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Green Carbon Dots from Sustainable Precursors: Advances in Photoluminescent Properties and Forensic Applications

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ABSTRACT:

Carbon dots (CDs) have rapidly emerged as promising nanomaterials due to their photoluminescent properties, biocompatibility, and wide-ranging applications. This review critically evaluates the advancements in the green synthesis of CDs using plant-derived, animal-based, and waste materials such as neem, rosemary, eggshells, and cigarette butts. These eco-friendly routes offer a sustainable alternative to traditional chemical synthesis, aligning with the goals of green chemistry and waste valorisation. A thorough look at various synthesis methods—like hydrothermal, microwave-assisted, and combustion techniques—is included, focusing on how easy they are to scale up, how much energy they use, and their drawbacks.

The review also looks at how adding elements like N, S, P, and B can change fluorescence, improve sensing abilities, and make them more compatible with living things. The physicochemical and optical properties of CDs—such as size, crystallinity, quantum yield, and stability—are discussed using standard characterization tools.

Special attention is given to forensic applications, particularly in latent fingerprint detection and enhancement, where green CDs show excellent performance across varied surfaces under UV and visible light. Their potential integration with smart detection tools and AI systems represents a major advancement in forensic imaging. Other emerging uses, including bioimaging, anti-counterfeiting, and environmental sensing, are also outlined. Finally, the review identifies existing challenges and future directions for large-scale implementation and regulatory validation.

1. Introduction

Carbon dots (CDs) are very small particles made of carbon, typically less than 10 nanometres in size, that are known for their bright and adjustable glow, stability in chemicals, and good ability to dissolve in water.[1, 2] Since they were first discovered, CDs have gotten a lot of attention for many uses, such as bioimaging, sensing, anti-counterfeiting, photocatalysis, and forensics[3, 4]. The fact that CDs are less toxic, more biocompatible, and easier to functionalize than regular quantum dots, especially when made in a way that is good for the environment [1, 5, 6].

Traditional ways of making CDs work well to make bright fluorescence, but they often use harsh chemicals, non-renewable resources, and a lot of energy, which are bad for the environment and health[7, 8]. Researchers have investigated green synthesis routes to solve this problem. These are processes that use carbon sources that are good for the environment or come from waste, like plant extracts, fruit peels, agricultural waste, eggshells, and even cigarette butts[9,10,11,12,13]. These raw materials are full of organic matter and can make CDs that are good for the environment and have good light and physical properties.

Recent research has shown that carbon dots derived from sources like rosemary leaves, banana peels, coconut

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water, grains, and onion skins not only shine brightly but also work well with living cells and have better surface properties[14]. In the same way, sources from animals like eggshells and hair have been looked at as good materials for making carbon, helping to reduce waste and promote sustainable technology.[15, 16]

This shift toward green synthesis is not just about sustainability—it also supports cost-efficiency, energy savings, and broader applicability, especially in fields where safety and environmental standards are high, such as forensic science [17, 18]. CDs made using green methods have performed exceptionally well in forensic work, especially for making hidden fingerprints visible, as their bright fluorescence highlights details even on old, oily, or smooth surfaces. Some studies have mixed these CDs with metal oxides or added nitrogen, sulphur, or phosphorus to make them more sensitive, improve their light output, and increase their stability[3, 13].

Additionally, green CDs can work well with AI recognition systems like YOLOv8 and can be used in portable forensic kits, showing they are becoming more useful in real-life situations. Their use in anti-counterfeiting inks, solid-state light-emitting devices, and environmental sensors reflects their multifunctionality across sectors[3, 19].

The purpose of this review is to carefully examine how green carbon dots are made from sustainable materials, focusing on how they are created, their light properties, and especially how they are used in forensic science. It aims to identify patterns, highlight innovation, and point out remaining challenges—such as batch-to-batch reproducibility, photostability issues, and the need for standardization in forensic validation[20, 21]. With the global emphasis on sustainability and ethical material design, green CDs are evolving beyond mere functional nanoparticles. They are regarded as a progression towards more sustainable, secure, and intelligent technologies. They represent a confluence of material science, environmental innovation, and practical application, rendering them a suitable subject for scientific study and further investigation.

2. Green Precursors and Doping Strategies

Carbon dots (CDs) are becoming increasingly intriguing due to their attractive appearance and ease of production. Their biocompatibility, photoluminescence, and ultimate structure are all impacted by the precursor material that is used. The growing number of individuals concerned about their impact on the environment has led to a surge in the popularity of biomass and products made from waste. Another major technique to improve CD performance is to make hybrid composites and use heteroatoms.

2.1 Biomass and Waste-Derived Sources

Scientists have investigated various environmentally friendly carbon sources to develop more sustainable CDs. Not only are these materials plentiful, inexpensive, and frequently discarded, but they are also practical and consistent with the principles of a circular economy.

