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Carbon quantum dots (CQDs) in forensic investigations: a review of current applications and future perspectives

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The advent of Carbon Quantum Dots (CQDs) has introduced transformative possibilities in forensic science, addressing longstanding challenges in the detection, analysis, and preservation of trace evidence. This review comprehensively examines CQDs, highlighting their synthesis methodologies, unique physicochemical properties, and diverse applications in forensic investigations. Emphasizing green, scalable, and cost-effective synthesis routes, the review explores CQDs' tunable fluorescence, exceptional optical characteristics, and biocompatibility, which contribute to their superior performance in forensic contexts. Specifically, CQDs have shown significant promise in areas such as crime scene analysis, fingerprint enhancement, drug identification, and toxicology, offering enhanced sensitivity, specificity, and precision in evidence detection. Despite their potential, the integration of CQDs into forensic workflows faces hurdles related to reproducibility, standardization, and regulatory compliance. Moreover, the convergence of CQDs with cutting-edge technologies like artificial intelligence and computational simulations presents an exciting frontier for advancing forensic methodologies, minimizing human error, and ensuring high throughput and accuracy in investigative processes. This review not only underscores the potential of CQDs to revolutionize forensic science but also identifies key challenges and proposes future directions for research, focusing on refining CQD-based applications and fostering seamless integration into forensic protocols. In summary, CQDs represent a promising and versatile toolset for the future of forensic investigations, driving significant improvements in analytical precision and efficiency.

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1 Introduction

Forensic science leverages scientific methods from fields like biology, chemistry, physics, and digital analysis to solve crimes and support legal proceedings. By collecting and analyzing evidence such as blood, hair, fingerprints, and digital data, forensic science aims to provide objective, evidence-based insights into criminal activities, reducing human error and bias.[1,2] The arrival of advanced techniques like chromatography, spectroscopy, and DNA analysis has significantly improved the accuracy and efficiency of investigations.[3,4] Given the evolving sophistication of contemporary criminal activity, there is a pressing need for innovative analytical strategies. In this context, carbon quantum dots (CQDs) have garnered significant attention as next-generation nanomaterials with exceptional potential for forensic applications.

One promising innovation is the use of carbon quantum dot (CQD) nanoscale carbon materials with exceptional optical properties, high biocompatibility, and tunable characteristics. These properties make CQDs valuable for chemical sensing, imaging, and detecting trace evidence.[5,6] Their ability to detect minute quantities of substances and reconstruct crime scenes offers a breakthrough in forensic science.[7] The existing literature lacks a comprehensive and current review of CQDs in forensic science, particularly across fingerprint visualization, drug detection, and biological stain analysis. This work fills that gap by not only summarizing recent advances but also offering critical insights into emerging trends, challenges, and future directions over the past few decades.

This review aims to critically examine the advancements in forensic investigations over recent decades through the lens of carbon quantum dots (CQDs), highlighting their emerging role, current limitations, and future prospects. Particular emphasis is placed on identifying the key challenges associated with the practical deployment of CQDs in forensic science. Furthermore, the review explores the transformative potential of integrating CQDs with cutting-edge technologies such as artificial intelligence and computational simulations, envisioning how such synergistic approaches could overcome existing barriers and pave the way for more efficient, accurate, and intelligent forensic methodologies.

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2 Synthesis and properties of carbon quantum dots (CQDs)

Carbon quantum dots (CQDs) are synthesized through various methods, including hydrothermal, solvothermal, and microwave-assisted techniques, each offering distinct advantages in terms of reaction conditions, efficiency, and scalability.[1,8,9] These methods typically involve carbonizing organic precursors like sugars or polymers to produce nanoscale particles.[3,10] The fluorescence properties of CQDs are particularly notable, as their emission spectra can be fine-tuned by adjusting particle size, surface functional groups, and doping elements.[9] These optical characteristics make CQDs highly sensitive probes for detecting specific molecules, and their excellent biocompatibility and ease of functionalization enhance their applicability in forensic science.[1,11]

2.1 Methods of synthesis

Carbon quantum dots (CQDs) have garnered significant interest in forensic science due to their unique optical properties and adaptability. To optimize these properties for specific applications, several synthesis methods have been developed, which can be broadly categorized into top-down and bottom-up approaches.[10]

Top-down methods involve breaking down bulk carbon materials into smaller nanostructures. Techniques like laser ablation, electrochemical cutting, and chemical oxidation are commonly used, where large carbon sources are fragmented to form CQDs. While effective, these methods often require complex equipment and offer less control over the CQDs' size and surface properties compared to bottom-up methods.[12]

In contrast, bottom-up approaches involve chemically synthesizing CQDs from smaller molecular precursors such as organic molecules or sugars. Hydrothermal synthesis, for example, is a widely used technique in which carbon sources like glucose or citric acid are heated under high pressure and temperature in an aqueous solution. This method produces CQDs with excellent photoluminescent properties and precise size control.[13] Other bottom-up techniques, like microwave-assisted synthesis and solvothermal synthesis, allow for more uniform and efficient production of CQDs with tailored sizes and surface functionalities. Microwave-assisted synthesis is particularly rapid and energy-efficient, while solvothermal methods enable control over surface chemistry by adjusting the solvent composition.[14,15]

Electrochemical synthesis, another recent advancement, uses an electric current to convert precursors into CQDs. This method is scalable, cost-effective, and offers precise control over both size and surface properties.[16,17] Each of these synthesis methods has distinct advantages, and the choice of technique depends on factors such as desired CQD characteristics, production scale, and application needs.[18] The continued development of these synthesis methods is key to unlocking the full potential of CQDs in forensic science and other fields.

