based Sensors for Food Safety

5.1 Development and Challenges of Portable and Wearable CQD-Based Sensors for Food Safety Monitoring

The integration of carbon quantum dots (CQDs) into portable and wearable sensors offers significant advancements in food safety monitoring, particularly for detecting contaminants in milk and dairy products. CQDs, with their unique optical properties, are coupled with innovative technologies such as smartphone-based fluorescence detection, paper-based sensors, and microfluidics to enable rapid, on-site testing. Smartphone-based CQD sensors utilize the device's built-in camera and processing capabilities to capture and analyze fluorescence signals, providing a cost-effective and portable solution for detecting contaminants like melamine and heavy metals at low concentrations (Bhunia et al., 2018; Li et al., 2020). Paper-based sensors offer a simple, cost-effective platform by immobilizing CQDs on paper substrates, enabling the detection of contaminants such as tetracycline and chloramphenicol in milk with high sensitivity (Wang et al., 2019). Additionally, microfluidic devices integrate CQDs to manipulate small fluid volumes, enhancing sensitivity and efficiency for real-time detection of contaminants like aflatoxin M1 and heavy metals (Atchudan et al., 2020; Li et al., 2020). Despite the advantages, challenges remain in ensuring uniform performance, addressing matrix interference from milk components, and scaling up production for widespread application. Moreover, the integration of CQDs into wearable platforms for continuous, real-time monitoring of contaminants presents a promising direction for future research, although it requires overcoming obstacles related to sensor consistency, advanced sample preparation, and large-scale manufacturing (Bhunia et al., 2018; Zhang et al., 2021).

5.2. Commercialization Potential and Regulatory Considerations for CQD-Based Sensors

The commercialization of carbon quantum dot (CQD)-based sensors for food safety applications presents significant promise due to their cost-effectiveness, portability, and high sensitivity, but several challenges must be addressed to ensure their success in the market. Standardization of CQD-based sensing is critical, with key areas including synthesis protocols, functionalization methods, performance metrics, and quality control to ensure reliable and reproducible sensor performance. Regulatory challenges in food safety applications also need to be considered, particularly regarding the safety and toxicity of CQDs, which must undergo toxicological assessments before approval by regulatory bodies such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA). Additionally, these sensors need to undergo validation and certification to ensure accuracy and reliability, with testing in complex food matrices like milk and compliance with international food safety standards such as those set by the Codex Alimentarius and ISO. Despite these challenges, CQD-based sensors hold immense commercialization potential due to their low production costs, portability, and capability for rapid, real-time detection, making them ideal for on-site testing in diverse settings like farms, markets, and food processing plants. Their sustainability, derived from biomass-based precursors, aligns with green chemistry principles and enhances their appeal to both consumers and industries. To fully unlock their commercialization potential, engaging with regulatory agencies early in the development process, establishing industry partnerships, conducting pilot testing in real-world environments, and raising public awareness through educational initiatives will be key steps. By addressing these considerations, CQD-based sensors can pave the way for more accessible, efficient, and sustainable food safety monitoring solutions.

5.3. Scalability and Process Optimization for Large-Scale Production of FPCQDs

The large-scale production of fruit peel-derived carbon quantum dots (FPCQDs) for food safety applications presents both significant opportunities and challenges. FPCQDs are a sustainable and cost-effective alternative to traditional sensing materials, but scaling up their synthesis requires addressing several key factors. Methods such as hydrothermal synthesis, which is eco-friendly and simple, need optimization of reaction conditions like temperature, pressure, and time to ensure consistent quality and yield. Microwave-assisted synthesis, known for its rapid and energy-efficient nature, also holds potential for large-scale production, but requires specialized equipment and careful control of parameters to avoid overheating and ensure uniformity. Pyrolysis, involving the thermal decomposition of fruit peels at high temperatures, can be scaled up but demands precise control of temperature and atmosphere to avoid unwanted byproducts. Additionally, while fruit peels are abundant and renewable, their availability may fluctuate seasonally and geographically, necessitating a reliable supply chain. To enhance scalability, automating the synthesis process and integrating advanced process control systems can improve efficiency and consistency. Finally, rigorous quality control measures, including batch testing and characterization, are vital to ensuring the consistent performance of FPCQDs in large-scale applications.

