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Solid-State Fluorescent Carbon Nanodots: Synthesis Strategies, Emission Mechanisms, and Emerging Applications A Systematic Review

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Abstract

Fluorescent carbon nanodots (CDs) have emerged over the past two decades as a biocompatible, low-cost, and structurally tunable alternative to semiconductor quantum dots and organic dyes. While CDs display strong photoluminescence in dilute solution, most formulations suffer from aggregation-caused quenching (ACQ) once concentrated into films, powders, or polymer matrices a limitation that has historically restricted their use in light-emitting diodes (LEDs), anti-counterfeiting tags, and solid dosage forms. This systematic review synthesizes recent primary literature (2022–2025) on strategies for achieving and stabilizing solid-state fluorescence in CDs, and on the industrial and biological applications this capability enables. Following a PRISMA-informed protocol, five peer-reviewed studies meeting predefined eligibility criteria were retained for narrative synthesis: a femtosecond-laser bottom-up synthesis elucidating the molecular-fluorophore origin of CD emission; a one-step, gram-scale, room-temperature synthesis exploiting J-aggregation to produce red-emitting electroluminescent CDs; a metal–organic-framework (MOF) encapsulation strategy yielding multicolor solid-state phosphors for LEDs; a Maillard-reaction-derived route generating CDs from thermally processed spices for food and nutraceutical applications; and an industrial upcycling route converting steel-plant coal-tar waste into CDs for fiber-reinforced polymer (FRP) composite tagging. Thematic synthesis identifies convergent solutions to ACQ supramolecular J-aggregation, rigid host-matrix immobilization (MOF, polymer, mineral), and dilute-matrix dispersion alongside a persistent unresolved debate over whether solid-state and even solution-phase CD emission originates from molecular fluorophores, graphitic-core quantum confinement, or crystallization-induced emission enhancement. Across the reviewed studies, quantum yields in the solid state ranged from 15% to over 80%, and demonstrated applications spanned electroluminescent displays, tunable white-light LEDs, forensic and industrial tagging, and food-derived nutraceutical carriers. The review concludes that mechanistic consensus remains

elusive because CD photophysics are precursor- and route-dependent, and that future work should prioritize standardized characterization protocols, life-cycle and toxicological assessment of waste-derived CDs, and scale-up of J-aggregation and MOF-encapsulation strategies for commercial optoelectronic and anti-counterfeiting applications.

1. Introduction

1.1 Background and significance

Carbon nanodots (CDs), sometimes termed carbon dots, carbon quantum dots, or carbon nanoparticles depending on synthetic origin and internal structure, are quasi-spherical carbon-based nanomaterials typically smaller than 10 nm that exhibit bright, tunable photoluminescence (PL). Since carbon nanoparticles with room-temperature fluorescence were first isolated in 2004 and formally named "carbon dots" in 2006, CDs have attracted sustained interest as a green alternative to heavy-metal-containing semiconductor quantum dots (SQDs) and to expensive, often environmentally persistent organic dyes and rare-earth phosphors (Zheng et al., 2023). Relative to these incumbent fluorophores, CDs offer low material cost, straightforward and often waste-valorizing synthesis routes, low intrinsic toxicity, high biocompatibility, and readily tunable surface chemistry arising from oxygen- and nitrogen-containing functional groups (Li, Zheng, Zhang, & Gong, 2024; De et al., 2025).

Despite these advantages, the translation of CDs from solution-phase fluorophores into solid-state functional materials has been persistently constrained by aggregation-caused quenching (ACQ). In dilute solution, CDs are spatially isolated and fluoresce efficiently; however, when concentrated into films, powders, or embedded at high loading in polymer matrices conditions required for most device and tagging applications the close packing of chromophoric units promotes non-radiative energy transfer, π–π stacking-induced quenching, and re-absorption effects that collectively suppress or extinguish PL (Zheng et al., 2023; Li et al., 2024). Because virtually every downstream application of CDs in light-emitting diodes (LEDs), anti-counterfeiting inks, sensors, and composite tagging requires the fluorophore to retain brightness in a solid or immobilized state, the search for reliable strategies to overcome ACQ has become one of the most active subfields of CD research in the past five years.

A second, closely related open question concerns the fundamental origin of CD photoluminescence itself. Some groups attribute emission to quantum-confinement effects analogous to those in inorganic quantum dots, in which particle size determines the electronic bandgap; others attribute emission to discrete molecular fluorophores small, often heterocyclic organic species that are either covalently bonded to, physically trapped within, or non-covalently decorating the surface of an otherwise weakly emissive carbon core (Astafiev et al., 2022). This "molecular fluorophore versus quantum confinement" debate is not merely academic: it directly determines which engineering levers (precursor chemistry, doping, particle size control, matrix rigidification) are most likely to yield bright, stable solid-state emitters, and therefore underpins the rational design strategies surveyed in this review.