2.2 Fluorescence properties and optical characteristics of (CQDs)

Carbon quantum dots (CQDs) are highly valued in forensic science for their remarkable fluorescence properties, which can be tuned by controlling their size during synthesis.[11] This size-dependent photoluminescence, due to the quantum confinement effect, allows CQDs to emit light across a wide range of wavelengths, from UV to visible and near-infrared regions.[1,12,19] Surface functionalization with chemical groups such as carboxyl or amine enhances their solubility and interaction with target molecules, improving their selectivity and stability in complex samples.[20,21]

CQDs also exhibit exceptional stability under diverse environmental conditions, making them ideal for long-term monitoring in forensic investigations. Their resistance to photobleaching and chemical degradation ensures they retain their fluorescence over extended periods, even under UV light or harsh conditions.[9,22] Furthermore, their size-tuning capability enables precise adjustment of optical properties, beneficial for applications like multi-color imaging or multiplexed detection.[23,24]

Overall, CQDs' tunable fluorescence, surface modification potential, and robustness make them valuable tools in forensic science, particularly for sensing, imaging, and evidence preservation in crime scene investigations. As research progresses, their application range will expand, offering significant advantages in detection and analysis.

2.3 Surface functionalization

The surface properties of carbon quantum dots (CQDs) play a pivotal role in their performance across a range of applications, especially in areas such as sensing, imaging, and forensic science. Surface functionalization involves modifying the surface chemistry of CQDs to enhance their inherent properties or enable specific interactions with target molecules.[25] This modification can optimize the optical properties of CQDs, increase their solubility in various solvents, and improve their overall stability, all of which are crucial for ensuring the reliability and accuracy of CQD-based technologies.[26]

One of the most effective ways to modify the surface properties of CQDs is by doping with heteroatoms, such as nitrogen, sulfur, or phosphorus. This process involves incorporating these heteroatoms into the CQD structure, which can significantly influence the optical and electronic properties of the dots.[27] Doping can enhance the fluorescence of CQDs, increase their solubility, and provide new reactive sites on the surface, making the CQDs more effective in various applications. For example, nitrogen-doped CQDs have been shown to improve fluorescence intensity and photostability, making them more suitable for long-term use in complex environments, such as in forensic analyses or biological sensing.[14,28]

In addition to enhancing fluorescence, doping with heteroatoms also modifies the electronic properties of CQDs, which can influence their behavior in electrochemical or optical sensing applications.[27] The increased chemical reactivity resulting from heteroatom incorporation is particularly valuable for sensor development, as it improves the sensitivity and selectivity of CQDs towards target molecules. This is especially beneficial for applications requiring the detection of low-concentration substances, such as in environmental monitoring or forensic sample analysis, where high sensitivity is essential for accurate results.

Another crucial aspect of surface functionalization is surface passivation, which involves coating the CQDs surface with polymers, small molecules, or surfactants to prevent undesirable aggregation.[29] Aggregation of CQDs can lead to a loss of photoluminescent properties and reduced performance in various applications, so surface passivation is vital for maintaining the uniformity and stability of CQDs in suspension. By passivating the surface, the dispersion of CQDs is improved, which in turn enhances their photoluminescent properties and overall stability in solution.[29–31]

In forensic applications, where consistent and reliable detection is critical, uniform dispersion of CQDs ensures that the sensor's response is both reproducible and accurate. Passivating CQDs with surfactants or polymers not only helps prevent aggregation but also stabilizes the CQDs in different solvents or under varying environmental conditions. This is particularly important for maintaining CQD functionality in complex samples, where aggregation could interfere with their ability to interact with specific analytes, potentially leading to false results.[1,32] Thus, surface passivation is key to enhancing the long-term stability of CQDs in practical applications, making them more suitable for use in forensic investigations and diagnostic tools.

In general, the surface properties of CQDs, including doping with heteroatoms and surface passivation, are critical factors in determining their performance for various applications. Doping with heteroatoms enhances fluorescence, solubility, and reactivity, making CQDs more effective in sensing and detection tasks, particularly in forensic and biological contexts. Surface passivation, on the other hand, ensures the uniformity, stability, and photoluminescence of CQDs, which are essential for consistent and reliable detection. These surface modifications not only improve the performance of CQDs in research but also expand their potential for real-world applications, where high performance, stability, and reproducibility are necessary.

2.4 Characterization techniques

To optimize the properties of carbon quantum dots (CQDs) for applications in sensing, imaging, and forensic investigations, various characterization techniques are essential. X-ray diffraction (XRD) provides insights into the crystallinity and graphitization of CQDs, influencing their electronic properties and stability. Fourier-transform infrared (FTIR) spectroscopy analyzes surface chemistry, revealing functional groups that impact reactivity and stability, crucial for enhancing CQD interactions in forensic applications.[1,33]

Transmission electron microscopy (TEM) offers high-resolution images of CQD morphology and size distribution, directly linked to their optical and chemical properties.[34,35] UV-vis spectroscopy assesses the absorption characteristics and electronic structure, essential for optimizing CQDs for specific optical applications.[36,37] Fluorescence spectroscopy, critical for evaluating photoluminescent properties, provides data on emission spectra, quantum yield, and photostability, all vital for forensic detection and analysis.[11,38] Together, these techniques enable the precise tailoring of CQDs for advanced applications, especially in forensic science, where reliable detection and performance are paramount.

Having explored the diverse synthesis strategies and structural characteristics of carbon quantum dots (CQDs), it is essential to understand how these properties translate into practical utility. The unique optical, chemical, and surface-functional features imparted during synthesis directly influence the performance of CQDs in forensic applications. The following section delves into these applications, highlighting how tailored synthesis approaches enhance their effectiveness in real-world forensic scenarios.

3 Mechanisms of CQDs in forensic applications

3.1 Fluorescence mechanism

Fluorescence is a key feature of carbon quantum dots (CQDs), driving their potential in forensic applications like trace evidence detection, bioimaging, and sensor development. The fluorescence properties of CQDs are influenced by factors such as size, surface chemistry, and the quantum confinement effect.[39–41] Smaller CQDs emit blue light, while larger ones emit red, offering tunable fluorescence for diverse detection needs. This size-dependent fluorescence is beneficial in forensic investigations, enabling the detection of multiple substances simultaneously with high sensitivity.[42,43]

Fluorescence emission is affected by both core and surface states. The core exhibits quantum confinement effects, while surface functional groups (*e.g.*, carboxyl, hydroxyl, amino) influence fluorescence stability and intensity.[20,44] In forensic settings, these tunable properties enable the detection of low concentrations of substances.[1,45] Fluorescence enhancement or quenching, influenced by environmental factors like pH or ion presence, further impacts CQD sensitivity.[11,32,46] Doping or surface modifications can enhance fluorescence for improved detection limits.[20,47]

Overall, the fluorescence properties of CQDs make them highly adaptable for forensic applications, where precise, sensitive, and specific detection is crucial. By manipulating size, surface chemistry, and environmental interactions, CQDs can be optimized for a range of forensic tasks.