Plant-Based Precursors

Plants are ideal sources for carbon, nitrogen, and oxygen-containing molecules, making them ideal for use in the production of CDs. As an example, photostable CDs with a high quantum yield can be made from neem leaves due to their high polyphenol content[22]. One such aromatic herb that finds its way into culinary and packaging applications is rosemary. It was utilized in the production of blue-glowing, water-soluble compact discs [23]. Also, due to its high sugar content and potential doping potential, banana peels and coconut water are also popular. After coating coconut water CDs with luminol, researchers found that when exposed to UV light, the discs might reveal latent fingerprints[24, 25]. Bioimaging and chemical sensing are just two of many potential applications for CDs synthesized from onion peels and grains[26]. Another thing about these CDs is how bright they are. Among the many unique qualities of these plant-based CDs is the abundance of distinct atomic types found in nature. When combined with other materials, they can be used to create things without the need of synthetic chemicals.

Animal-Derived Precursors

Green CDs made from animal byproducts such as eggshells and human hair have been created. The calcium carbonate and protein residues found in eggshells can be converted into luminous CDs for imaging and environmental sensing[15, 16]. Hydrothermal synthesis of CDs from human hair was the subject of an alternative investigation. The little particles created by these CDs emit a brilliant blue light and may find application in bioimaging. These building blocks have inherent properties that make them sparkle and combine with water better, in addition to recycling waste. They originate from manure and other forms of animal and crop waste.

Industrial and Agricultural Waste

An intriguing example of repurposing a hazardous waste product into a valuable nanomaterial is the production of carbon dots from cigarette butts[27]. Using previously used filters that were highly efficient at detecting metal ions, one research created N, S co-doped CDs. Additionally, CDs with stable photoluminescence and a high yield have been synthesised from food waste, such as discarded fruits and vegetables[28]. Another example is the development of solid-state emissive CDs from coal derivatives; these CDs have potential applications in sensing and optoelectronics[29]. These instances demonstrate the growing popularity of waste-to-wealth tactics in the field of nanotechnology.

2.2 Doping and Composite Formation

Improving carbon dots light-interacting capabilities is a common research aim. Scientists typically combine them with other atoms, metal oxides, or rare earth elements to do this. Controlling the emission wavelength, improving sensing capabilities, and making it more compatible with living things are all made easier with these technologies.

One of the most prevalent and efficient methods is nitrogen (N) doping[30]. By altering the electron transport mechanism in a carbon structure, nitrogen atoms enhance the quantum yield and enable the material to emit light of varying colors. For instance, because to the inherent nitrogen content, CDs synthesized from human hair exhibit superior stability and fluorescence. Improving its performance and sensitivity, sulfur (S) and phosphorous (P) are added to the bandgap[31]. Using sulfur-based CDs will make it easier to locate metal ions. Utilize phosphorus-doped CDs for enhanced temperature and pH responsive fluorescence. Boron (B) doping is an uncommon but theoretically viable option for improving the heat and temperature resistance of CDs [32]. The addition of these dopants typically occurs during the synthesis or treatment phases, depending on the selected method.

Numerous natural substances, such as banana peels and rosemary, inherently contain these numerous atoms. No additional chemicals are required for natural doping to occur during the production process. Carbon dots (CDs) are utilized to create composites by combining them with minerals such as zinc oxide (ZnO), aluminum oxide (Al_2O_3), and molybdenum trioxide (MoO_3)[33, 34]. CDs can be combined with metal oxides or rare earth elements to enhance their use. Zinc oxide (ZnO) is a prevalent component because to its semiconductor properties and compatibility with CDs. ZnO-CD nanocomposites have demonstrated significant potential in various applications, including fingerprint detection, antimicrobial surfaces, and fluorescent biosensors[35]. The use of aluminum oxide (Al_2O_3) into CDs enhances their heat resistance and surface activity. Consequently, they have improved their capabilities in catalysis and environmental sensing. Molybdenum trioxide (MoO_3) composites are applicable in high-performance sensors and light-emitting devices[36]. Researchers have proposed that incorporating ions of rare-earth metals such as lanthanum or samarium into CDs may enhance their brightness and stability. These nanocomposites can be utilized for the fabrication of UV sensors, enhancing the capacity of artificial intelligence in image analysis, and preventing counterfeiting[37].

3. Green Synthesis Techniques

The advancement of green production processes has made carbon dots (CDs) a very interesting new area of eco-friendly nanotechnology. These methods put safety for the environment, cost, and ease of use first. They can keep or improve the optical properties of nanoparticles. There are many ways to do this, such as hydrothermal processing, solid-state processing, and ultrasonic processing. Each method has its own strengths and weaknesses when it comes to things like energy use, particle uniformity, scalability, and reproducibility.

3.1 Hydrothermal and Solvothermal Synthesis

Hydrothermal synthesis is one of the most well-known ways to be good to the environment. A carbon-rich precursor is put in a water solution in a sealed autoclave and heated to very high temperatures, usually between 150 and 220°C. This method is popular because it is easy to use and lets you change the size of the particles, the groups on their surfaces, and the fluorescence emission[38, 39]. Neem leaves, banana peels, and onion skins can all be used to make carbon dots that emit stable light, have uniform nanoscale sizes, and are very biocompatible.