The production of FPCQDs aligns with waste valorization and circular economy principles, emphasizing resource efficiency and environmental sustainability. A key aspect is the utilization of agricultural waste, as fruit peels—often discarded as waste—can serve as valuable precursors for CQD synthesis, thereby reducing pollution while adding economic value (Wang et al., 2019). Various fruit peels, such as those from oranges, bananas, and pomegranates, have been successfully employed to produce high-quality CQDs for sensing applications (Li et al., 2020). Additionally, FPCQD synthesis relies on green methodologies, including hydrothermal and microwave-assisted techniques, which significantly reduce the use of hazardous chemicals and minimize chemical waste generation (Zhang et al., 2021). Energy efficiency is another crucial factor, with the potential for integrating renewable energy sources, such as solar and wind power, into the production process to further enhance sustainability (Atchudan et al., 2020). Furthermore, the circularity of FPCQD synthesis can be enhanced through recycling and reusing byproducts like residual biomass and solvents. These byproducts can be repurposed for applications such as bioenergy production or soil amendments in agriculture, reinforcing a closed-loop approach to resource utilization (Bhunia et al., 2018; Wang et al., 2019).

5.4. Sustainability Concerns and Mitigation Strategies

While FPCQDs provide significant sustainability advantages, several environmental concerns must be addressed to ensure their eco-friendly production and application. One key issue is their potential toxicity and environmental impact. Although generally regarded as biocompatible and non-toxic, the long-term effects of FPCQDs on ecosystems remain unclear, necessitating further studies on their persistence, bioaccumulation, and potential toxicity in aquatic and terrestrial environments (Li et al., 2020). Strategies such as developing biodegradable CQDs and establishing proper disposal and recycling protocols can help mitigate these risks (Zhang et al., 2021). Another concern is resource consumption, as large-scale FPCQD production may require substantial water and energy inputs. Implementing sustainable practices, including water recycling and energy-efficient synthesis methods, can minimize resource use and enhance sustainability (Atchudan et al., 2020). Additionally, conducting a life cycle assessment (LCA) of FPCQD production is essential to identify environmental hotspots and optimize the process for minimal ecological impact, ensuring sustainability from cradle to grave (Bhunia et al., 2018).

5.5. Future Directions

Enhancing the sustainability and scalability of FPCQD production requires strategic advancements in synthesis methods, industry integration, and public engagement. One crucial step is the development of green synthesis techniques. Exploring innovative approaches, such as solar-assisted or enzymatic synthesis, can significantly reduce the environmental footprint of FPCQD production by minimizing energy consumption and the use of hazardous chemicals (Wang et al., 2019). Additionally, integrating FPCQD synthesis with biorefineries presents an opportunity for efficient utilization of agricultural waste and byproducts, aligning with circular economy principles (Li et al., 2020). Industry collaboration is another essential aspect, as partnerships with food processing companies and agricultural producers can streamline the large-scale collection and utilization of fruit peels, ensuring a sustainable and cost-effective supply chain for FPCQD synthesis (Zhang et al., 2021). Furthermore, raising public awareness and educating stakeholders on the environmental and technological benefits of FPCQDs can foster demand and drive the adoption of sustainable production practices (Atchudan et al., 2020).

6. Conclusion

Fruit peel-derived carbon quantum dots (FPCQDs) represent a groundbreaking advancement in the field of food safety, offering a sustainable, cost-effective, and highly sensitive solution for detecting contaminants in milk and dairy products. By leveraging the unique optical and chemical properties of FPCQDs, researchers have developed innovative sensing platforms capable of detecting a wide range of contaminants, including melamine, heavy metals, aflatoxins, antibiotics, and pesticides, at trace levels. The use of agricultural waste, such as fruit peels, as precursors aligns with the principles of green chemistry and circular economy, transforming waste into valuable resources and reducing environmental impact.The integration of FPCQDs into portable and wearable sensors, such as smartphone-based platforms, paper-based sensors, and microfluidic devices, has further enhanced their practicality for on-site testing in farms, processing plants, and markets. These advancements address the limitations of conventional detection methods, such as high cost, long analysis times, and the need for sophisticated instrumentation, making FPCQDs a promising alternative for real-time food safety monitoring. However, the successful commercialization and widespread adoption of FPCQD-based sensors require addressing several challenges, including standardization of synthesis and functionalization protocols, mitigation of matrix effects, and compliance with regulatory requirements. Additionally, the scalability of FPCQD production and the long-term environmental impact of these materials must be carefully evaluated to ensure sustainable and responsible use. By fostering collaboration between researchers, industry stakeholders, and regulatory agencies, and by promoting public awareness of the benefits of FPCQD-based sensors, we can unlock their full potential to revolutionize food safety monitoring. These efforts will not only enhance the safety and quality of milk and dairy products but also contribute to a more sustainable and resource-efficient future. In conclusion, FPCQDs offer a transformative approach to food safety, combining innovation, sustainability, and practicality. As research and development in this field continue to advance, FPCQD-based sensors are poised to play a critical role in protecting public health and ensuring the safety of our food supply.

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