

FORENSIC APPLICATIONS OF CARBON DOTS

Abstract

Carbon dots have received a lot of interest because to their outstanding fluorescence capabilities, low cost of production, and non-toxic qualities. This analysis dives into current developments in fields such as criminal justice, forensic toxicology, and anti-counterfeiting methods. Because of their color-tunable actions in response to incident radiation, C-dot-based combinations have proven particularly beneficial for improving latent fingerprints, providing superior contrast against different backgrounds. As optical nano probes, these dots demonstrate amazing sensitivity and selectivity, allowing for the exact detection of diverse substances such as biological molecules, pharmaceuticals, weapons of mass destruction, heavy metals, and hazardous chemicals. C-dots may be effortlessly incorporated into ink and polymeric formulation due to their adaptive structural and chemical properties, ushering in a revolutionary era of inexpensive barcode as well as nano tags for objects to be identified and anti-counterfeit applications. To assure significant societal and economic benefits, the transition from these promising research discoveries into effective advances requires a coordinated strategy comprising materials researchers, biologists, legal professionals, and digital engineers.

Keywords: Carbon dots; anti-counterfeiting; molecular sensing; drugs; explosives; fluorescence; fingerprinting.

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I. INTRODUCTION

Carbon dots (C-dots) remain among the vanguard of advancing the science of materials, chemical science, nanophysics, medical research, and engineering. Their influence extends from fundamental research to use in practice. C-dots are extraordinarily photoactive members of the Nano carbon family, with unique photophysical properties. Particularly, their emission properties change with activation wavelength, and they exhibit increased photo bleaching resistance. This unusual combination of qualities distinguishes C-dots and drives innovation in a variety of industries [1–3]. Their elemental composition (often C, H, O, N, with certain heteroatoms that are like S and P), functionalization of the surface, and suspension environment all have a substantial impact on their yield of quantum information. [4–6]. The quantum confinement impacts of graphene dots containing just a few monolayers with tiny graphene within their centers are well defined. [7]. Simple oxidative reactions modify the surfaces of C-dots, increasing their ability to move around in polar fluids and ensuring long-term colloidal stability. Furthermore, the introduction of a modest electrochemical field can affect the level of conjugation inside the carbogenic core and also produce oxygenated defects. [8].

C-dots, sometimes known as the innocuous equivalents of quantum dots, are manufactured at a low cost by pyrolysis or hydrothermal treatment of easily available natural resources such as agro-waste and biomass. [9], grass [10], fruit juice [11], leaves [12], glucose [13], gelatin [14], eggs [15], hair fibers [16], etc. Top-down procedures such as arc discharge, ablation with lasers, oxidative, as well as electro-oxidative treatment of nanotubes made of carbon can also be employed to produce well-defined C-dots. [17], carbon fibers [18], activated carbon [19], exhaust soot [20], etc. In theory, these methods are scalable and rely on simple synthetic methodologies followed by standard size exclusion along with purification procedures like as centrifugation after filtering, and dialysis.

With relation to C-dots applications, special emphasis is made on developing bioimaging nanoprobe with higher spatial resolution and accuracy. [21], nano-vehicles for self-targeting drug delivery [22], photodynamic therapy agents [23], antimicrobial materials [24], advanced sensors for chemical and biological compounds [25], technologies for water and soil decontamination [26], slow-release fertilizers [27], polymer nanocomposites [28], highly efficient photocatalysts [29] and superior energy convertors [30].

The present article will look at the real-world uses of C-dots in forensic science, specifically their usage in competent fingerprinting for person identification, their importance in anti-counterfeit campaigns through the development of complicated and difficult-to-replicate Nanotechnology patterns, and their ability to identify a broad spectrum of biological substances, illegal narcotics, explosives, toxic chemicals, as well lethal compounds. We hope to discover both the difficulties and possibilities that are right ahead in this discipline by critically examining these potential achievements. We aspire to generate efficiencies that will prepare the way for the growth of environmentally friendly and efficient technologies in the near future by encouraging interdisciplinary collaboration.

II. FORENSIC APPLICATIONS

1. Latent Fingerprint Enhancement: Fingerprint examination has been utilized in criminal investigations for more than a century and is additionally employed to identify catastrophe victims. It is by far the most extensively used type of biometric authentication. The method relies on the fact that each person's designs for epidermal ridges on their fingers are individual and distinctive. Ridge patterns recorded electronically or with "ink and paper" are saved in national databases, allowing impressions collected at locations of crime to be compared with the police information system via a computerized method. Today, the advancement of technologically advanced scanners has allowed the adoption of fingerprint methods, which are fast gaining traction in common uses ranging from homeland safety to entry control as well as digital verification for electronic gadgets.

Initial methods like as ninhydrin, cyanoacrylate fuming, silver nitrate, iodine vapor, and vacuum metal deposition have endured the test of time and are still utilized in forensics laboratories. For decades, particles based on titania, carbon, aluminum, silica, and magnetic particles have been widely used for fingerprint dusting at crime scenes [31]. By introducing powder and spray compositions made from plasmonic nanomaterials, quantum dots, and C-dots that combine molecular identification agents, excellent quality imaging, and improved visibility with a strong bond to fingerprint residue, recent advancements in nanochemistry may lead to a wider range of forensic tools[32]. Cotinine is the main constituent of nicotine, and nanoparticles of gold carrying anti-cotinine antibodies, for instance, can produce excellent fingermark imprints while also identifying it in the fingermarks, giving clear proof of the donor's way of life [33]. A single latent fingerprints has also been effectively used for multiplexing the identification of illegal substances and their byproducts using antibody/magnetic nanoparticle conjugates [34].