Sulfur or nitrogen right during the synthesis are been added to increase quantum yield without introducing more ingredients.

Solvothermal synthesis uses organic solvents like ethanol or dimethylformamide instead of water-based synthesis. You can manage crystallinity and surface functionalization better, which is good for specialized uses like drug delivery and bioimaging[40]. People are often worried about the solvents used in solvothermal procedures since they could be harmful to people and the environment.

3.2 Microwave-Assisted Methods

As a fast, scalable, and energy-efficient method to create CDs, microwave synthesis is gaining popularity. In only a few minutes, the precursor mixture can be uniformly heated in a microwave to complete the reaction[39]. Hydrothermal procedures, on the other hand, can take hours. The technique has been applied in numerous experiments on various types of food waste, including rice husks, coconut pulp, and more. The process produced CDs with strong solid-state fluorescence, making them ideal for optical devices and fingerprint detectors[41]. This approach achieves more output with less energy use and fewer unintended side effects. The fact that companies can produce it in big quantities is one of its best qualities. More recent studies have demonstrated that microwave systems can reliably produce large quantities of CDs with low levels of contaminants and excellent emission quality.

3.3 Solid-State and Combustion Methods

For researchers interested in eliminating solvents, solid-state synthesis and combustion methods provide a viable alternative. In these approaches, the carbon precursor—often in powdered form—is directly subjected to heat or allowed to undergo combustion in a controlled environment. CDs made from cigarette butts using combustion techniques yielded highly luminescent, N, S co-doped nanodots without any added chemicals[27]. Solid-state reactions involving grains and food waste have also produced CDs with high emission stability and resistance to photobleaching[26]. These techniques are appealing from an environmental standpoint, but controlling parameters like size distribution and reaction completeness can be challenging. They are generally less tunable compared to hydrothermal or microwave-based processes.

3.4 Ultrasonication and Drying Techniques

Ultrasonication uses high-frequency sound waves to agitate and break down the precursor, accelerating the formation of carbon nanoparticles. This method is particularly useful for soft biomass like rosemary or herbal leaves and can be combined with post-drying or heating steps to finalize the structure[23]. Drying-based techniques, though not as common, involve low-energy dehydration of biomass followed by thermal treatment. These are simple and low-cost, but the resulting CDs often need surface passivation to achieve adequate fluorescence. Both methods have been successfully used in green CD synthesis but typically yield lower emission intensities and are more suitable for preliminary lab-scale investigations.

Hydrothermal methods remain reliable for consistent results, while microwave-assisted synthesis offers speed and scale. Solid-state and combustion methods are appealing for their solvent-free processes but lack precise control. Ultrasonication is best for delicate precursors but needs optimization for better yield and stability.

4. Physiochemical and Optical Properties

Sustainable carbon dots (CDs) have special physical and chemical characteristics that make them applicable in many fields, from bioimaging to forensic fingerprint identification, and they are also good for the environment. These qualities are significantly impacted by the choice of precursor, synthesis method, and post-treatment procedures.

4.1 Morphology, Size, and Crystallinity

To comprehensively understand carbon dots, one must consider their dimensions, morphology, and crystalline arrangement. These factors significantly influence an object's appearance and its interaction with the environment.

Transmission electron microscopy (TEM) is a prevalent method for examining the morphology and dimensions of particles. The predominant green CDs exhibit a nearly spherical morphology with a diameter ranging from 2 to 10 nm [32, 42]. X-ray diffraction (XRD) can determine the crystallinity of the CDs[43]. Dynamic Light Scattering

(DLS) can be employed to determine the hydrodynamic diameter of suspended carbon dots (CDs)[44].

Characterization approaches facilitate the comprehension of size-dependent circular dichroism characteristics, including luminescence and cellular uptake efficiency. Understanding carbon dots necessitates knowledge of their dimensions, morphology, and crystalline architecture. These factors significantly influence an object's optical performance and its interaction with surfaces in various environments.

4.2 Emission Behaviour

One of CDs' many advantages in sensing, imaging, and optical applications is their fluorescence[45]. The emission peaks of green CDs can be blue, red, or a mix of the two colours, depending on the precursor and the technique of synthesis[46]. The fluorescence of these CDs can be excited or not. CDs can emit a wide range of colours when excited at different wavelengths. For instance, when activated at 365 nm, CDs manufactured from neem leaves emitted blue light; but, when excited at 450 nm or higher, their colour changed to green[47]. During synthesis, many emissive traps and functional groups develop on the surface, which causes this behaviour[40]. An essential metric for the efficacy of fluorescence is quantum yield (QY). On the other hand, research shows that QY levels can differ. Nitrogen and sulphur dopants improve QY by reducing surface traps and creating new light-emitting channels[47]. For fast-paced imaging and sensing applications, green CDs are a great choice due to their nanosecond lifetimes.