3.2 Chemical reactivity and interactions

The chemical reactivity and molecular interactions of carbon quantum dots (CQDs) significantly enhance their utility in forensic applications.[1,40] By modifying their surface chemistry, CQDs can selectively interact with target analytes, improving detection specificity and sensitivity. Functional groups like –OH, –COOH, and $–NH_2$ enable CQDs to bind with various molecules, including organic compounds, metal ions, and biological molecules, making them valuable for detecting substances like drugs, explosives, and toxins.[48] This selective interaction, coupled with fluorescence modulation, enables rapid detection even at trace levels.[49,50]

CQDs also interact with proteins *via* electrostatic forces and hydrogen bonding, expanding their use in biomolecular sensing. These interactions are crucial for identifying proteins in forensic contexts, such as biomarkers or bodily fluids at crime scenes.[51,52] Their ability to detect low concentrations of target proteins further enhances their forensic potential.

Additionally, CQDs' ability to interact with DNA is valuable for genetic analysis in forensic science. By binding to DNA through electrostatic and hydrogen bonding, CQDs enable highly sensitive and rapid DNA detection, improving forensic identification and genetic marker analysis.[51,53] This makes CQDs crucial for both forensic investigations and molecular diagnostics. Overall, CQDs' ability to interact with small molecules, proteins, and DNA provides exceptional sensitivity, specificity, and versatility, making them powerful tools in forensic detection and analysis.

4 Applications of CQDs in forensic science

Carbon quantum dots (CQDs) have become a versatile tool in forensic science due to their enhanced sensitivity, non-toxicity, and tunable optical properties.[54] These features make them ideal for precise, non-invasive forensic applications, such as trace evidence detection and biological sample analysis.[11] CQDs' excellent biocompatibility and customizable optical properties enhance their use in crime scene investigations, biomarker identification, and toxic substance detection, improving the speed, accuracy, and sensitivity of forensic analyses.

4.1 Crime scene investigation

Carbon quantum dots (CQDs) have emerged as a powerful tool in crime scene investigations due to their unique fluorescence properties, which offer high sensitivity and precision for detecting trace evidence.[55] Their non-toxic nature and tunable optical characteristics make them safer and more versatile than traditional forensic methods, significantly improving detection capabilities.[55]

CQDs excel in detecting trace evidence that traditional methods often miss. For example, they have been successfully used to detect bloodstains on various surfaces, which can be challenging with UV light or chemical reagents.[56] Their strong fluorescence under UV light helps visualize blood and other trace evidence, such as hair, fibers, and chemical residues. Furthermore, CQDs can be surface-functionalized to selectively bind to specific molecules, such as proteins in blood, enhancing detection precision and reducing false positives.

Unlike traditional techniques, which may struggle with faint or degraded traces, CQDs provide consistent and bright fluorescence, even under difficult conditions. This ensures that even minute evidence can be detected, improving investigative outcomes. Additionally, CQDs' versatility allows them to be adapted for a wide range of forensic applications, making them invaluable for complex crime scenes involving various types of evidence.[57]

4.1.1 Detection of biological fluids. Carbon quantum dots (CQDs) are highly effective for detecting biological fluids, such as blood, saliva, and semen, which are crucial in forensic investigations.[58] Their strong fluorescence properties and ability to interact with specific proteins, like hemoglobin in blood, enhance the visibility of faint or partially cleaned bloodstains, making them more detectable than traditional methods.[59] CQDs also provide precise detection of other biological fluids, like semen and saliva, by selectively binding to proteins, resulting in clear fluorescence signals.[14,60] Unlike chemical reagents or UV light, CQDs offer non-toxic, non-destructive, and highly sensitive detection, even in the presence of background materials, improving specificity and reducing false positives.[61,62] Their tunable fluorescence makes them adaptable to different types of forensic evidence, enhancing crime scene analysis.

4.1.2 Trace evidence and fiber analysis. Carbon quantum dots (CQDs) are highly effective in detecting trace evidence, such as fibers, hair, and other microscopic materials often left at crime scenes.[6] Their unique optical properties enhance the visibility of even the smallest particles, ensuring that trace evidence is detected with high sensitivity.[11] CQDs improve fiber visibility under fluorescence microscopy, making them stand out for easy collection and analysis.[63] Their versatility in adhering to both synthetic and natural fibers[64] allows forensic scientists to work with a wide range of materials, improving the accuracy of fiber analysis. The high sensitivity of CQDs enables precise identification of trace evidence, reducing false negatives.[65] Additionally, CQDs can be used under various lighting conditions, further enhancing their applicability in complex crime scenes.[66] Overall, CQDs offer a powerful, non-destructive tool for detecting and analyzing trace evidence, playing a crucial role in forensic investigations.

4.1.3 Visualizing fingerprints. Carbon quantum dots (CQDs) are revolutionizing fingerprint detection in forensic science by offering a more sensitive and versatile alternative to traditional methods like powder dusting or chemical reagents.[67] Unlike traditional techniques, which can be limited by surface texture and environmental conditions, CQDs enhance the contrast of latent fingerprints, making them visible under UV light, particularly on non-porous surfaces like glass, metal, and plastic.[68] The strong fluorescence and tunable emission of CQDs improve the visualization of faint or challenging fingerprints, even under adverse conditions. Additionally, CQDs are non-toxic and non-destructive, preserving the integrity of the print for further analysis.[66] This makes CQDs a valuable tool for more accurate and reliable fingerprint identification, offering significant improvements over conventional methods. Table 1 highlights the advantages of CQDs compared to other materials.