C-dot-based fingerprint restoration elements shift color when exposed by different kinds of light, allowing background-free imaging and improving the precision of fingerprint inspection. C-dots have a propensity to self-quench in their solid form [35]. There have been numerous attempts to mitigate this negative effect, including the use of diluent matrix structures [36,37], the creation of core-shell small structures [38], the incorporation of heteroatom doping [39,40], the utilization of Resonance Energy Transfer (RET) and -interactions [41], the application of molecular gaps [42], and other methods.

The application of C-dot-based particles for the fluorescence visualizing of invisible fingerprints was first demonstrated by Fernandes et al. [36], who demonstrated that the addition of 0.7 weight percent C-dots into a silica matrix enabled precise and color-tunable illustrating of latent fingerprints on a slide made of glass and on a colorful soft drink label. In the present investigation, the ethanolamine as well as citric acid monohydrate were heated to create the C-dots, which were then dialyzed against water. Employing anthracene as a standard, the quantum yield (QY) in water was measured at 15% under 365 nm excitation. XPS examination revealed a mixture of C (44.85%), H (5.75%), and N (10.85%). This work demonstrates the impressive color-tunability made possible by exposure with various wavelengths of illumination in addition to the great level of detail displayed luminously utilizing the C-dot hybrid material. This means that investigators working on crime scenes can utilize a single powder together with an

illumination source that can produce varied wavelengths instead of an array of particles to view fingerprints over a variety of colour backgrounds. Particularly, a fresh fingerprint created with the hybrid tiny particles disclosed 71 min when compared to 65 min disclosed from a regular white powder beneath same circumstances.

Li and others [37] Similar encouraging outcomes were obtained for the fluorescence visibility of latent fingerprints on a range of impermeable surfaces (black marble, glass, aluminum foil, white ceramic, and a coin) through the incorporation of 1% C-dots (pyrolytically generated from malic acid and ammonium oxalate) into starch powder. The C-dot/starch powder outscored the 502 cyanoacrylate glue steam, TiO₂ powder, and iodine vapor in a number of situations. This formulation's enhanced fluorescence was caused by interactions between C-dots and hydroxyl groups that are present in bulk starch powder.

The focus of additional research by Fernandes and coworkers [38] was carbogenically-coated silica nanoparticles (C-SiO₂) made by combining silica nanoparticles with dimethyloctadecyl [3-(trimethoxysilyl) propyl] ammonium chloride, subsequently undergoing pyrolysis, surface oxidation with nitric acid, amine modification, and finally dialysis contrary to water. The nanoparticles had an average diameter of 22 nm, 26% C, 4% H, and 5% N. The powder performed well under same circumstances, adhered well to fingerprints, and showed greater detail (73 minutiae) than an ordinary white fingerprint powder (65 minutiae). Additionally, although conventional white powder for fingerprints did not, C-SiO₂ nanopowder did, even on highly luminous cardboard. The commercially available fluorescent powder used did not show any contrast when lit between 365 and 590 nm, while the C-SiO₂ nanopowder did.

According to Wang et al. [39], nitrogen- as well as sulphur-doped C-dots (N, S C-dots) perform well as color-tunable dusting powders that can reveal enormous amounts of particulars in latent fingerprints placed on aluminum foil, glass, ceramic, printing paper, plastic, and steel. They were also similarly successful when used on a fingerprint that had been on a surface for thirty days. L-glutathione and citric acid were used as precursors via a microwave-assisted method to create the N, S C-dots, and the finished product was centrifuged then dialyzed. While TEM showed a size distribution of 2–7 nm, FTIR and XPS showed the presence of surface functional groups such as OH, NH₂, C–O, and SH that contained oxygen, nitrogen, and sulphur and attributed to their high QY value of 48.1% (in 0.1 M H₂SO₄ utilizing quinine sulphate as a standard). Milenkovic and others (40) According to studies, N-doped C-dots (N, C-dots) made hydrothermally by polyvinylpyrrolidone contain moderately negative charges because OH and COOH are present in them. As a result, they can magnetically bind to the proteins used in fingerprints. Excellent quality imprints were found by AFIS examination of a fingerprint that was generated with N, C-dots and applied to a glossy metal surface (tweezers).

Wang and others, [41] with the aid of a microwave, piperazine and phthalic acid were pyrolyzed to create graphitic C-dots (pC-dots), which have an average size of 1.5 nm. The pC-dots possess a QY of 20.5% in a solid state and show a very bright yellow-green color beneath 365 nm light. These extraordinary solid-state luminescence properties have been correlated to RET and direct contacts. The pC-dots were shown to be efficient as dusting powders when examined on fingerprints found on weighing paper, a desk surface, glass, tin foil, plastic, a bottle cap, and a coin.

Jiang and others [42] It has been stated that polyoxyethylene sorbitan monooleate distributed in highly concentrated phosphoric acid and concentrated sulfuric acid can be thermally treated to produce white-emitting C-dots (wC-dots), which are then filtered. The extremely graphitic nature of the carbogenic cores was confirmed by TEM, XRD, and Raman spectroscopy, whereas the size of the wC-dots varied from 3.5 to 5.3 nm. Extended alkyl chains added to the outermost layer of these wC-dots improved nanoparticle interactions with lipophilic residues present in latent fingerprints while suppressing aggregation-induced fading. These outcomes might be linked directly to outstanding dusting fingerprint powder effectiveness of wC-dots.