Beyond the specific mechanistic and engineering questions addressed by this review, the broader significance of solid-state CD research derives from the scale of the application space it touches. Solid-state emissive materials underpin the global lighting and display industry, in which conventional phosphor technologies depend heavily on rare-earth elements (europium, cerium, dysprosium) whose extraction is geographically concentrated, environmentally damaging, and subject to significant price volatility, or on semiconductor quantum dots containing regulated heavy metals such as cadmium (Li et al., 2024). A biocompatible, waste-derivable, and potentially low-cost carbon-based alternative capable of matching or approaching the brightness of these incumbent technologies would carry implications not only for consumer electronics and general lighting, but also for security printing and anti-counterfeiting (an application directly

explored by two of the studies synthesized in this review), industrial traceability, and, more speculatively, for food science and nutraceutical delivery given the demonstrated biocompatibility of many CD systems. The present review is therefore motivated by both a fundamental materials-science question how does solid-state CD emission actually arise, and how can it be engineered rather than discovered by trial and error and a translational one: which of the several proposed engineering strategies are closest to yielding commercially viable, durable, solid-state fluorescent products.

It is also worth situating this review methodologically. Because fabricating new carbon nanodots, running spectroscopic characterization, or generating original device performance data lies outside the scope of a literature-based review, this study does not report new experimental results. Rather, consistent with the definition of a systematic review as a form of secondary research, it applies a structured, transparent, and reproducible methodology (detailed in Section 3) to identify, appraise, and synthesize findings that have already been generated, characterized, and peer-reviewed by the original research groups. This distinction is important both for scientific integrity and for the intended contribution of the present work: rather than generating new empirical claims about carbon nanodot photophysics, this review aims to organize, compare, and critically evaluate the claims already present in the recent literature, so as to make the current state of mechanistic understanding and engineering practice more legible to researchers entering or working within this fast-moving subfield.

1.2 Research questions

This systematic review was guided by four research questions:

1. **RQ1** What synthesis strategies have been reported (2022–2025) for producing carbon nanodots with solid-state or aggregation-resistant fluorescence?
2. **RQ2** What mechanistic explanations do the reviewed studies offer for solid-state emission, and how do these relate to the broader molecular-fluorophore-versus-quantum-confinement debate?
3. **RQ3** What strategies have been employed to mitigate aggregation-caused quenching, and how do their reported photoluminescence quantum yields (PLQYs) compare?
4. **RQ4** What application domains (optoelectronic, industrial, biological/nutraceutical) have been demonstrated using solid-state fluorescent CDs, and what does this suggest about the maturity and translational readiness of the field?

1.3 Scope and rationale for a systematic review

Given the heterogeneity of CD synthesis routes hydrothermal, solvothermal, microwave-assisted, laser-based, and thermally driven Maillard chemistry and the diversity of proposed emission mechanisms, a systematic, PRISMA-informed synthesis of recent primary literature offers value beyond a conventional narrative review by making the search, eligibility, and extraction process transparent and reproducible. This review does not report new experimental data; rather, it applies systematic review methodology to synthesize, compare, and critically evaluate findings already published in peer-reviewed sources, in line with recognized standards for evidence synthesis in the physical and materials sciences.

2. Literature Review

2.1 Historical trajectory of carbon nanodot research

CDs were first observed as a fluorescent by-product during the purification of single-walled carbon nanotubes by arc-discharge methods, and were subsequently deliberately synthesized and named "carbon dots" following further characterization work in the mid-2000s (Zheng et al., 2023). Over the subsequent decade, the field diversified rapidly along two broad synthetic philosophies: "top-down" methods that fragment larger carbon sources (graphite, carbon fibers, biomass char) into nanoscale particles via oxidative or physical cleavage, and "bottom-up" methods that build CDs through the polymerization, cyclization, or carbonization of small-molecule precursors such as citric acid, amines, and aromatic compounds under hydrothermal, solvothermal, or microwave-assisted conditions (Astafiev et al., 2022; Zheng et al., 2023).

Hydrothermal and solvothermal syntheses, while simple and scalable, generally require elevated temperature and pressure, which introduces structural defects, raises energy consumption, and constrains large-batch industrial production due to safety considerations (Zheng et al., 2023). These same reaction conditions also tend to broaden the emission linewidth and produce excitation-dependent PL, a spectral signature widely though not universally interpreted as evidence of a heterogeneous population of emissive states within a single CD sample.

As the synthetic toolkit for CDs matured through the 2010s, application-oriented research diversified along several parallel tracks. In bioimaging and biosensing, the combination of low cytotoxicity, resistance to photobleaching relative to organic dyes, and surface chemistry amenable to bioconjugation made CDs attractive fluorescent labels for cellular and in vivo imaging. In photocatalysis and energy conversion, CDs' broad optical absorption and electron-donating/accepting capacity motivated their incorporation as co-catalysts or light-harvesting sensitizers in composite photocatalytic systems. In optoelectronics the application domain most directly relevant to the present review early efforts to incorporate CDs into light-emitting diodes recognized quickly that the same photophysical behavior that made CDs attractive as solution-phase imaging probes (bright, size- and excitation-tunable PL) did not transfer straightforwardly to the solid state, where devices necessarily require densely packed or thin-film emissive layers. This solution-to-solid-state translation gap has, over the past five years, become one of the defining technical challenges motivating the corpus of studies synthesized in this review.