4.2 Chemical detection

Carbon quantum dots (CQDs) are gaining significant attention for their versatility in chemical detection, especially in forensic

Table 1 Comparative analysis of carbon quantum dots (CQDs) and other materials used in forensic applications

Material	Sensitivity	Biocompatibility	Stability	Cost	Typical use	Limitations	Ref.
Carbon quantum dots (CQDs)	High (tunable fluorescence)	High	Good (photostable)	Low	Fingerprints, stains, drug residues	Limited standardization, varying specificity	41 and 69
Gold nanoparticles	Very high (plasmonic resonance)	Low to moderate	High	High	Sensing, bio-labeling	Expensive, low biocompatibility	70
Luminol	High (chemiluminescence)	Low	Moderate (light-sensitive)	Low	Blood detection	False positives; short luminescence lifespan	71
Magnetic powders	Moderate	Low	High	Moderate	Latent fingerprints	Surface damage, lower resolution	72

applications. Their unique fluorescence properties enable the detection of a wide range of substances, making them valuable tools at crime scenes. CQDs are being explored for their potential to identify chemicals commonly encountered in criminal investigations, such as drugs, explosives, and poisons.[73] What sets CQDs apart is their ability to be finely tuned to respond to specific chemicals, allowing for the detection of even trace amounts of substances within complex mixtures.[74] This capability is particularly beneficial for identifying toxic compounds, like heavy metals or illicit drugs, where CQDs interact with particular ions or molecules. These interactions trigger measurable changes in fluorescence, which can be easily detected using portable and user-friendly devices.

4.2.1 Toxic substances. CQDs have emerged as highly effective nanomaterials in the detection of toxic substances, including poisons and harmful chemicals commonly encountered in forensic investigations.[1] Their unique optical properties, particularly fluorescence, have proven to be invaluable in identifying minute quantities of hazardous compounds. Recent studies have highlighted the ability of CQDs to interact selectively with specific toxins, such as cyanide, ricin, and other chemical agents, thereby enabling rapid and accurate detection.[75]

One of the key advantages of CQDs in forensic applications lies in their ability to be functionalized. Functionalization refers to the process of chemically modifying CQDs to enhance their affinity for particular target molecules. This allows CQDs to selectively bind to toxic substances, inducing a distinct alteration in their fluorescence emission. As a result, fluorescence-based detection methods can provide real-time, sensitive measurements of toxic compounds at trace levels. For instance, recent advances have shown that the fluorescence response of CQDs can be finely tuned, making them particularly effective for the identification of a wide range of poisons.[75]

Furthermore, CQDs exhibit remarkable sensitivity, which is crucial in forensic science where even minute traces of toxins can have significant implications for criminal investigations. The ability of CQDs to detect low concentrations of toxic substances ensures that forensic experts can reliably identify and quantify these agents, even in complex environmental samples.[1] This capability has been validated by recent research, where CQDs successfully identified toxic compounds in biological fluids and other forensic samples with high precision. Such advancements underscore the potential of CQDs to revolutionize toxicological screening, offering a fast, cost-effective, and reliable tool for law enforcement and forensic laboratories.

Overall, CQDs are gaining increasing recognition as a promising tool for forensic toxicology. Their high sensitivity, coupled with their ease of functionalization and selective binding capabilities, makes them an indispensable asset in modern criminal investigations.[76] As the field of nanomaterials continues to evolve, further research into the optimization of CQDs for forensic applications is likely to enhance their detection capabilities, expanding their use in toxicological analysis.

4.2.2 Detection of drugs. The other significant forensic application of CQDs is their role in the detection of narcotics and controlled substances. Given the rising concerns over drug-related crimes, accurate, rapid detection methods are essential for law enforcement agencies.[77] CQDs have emerged as a promising tool in this domain, particularly due to their unique optical properties, such as fluorescence and photoluminescence, which can be finely tuned to interact with specific drug molecules. When CQDs come into contact with narcotics like cocaine, heroin, or methamphetamine, they exhibit distinct fluorescence changes, enabling the identification of even trace amounts of these substances.[78] This phenomenon is leveraged in the development of portable drug detection devices that provide on-the-spot, non-invasive testing, critical for field investigations.

Recent research has highlighted the sensitivity and specificity of CQD-based sensors for drug detection. For instance, studies by Eliboev *et al.*[79] demonstrated how CQDs, with their high surface area and functionalizable nature, could be engineered to selectively interact with drugs, resulting in notable fluorescence shifts. These advancements have proven invaluable in forensic investigations, allowing law enforcement to conduct real-time analysis, without the need for complex laboratory setups.[43] Furthermore, the low cost, ease of use, and ability to detect minute quantities of substances make CQD-based sensors a game-changer for both large-scale narcotics operations and field-based drug testing.[43]

The potential for CQDs in narcotics detection extends beyond their chemical interactions. Their versatility in different forms such as nanoparticles or films further enhances their applicability across various platforms, from handheld devices to integrated sensor arrays.[43] Recent studies also emphasize how integrating CQDs with other materials, such as polymers or conductive substrates, can further improve the performance of these sensors, boosting their sensitivity and stability.[76] This combined approach is expected to enhance the robustness and reliability of CQD-based sensors, making them indispensable in forensic analysis, where precision and speed are paramount.

4.2.3 Explosives detection. In recent years, CQDs have emerged as a valuable tool for detecting explosives at crime scenes, providing an innovative approach to forensic investigations.[80] The unique optical properties of CQDs, particularly their fluorescence and photoluminescence, allow them to interact selectively with explosive chemicals, such as trinitrotoluene (TNT) and hexogen (RDX).[81] Upon exposure to these hazardous substances, CQDs undergo measurable fluorescence changes, making them highly effective in detecting even trace amounts of explosive residues. This interaction forms the basis for the development of highly sensitive, portable sensors capable of identifying explosive traces in diverse settings, from airport security to crime scenes.[81]

Recent research has underscored the significant potential of CQDs in explosive detection. Packirisamy, *et al.*[9] highlighted the remarkable sensitivity of CQD-based sensors, which can detect minute concentrations of explosives with high specificity. This capability is particularly important in the context of criminal investigations, where timely and accurate identification of explosive residues can significantly enhance both safety and investigative efficiency. Moreover, the adaptability of CQD sensors integrating easily into handheld devices, wearable technologies, or even drone-based detection systems expands their potential applications in practical scenarios.