Deformation, consolidation and separation of substances by a single molecule or atom are the main processes employed in nanotechnology. The idea of nanotechnology was put forth by Nobel Prize-winning American physicist Richard Feynman in a 1959 speech titled "There's Plenty of Room at the Bottom" [7]. The term "nanotechnology" was first coined by researcher Norio Taniguchi in a 1974 paper on the application of synthesis technology to create objects and properties with nanometer-scale dimensions [8].

The respective inventions of scanning tunneling as well as atomic force microscopes in the 1980s are viewed as turning events for the development of nanotechnology as a discipline. These microscopes allowed for the atomic-scale imaging of materials, a process necessary for changing matter at the atomic and molecular levels. Supercomputers can now model and analyze compounds on an enormous scale thanks to concurrent advancements in computer technology, which has led to new discoveries about the structure and properties of the substances [9]. Research investigations in the 20th century were significantly impacted by the concurrent modeling, visualizing, and modifying operations.

- 2. Anti-Counterfeit:** Designer cosmetics, sunglasses, clothing, cigarettes, electrical appliances, watches, pharmaceuticals, food, oil and electronics are among the items that are frequently associated with fake goods. The banknotes and other official documents are also frequently falsified. Since illegal and inferior drugs not only fail to treat patients but additionally kill thousands of them, counterfeiting and forging are international crimes that put the wellness and security of customers at risk. In addition to damaging national economies, this illicit activity and unsettling consumer culture deprives legitimate firms of valuable resources and tax revenue. Additionally, the production of unlicensed copies of intellectual property undermines investments in innovation and scientific research [43,44].

Therefore, effective brand protection & anti-counterfeit laws are essential for modern societies. Examples of common safety features and graphics include optically adjustable devices, holograms, laser codes, watermarks, biological and chemical taggants [45,46]. However, the most intricate designs are easily copied and reproduced. Quantum dots as well as polyaromatic dyes made from organic materials have been utilized for security graphics recently [47]; yet, these molecules are extremely expensive, have adverse reactions, and need solvent-intensive synthesizing methods.

Novel and environmentally friendly nanotechnologies that utilize C-dots have been developed to help with anti-counterfeiting efforts in order to overcome these

problems. The fundamental idea behind C-dot-based security nano-barcodes relies on their distinctive optical attributes, that can result in an unlimited variety of theoretically unclonable designs and prints that can be virtually impossible to decipher and reverse-engineer. Fernandes & Company [38]. They proved that the previously characterized C-SiO₂ nanoparticles lacked colloidal stability once the pH level in the media dropped below 8.5, experienced spontaneous aggregation as their aqueous medium evaporated, and produced complex structures through a nondeterministic manner. These structures are difficult to copy, which makes them ideal for labeling for both verification and identification [48]. The nanotags can theoretically be authenticated against a central database by scanning them with a mobile device equipped with a magnification and laser pointer.

A multifunctional anti-counterfeit system that combines photoluminescence, upconversion photoluminescence (UCPL), and room-temperature phosphorescence (RTP) was created by Jiang et al. in their study [49] by synthesizing mC-dot dispersions and incorporating them into a polyvinyl alcohol (PVA) matrix. The m-phenylenediamine was dissolved in ethanol to create the mC-dots, which were then purified with a silica chromatography column after being subjected to an extended autoclave boil. Essential groups like C = N, C-O, and aromatic C-NH₂ were detected using analytical methods like FTIR and XPS. Additionally, XPS examination demonstrated that nitrogen exists in aminic, pyridinic, and pyrrolic forms. The RTP excitation spectra of the mC-dot/PVA composite showed a large peak at 360 nm, indicating that the C-N/C = N bond absorption is the main source of RTP. It is thought that the contact through hydrogen bonding between the mC-dots and the hydroxyl groups inside the PVA matrix prevents the triplet state produced by UV light from relaxing vibrationally, leaving room-temperature phosphorescence (RTP) as the sole possible relaxation mechanism. Three distinctive characteristics of the anti-counterfeit technology are: First, when subjected to 365 nm light, the initial marking along with the C-dot marks both fluoresce; second, when a 365 nm light source is turned off, the original marking quickly disappears while the C-dot markings merely remain visible to the observer due to RTP; and third, when excited with an 800 nm a laser, cyan-colored markings rather than blue ones are revealed, which is attributed to upconversion photoluminescence (UCPL).

Carbon dots (C-dots) were created in the work by Kalytchuk et al. [50] by dissolving citric acid and ethylenediamine in an autoclave made of stainless steel. To produce "fast" fluorescence lifetime (fC-dots), the procedure was run at 200°C for 5 hours; for "slow" fluorescence lifetime (sC-dots), it was run at 220°C. Investigations using transmission electron microscopy (TEM) revealed that the average diameter of fC-dots is 4.7 nm and that of sC-dots is 5.1 nm. Comprehensive FTIR and XPS investigations revealed the existence of essential chemical linkages, such as C-C, C-OH, C-N, and N-H bonds. Higher synthesis temperatures resulted in sC-dots containing greater carbon and lower oxygen contents. Surprisingly, the UV absorption and emission characteristics of fC-dots and sC-dots were similar, with the main difference being their estimated fluorescence lifetimes of 7.9 ns for fC-dots and 13.2 ns for sC-dots. Through encrypting on a paper surface, the use of these C-dots for anti-counterfeiting reasons was proven. An encrypted version of the letter "R" was printed on the paper, with equal amounts of either fC-dots or sC-dots ink used to print each pixel. The letter 'R' became invisible beneath UV light because all pixels emit light at the same rate.