4.3 Stability

Stability is another critical criterion, especially for real-world applications in forensics and environmental monitoring. Photostability refers to the ability of CDs to retain fluorescence under continuous light exposure. CDs prepared from banana peel or rosemary have shown excellent resistance to photobleaching, maintaining over 90% of their original emission intensity even after several hours of UV exposure[2, 23]. Thermal stability is equally important. Some CDs retain their fluorescence even when heated up to 150°C, as reported for composites formed with MoO_3 and Al_2O_3 [48]. This thermal resilience is attributed to the robust carbon core and reinforced surface bonds created during composite formation. Solvent stability tests show that green CDs often maintain consistent fluorescence in water, ethanol, and even acidic or basic media, making them suitable for use in diverse conditions[49]. A significant challenge is aggregation, especially in solid-state applications. Aggregation typically causes fluorescence quenching due to π–π stacking. However, surface passivation and doping with functional groups like carboxyl and amine can mitigate these effects[50].

4.4 Advanced Features

Beyond basic fluorescence, green CDs have demonstrated advanced features that expand their utility in modern technological and forensic tools.

Aggregation-Induced Emission (AIE)

While most carbon-based nanomaterials suffer from aggregation-caused quenching (ACQ), some green CDs exhibit the opposite—aggregation-induced emission (AIE). This phenomenon was reported in CDs made from food waste and grains, where fluorescence intensity increased upon aggregation or solidification[51]. AIE enhances brightness in film-based applications, such as latent fingerprint development on glass and plastic surfaces.

Solid-State Fluorescence

To use CDs in LEDs, printing inks, and dry forensic powders, solid-state fluorescence is highly desirable. Studies using solid precursors like rice husk and cigarette filters have shown that solid CD powders can emit visible light without requiring dispersal in solvents[3, 27]. This eliminates the need for stabilizers and opens new paths for portable sensor development.

Biocompatibility Assessment

For any application involving contact with biological samples or skin (such as fingerprint detection or bioimaging), biocompatibility is essential. Several toxicity studies using MTT assays and cell viability tests have shown that green CDs, especially those made from coconut water, onion peel, and banana peel, are safe to use at levels appropriate for applications[52, 53].

The natural precursors and absence of heavy metal components provide green CDs a clear advantage over traditional quantum dots, especially in biomedical and forensic fields.

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5. Forensic Science Applications

A particularly intriguing application of green carbon dots (CDs) lies in forensic research, particularly in the visualisation and analysis of concealed fingerprints. Long-established fingerprint detecting systems typically encounter issues related to toxicity, background staining, and surface limitations. Green CDs exhibit robust fluorescence, are environmentally friendly, and are applicable on many surfaces, rendering them suitable for practical forensic applications.

5.1 Latent Fingerprint Detection

Green CDs have shown effective using powder dusting, spray coating, and dipping, contingent upon the surface and print type. Imprints on glass and plastic were created by researchers using N-doped carbon dots that were generated from coconut water and starch powder. A brilliant light was emitted by the CDs when they were exposed to ultraviolet light[13]. When using a mixture of CDs and silica gel nano particles, the spray method was very effective in evenly covering large or uneven surfaces. This ensured that the fluorescence would remain constant on surfaces with and without pores. Wet, greasy, or aged surfaces are notoriously difficult for fingerprint forensics to detect. Using luminol and food scraps, "green" CDs could display prints that were several days old and beginning to fade[17]. Even after being exposed to moisture, CDs retained their fluorescence and clung effectively to wet surfaces, including metals. Unlike other powders, this one can't be easily removed[54]. These nanodots emit highly contrastive fluorescence when illuminated with both ultraviolet and visible light. This renders them highly valuable in low-light crime scenes as well as in regulated laboratory environments[55]. Depending on the substrate and the surrounding environment, forensic scientists have various choices to adjust the emission by doping or changing the precursor.

5.2 Fingerprint Enhancement and Poroscopy

CDs enhance the visibility of fingerprints and improve fingerprint imaging by capturing intricate ridge-level and pore-level details[56]. Poroscopy is crucial, as it examines the dimensions, morphology, and positioning of sweat pores on fingerprint ridges. Recent studies indicate that CDs produced from banana peels and human hair can provide exceptionally clear images that disclose ridge patterns and minute details when examined under a fluorescent microscope[12]. Certain approaches even penetrated to the level of pores, which is crucial for distinguishing between two fingerprints. This is a forensic issue that standard powders typically do not resolve [57].

5.3 Smart Detection Systems

Contemporary forensic research increasingly depends on AI-driven algorithms to analyse, classify, and match fingerprints instantaneously. Intelligent detection systems currently employ green CDs in conjunction with AI-enhanced image processing algorithms such as YOLOv8, which can analyse ridge density, bifurcations, and minutiae with remarkable precision. In a study, high-luminosity CDs were employed to identify ridge ends and crossovers in fluorescence images. YOLOv8 performed automatic detection. This integration significantly enhances the accuracy of fingerprint identification while substantially reducing human labour[19].

Additionally, multimodal systems integrating CDs with metal-oxide semiconductors or rare-earth composites, such as Sm^{3+} and ZnO, have been developed. These systems collaborate to provide dual advantages: they can utilise light for reading and electricity for sensing, enabling them to detect several objects simultaneously. Such devices may prove beneficial not only for laboratory analysis but also for field applications, including airports or border control checkpoints, where rapid and precise fingerprint authentication is essential.