2.1.1 Defining aggregation-caused quenching in the CD context

Although ACQ is a phenomenon long recognized in conventional planar aromatic organic fluorophores where it is often discussed alongside the complementary phenomenon of aggregation-induced emission (AIE), in which certain molecular designs instead brighten upon aggregation its specific manifestation in CDs is complicated by the intrinsic structural heterogeneity of the nanomaterial class. Unlike a single, well-defined small-molecule dye, a typical CD sample may contain a distribution of particle sizes, a mixture of graphitic and amorphous carbon domains, and a heterogeneous population of surface functional groups and, in some interpretations, discrete surface-bound molecular fluorophores. This heterogeneity means that ACQ in CDs may arise from multiple concurrent mechanisms operating simultaneously inter-particle energy transfer between chromophores of differing emission energy, direct π–π stacking between planar aromatic domains on adjacent particles, and self-absorption/re-emission losses within a dense particle assembly rather than from a single, cleanly isolable photophysical process. This mechanistic complexity is itself part of the motivation for the mechanism-focused synthesis undertaken in Section 4.3 of this review.

2.2 The molecular-fluorophore versus quantum-confinement debate

A substantial body of literature attributes CD PL to quantum confinement: as particle size decreases toward the nanoscale, the effective electronic bandgap increases, producing size-tunable emission analogous to inorganic quantum dots. Consistent with this framework, De et al. (2025) reported that carbon nano-dots derived from coal tar pitch, with particle sizes below 5 nm after purification, "exhibit unique fluorescence properties due to quantum confinement effects, which influence their electronic characteristics and result in distinct emission profiles" (p. 3 of 9), and Li et al. (2024) observed that the bandgap energy of their multicolor CDs decreased systematically from 2.68 to 1.94 eV as average particle size increased from blue- to red-emitting populations, a trend consistent with a quantum-size effect.

A competing and increasingly influential body of work, however, locates the origin of fluorescence not in the carbon core itself but in discrete molecular fluorophores that are either covalently incorporated into, or non-covalently associated with, the CD surface. Astafiev et al. (2022), using femtosecond-laser synthesis of

nitrogen-doped carbon nanodots from pyridine and benzene, provided some of the most direct mechanistic evidence for this view. Using anisotropy decay kinetics, pH-dependence measurements, and time-resolved area-normalized emission spectroscopy (TRANES), the authors demonstrated that pyridine-derived carbon nanodots (p-CNDs) possess at least three spectroscopically distinct peripheral fluorophores, formed by oxidation of surface-bound pyridine rings, with emission maxima at 420–430, 450, and 500–520 nm. Critically, they found that "the main contribution to the luminescence of both b- and p-CNDs is made by small fluorescent segments (peripheral fluorophores) decorating the nanoparticle core," while "the carbon nanoparticle itself and polycyclic aromatic structures of the nanoparticle core evidently play a limited role in the photoluminescence mechanism." This finding aligns with earlier reports that nitrogen-doped CDs synthesized from citric acid and amine donors are frequently contaminated by independently formed molecular fluorophores such as citrazinic acid derivatives, which can dominate the observed PL and confound interpretation of "true" carbon-core emission.

A third, hybrid explanation most clearly articulated by Zheng et al. (2023) proposes that solid-state fluorescence in some CD systems arises not from the carbon core nor from isolated molecular fluorophores in the conventional sense, but from a well-defined small organic molecule that undergoes **crystallization-induced supramolecular self-assembly**. In their room-temperature synthesis, cyclization of o-phenylenediamine and 4-dimethylamino phenol produced a single organic species, 2-(dimethylamino) phenazine, which self-assembled during crystallization into a J-aggregate structure. Because adjacent phenazine molecules were arranged in a misaligned, non-covalently bonded (Van der Waals and hydrogen-bonded) parallel stack, the material avoided the face-to-face π–π stacking that typically produces H-aggregate-type fluorescence quenching, and instead exhibited intense solid-state red emission at 637 nm. Density functional theory (DFT) calculations further showed that the excited state possessed charge-transfer (CT) character consistent with the compound's donor–π–acceptor (D-Π-A) molecular architecture, and that this CT character and hence the emission wavelength was systematically modulated by solvent polarity.

Collectively, these three mechanistic frameworks are not necessarily mutually exclusive within a single review corpus: quantum confinement may dominate in graphitic-core, top-down-derived CDs; discrete molecular fluorophores may dominate in bottom-up, low-temperature aromatic-precursor CDs; and supramolecular self-assembly/J-aggregation may govern emission specifically in the solid state for select rigid, planar molecular CD precursors. This mechanistic plurality is itself a central finding of the present review and is discussed further in Section 5.

2.3 Aggregation-caused quenching and existing mitigation strategies

ACQ in CDs is most commonly attributed to a combination of (a) non-radiative Förster resonance energy transfer between closely packed chromophores, (b) π–π stacking of aromatic domains that opens non-radiative relaxation pathways, and (c) self-absorption/re-absorption of emitted photons within a dense particle assembly (Li et al., 2024). Prior to the studies reviewed here, two general mitigation philosophies had been established in the literature: (i) doping CDs into a non-emissive polymeric host material (e.g., polyvinyl carbazole) to physically separate chromophores, and (ii) surface passivation to reduce inter-particle π–π interactions. Both approaches carry known limitations: host-guest doping systems often suffer from inefficient energy transfer between host and CD, incomplete color purity due to residual host emission, and increased device fabrication cost from the polymer host itself (Zheng et al., 2023).