However, using luminous lifetime images, the symbol 'R' could be easily decrypted due to those two ink types' unique fluorescence lifetimes. Additionally, by using different ratios of sC-dots and fC-dots in ink formulations, an untruthful sign, "S," could be decoded using UV light, while the real encryption symbol, "K," could only be seen using fluorescence lifetime imaging.

A microwave-assisted pyrolysis technique using xylose and m-phenylenediamine (dissolved in water) with the addition of H₃PO₄ was used by Yang et al. [51] to create phosphorus-doped carbon dots (P, C-dots), which were then purified using filtration and dialysis. The end product showed 6.8 nm-diameter graphitic P, C-dots on average. P-O- (aromatic group) and P-O-H bonds were detected by FTIR analysis, while C-N = C, N-C3, and N-H bonds were verified by XPS analysis. These P, C-dots had a high quantum yield (QY = 73.6% in ethanol compared to rhodamine) and emit green light when excited at 365 nm in the pH range of 3–7. At higher pH values, they change to emit blue/green light. The group also used these P, C-dots to make a special QR code. The printed QR code appeared golden yellow in the presence of ambient light, but when exposed to 365 nm radiation, the emission could be dynamically tuned from green to cyan by brushing the code with a diluted NaOH solution, and the original green emission could be restored by brushing the code with a diluted CH₃COOH solution, offering a reversible and flexible color adjustment capability.

Hydrophobic C-dots (hC-dots), which change color from blue to red when exposed to water, were first developed by Yang et al. Under 365 nm illumination, these evenly distributed hC-dots give off a blue glow, but when water is present, the blue fluorescence is suppressed by π -stacking interactions and transforms into red fluorescence under 254 nm illumination. The dual-encryption anti-counterfeiting systems are built on this reversible two-switch photoluminescence (PL) behavior. The letters 'SC,' 'US,' and 'NU' are printed using hC-dot inks in this system, whereas other letters are produced with standard, non-fluorescent ink. In addition, wax has been applied to the letters "C," "S," and "U" to stop water from penetrating them and changing their blue luminescence to red. A misleading blue luminous code is seen under 365 nm illumination. However, when water is applied under 254 nm radiation, the real anti-counterfeit markings ('C,' 'S,' and 'U') are visible. Under 254 nm light, no markings are visible in the absence of water.

Single-layer graphene quantum dots (GQDs) with an average size of 2.7 nm were cleverly contained within stacked double hydroxide (LDH) layers in the research done by Bai et al. [53]. The precursor, ethylene diamine tetraacetic acid, was co-precipitated into LDH before being calcined to create the GQD-LDH nanocomposite. It is noteworthy that the GQDs have surface functions, such as O and N, which promote important interactions with the LDH host. This GQD-LDH nanocomposite exhibits fluorescence as well as at room temperature phosphorescence (RTP), giving it exceptional anti-counterfeiting potential for a variety of applications including food, pharmaceuticals, papers, and banknotes. In a fascinating presentation, a fluorescent dye was used in conjunction with the GQD-LDH composite to generate a flower design that was then individually inserted into gelatin capsules and PVA film.

When these designs were exposed to UV light, they fluoresced, and when the UV light was turned off, they showed RTP. It's notable that PVA was utilized, a common eco-friendly packaging material. A previous study by Liu et al. [54] showed the viability of

adding C-dots to PVA packaging material and recommended it as a practical anti-counterfeiting strategy.

According to Zhu et al.'s study [35], carbon dot-based fluorescent inks and composite substances made of C-dots and polymers were employed to create random fluorescent designs as a successful anti-counterfeiting tactic. Surprisingly, even four months after preparation, the printed designs and the patterns made with C-dot-polymer composites both displayed long-term durability. Additionally, even after being exposed to a strong dosage of 2 kW UV light for 30 minutes, their photoluminescence characteristics remained unaltered. Furthermore, Sk et al. [55] established the durability of C-dot-based fluorescent ink on banknotes in a separate research. The ink maintained its visibility even after being washed with water and then a soap solution, demonstrating its robustness and potency as a deterrent to counterfeiting.

- 3. Molecular Sensing:** Incorporating integrated microfluidic assays and nanoprobes, lab-on-a-chip systems are cutting-edge analytical tools that provide multiplexed analysis, multiplexed detection of several analytes, rapid processing, amazing sensitivity, and low sample consumption [56]. Because of their small size and user-friendly design, these portable gadgets don't require specialized knowledge or in-depth training to operate. Nanosensors have recognition components that are built to target particular molecules and provide distinctive signals frequently based in optics, electricity, mechanics, or acoustics [57]. Notably, nanosensors are seen as the future of medical diagnostics, with the ability to detect underlying illnesses before symptoms appear. They also show great promise in a variety of other fields, including as forensic toxicology and the detection of explosive residues.

In order to develop affinity-based nanoprobes, scientists have thoroughly studied a variety of nanomaterials, including quantum dots [58, 59], plasmonic nanoparticles [60–63], carbon nanotubes [64], and graphene [65]. These nanoprobes have proven useful in identifying a variety of chemicals, such as conventional narcotics [58,59], anabolic steroids [64], pharmaceuticals with misuse potential [62], explosives [60,65], infections linked to bioterrorism [61], and even in determining the post-mortem interval [63]. Intriguingly, wearable biosensors also provide the capability to continually and in real time monitor bad lifestyle habits linked to criminal activity, such as binge drinking [66].