The benefits of CQD-based detection systems extend beyond their high sensitivity. Their ability to rapidly respond to explosive residues allows law enforcement agencies to perform on-the-spot analysis without waiting for lengthy laboratory results.[43] The cost-effectiveness of CQDs, coupled with their non-toxic and environmentally friendly nature, positions them as a sustainable alternative to traditional explosive detection methods. Furthermore, the continued development of CQD-based sensors, particularly through functionalization and composite formation with materials like polymers and metal–organic frameworks, is expected to further enhance their selectivity, stability, and versatility.[79] This ongoing research is crucial for addressing the evolving demands of explosive detection, making CQDs an indispensable component in modern forensic science.

4.3 Toxicology and biomarker identification

In recent years, CQDs have garnered significant attention in the field of toxicology and biomarker identification, owing to their ability to offer detailed insights into biochemical interactions within living organisms.[82] This characteristic makes them invaluable tools for forensic investigations, particularly those concerning poisoning or disease-related cases. Their unique combination of optical properties, biocompatibility, and functional versatility has positioned CQDs as a cutting-edge technology for detecting toxic substances in complex biological systems, thus facilitating more accurate and timely investigations in forensic toxicology.

CQDs have proven especially effective in toxicology, where they are employed to trace poisons and drugs potentially used to incapacitate or harm victims. Unlike traditional detection methods, CQDs provide a non-invasive and highly sensitive approach, enabling the identification of toxic agents at trace levels.[83] Their non-toxic nature ensures their safe use within biological environments, where they can be utilized for applications such as cellular imaging, drug analysis, and biomarker detection. Recent studies have emphasized the potential of CQDs in detecting a broad spectrum of harmful substances, including poisons, illicit drugs, and even overdose-inducing compounds.[84] Moreover, their surface properties can be easily tailored through functionalization, allowing them to selectively interact with biomolecules of interest. This versatility is particularly useful in identifying biomarkers indicative of poisoning, drug overdoses, or genetic markers linked to various diseases.

For instance, CQDs have been integrated into innovative diagnostic tools for monitoring chemical exposure in living organisms and pinpointing subtle biochemical changes caused by poisoning or adverse drug reactions. Studies by Ali *et al.*[85] have demonstrated how CQDs can bind selectively to specific molecular targets, enabling the detection of biomarkers for chemical toxicity or metabolic disruptions associated with certain diseases. This emerging capability is revolutionizing toxicological assessments, making it possible to perform real-time, precise diagnostics that were once restricted to laboratory settings. The application of CQDs in toxicology not only enhances the specificity and sensitivity of detection but also provides a rapid, cost-effective alternative to traditional toxicological methods.[83]

The growing body of research underscores the potential of CQDs to transform toxicological investigations by offering a robust platform for the detection of harmful substances and disease biomarkers.[74] As research continues to advance, the development of more refined CQD-based systems, coupled with enhanced surface modifications, is expected to further improve their diagnostic accuracy and expand their applications in personalized medicine and forensic science.[5]

4.3.1 Cellular imaging. CQDs have emerged as powerful imaging agents in toxicology, offering a unique and insightful approach to tracking cellular responses to toxins. These nanoparticles are particularly advantageous due to their excellent biocompatibility, which enables their safe integration into living cells without inducing toxicity.[86] Their fluorescence properties make CQDs ideal for real-time, non-invasive monitoring of cellular activities, allowing researchers to observe the uptake and distribution of toxic substances within cells. By utilizing CQDs in this way, it becomes possible to track the cellular pathways activated in response to chemical exposures, providing valuable information for understanding the toxicological mechanisms at play.[87]

Recent studies have underscored the transformative potential of CQDs in toxicological research, particularly their ability to monitor the dynamic interactions between cells and toxicants at the molecular level. For instance, Pan *et al.*[88] demonstrated how CQDs, with their tunable fluorescence and surface functionalization capabilities, can be used to visualize the cellular uptake of poisons, such as heavy metals or industrial chemicals, in real-time. This ability to monitor cellular pathways in response to toxins not only enhances our understanding of toxicity but also contributes to forensic investigations by revealing how specific substances affect tissues in both human and animal models. As forensic toxicologists seek to identify the impact of harmful substances on cellular functions, CQDs provide an invaluable tool for examining the intricate biochemical changes that occur during poisoning events, thus enabling more accurate and timely conclusions.

Moreover, the versatility of CQDs allows for the exploration of various toxicological scenarios, from drug overdoses to environmental poisoning. Their capability to be engineered for selective binding with specific biomarkers or toxins further enhances their utility, making them ideal for targeted imaging applications.[89] Studies have shown that CQDs can be incorporated into complex *in vitro* and *in vivo* systems to map the physiological effects of toxic agents in real time, a feature that traditional methods cannot easily replicate.[85] This innovative use of CQDs not only aids in understanding the molecular mechanisms of poisoning but also supports the development of diagnostic tools that are crucial in forensic toxicology.[90]

In general, the ability of CQDs to track cellular responses to toxins and visualize the pathways activated in response to chemical exposure makes them an indispensable asset in modern toxicological research. As the field continues to evolve, the integration of CQDs with advanced imaging technologies holds the promise of providing even deeper insights into the complex effects of poisons and toxins on biological systems, thus enhancing both forensic investigations and public health research.