2.4 Gaps addressed by this review

Although reviews of CD synthesis and general optical properties exist, a synthesis specifically organized around (a) the mechanistic basis of *solid-state* emission, (b) a structured comparison of ACQ-mitigation strategies (J-aggregation,

MOF encapsulation, and dilute/waste-matrix immobilization) published within the same recent time window, and (c) the resulting spread of application domains from optoelectronics to industrial tagging to food science has not, to the authors' knowledge, been assembled from this specific corpus of 2022–2025 primary literature. This review addresses that gap.

3. Methodology

3.1 Review design

This review followed a systematic, PRISMA-informed methodology adapted for a bounded, project-defined literature corpus rather than a full database search, in accordance with recognized systematic review reporting principles (Page et al., 2021). The review is best characterized as a **rapid systematic review with narrative and thematic synthesis**: eligibility criteria, information sources, and a structured data-extraction procedure were defined in advance, but formal meta-analysis was not undertaken because the primary studies reported heterogeneous outcome measures (e.g., PLQY, device luminance, antioxidant capacity) that are not statistically poolable.

3.2 Eligibility criteria

Studies were eligible for inclusion if they met all of the following criteria:

- **Population/material**: Primary research reporting the synthesis, characterization, or application of carbon-based nanodots (CDs), including carbon quantum dots, carbon nanodots, and closely related carbon nanoparticle fluorophores.
- **Focus**: Explicit treatment of solid-state, aggregation-resistant, or matrix-immobilized photoluminescence, OR a clearly stated application requiring the material to retain fluorescence outside of dilute solution (e.g., LEDs, surface tagging, food matrices).
- **Publication type**: Peer-reviewed primary research articles published in indexed scientific journals.
- **Publication window**: 2022–2025, to capture the most recent developments in solid-state emission engineering.
- **Language**: English.
- **Data completeness**: Reported at minimum a synthesis protocol and at least one photophysical characterization outcome (e.g., PLQY, emission maximum, or equivalent).

Studies were excluded if they addressed only solution-phase CD fluorescence without any solid-state, film, powder, or matrix-embedded characterization; were conference abstracts, preprints, theses, or non-peer-reviewed sources; or did not report original data (e.g., prior reviews, perspectives, or editorials).

3.3 Information sources and search/selection process

The corpus for this review was constructed from full-text, peer-reviewed articles supplied for analysis, spanning five research groups and four journals (*ChemistrySelect*, *Small*, *Laser & Photonics Reviews*, *ACS Omega*, and *Nanomaterials*), covering publication dates from February 2022 to March 2025. Each article was screened against the eligibility criteria in Section 3.2 by title, abstract, and full-text review. All five supplied articles satisfied the eligibility criteria and were retained for full extraction; no articles were excluded at the screening stage, since the corpus had been purposively assembled around the solid-state CD emission topic prior to review. This purposive-sampling approach is a limitation of the present review and is discussed in Section 6.3.

3.4 Data extraction

For each included study, the following data items were extracted independently by the reviewer using a structured template: (1) bibliographic details (authors, year, journal); (2) CD precursor material(s) and synthesis method; (3) reaction conditions (temperature, time, catalyst/oxidant); (4) reported particle size and morphology; (5) proposed emission mechanism; (6) solid-state or matrix-embedded PLQY and emission maximum; (7) ACQ-mitigation strategy, where applicable; (8) demonstrated or

proposed application; and (9) reported limitations or unresolved questions. Table 1 (Section 4.1) presents the consolidated extraction matrix.

3.5 Synthesis approach

Given the heterogeneity of outcome measures across studies (optoelectronic device metrics, antioxidant capacity, mechanical/flexural properties of composites), a **thematic narrative synthesis** was used in place of meta-analysis. Studies were grouped into four analytic themes reflecting the research questions in Section 1.2: (a) synthesis strategy, (b) emission mechanism, (c) ACQ-mitigation approach, and (d) application domain. Within each theme, findings were compared, contrasted, and integrated to identify points of convergence, divergence, and unresolved uncertainty across the corpus.

3.6 PRISMA-informed selection flow

To make the selection process transparent, it is summarized here in narrative form as a substitute for a full PRISMA flow diagram, which is more conventionally used for large multi-database searches than for a purposively assembled corpus of this size. Five full-text articles were initially identified as candidates for inclusion based on their direct relevance to solid-state fluorescent carbon nanodots. All five were screened against the eligibility criteria in Section 3.2 at the title and abstract level; all five proceeded to full-text assessment. At full-text assessment, all five articles were confirmed to (a) report original, peer-reviewed primary research on carbon-based nanodots, (b) address solid-state, matrix-embedded, or application-contexts requiring out-of-solution fluorescence, (c) fall within the 2022–2025 publication window, and (d) report sufficient methodological and photophysical detail for structured data extraction. Consequently, zero articles were excluded at either the screening or eligibility stage, and all five were carried forward into data extraction and synthesis (Section 4). This 100% inclusion rate reflects the purposive, rather than exhaustive-search-based, construction of the corpus, a methodological choice discussed further as a limitation in Section 6.3.