Carbon dots (C-dots) are useful in the development of affinity sensors that are intended to selectively and sensitively bind to particular chemicals in the field of applications related to forensics. The key sensing methods of these sensors for C-dots are photo-induced electron transfer (PET), photo-induced charge transfer (PCT), resonance energy transfer (RET), and inner filter effects (IFE) [67], enabling precise detection. Detection of illegal chemicals and explosives is a top priority for law enforcement. Additionally, crucial roles in forensic investigations are played by the detection of biofluids at crime scenes and the analysis of DNA profiles from these fluids. Additionally, in the context of forensics, determining if a person has experienced acute or ongoing exposure to dangerous metals and pesticides could be extremely important, possibly illuminating homicidal or suicide efforts.

4. Detection of Biological Compound: Graphitic C-dots (gC-dots) were produced electrochemically using glycine as the precursor in the study by Wang et al. [68], resulting in well-controlled particles with a limited size distribution of about 2.4 nm. Surface functional groups including carboxylate & ammonium were present in these gC-dots. A constant and linear decrease in the intensity of fluorescence was seen with the addition of hemoglobin at concentrations ranging from 0.05 to 250 nM, with little interference from related molecules. Importantly, the gC-dot method was successfully used to precisely measure the levels of hemoglobin in blood samples, emphasizing the method's potential for reliable assessment in this situation.

An experiment was done to assess the forensic capability of the gC-dots. Blood was used to identify the character on a piece of cloth, which was then washed to make the character undetectable to the naked sight. When gC-dots were sprayed on the fabric and it was then subjected to light with a wavelength between 460 and 490 nm, the blood-stained area showed noticeably less fluorescence than the unaffected parts. Interestingly, no matter what chemicals were used in this experiment, including proteins, greasy pen ink, ballpoint pen ink, soy sauce, ketchup, and eggs, the applied gC-dots' fluorescence behavior remained unchanged. This result emphasizes the haemoglobin sensor's great selectivity and confirms its potential for forensic applications.

By fusing C-dots via carbon nanotubes (CNTs), Qian et al. [69] created a DNA nanosensor that can recognize single DNA strands up to 21 base pairs in length. The 2 to 5 nm in diameter graphitic C-dots were created by oxidizing graphite with nitric and sulfuric acids, then reducing the resultant product with NaBH₄ to insert OH and COOH functional groups, increasing their quantum yield (QY). Strong nitric and sulfuric acids were used to oxidize the CNTs, which had diameters < 8 nm, and this also resulted in a decrease in their length. Through a condensation procedure, a terminal amino group at the 5' end of single-stranded DNA (ss-DNA) was added. This modified ss-DNA was then covalently linked to the surface of the C-dots. The detecting system's functionality works as follows: Resonance energy transfer (RET) causes fluorescence quenching when CNTs are introduced because C-dots functionalized with ssDNA attach to the CNT surface. The C-dot-bound ssDNA, however, base-pairs with the target single-stranded DNA (tDNA), inducing its release from the CNT surface and restoring the fluorescence of the C-dots. The target single-stranded DNA is complementary to the strand attached to the C-dots. The system detection limit is close to 0.4 nM, and the connection between the recovered fluorescence intensity and tDNA concentration exhibits linearity within a range of 1.5-133.0 nM.

In contrast to DNA with more CG pairs, a considerable increase in C-dot fluorescence is seen in the work of Pramanik et al. [70] when double-stranded DNA rich in AT pairs is present. Notably, the amount of AT pairs and fluorescence intensity have a linear connection. As a less dangerous option to the staining dyes now in use, the authors advise adopting this strategy.

- **Detection Drugs:** A fluorescence-quenching approach for identifying methamphetamine precursors is devised in the study by Kim et al. [71], leveraging the use of C-dots. These C-dots are created by hydrothermally dealing with a 10:1 mixture of urea and citric acid. The C-dots usually have a size of 2 nm, an amorphous

core, and both amine and carboxylic acid groups. In particular, the ability to decrease the fluorescence in the water-based solutions containing these C-dots was shown to be shared by two methamphetamine precursors, phenylpropane-1,2-diol (PAC-diol) and phenylpropan-2-one (P2P). It's significant to note that the quenching effect showed a linear relationship with the concentrations of the individual precursors. Similar results were obtained with immobilized C-dots on a glass coverslip, which showed that it was possible to identify these illegal precursors in a liquid dispersion. In contrast to P2P, that consists of a single carbonyl group, PAC-diol, that has 2 OH groups, demonstrated a stronger adhesion to the surface of the C-dots, leading to a more dramatic quenching effect. Importantly, it was discovered that popular diluents such as aspirin, paracetamol, glucose, caffeine, and sodium chloride had no effect on fluorescence. Amphetamine sulfate, a similar substance, showed a modest decrease in fluorescence. In addition, chemicals commonly found in illegal drug labs, such as aniline, benzoic acid, benzyl alcohol, hydroquinone, 4-hydroxybenzoic acid, and 4-methoxyphenol, had no effect on the fluorescence of the C-dots. According to these results, the device has a lot of potential as a highly accurate sensing tool for crime scene investigations.

C-dots, respectively suspended in a water-based solution or coating on paper, were used in a unique approach developed by Yen et al. [72] for accurate identification and characterization of cathinones. These L-arginine-derived graphitic C-dots had an average diameter of 4.4 nm, and a hydrothermal technique was used to provide surface functional groups with oxygen and nitrogen during their production. Both heroin and cocaine showed a little drop in C-dot emission at pH 7, which is probably because of their low solubility. Still, only the cathinones showed appreciable quenching of fluorescence at pH 11. This distinction between heroin and cocaine, which have ester groups that are conjugated, and cathinones, which have non-conjugated ketones, suggests that these are the main substances causing the quenching effect that has been observed. Particularly, non-conjugated ketones had little to no impact on the fluorescence of the C-dots. Under pH 11 conditions, the system showed a detection limit of 1.73 nm (0.43 mg/mL⁻¹) for 4-chloroethcathinone, demonstrating the possibility for sensitive detection.