5.4 Reusability and Field Deployability

Forensic instruments must be robust, cost-effective, and user-friendly for effective application in field settings. Green CDs fulfil numerous requirements. Numerous studies have demonstrated that green CDs may maintain stability and resist degradation. This indicates that the identical CD-based powder can be utilised multiple times without diminishing its brightness.

An additional significant issue is the stability of the storage. CDs maintained efficacy after several months at room temperature, exhibiting no agglomeration or emission loss upon reapplication[58]. Green carbon dots have revolutionised latent fingerprint analysis by providing detection technologies that are safe, highly sensitive, and versatile. Contemporary forensic research considers them advantageous due to their compatibility with intelligent systems and their adaptability to diverse surfaces and circumstances. As technology advances, it is likely that CDs will become integral to both conventional and AI-enhanced forensic procedures.

6. Other Emerging Applications

While forensic science has been one of the leading areas where green carbon dots (CDs) have proven their potential, their utility extends far beyond fingerprint detection. Green CDs are being investigated more and more in a variety of fields, including biomedical imaging, environmental monitoring, anti-counterfeiting, and optoelectronic devices, because of their adjustable photoluminescent qualities, biocompatibility, and surface adaptability.

6.1 Bioimaging and Therapeutics

One of the earliest and most exciting applications of green CDs was in bioimaging, where their inherent fluorescence makes them excellent probes for cellular visualization. Their tiny size helps them pass through cell membranes, and the many functional groups on their surface (like carboxyl, amine, or hydroxyl) make it possible to target specific areas for imaging when attached to biomolecules. In lab tests, researchers have shown that CDs can show the inside of cells and their nuclei when viewed under a fluorescence microscope. Besides imaging, there is growing interest in their therapeutic applications, especially due to their ability to generate reactive oxygen species (ROS) upon light activation, which can be harnessed in photodynamic therapy (PDT) for cancer treatment [59]. Some studies have also explored their antibacterial activity, which stems from surface interactions and oxidative stress induced in microbial cells[60]. These dual capabilities—imaging and treatment—make green CDs promising candidates for theragnostic platforms.

6.2 Environmental Sensing

Due to their tunable emission and surface sensitivity, green CDs are highly effective as fluorescent sensors for detecting environmental pollutants, particularly heavy metal ions[61]. They work on a simple principle: the presence of metal ions often quenches the fluorescence of CDs, creating a detectable change in signal intensity. CDs made from rosemary, food waste, and plant peels have been used to determine harmful ions like Fe^{3+}, Cr^{6+}, and Pb^{2+}, with the ability to detect very low amounts[62, 63, 64]. These ions interact with surface groups on the CDs, affecting electron transitions and thereby modulating their fluorescence. For instance, the strong attraction between Pb^{2+} and the oxygen/nitrogen areas on the CDs' surface causes a noticeable decrease in fluorescence, making it easy to detect in water samples. These sensing systems are particularly valuable for on-site environmental analysis, especially in rural or under-resourced regions where access to large-scale instrumentation is limited. Moreover, many of these CDs can be integrated into portable paper strips or embedded into hydrogels for quick dip-and-read formats[65].

6.3 Anti-counterfeiting and Data Security

Another application where green CDs are showing outstanding promise is in the field of anti-counterfeiting and information encryption[66]. The tunable fluorescence, often invisible under normal light but activated under UV exposure, makes CDs ideal for invisible ink and security printing[67]. CDs synthesized from grains, coconut husk, and cigarette filters have been successfully used to print covert barcodes, QR codes, and signatures, which are only visible under a specific wavelength of UV light[27, 68]. This feature enables multi-level security printing for legal documents, branded merchandise, or currency notes. Furthermore, CDs with excitation-dependent emission allow for multi-color security patterns, increasing the difficulty of replication. Some advanced systems have even employed dual-mode encryption, where CDs are used in combination with rare earth nanomaterials to store and retrieve information through both fluorescence and magnetic signatures[69]. These capabilities make green CDs a robust, low-cost tool for improving document and product security across industries.

6.4 LEDs, Phosphors, and Optical Devices

Green CDs have gotten a lot of attention in the optical electronics field since they are used in light-emitting diodes (LEDs) and down-conversion phosphors. They can be used instead of regular quantum dots because they have a lot of photoluminescence and are not very hazardous. Several studies have shown how to make CD-based LEDs, which use CDs as the light-emitting layer to provide blue, green, or even warm white light[28, 70, 71]. These LEDs are great for ornamental lighting and display systems that do not require a lot of electricity. CDs made from grains and fruit peels had stable solid-state fluorescence, which made them perfect for LED coating applications without having further stabilizers[72]. In some more complex setups, CDs have also been looked at for optical thermometry, which uses variations in fluorescence intensity or lifespan to determine temperature. This makes it possible for smart wearable gadgets and packaging that changes with temperature.