4.3.2 Targeting specific biomarkers. Beyond their application in cellular imaging, CQDs have shown considerable promise in targeting and identifying specific biomarkers, such as proteins or genetic markers, which are indicative of poisoning or disease. This capability is due to the tunable surface properties of CQDs, allowing them to be functionalized for selective binding with biomolecules of interest. By modifying the surface chemistry of CQDs, researchers can design them to interact with protein biomarkers associated with toxic exposure, such as those linked to organ damage.[43,91] These biofunctionalized CQDs provide a novel, sensitive, and specific method for detecting markers of toxicity or disease, even at low concentrations, enhancing their application in forensic toxicology.

Recent research highlights the growing importance of CQDs in forensic investigations, particularly in the identification of biomarkers tied to poisoning, drug overdoses, or disease-related injuries. For instance, Rasheed *et al.*[43] demonstrated how CQDs, through surface modifications, could be engineered to selectively bind to proteins indicative of liver or kidney damage caused by toxic substances. This ability to target and detect specific biomarkers has significant implications for forensic toxicology, where identifying the presence of these biomarkers provides critical evidence in cases involving deliberate poisoning, accidental overdose, or even criminal activities such as poisoning-related homicides. Furthermore, CQDs' versatility allows them to be adapted to various detection platforms, such as biosensors or diagnostic assays, making them a powerful tool in real-time, on-site toxicological assessments.

Additionally, the ability of CQDs to target genetic markers opens new avenues in understanding the molecular mechanisms of diseases induced by toxic substances. For example, CQDs can be functionalized to detect genetic alterations that occur as a result of exposure to carcinogens or other harmful environmental factors. This capability not only aids in identifying individuals at risk of disease but also provides valuable data for the forensic investigation of toxin-induced genetic damage. As forensic toxicologists continue to refine these applications, the integration of CQDs into multi-modal diagnostic systems promises to further elevate their role in both investigative and public health contexts.

4.4 Counterfeit detection

CQDs are gaining recognition for their innovative forensic applications, one of the most notable being in the detection of counterfeit documents, currency, and materials.[76] As the global problem of financial fraud and document falsification intensifies, the need for highly effective counterfeit detection methods has become crucial.[76] CQDs offer a solution with their unique optical properties, especially fluorescence, which can be harnessed in inks or coatings applied to documents and currency. This characteristic enables materials to be easily identified as genuine or counterfeit under UV light, offering an added layer of security.[92] Notably, this technique is non-invasive, rapid, and highly precise, making it an invaluable tool in forensic investigations where authentication is vital. By incorporating CQDs, forensic experts can swiftly verify the legitimacy of materials involved in criminal activities, improving efficiency in investigations that deal with financial crimes, forgery, or fraud.

The potential applications of CQDs in forensic science continue to expand, driven by their unique properties, which make them ideal for a wide array of investigative purposes. As the field evolves, the continual advancement of CQD synthesis and functionalization is expected to enhance their performance, leading to even greater accuracy and speed in forensic analyses. This forward momentum in CQD-based technology promises to revolutionize various forensic practices, enabling more effective, real-time assessments and improving investigative outcomes. Despite the promising potential of carbon quantum dots (CQDs) in forensic applications, several critical challenges hinder their widespread adoption. Key limitations include the difficulty in achieving consistent reproducibility in CQD synthesis, the extended time and resource-intensive nature of optimization processes, and the environmental impact associated with waste generation. To address these constraints, strategic integration of CQD technology with complementary analytical and material science techniques is essential. Nevertheless, substantial barriers persist, particularly in aligning CQD-based methodologies with existing forensic standards, ensuring regulatory compliance, and gaining legal acceptance. Advancing CQDs in forensics thus requires a multidisciplinary approach focused on sustainable synthesis, protocol standardization, and robust validation frameworks. Table 2 highlights the wide-ranging forensic applications of CQDs across various specialized fields.

5 The integration of CQDs, AI and simulation technologies

The rapid evolution of forensic science has been significantly shaped by the introduction of innovative materials and advanced computational techniques. Among the most promising developments in recent years are the combined applications of Carbon Quantum Dots (CQDs), Artificial Intelligence (AI), and simulation technologies. Together, these technologies enhance the capabilities of forensic professionals, enabling faster, more accurate, and comprehensive crime scene analyses, and ultimately, accelerating justice outcomes.

5.1 Carbon quantum dots (CQDs) in forensic science

As explained in the previous sections, CQDs are nanoscale carbon-based materials that exhibit unique optical properties. Due to these properties, CQDs have found significant applications in a variety of forensic settings. They are particularly useful in the detection and analysis of biological fluids, trace evidence, and latent fingerprints. CQDs can also be functionalized with specific chemical groups, making them suitable for detecting a wide range of substances such as drugs, explosives, and toxic chemicals.[99,100]

Forensic scientists have successfully employed CQDs to enhance the sensitivity and specificity of chemical detection in crime scenes. For example, CQD-based sensors have been used to detect minute amounts of blood, urine, and semen, which may otherwise go unnoticed in traditional forensic analyses. This property of CQDs extends to the detection of latent fingerprints, as they can be applied to surfaces where traditional methods may fail to visualize prints.[9] In addition to surface analysis, CQDs have applications in toxicology, where they are used as imaging agents to study the absorption and distribution of toxins within biological systems.