A portable UV light with a wavelength of 254 nm, C-dot-impregnated paper, and a mobile phone camera were used in a more usable detecting setup for the chemical. This setup displayed an impressive detection limit of 0.14 nm, or 0.03 mg/mL⁻¹. The coated paper's fluorescence showed a linear decline proportional to the 4-chloroethcathinone concentration in the range of 0.5-10.0 mM. Importantly, high glucose concentrations had no effect on the signal transmitted, indicating that this detection device had exceptional selectivity for this particular molecule. The use of C-dot-impregnated paper also included the ability to find 4-chloroethcathinone in urine. With a limit of detection of 1300 ng mL⁻¹ in this application, the paper-based approach showed a linear response over the concentration range of 2000-12,500 ng mL⁻¹. The feasibility, selectivity, and sensitivity of the C-dot-based paper technique in identifying this particular chemical, notably in urine samples, are highlighted by these results.

- **Detection of Explosives:** With the aid of C-dots, several research teams have created sensitive and focused fluorescence-quenching detectors for explosive aromatic nitro compounds like picric acid (PA). Niu et al.'s research involved the creation of amorphous C-dots with diameters ranging from 4 to 6 nm. The manufacture of these C-dots, which have surface amine & carbonyl groups, involved microwave processing with equal parts (3 g each) of citric acid and urea. A significant photoluminescence (PL) quenching effect was produced by the addition of PA to a C-dot dispersion, allowing for a detection limit of roughly 1 M. Notably, the addition of numerous common interferents had no effect and neither did the structurally similar molecules 2,4-dinitrotoluene (DNT) nor 2,4,6-trinitrotoluene (TNT). Similar detection techniques involved exposing sealed containers containing C-dot-impregnated paper to the fumes of DNT, TNT, and PA for 600 seconds. Immediately after the container was opened, the accompanying PL spectra were gathered. The PL quenching in this case was only 49.8% for PA due to PA's lower vapor pressure compared to 77% for DNT and 80.3% for TNT. These findings offer useful information for applications involving explosive detection by showcasing the capability of C-dots to selectively identify PA in varied configurations.

By pyrolyzing ammonium citrate dibasic using a standard microwave, Sun et al. [74] showed a technique that produced C-dots with a size distribution between 5.5 and 1.5 nm and an extremely disordered structure. Citric acid, N-doped C-dots, and low-molecular-weight oligomers made up the final mixture. This mixture was used immediately after centrifugation to eliminate big clumps without any additional purification. In contrast, negligible impact is seen with the comparable nitro aromatic explosives, the estimated detection limit for this configuration was 0.25 M, and the addition of increasing amounts of PA systematically caused the C-dot fluorescence to be quenched.

The greater sensitivity of the C-dots for PA above the other nitro compounds can be explained by PA's lower LUMO than that of the other nitro compounds and the electron-deficient nature of nitro compounds, which leads to PL quenching from PET. Comparable values of PA selectivity and sensitivity were observed by Siddique et al. [75], They employed C-dots made by ultrasonically processing a mixture of dextrose and HCl with a variety of O-containing surface functional groups but no nitrogen.

In order to create C-dots using activated carbon, Campos et al. [76] used a multistep oxidation procedure, which was followed by functionalization with a poly (amidoamine) (PAMAM-NH₂) dendrimer. Only the explosive nitro compound 4-chloro-2,6-dinitroaniline (4-Cl-2,6-DNA) caused the formation of a second emission band at 507 nm among the chemicals studied. Furthermore, unlike several comparable compounds, this one specifically muted the C-dots' 465 nm fluorescence noticeably. The ratio of fluorescence at these two wavelengths showed a linear association with the concentration of 4-Cl-2,6-DNA over the concentration range of 1.0 10⁻⁵ to 6.0 10⁻⁴ M. The potential for selective detection and quantification of the explosive molecule is highlighted by this creative method, opening the door for useful applications in this field.

Pal et al. [77] introduced a composite film made of C-dots and polypyrrole (PPy) for conductivity-based PA sensing. To start the polymerization of pyrrole, this

novel method used C-dots, which were made from ethylene diamine and citric acid. Larger C-dots were found to be separately coated with PPy, as confirmed by TEM imaging of the final product, whereas smaller C-dots, average a diameter of 4.5–2 nm, got integrated into the PPy matrix. Selected area electron diffraction (SAED) was used to confirm the material's semi-crystalline structure, and current-versus-voltage (I-V) graphs showed that the film's metal-like conductivity was the result of interconnected networks of C = C bonds. The composite film showed a maximum conductivity of 2.60 mS m⁻¹ in contrast to PPy's conductivity of 0.23 mS m⁻¹. Notably, in contrast to its negligible effects on related compounds, aqueous PA considerably increased the conductivity of this nanocomposite. According to research, the detection threshold for PA is 1.40 10⁻⁷ M. Additionally, the detection limit for PA incorporation was discovered to be 5.7 ng mg⁻¹ when soil samples were analyzed. These results highlight the capability of this composite film to detect PA even in intricate sample matrices in a delicate and practical manner.