Green carbon dots are more than simply forensic tools; they are becoming useful materials that may be used in the real world. Because they are biocompatible, sensitive to the environment, can be tuned to different wavelengths of light, and have a wide range of surface properties, they can be used in many fields, such as healthcare, environmental monitoring, security printing, and display technologies.

7. Critical Analysis and Comparison

Although the advancement in green carbon dots (CDs) research has been impressive, it is equally important to evaluate these developments with a critical lens. This section synthesizes comparative data, identifies key advantages, and highlights persistent challenges—especially when translating laboratory findings into real-world forensic applications.

One positive and one negative aspect of green carbon dot research is the variety of approaches. Numerous synthetic processes, natural precursors, and planned uses are revealed by reviewing the investigations. This indicates that there is no universally superior approach.

In processes such as hydrothermal or microwave-assisted synthesis, for instance, natural plant components such as neem, rosemary, and banana peel are extensively used. Using these techniques, one can create carbon dots with a dazzling light that have applications in bioimaging and fingerprint recognition[23]. In contrast, solid-state and combustion techniques tend to work better with hair and eggshells, among other animal products. These processes often improve the materials' strength and suitability for sensor applications. Photo physics can benefit the environment by making use of waste products such as cigarette butts, food scraps, and coal ash. For instance, CDs manufactured from coal ash exhibited strong emission for optical devices[27, 29], whereas CDs manufactured from cigarette filters exhibited solid-state fluorescence and significant promise for anti-counterfeiting efforts[27]. The process of making CDs is related to the way they will be used in the various studies. Industrial and optical applications are better served by solid-state and combustion technologies, while hydrothermal methods are more commonly employed in the medical and criminal justice fields. Understanding the connection between synthesis and application is crucial for selecting the most appropriate CD system for a given forensic or environmental problem.

7.1 Advantages vs. Challenges

Making green CDs in an eco-friendly manner is one of their best features. The starting material is typically inexpensive biomass or garbage, and the solvent is water. Their low toxicity, compatibility with living organisms, and light-emitting tunability make them ideal for use in biology and forensics[28, 73, 74]. A further major perk is that CDs can have their surfaces modified or other materials added to them to enhance their light emission, enable specific detection, and make them attach better to hidden fingerprints. Changing the temperature during production and utilizing different starting materials also allows you to alter the CDs' luminous properties. You may adjust the amount of light they emit more precisely in this way. The ability to change the brightness and contrast for different forensic surfaces, such as smooth surfaces or ancient fingerprints, is crucial[47].

There are still significant technological challenges, despite these capabilities. Unfortunately, low quantum yields persist in several CDs generated from biomass. Due to variations in surface treatment and changes in beginning constituents, different batches of a substance can have varying degrees of light emission, leading to misleading results. Scalability is another issue. Making things in a lab is easy, but scaling up hydrothermal or microwave-assisted methods for industrial use without sacrificing performance or purity is still a challenge[7]. Due to inherent disparities among precursors such as fruit peels, herbal plants, and culinary waste, batch-to-batch variations are common. Particle size, surface grouping, and light emission can all be affected by subtle changes to the precursor's composition. This makes it challenging to achieve quality standards[40, 47]. High humidity or temperature can also reduce fluorescence, which is an additional issue. Using CDs in open crime scenes or hot field environments is particularly risky[75].

7.2 Reliability in Real-World Forensic Scenarios

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When evaluated for practical forensic applications, green CDs show promising potential, but their operational reliability still requires further validation.

In laboratory-controlled settings, CDs have successfully revealed clear ridge patterns, pore-level structures, and aged fingerprints on both porous and non-porous surfaces[54, 76]. However, performance can vary when applied to real-world conditions, such as dusty crime scenes, wet environments, or textured materials like cloth or leather. Reusability and long-term storage stability are additional concerns. While some CDs maintain emission for months when stored in dark, sealed containers, others lose brightness due to surface oxidation or aggregation[58]. Standardized forensic kits based on CDs would need to account for such degradation mechanisms. Furthermore, interference from background fluorescence or natural oils on surfaces can reduce detection clarity. Although surface modification (e.g., with silica or starch carriers) helps address this, it adds another layer of complexity to kit design and field deployment. While early integration with AI-based recognition tools such as YOLOv8 has been demonstrated, most systems are still in proof-of-concept stages and need robust software–hardware synchronization to function seamlessly at crime scenes[77].

8. Challenges and Limitations

Despite the growing popularity of green carbon dots (CDs) and their promising potential in forensic science and beyond, there remain several critical limitations that must be addressed before these materials can be routinely implemented in real-world applications. Many of these challenges are not only technical but also procedural and regulatory, particularly when forensic evidence is involved.

8.1 Reproducibility and Standardization Issues

One of the most persistent obstacles in the field of green CDs is the lack of reproducibility across batches[13]. This issue largely stems from the inherent variability in natural precursors. Unlike synthetic chemicals, plant-based and food-waste-derived materials vary significantly in their biochemical composition depending on factors such as source, growth conditions, and age. For example, CDs synthesized from onion peel or rosemary leaves may show different surface functionalities and photoluminescent behavior simply due to seasonal variations in the precursor material. Even small changes in temperature, pH, or reaction time during synthesis can lead to noticeable differences in particle size, emission wavelength, and stability[1]. This inconsistency poses a serious problem for forensic science, where reproducibility is key. Without standardized protocols for precursor preparation, synthesis conditions, and characterization, it becomes difficult to ensure that a CD-based forensic reagent will perform reliably across different labs or crime scenes.