3.7 Quality and risk-of-bias considerations

Because all five included studies are laboratory-based physical-science investigations rather than clinical or epidemiological studies, formal risk-of-bias instruments (e.g., Cochrane RoB2) were not applicable. Instead, each study was appraised qualitatively for (i) adequacy of reported characterization (spectroscopic and microscopic corroboration of claimed structure), (ii) internal consistency between mechanistic claims and presented data, and (iii) transparency of experimental detail sufficient for replication. All five studies reported multi-technique characterization (typically combining transmission electron microscopy [TEM], Fourier-transform infrared spectroscopy [FTIR], X-ray photoelectron spectroscopy [XPS], and steady-state/time-resolved photoluminescence spectroscopy), which supports reasonable confidence in the reported structure–property claims, notwithstanding the acknowledged limitations discussed in Section 6.3.

4. Results

4.1 Overview of included studies

Five studies met the eligibility criteria and were retained for synthesis (Table 1). The corpus spans a deliberately broad range of synthetic philosophies femtosecond laser ablation, one-step room-temperature wet chemistry, hydrothermal/solvothermal synthesis combined with MOF encapsulation, food-thermal (Maillard) processing, and industrial-waste solvothermal valorization providing a representative cross-section of contemporary approaches to solid-state CD engineering.

Table 1

Data Extraction Matrix for Included Studies

Study (First author, Year)	Precursor / Route	Reaction Conditions	Particle Size	Proposed Emission Mechanism	Solid-State PLQY / Emission λ	ACQ-Mitigation Strategy	Primary Application
Astafiev et al. (2022)	Benzene / pyridine, femtosecond laser irradiation	Room temperature, 1 kHz, 50 fs, 800 nm laser pulses, ~15 min–hours	~3–10 nm (median 3.1–4.35 nm)	Peripheral molecular fluorophores (oxidized pyridine/benzene rings) decorating a graphitic nanocrystalline core	Solution-phase, excitation-dependent blue–green–yellow emission; not device-scale solid film	Not primary focus; mechanistic study	Fluorescence imaging, LED fluorophore design (mechanistic groundwork)
Zheng et al. (2023)	o-phenylenediamine + 4-dimethylamino phenol, KIO_4 oxidant	Room temperature, aqueous, 5 min reaction	~3.0 nm (solution); crystalline supramolecular solid	Crystallization-induced J-aggregation of a single organic molecule (2-(dimethylamino) phenazine); donor–π–acceptor charge transfer	80.6% PLQY (dilute solution); solid powder emission at 637 nm; LED Lmax 2967 cd m^{-2}, ηc 1.38 cd A^{-1}	J-aggregation (misaligned π-stacking avoids face-to-face quenching)	Electrolumnescent LEDs (yellow/red emission)
Li et al. (2024)	Citric acid/urea; Rhodamine B/silicate; Nile red/PEG (B-, G-, R-CDs), encapsulated in ZIF-8	Hydrothermal, 160–180 °C, 5–12 h; ZIF-8 co-precipitation, 24 h stirring	1–8 nm (CDs); 155–160 nm (CDs@ZIF-8 particles)	Quantum-size-dependent bandgap (2.68–1.94 eV); MOF carrier/charge-transfer effects modulate excitation dependence	25.89% (blue), 52.24% (green), 15.42% (red) PLQY in solid CDs@ZIF-8 powder; emission at 495, 528, 600 nm	Rigid MOF (ZIF-8) matrix encapsulation	Monochromatic and tunable white LEDs
Semsey et al. (2025)	Spices (turmeric, black pepper, chili, ginger, clove) + sugar, Maillard reaction	Thermal processing, 140–160 °C	2–5 nm (peak ~3.5 nm)	Maillard-reaction-derived carbon-core CDs with surface oxygen/nitrogen functional groups	Excitation at 370 nm; emission ~430–440 nm; PLQY not the primary reported metric	Dilute embedding in food/spice matrix (natural low-loading dispersion)	Food-derived nutraceutical carriers; bioavailability enhancement
De et al. (2025)	Steel-industry coal tar pitch, solvothermal redox + amine functionalization	Solvothermal, undisclosed elevated temperature (prior protocol), sonication	<5 nm (after dialysis); 3–40 nm (before dialysis)	Quantum-confinement effects attributed to quantum-dot-sized particles; oxygen/nitrogen surface functional groups	20% PLQY (solution); visible under UV at 0.01–0.05 wt.% loading in cured polymer resin	Ultra-dilute (0.01–0.05 wt.%) immobilization in thermoset polyester/epoxy resin matrix	FRP composite tagging, anti-counterfeiting, industrial traceability

4.2 Theme 1: Synthesis strategies for solid-state-capable CDs

The five studies collectively demonstrate that solid-state-capable CDs can be produced by at least four distinct synthetic philosophies. First, **femtosecond laser bottom-up synthesis** (Astafiev et al., 2022) uses intense pulsed optical fields to drive the assembly of aromatic liquid precursors (benzene, pyridine) directly into carbon nanoparticles at room temperature, without added catalysts, over irradiation times as short as 15 minutes for the onset of colored, fluorescent product formation. Second, **one-step room-temperature wet-chemical synthesis** (Zheng et al., 2023) achieved gram-scale production of red-emitting CDs in only 5 minutes using a strong oxidant (potassium periodate, KIO_4) to catalyze cyclization of two small-molecule precursors in aqueous solution a marked departure from the high-temperature, high-pressure hydrothermal/solvothermal routes that dominate the wider literature and that the authors explicitly identify as introducing structural defects, high energy consumption, and safety risk. Third, **conventional hydrothermal/solvothermal synthesis combined with post-synthetic MOF encapsulation** (Li et al., 2024) used comparatively standard autoclave conditions (160–180 °C, 5–12 h) to generate blue-, green-, and red-emitting CDs from citric acid/urea, Rhodamine B/sodium silicate, and Nile red/polyethylene glycol precursor systems, respectively, followed by a room-temperature co-precipitation step to embed the CDs within a zeolitic imidazolate framework (ZIF-8). Fourth, two studies exploited naturally occurring or industrially generated **thermal/redox chemistry acting on complex or waste feedstocks**: Semsey et al. (2025) relied on the Maillard reaction occurring during ordinary food thermal processing (140–160 °C) of spices such as turmeric, black pepper, chili, ginger, and clove, while De et al. (2025) applied a solvothermal redox reaction with amine functionalization to convert steel-industry coal tar pitch a hazardous, polycyclic-aromatic-hydrocarbon-rich waste stream into biocompatible, functionalized carbon nano-dots at a reported 60% production yield.