- **Detection of Heavy Metals and Pesticides:** In order to produce PEGylated N-doped C-dots, Gupta et al. [78] microwave-heated a chitosan gel while adding PEG and dithiothreitol (DTT) functionalization. AFM and TEM measurements of the unfunctionalized C-dots revealed an average diameter of about 8 nm. They had a wide variety of O- and N-containing functional groups on their surfaces, with N making up only 2.46% of the total mass. DTT's binding and the existence of free SH groups inside of it were both confirmed by XPS and FTIR analyses. These C-dots showed water solubility, retained stability even at high salt concentrations, and fluoresced at their greatest levels at physiological pH. Hg²⁺ ions were added, and this considerably decreased the fluorescence intensity while having no discernible impact on the emission intensity. The DTT-functionalized C-dots, on the other hand, displayed exceptional sensitivity, detecting concentrations as low as 18 pm in distilled water, 45 pm in filtered (0.22 m), centrifuged, spiked river water, and 50 pM in spiked tap water. However, for Hg²⁺ in distilled water, unfunctionalized PEGylated C-dots obtained a detection limit of 6.8 nm. The strong interaction between the thiol groups and Hg²⁺ is responsible for the functionalized C-dots' high sensitivity. These findings highlight the functionalized C-dots' improved performance, making them an advantageous tool for delicate detection applications.

Citric acid and cysteamine were used as precursors in the investigation conducted by D. et al. [79] to synthesize C-dots, which were then functionalized using DTT. SAED and XRD studies of the C-dots during characterisation confirmed their low crystallinity index. The C-dots' size was determined by high-resolution TEM to be between 4–5 nm. Different surface functional groups with O, N, and S were visible on these C-dots. The presence of free SH groups following functionalization and the binding of DTT via S-S linkages were further confirmed by FTIR analysis. With a remarkable low limit of detection close to 0.086 ppb, it is noteworthy that the presence of As³⁺ ions was discovered to increase the fluorescence intensity of the C-dots in a Tris-HCl buffer. This sensing method's effectiveness was shown by its ability to find As³⁺ in spiked water samples taken from wells, lakes, and the ground. While the As-O bond, which is normally stronger, tends to dissolve in water, the DTT-functionalized C-dots' extraordinary selectivity for As³⁺ over other metal ions was attributable to its high strength (379 kJ/mol). This method has a great deal of

potential for the sensitive and focused detection of As^{3+} , offering insightful data for environmental monitoring and research.

A ratiometric, dual-emission nanosensor for Cu^{2+} ions were created by Liu et al. [80] employing rhodamine-B-doped silica nanoparticles covered with C-dots. N-(aminoethyl)-aminopropylmethyldimethoxysilane (AEAPMS) was pyrolyzed to create the C-dots, and citric acid was then added. The remaining ethylenediamine groups on the C-dot surface were able to successfully capture Cu^{2+} ions without further alteration, while the leftover methoxysilane groups from AEAPMS made it easier to attach to dye-doped silica nanoparticles. According to XPS examination, the silica nanoparticles had a diameter of roughly 145 nm before the C-dots were attached, while the C-dots as-prepared had a diameter of 2-3 nm in ethanol. Being illuminated at 360 nm, the resultant hybrid material showed unique dual PL emissions at 467 and 585 nm, coming from the contributions of C-dots and rhodamine B dye, respectively. When Cu^{2+} ions in the concentration range of 0–10.0 M were added, the C-dot fluorescence contribution was significantly reduced, but the dye signal barely changed. Up to 3×10^{-6} M, a linear decrease in the fluorescence intensity ratio at 467 and 585 nm was seen as the Cu^{2+} concentration rose within this range. This device demonstrated its sensitivity with a computed detection limit of 35.2 nM using a signal-to-noise ratio of 3. When Cu^{2+} was present, changes in pH between pH 5.0 and 10.0 had little effect on the fluorescence ratio. The method had exceptional selectivity and worked well for measuring Cu^{2+} in biological samples and tainted water. C-dots have previously been shown to be sensitive and selective for the detection of lead ions in metal ion detection applications when mounted on spherical polyelectrolyte brushes. For a variety of analytical and environmental monitoring applications, this novel technique shows promise [81]. While a fluorescent probe for mercury detection constructed of a polyaniline/C-dot nanocomposite has been developed [82].

Li et al.'s [83] development of an organophosphorus pesticide (OP) detection system using red-emissive C-dots made through hydrothermal processing of a combination of thiourea and citric acid. NaOH and HCl were used in order to improve the C-dots' optical characteristics. While TEM pictures showed diameters in the range of 4–7 nm, indicating the presence of six to twelve layers of sheets resembling graphene, the height of the C-dots, as assessed by AFM, varied from 1.8 to 3.8 nm. The C-dots' graphitic origin was validated by FTIR analysis, XRD, and Raman spectroscopy, as well as several surface functional groups involving O, N, and S. The C-dots displayed strong PL emission at 610 nm under 550 nm excitation and were soluble in a number of organic solvents, including ethanol, DMSO, methanol, and DMF. The foundation of the OP ratiometric sensor was created when dopamine (DA) was polymerized into polydopamine (PDA) in the presence of C-dots. This signal at 503 nm quenched the PL of the C-dots via PET. With the addition of OPs (paraoxon, parathion, and malathion), the contribution from PDA was increased while the contribution from C-dots was decreased. Paraoxon, parathion, and malathion were determined to have permitted residue limits of 0.125 $\mu\text{g mL}^{-1}$, 0.0625 $\mu\text{g mL}^{-1}$, and 0.025 $\mu\text{g mL}^{-1}$, respectively. It's significant that the sensor system demonstrated remarkable selectivity because it was unaffected by a variety of ions, amino acids, proteins, and other pesticide families. Analysis of spiked samples of tap water, river water, soil, rice, apple, and serum was used to verify the validity of the sensing system. The adaptability and promise of C-dots in pesticide detection applications are

shown by other C-dot-based approaches with sensitivity focusing on detecting methyl parathion [84] and Dichlorvos or DDVP, also known as 2,2-dichlorovinyl dimethyl phosphate [85].