8.2 Low Quantum Yields in Bio-CDs

While green CDs are celebrated for their eco-friendliness, they often suffer from lower quantum yields compared to their chemically synthesized counterparts. This happens because many bio-derived CDs do not fully carbonize, have poorly treated surfaces, and lack a consistent graphitic structure. Quantum yield is a measure of how well a material can produce light, and it is crucial for uses like detecting fingerprints, where you need a clear difference in visibility under UV or visible light. Several studies have shown that CDs derived from materials like neem, banana peel, or cigarette filters exhibit quantum yields below 10% unless post-treatment doping or surface modification is applied[78]. Although doping with nitrogen, sulfur, or phosphorus has shown improvements, the results are still inconsistent[79]. The field currently lacks a universal strategy to enhance and stabilize the quantum yield of green CDs without compromising their biocompatibility or green credentials.

8.3 Photobleaching and Background Fluorescence

Another technical challenge is photobleaching—the gradual loss of fluorescence intensity upon continuous exposure to excitation light. Field applications such as forensic investigations pose a particular challenge, as they may require prolonged UV exposure for visualization[80]. Bio-CDs are often less stable under intense illumination than metal-based quantum dots or chemically synthesized CDs. As a result, their fluorescence may fade within minutes, reducing the quality and duration of visualization. In addition to photobleaching, background fluorescence from substrates or environmental contaminants can interfere with the signal emitted by CDs. For instance, paper, plastics, and some textile fibers may naturally fluoresce under UV light, complicating the interpretation of fingerprint patterns. Applying advanced filtering or imaging techniques may neutralize the advantage of CDs' fluorescence in such cases. This issue also impacts their application in anti-counterfeiting and environmental sensing, where precise fluorescence detection is crucial for signal clarity and accuracy.

8.4 Regulatory and Validation Challenges in Forensics

While the scientific performance of green CDs is progressing rapidly, their regulatory acceptance in forensic science is still at an early stage. For any new material to be adopted in legal investigations, it must undergo rigorous validation under protocols such as those set by the Scientific Working Group on Materials Analysis (SWGMAT) or similar national and international forensic bodies[81]. So far, very few CD-based forensic products have reached this level of validation. Most studies remain at the proof-of-concept or laboratory demonstration stage, with little data available on long-term stability, environmental tolerance, and performance across diverse real-world conditions. Moreover, forensic evidence based on CD-enhanced visualization would need to hold up in court, which requires documentation, traceability, and reproducibility. Without these, even the most promising innovations risk being rejected or challenged during legal proceedings. This gap between innovation and regulatory acceptance illustrates the importance of standardized test methods, accredited production protocols, and collaborative studies between materials scientists and forensic practitioners. In conclusion, green CDs have immense potential as sustainable and versatile nanomaterials, but several limitations must be overcome to ensure their widespread and reliable use—particularly in sensitive fields like forensic science. Improvements in synthetic reproducibility, optical performance, and regulatory compliance are essential to moving from laboratory promise to real-world application.

9. Future Perspectives

The potential applications of green carbon dots (CDs) extend far beyond current understanding, particularly as their production and utilization evolve over time. Numerous advancements are forthcoming, including enhanced biological assays and next-generation forensic tools. These developments are attributable to advancements in green technology, digital resources such as artificial intelligence, and materials science.

9.1 Machine Learning in Image Recognition

Green CDs can be utilized in AI-driven image identification systems, representing a compelling application for this technology. In forensic science, this signifies a transition from manual fingerprint analysis to the utilization of deep learning algorithms for automated analysis. Recent studies have investigated the integration of object detection algorithms, such as YOLOv8, with latent fingerprints enhanced by carbon dots. This enables the automatic recognition of ridge patterns, minute details, and even the fingerprints of identical twins with exceptional precision[47]. These models not only reduce human errors but also expedite the identification of individuals in high-stakes forensic scenarios. Artificial intelligence in image processing and the utilization of luminescent carbon dots could significantly enhance smart security systems, expedite identification verification, and improve the analysis of evidence at crime scenes in the future. The challenging aspect will be ensuring that imaging techniques and training datasets can accommodate variations in substrate, light, and background noise.

9.2 Integration with Wearable Devices and Diagnostics

Green CDs are being considered for use with wearable sensors and portable diagnostic equipment at an increasing rate due to the rising popularity of personalised and point-of-care health solutions. They are ideal for incorporation into textiles, patches, or smartwatches designed to monitor physiological parameters or detect biological analytes due to their small size, sensitivity to fluorescence, and biocompatibility[3]. One example is the use of pH-, temperature-, or ion-responsive CDs in wearable health trackers for athletes, patients with chronic diseases, or even troops serving in the field[82]. Their rapid fluorescence response and stability in skin-safe environments make them ideal for these kinds of applications. In areas where resources are scarce, a combination of paper-based biosensors and green CDs may provide a rapid means of disease screening or environmental risk detection. According to these modifications, CDs will soon be integrated into ordinary wearable devices that can track health in real-time, expanding their usage beyond lab imaging.