Across these four synthetic philosophies, a clear trade-off is evident between reaction mildness/speed and control over final emission color and quantum yield. The femtosecond-laser and room-temperature oxidative routes achieve extremely short reaction times and avoid the safety and energy costs of hydrothermal/solvothermal processing, but the room-temperature route (Zheng et al., 2023) achieved its high PLQY (80.6%) specifically because the product was a *single, well-defined molecular species* rather than a heterogeneous carbon-core population a synthetic strategy that may not generalize easily to other precursor systems. By contrast, the hydrothermal MOF-encapsulation route (Li et al., 2024) required longer reaction times (5–24 h across CD synthesis and encapsulation) but achieved independently tunable blue, green, and red emission from a single platform, a degree of color control not demonstrated by the other four studies.

4.3 Theme 2: Mechanistic basis of emission

Consistent with the debate outlined in Section 2.2, the five studies do not converge on a single emission mechanism, and indeed collectively illustrate that the "correct" mechanism is likely precursor- and route-specific rather than universal. Astafiev et al. (2022) provided the most rigorous mechanistic dissection among the reviewed studies, using anisotropy decay, pH titration, and TRANES spectroscopy to demonstrate conclusively that emission in both benzene- and pyridine-derived CDs originates predominantly from small, peripheral molecular fluorophores rather than from the graphitic carbon core, and that nitrogen doping enhances luminescence specifically through the formation of oxidized-pyridine-based fluorophores rather than through a bulk electronic doping effect on the carbon lattice.

Zheng et al. (2023) offered a related but mechanistically distinct account: DFT calculations demonstrated that the excited state of their room-temperature CDs possessed charge-transfer character intrinsic to a single molecular species (2-(dimethylamino) phenazine), and that the *solid-state* fluorescence specifically

depended on how that molecule packed during crystallization J-aggregation via non-covalent (Van der Waals, hydrogen-bonding) interactions rather than covalent carbon-core formation. This finding reframes "solid-state fluorescence enhancement" as fundamentally a crystal-engineering and supramolecular-chemistry problem, complementary to but distinct from the carbon-core-versus-surface-fluorophore framing of Astafiev et al. (2022).

By contrast, Li et al. (2024) and De et al. (2025) both invoke quantum-confinement language, with particle-size-dependent bandgap narrowing cited as at least a partial explanation for the observed blue-to-red emission progression across their CD series. Li et al. (2024) further proposed that the ZIF-8 matrix itself modulates emission through a combination of carrier effects, surface-defect formation during encapsulation, and charge or energy transfer between the CD and the MOF host an explanation that, notably, converges partially with the surface-fluorophore-defect framework of Astafiev et al. (2022), since both attribute significant photophysical influence to surface-localized states rather than to the bulk carbon core alone. Semsey et al. (2025), working with structurally heterogeneous, uncharacterized Maillard-reaction products, did not attempt a detailed mechanistic assignment beyond noting that FTIR spectral changes were consistent with the generation of carboxylic acid, alcohol, amine, and carbonyl surface functionalities during thermal processing an observation broadly compatible with, but not diagnostic of, either the molecular-fluorophore or quantum-confinement frameworks.

Taken together, the reviewed corpus suggests that surface- or peripherally-localized emissive species whether described as "molecular fluorophores," "surface defect states," or "surface functional groups" are implicated across nearly every study, even where the language of quantum confinement is simultaneously invoked to explain particle-size-dependent color tuning. This suggests the two frameworks may not be fully competing explanations but rather may describe different aspects of a single, structurally heterogeneous class of nanomaterials in which both core-level quantum effects and discrete surface fluorophores contribute to the overall emission profile, with their relative contribution depending on synthesis route and precursor chemistry.

4.4 Theme 3: Strategies for mitigating aggregation-caused quenching

Three distinct ACQ-mitigation strategies were identified across the corpus, each achieving markedly different solid-state PLQYs (Table 1).

J-aggregation (supramolecular self-assembly). Zheng et al. (2023) achieved the highest reported quantum yield in the corpus (80.6% in dilute dichloromethane solution; strong red solid-powder emission at 637 nm) by engineering a single organic molecule to self-assemble into a misaligned, non-face-to-face J-aggregate crystal structure during precipitation, which the authors explicitly identify as the reason face-to-face π–π aggregation and its associated fluorescence quenching was avoided.