5.2 Artificial intelligence (AI) for enhancing forensic analysis

AI systems, particularly those employing machine learning and deep learning algorithms, have transformed forensic science by enabling the efficient analysis of vast and complex datasets. When integrated with CQDs, AI enables forensic scientists to process and interpret data from CQD-based sensors with enhanced precision. AI-powered algorithms can recognize subtle patterns in chemical compositions, biological markers, or fingerprint data that would be challenging to detect through manual inspection alone.[101]

Table 2 Summary of CQD forensic applications: types, detection targets, key advantages, and limitations with supporting references

Application	Detection target	CQD advantage	Limitations	Ref.
Latent fingerprint detection	Sweat/oil residues on porous & non-porous surfaces	High fluorescence, surface tunability, strong adhesion	Reduced performance on aged prints or complex substrates	93
Forensic drug analysis	Illicit drug residues (*e.g.* morphine, methamphetamine)	Rapid sensing, selective quenching/enhancement mechanisms	Cross-reactivity with other substances; limited standardization	94 and 95
Biological stain identification	Blood, saliva, semen	Biocompatibility, label-free imaging, photostability	Sensitivity may vary with dilution and substrate	96
Explosive detection	TNT, DNT, RDX	High sensitivity *via* fluorescence quenching	Need for surface modification for selectivity	97
Document forgery detection	Inks, paper coatings	Enhanced contrast under UV, easy integration with substrates	Limited resolution for detailed alterations	98

For instance, AI can be applied to chemical detection systems where it can distinguish between multiple compounds, identify toxic substances in biological samples, or even predict the chemical structure of unknown compounds. By using large databases of known substances and correlating these with data collected from CQD-based sensors, AI can offer powerful diagnostic tools to forensic investigators. Additionally, AI models can be used for predictive analysis, which allows forensic experts to estimate the potential behavior of substances under varying environmental or biological conditions. This predictive capability is especially valuable when analyzing the toxic effects of drugs or poisonous substances in criminal investigations.[102]

Moreover, AI systems facilitate automated image analysis for fingerprint identification and facial recognition, enabling quicker identification of suspects from surveillance footage. By continuously improving the accuracy of these analyses, AI optimizes the entire forensic process, ensuring that key evidence is not overlooked during investigations.[103]

5.3 Simulation technologies in forensic science

Simulation technologies allow forensic scientists to model complex physical and chemical processes, providing critical insights into how substances behave under various conditions. The combination of CQDs and simulation models allows for a more comprehensive understanding of chemical interactions, biological processes, and environmental variables. For example, by simulating the behavior of toxic substances inside the human body, researchers can predict how a specific poison or drug would affect a victim, helping to determine the cause of death or exposure.[99]

Simulations can also play a pivotal role in crime scene reconstruction, where they allow forensic experts to model various scenarios based on available evidence, such as blood spatter patterns or trajectory analysis of projectiles. The integration of AI in these simulations further enhances their predictive capabilities, enabling the creation of virtual crime scenes that help investigators visualize the sequence of events more accurately.[104,105]

For instance, in the case of drug overdoses, simulations could model how substances enter and affect the body, providing insights into the timeline of events leading to the overdose. Similarly, simulation-based predictions could help in understanding how chemicals released at a crime scene might interact with the environment, providing more accurate information about the timing and spread of the substances.[106,107]

5.4 Synergistic impact of CQDs, AI, and simulation technologies

The future of forensic science lies in the synergistic integration of CQDs, AI, and simulation technologies. This triad of technologies holds the potential to transform forensic practices, from evidence collection to analysis and decision-making. The combined use of these technologies promises: enhanced accuracy and speed: AI and simulation tools can rapidly process data from CQD-based sensors, reducing human error and speeding up investigations. The ability to interpret large datasets and predict outcomes allows forensic professionals to draw conclusions more efficiently.[103] Predictive capabilities: simulation technologies, powered by AI, can model various forensic scenarios, helping investigators understand potential future outcomes based on current evidence. This predictive power is invaluable in solving complex criminal cases or identifying criminal behaviors before they occur.[108,109] Portable forensic tools: the integration of CQDs with AI and simulation technologies could lead to the development of field-deployable forensic tools, allowing law enforcement to conduct on-site analysis in real time. These portable devices would revolutionize the speed of evidence collection and provide immediate insights that may otherwise require lab-based testing.[6,110] Cost-effective analysis: by automating certain aspects of forensic investigations, AI and simulation technologies can reduce labor costs and improve the overall efficiency of forensic laboratories, leading to faster turnaround times in criminal investigations. Ultimately, the integration of these technologies promises to transform forensic investigations, enabling faster, more accurate, and more comprehensive analysis for justice systems worldwide.

As previously discussed, the convergence of artificial intelligence (AI), simulation technologies, and carbon quantum dots (CQDs) holds significant promise for advancing forensic science. CQDs offer high sensitivity and selectivity for the detection of trace substances, while AI facilitates rapid and accurate analysis of complex forensic data. Simulation technologies further contribute by enabling detailed reconstructions of crime scenes, improving the interpretation of spatial and temporal evidence. The integration of these technologies forms a synergistic framework that enhances the precision, efficiency, and reliability of forensic investigations. By streamlining evidence processing, reducing subjective bias, and accelerating decision-making, this multidisciplinary approach has the potential to transform current forensic methodologies.

6 Challenges in using CQDs in forensic investigations

The scalability, cost, and control over the properties of carbon quantum dots (CQDs) are key challenges for their widespread adoption in forensic science.[111] Methods like hydrothermal and solvothermal processes, though effective in labs, are energy-intensive and expensive when scaled. Ensuring batch-to-batch consistency in size, fluorescence, and quality is difficult as minor variations in synthesis parameters can lead to significant differences in CQD properties.[112] Therefore, optimizing scalable, cost-effective synthesis methods remains crucial for practical forensic use.

While CQDs are considered safer than traditional quantum dots, concerns about their biocompatibility and potential toxicity remain, particularly in forensic applications involving biological samples.[74] Surface modifications and contaminants during synthesis can introduce harmful elements, potentially causing cytotoxicity and biological interference.[113] Ensuring non-toxic functionalization and rigorous quality control during manufacturing is vital to prevent cellular toxicity and preserve the integrity of biological evidence in forensic investigations.

Despite being less toxic than metal-based quantum dots, CQDs pose environmental risks, especially regarding waste disposal, nanotoxicity, and long-term ecosystem impact.[114] The solvents and reagents used in CQD synthesis can be harmful if not properly managed, and the biodegradability and environmental behavior of CQDs need further research.[115] To ensure sustainable use in forensic science, greener synthesis methods and eco-friendly functionalization strategies are essential.