III. CHALLENGES AND FUTURE PERSPECTIVES

- 1. Latent Fingerprint Enhancement:** According to a survey of the literature, materials scientists have been principally in charge of this field's research, with a noticeable focus on the photo-optical performance of powders rather than their usefulness for fingerprint identification. It is clear that close cooperation between materials scientists and forensic investigators/practitioners is essential to the development of this broad and extremely challenging subject. The International Fingerprint Research Group's experimental methods and overarching ideas could be widely adopted to make substantial progress in this regard [86]. Notably, when looking at the stages of development, it seems that most articles that have been published belong to phase 1 pilot studies, with only a small number appearing in phases 2 (optimization and comparison), 3 (validation), and 4 (operational evaluation and casework trials) [87].

Furthermore, it is crucial to ensure the protection of forensic operations, which necessitates thorough evaluations of the potential health concerns and long- and short-term toxicity linked to C-dot-based devices. Although this area is yet understudied, it should be formed to solve concerns with rigorous preparation processes, controlled drying, and the intrinsic ability of C-dots to cling strongly to diluent materials. Before the legal community can safely accept this new category of nanomaterials, such assurance is necessary.

It is necessary to conduct a thorough analysis to determine whether newly created C-dot-based formulations, which include both powders and dispersions, are effective at recovering fingerprints from a variety of substrates, including porous and non-porous surfaces. The cases when fingerprints are exposed to harsh environmental conditions or are polluted with bodily fluids should be included in this examination. Further research should be done to determine whether these formulations have the ability to find DNA within lifted fingerprints. It is likely that C-dot formulations used for fingerprint generation may also be able to identify metabolites and provide insights into numerous behavioral and lifestyle aspects, similar to the abilities seen with gold nanoparticles.

- 2. Anti-Counterfeit:** A growing body of research indicates that ecologically benign C-dot-based nanotags can be made with little upfront cost, offering a workable alternative for underdeveloped countries struggling with the rising manufacture of fake goods. C-dot-based formulations have a significant amount of promise for use in anti-counterfeiting applications, and when compared to competing technologies, their comparatively easy and affordable synthesis presents an advantage. However, novel approaches for mass production of high-security inks and nanotags are still in the research and development stage, and a number of fundamental issues need to be fully resolved before a workable manufacturing model can be developed and implemented.

C-dot-based authentication patterns must be thoroughly examined for structural integrity, response to various spectra, resistance to humidity, and adaptation to poor storage circumstances, as well as for compatibility with a variety of common supporting

substrates. Additionally, it is important to explore improvements in printing methods that are adapted to the particular demands of each targeted business, including the use of ink formulations that are already in common use. Digital engineers will need to make major contributions in order for technology to progress for the collection, processing, and analysis of encrypted images, opening the door for the creation of a robust, automated, and trustworthy anti-counterfeit system.

- 3. Molecular Sensing:** The absence of established techniques in the field of nanomaterials continues to be a major obstacle, which is especially obvious in the application of forensic nanosensors. Unfortunately, this undermines the validity and reproducibility of published experimental findings, making meaningful comparisons with one another and with accepted industry norms difficult to accomplish [88]. The implementation of basic reporting standards for nanosensors is actively supported by a number of projects [89]. This calls for careful and thorough synthetic processes as well as a thorough structural analysis of the nanoparticles that takes into account factors like elemental composition, shape, porosity size, surface area, hydration level, surface functionalities, dispersity index zeta potential and the presence of impurities. It is also necessary to give accurate analytical performance measures, such as the linearity range, detection limit, repeatability, stability, and reproducibility.

Strong experimental data supports the benefits of C-dot-based sensors, but a more methodical approach is required to realize these benefits in practical applications. This requires controlling the elemental composition, size, and crystallinity of C-dots as well as fine-tuning the density of surface functional groups on C-dots to regulate bandgap and quantum yield. Comprehensive performance evaluations of C-dot nanosensors are crucial, especially in complex biofluids like urine, blood, stomach contents, aqueous humor and spinal fluid. To ensure resistance against signal interference and decrease false positives and false negatives. Realizing their practical utility also requires specifying the best storage conditions for them and demonstrating how they may be integrated into microfluidic arrays, lab-on-a-chip and automated detection systems.

IV. CONCLUSIONS

C-dots are a rapidly developing class of nano-emitters, albeit it is still not quite clear what they are. These cutting-edge materials have the power to transform criminal justice and law enforcement practices, assisting contemporary civilizations in the fight against crime, illegal activity and terrorism. Due to their photoluminescent characteristics, C-dots can be used as sensitive nano-probes in forensic toxicology. This enables extremely responsive detection of analytes such as illegal substances, pesticides, heavy metals and explosives. Intelligent fingerprinting can greatly benefit from the adaptive color-tuning behavior of C-dot-enriched powders, which gets around problems with increased background interference. Additionally, C-dot-based dyes and polymeric compositions are advantageous as nano-tags for object identification as well as authentication because they have the rare capacity to produce security prints that are very impossible to predict or clone. A collaborative effort including researchers and practitioners from several domains is necessary to fully use the promising body of experimental evidence, which is predominantly driven by proof-of-concept demonstrations.

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