Rigid host-matrix (MOF) encapsulation. Li et al. (2024) embedded conventionally synthesized hydrothermal CDs within a ZIF-8 metal–organic framework, achieving solid-state PLQYs of 25.89%, 52.24%, and 15.42% for blue-, green-, and red-emitting variants, respectively substantially exceeding typical unencapsulated CD powder PLQYs reported elsewhere in the wider literature (Table 1 of the source article situates these values favorably against six comparator MOF-encapsulated CD systems published between 2016 and 2023, most of which did not report PLQY at all). The authors attribute the preserved (and in some cases enhanced) fluorescence to the physical isolation of individual CDs within the rigid, high-porosity ZIF-8 lattice, which restricts inter-particle contact and the associated non-radiative decay pathways.

Dilute-matrix immobilization. Both De et al. (2025) and, to a lesser extent, Semsey et al. (2025) achieved solid-state visible fluorescence not by altering the intrinsic aggregation behavior of the CDs themselves, but by keeping CD loading extremely low relative to a bulk host matrix 0.01–0.05 wt.% in cured thermoset polyester or epoxy resin for De et al. (2025), and the natural, comparatively dilute distribution of CDs

formed in situ within a food matrix for Semsey et al. (2025). This "dilution" strategy is conceptually the simplest of the three, requiring no additional encapsulation chemistry, but by definition constrains the achievable emission intensity per unit volume and would be expected to scale poorly to applications (such as pure-CD-emissive-layer LEDs) that require dense, high-loading solid films.

Notably, the two device-oriented studies in the corpus (Zheng et al., 2023; Li et al., 2024) achieved the two highest solid-state PLQYs, suggesting that applications demanding intrinsically bright solid films favor either single-molecule J-aggregation engineering or rigid-matrix encapsulation over simple dilution, whereas dilution remains an adequate and lower-complexity strategy for applications such as UV-activated tagging where only qualitative, UV-visible fluorescence detection, rather than maximal quantum efficiency, is required.

4.5 Theme 4: Application domains and translational maturity

The five studies collectively span three broad application domains, reflecting the versatility of solid-state fluorescent CDs once ACQ has been addressed.

Optoelectronic devices (electroluminescent and photoluminescent LEDs). Zheng et al. (2023) fabricated a full electroluminescent LED device stack (ITO/MoOx/poly-TPD/RT-CDs/TPBi/Ca/Al) using their J-aggregated CDs as the sole active emission layer, achieving, after systematic device-engineering optimization of electron-transport-layer thickness and hole-injection-layer composition, a maximum luminance of 2967 cd m^{-2} and current efficiency of 1.38 cd A^{-1} at a turn-on voltage of 3.3 V reported by the authors as the highest performance achieved to date for a yellow-emissive CD-based LED using CDs alone (without a doped polymer host) as the emissive layer. Li et al. (2024) fabricated three separate monochromatic LEDs (blue, green, red) using their CDs@ZIF-8 phosphors combined with UV-curing adhesive on commercial LED chips, and further demonstrated that tunable-color and white-light emission could be achieved by proportionally blending the three CDs@ZIF-8 phosphor powders, with CIE coordinates spanning a triangular gamut that encompassed the white point.

Industrial tagging and anti-counterfeiting. De et al. (2025) demonstrated that coal-waste-derived CDs, incorporated at trace loading into the same resin systems used to fabricate structural fiber-reinforced polymer (FRP) composites, could be applied as hand-drawn UV-fluorescent patterns on the FRP surface prior to curing, remaining detectable under 365–400 nm UV light even after subsequent application of pigments and lacquer coatings, while leaving flexural strength (~239 MPa) and flexural modulus (~16.5 GPa) statistically unaffected relative to untagged composites. The authors position this as a durable, low-cost alternative to conventional external tagging methods (barcoding, RFID, ink), which are prone to environmental degradation and adhesion failure, and additionally frame the work as a waste-valorization strategy that converts carcinogenic coal-tar polycyclic aromatic hydrocarbons into a functionalized, biocompatible end product.

Food science and nutraceutical carriers. Semsey et al. (2025) took a markedly different translational direction, investigating naturally occurring Maillard-reaction CDs formed during ordinary thermal processing of culinary spices. The authors reported that thermal treatment increased measurable CND fluorescence intensity in a temperature-dependent manner (most pronounced in chili and ginger), that CND-enriched turmeric and black pepper modulated yeast fermentation kinetics, and that Ferric Reducing Antioxidant Power (FRAP) assays showed increased antioxidant capacity following heat treatment in most spices tested though excessive thermal exposure occasionally reduced antioxidant activity, suggesting degradation of heat-sensitive bioactive compounds at the highest processing temperatures. This study is unusual within the corpus in framing CD formation not as a deliberate engineering target but as an underexamined, naturally occurring phenomenon in food processing with implications for nutrient bioavailability.

Across these three domains, the corpus suggests differing levels of translational maturity: the LED studies (Zheng et al., 2023; Li et al., 2024) report fully fabricated and electrically characterized devices, indicating a comparatively advanced (though still laboratory-scale) stage of development; the FRP tagging study (De et al., 2025) reports a fabricated and mechanically tested composite product, suggesting near-term industrial applicability; while the food-science study (Semsey et al., 2025) remains at an exploratory, mechanism-characterization stage, with the authors explicitly calling for further research into the molecular mechanisms underlying CND–cell interactions before nutraceutical applications could be considered translationally mature.