Forensic science requires consistency and reliability in results, but variations in CQD properties, like size and fluorescence, due to synthesis conditions pose significant challenges.[116] Lack of standardized protocols across laboratories results in discrepancies that hinder the adoption of CQDs in forensic applications. Standardizing synthesis, functionalization, and application methods is essential to ensure reliable and reproducible results in criminal investigations.[99]

The integration of CQDs with AI and simulation technologies in forensic investigations holds promise, but challenges like data security, standardization, and ethical issues in AI decision-making must be addressed.[117] Ensuring that CQD-based sensors are durable and AI algorithms are trained on diverse, high-quality data will be crucial for their successful application in forensic settings.

In summary, while CQDs offer significant potential for forensic science, challenges in synthesis, toxicity, environmental impact, reproducibility, and integration with other technologies need to be addressed for their effective and widespread use. While regulatory frameworks for CQD-based methods are still emerging, organizations like SWGDRUG and ENFSI have begun recognizing the need for standardized evaluation of nanomaterial-based forensic tools. Although formal approval pathways remain limited, preliminary efforts signal a shift toward integrating CQDs into validated forensic protocols.

7 Future directions in CQD forensics

To enhance the applicability of CQDs in forensic science, advanced functionalization techniques are key. By doping CQDs with heteroatoms or conjugating them with specific ligands, their sensitivity and selectivity for detecting substances like toxins, DNA, and proteins can be significantly improved.[58] This allows for more precise detection in forensic cases, such as drugs, explosives, and biological markers. Future research will likely focus on multi-functional CQDs that can serve both as sensors and imaging agents, streamlining forensic procedures and improving efficiency.[115]

CQDs integrated into portable detection devices represent a major advancement for on-site forensic analysis. These portable systems can detect CQD-based fluorescence or optical signals in real-time, enabling rapid field testing for substances such as biological fluids, drugs, and explosives.[118] Such devices would be especially beneficial for remote or time-sensitive crime scenes, improving investigative efficiency and reducing the reliance on lab testing.[1]

CQDs are poised to transform forensic science through multi-analyte detection systems, enabling simultaneous detection of multiple substances within a single analysis. This would streamline forensic processes, reducing time and resource consumption compared to traditional methods.[58] CQD-based sensors could simultaneously detect drugs, toxins, and genetic markers, offering a comprehensive forensic profile from a single sample. Such advancements would significantly enhance the breadth and speed of forensic investigations, making them more efficient and cost-effective.[14,119]

For CQDs to be widely accepted in forensic science, they must meet strict legal and regulatory standards. These standards ensure that CQD-based techniques are validated, reliable, and reproducible for use in court.[99] Protocols for handling and documenting CQD-based evidence are essential to maintaining the integrity of the judicial process. Clear regulations for CQD synthesis, functionalization, and compatibility with existing forensic methods will be critical for their adoption and legal admissibility.[115]

Integrating CQDs with AI and simulation technologies has the potential to revolutionize forensic investigations. This integration could provide real-time, on-site forensic tools that deliver precise and efficient analyses, transforming investigative practices and accelerating justice outcomes. Interdisciplinary collaboration will drive the development of advanced, user-friendly forensic tools, ensuring that these technologies significantly enhance forensic capabilities.[117]

In summary, the future of CQDs in forensic science lies in advancing their functionalization, integrating them with portable devices, enabling multi-analyte detection, and addressing legal and regulatory hurdles. These innovations will improve forensic investigations, making them faster, more accurate, and cost-effective.

8 Conclusion

The integration of CQDs into forensic science presents an exciting and transformative opportunity for advancing investigative techniques. Their distinctive characteristics such as high fluorescence, biocompatibility, and ease of functionalization offer a versatile platform to enhance various forensic processes, from crime scene investigations to chemical detection and toxicology. CQDs have shown great promise in improving the sensitivity, speed, and accuracy of traditional forensic methods, such as biological fluid detection, trace evidence analysis, and latent fingerprint visualization. Additionally, their application in identifying toxic substances, drugs, explosives, and biomarkers has proven invaluable, allowing forensic experts to obtain critical information with remarkable efficiency.

As the field of forensic science continues to evolve, CQDs stand out as a powerful tool that could significantly reduce the time required for analysis and increase the reliability of evidence in criminal investigations. With ongoing advancements in their synthesis, functionalization, and integration into portable technologies, CQDs hold the potential to revolutionize forensic methodologies, particularly in the context of field-based applications.

Nevertheless, the widespread adoption of CQDs in forensic science will depend on overcoming key challenges, including scalability in production, toxicity concerns, and the establishment of standardized protocols. As these hurdles are addressed, CQDs are likely to become an essential component in forensic analysis, offering precise, rapid, and non-invasive solutions for evidence detection and criminal justice. Looking forward, the future of forensic investigations will benefit immensely from the unique advantages of CQDs, paving the way for more effective and efficient criminal justice outcomes.

In general, carbon quantum dots represent a breakthrough technology with the potential to redefine the landscape of forensic science, offering new dimensions of sensitivity, specificity, and versatility for a broad range of applications, ultimately transforming forensic investigations in ways that will benefit both investigators and the pursuit of justice.

The integrated approach combining CQDs, AI, and simulation technologies not only enhances the effectiveness of forensic investigations but also opens new avenues for the future of criminal analysis, providing smarter, faster, and more reliable methods for solving complex cases.

Abbreviations

AI	Artificial intelligence
CQD/s	Carbon quantum dot/s
DNA	Deoxyribose nucleic acid
DNT	Dinitrotoluene
ENFSI	European network of forensic science institutes
GC-MS	Gas chromatography-mass spectrometry
FTIR	Fourier-transform infrared
IR	Near-infrared
PCR	Polymerase chain reaction
RDX	Hexogen
SWGDRUG	Scientific working group for the analysis of seized Drugs
TEM	Transmission electron microscopy
TNT	Trinitrotoluene
UV	Ultra violet
XRD	X-ray diffraction

Conflicts of interest

There are no conflicts to declare.

Data availability

This article is a review and does not include new experimental data, code, or datasets generated by the authors. All data and references discussed in this review are publicly available and appropriately cited within the manuscript. No additional supporting datasets were generated or analyzed during the preparation of this work.

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