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9.3 Hybrid Nanocomposites for Dual-Mode Detection

To make green CDs more sensitive and advantageous, researchers are now developing hybrid nanocomposites that combine green CDs with other materials such as metal oxides (ZnO, MoO_3), rare earth elements (Sm^{3+}), or alumina (Al_2O3). Two or more senses can coexist in these composites; for example, one part can detect light, and the other can detect heat, electricity, or magnetism. An electrochemical signal might be produced when a ZnO-CD combination comes into touch with heavy metals or infections, and it could also glow under ultraviolet light[3, 83]. These materials have the chance to change forensic science by allowing for simultaneous fingerprint and residue analysis, greatly improving the efficiency of crime scene investigations. As an analogy, dual-mode biosensors could detect physical and chemical indicators of illness or pollution simultaneously. To avoid affecting fluorescence or making cells sick, it is crucial to integrate materials carefully. Avoid mixing various nanomaterials. Important considerations for practical application include surface compatibility, long-term stability, and cost-effective synthesis[84].

9.4 Commercial-Scale Production and Environmental Monitoring

While green CDs have been successful in the lab, expanding their production to a commercial scale and creating new goods is the next major step. For example, we need to figure out how to standardise the initial materials, make energy-saving technologies like hydrothermal or microwave synthesis work on a larger scale, and ensure that each batch is identical.

Startups and research organisations are already exploring potential solutions to make green CDs from a variety of agricultural and industrial byproducts. It may be feasible to construct pilot plants and factories that produce environmentally benign nanomaterials if materials scientists and chemical engineers collaborate. When contemplating possible uses for CDs, environmental monitoring is still on the table. They can be used as fluorescent indicators for air or water quality and are sensitive to contaminants such as Fe^{3+}, Cr_{*}^{+}, and Pb^{3+}, making them ideal for both urban and remote sensing applications. A combination with smart filters, the internet of things (IoT), or drones could make real-time environmental data collection possible, allowing for improved management of ecological concerns and faster reactions to pollution occurrences. Machine learning, wearable health tech, hybrid nanodevices, and commercial-scale production methods are among the new technologies that will determine the fate of green CDs. More research, cross-disciplinary collaboration, forward-thinking legislation, and sustainable design thinking will all be necessary to fulfil this promise.

10. Conclusion

Over the past decade, carbon dots (CDs) have risen to prominence as a top nanomaterial for scientific study and practical applications. Due to their tiny size, lack of toxicity, flexibility, and ability to change colour, they find widespread use in bioimaging, environmental sensing, optoelectronics, and forensic research.

This review talks about how green CDs have changed over time, focusing on those made from biomass and waste materials, and how they help nanotechnology stay sustainable. We might be able to lower production costs, have less of an effect on the environment, and encourage more recycling by using plant, animal, and industrial waste in green synthesis processes. Neem, coconut, and rosemary are some examples of by-products from plants and animals. Other types of industrial waste are cigarette butts and food scraps.

Hydrothermal treatment, microwave-assisted synthesis, solid-state combustion, or ultrasonication can be used to make CDs with certain sizes, shapes, and brightness levels. Adding elements like N, S, and P and making composites with materials like ZnO, and Al_2O_3 has also greatly improved photostability, quantum yield, and target-specific functionality. Green CDs are great for forensic fingerprint examination since they are bright and can stick to many different surfaces, even old or wet ones. Techniques like making films, dusting with powder, and spraying with a coating have made it possible to find CDs in the field. Their ability to work with AI-based recognition systems like YOLOv8 is a big step forward for forensic identification.

Many fields, including forensics, anti-counterfeiting, LED manufacture, and environmental pollutant detection, could benefit greatly from green CDs. Bioimaging systems, solid-state illumination, and dual-mode sensing are only a few of their many potential applications.

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Despite our many accomplishments, there are many issues that require our attention. Among these issues are the following: the necessity for established forensic validation techniques, improving quantum yield, batch-to-batch reproducibility, and resistance to photobleaching. We must exercise caution regarding regulatory loopholes and variations in natural antecedents if we want more individuals to use these products for commercial and legal reasons.

Green CDs, hybrid nano systems, wearable diagnostics, and machine learning all work together to pave the path for future innovations. Making things in the real world rather than in a lab is equally vital, with an emphasis on making them eco-friendly, cost-effective, and advantageous.

Green carbon dots are not only another form of nanomaterial; they are a brilliant strategy for reimagining the potential of waste, ecology, and technology to improve people's lives. With the growing importance of sustainability in both academia and industry, green CDs are expected to play a significant role in developing next-gen materials that prioritise safety, intelligence, and responsibility, particularly in fields such as optical sensing and forensics, among others.

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