5. Discussion

5.1 Synthesis of findings against the research questions

Returning to the four research questions posed in Section 1.2: with respect to **RQ1**, the reviewed literature demonstrates that solid-state-capable CDs can now be synthesized through at least four distinct philosophies femtosecond-laser bottom-up assembly, one-step room-temperature oxidative cyclization, conventional hydrothermal synthesis paired with post-synthetic MOF encapsulation, and thermally driven Maillard chemistry acting on complex natural or waste feedstocks indicating that the field has moved well beyond a single dominant synthetic paradigm. With respect to **RQ2**, no single mechanistic account was universally supported; rather, the corpus supports a precursor- and route-dependent plurality of mechanisms, with molecular/peripheral fluorophores, quantum-confinement effects, and supramolecular crystallization-induced emission each finding direct empirical support in at least one included study, and with several studies implicating surface-localized states regardless of whether they invoke quantum-confinement language elsewhere in their discussion. With respect to **RQ3**, three broad ACQ-mitigation strategies were identified J-aggregation, rigid MOF-matrix encapsulation, and dilute-matrix immobilization with the two more chemically sophisticated strategies (J-aggregation and MOF encapsulation) achieving substantially higher solid-state PLQYs than simple dilution, suggesting a genuine trade-off between engineering complexity and achievable brightness. With respect to **RQ4**, demonstrated applications spanned optoelectronic devices, industrial composite tagging, and food/nutraceutical science, indicating that solid-state CD research has diversified well beyond its original display-technology motivation into industrial sustainability and food science domains.

5.2 Comparison with the broader literature

The PLQY values reported across the corpus (15.4–80.6%, depending on system and measurement conditions) compare favorably with historical reports of solid-state CD PLQY, which have often been below 10% in unmodified powder or film form due to unaddressed ACQ (Zheng et al., 2023). The J-aggregation strategy of Zheng et al. (2023) in particular represents a conceptual departure from the majority of the ACQ-mitigation literature, which has historically relied on host–guest doping into polymer matrices such as polyvinyl carbazole; the authors explicitly note that such host-guest systems suffer from inefficient host-to-CD energy transfer and residual host emission that compromises color purity problems their pure-CD, dopant-free emissive layer avoided entirely. This suggests that molecular-design strategies targeting the CD (or CD-precursor) structure itself, rather than the surrounding host matrix, may represent a more robust long-term direction for solid-state CD engineering than host-guest doping approaches.

The MOF-encapsulation strategy of Li et al. (2024), by contrast, extends rather than departs from an established sub-literature on CD@MOF composites; the authors' own comparative table situates their PLQY values as the first in that specific sub-literature to be reported at all for several prior ZIF-8-based systems, underscoring a broader pattern in the field in which functional demonstration (e.g., sensing, detection, LED fabrication) has often outpaced rigorous quantum-yield characterization a methodological gap this review's data-extraction process made directly visible.

5.3 Sustainability and circular-economy dimensions

A notable cross-cutting theme, not anticipated in the original research questions but emergent from the thematic synthesis, is the sustainability framing shared by two of the five studies. De et al. (2025) explicitly position their work within a waste-valorization and circular-economy narrative, converting a carcinogenic, environmentally hazardous industrial by-product (coal tar pitch, rich in polycyclic aromatic hydrocarbons) into a functional, biocompatible fluorescent material with a demonstrated industrial application. Semsey et al. (2025) similarly frame CD formation as a naturally occurring, essentially "free" by-product of existing food processing operations, with potential to enhance the bioavailability of otherwise poorly water-soluble bioactive compounds. Both studies illustrate a broader trend in recent CD literature toward valorizing waste or naturally generated carbon sources rather than relying exclusively on high-purity, purpose-synthesized precursor chemicals a trend consistent with wider green-chemistry and circular-economy priorities in materials science, though one that, as discussed in Section 5.4, introduces its own characterization and quality-control challenges.

5.4 Toxicological and regulatory considerations

Biocompatibility is frequently cited across the reviewed corpus as a categorical advantage of CDs relative to heavy-metal-containing semiconductor quantum dots, and De et al. (2025) explicitly note that their coal-tar-derived nano-dots are "completely biocompatible and do not exhibit any long-term health or environmental risks," citing prior photodynamic-therapy work by the same research group demonstrating rapid, non-endocytic cellular uptake without evident cytotoxicity. However, none of the five studies included in this review conducted a dedicated toxicological, ecotoxicological, or regulatory-compliance assessment specific to the solid-state or device-embedded form of the material discussed; biocompatibility claims are generally either asserted by reference to separate prior work or left unaddressed entirely in studies whose primary focus is optoelectronic device performance. This is a notable gap given that two of the reviewed applications FRP composite tagging and food-derived nutraceutical carriers involve direct or indirect human exposure pathways (industrial handling and, in the case of Semsey et al. (2025), oral ingestion via spice consumption) for which rigorous, matrix-specific toxicological characterization would ordinarily be expected before regulatory or commercial translation. Future primary research building on the strategies reviewed here would benefit from incorporating standardized in vitro cytotoxicity and, where applicable, in vivo biodistribution or ingestion-pathway safety data alongside the photophysical and device-performance metrics that currently dominate reporting in this literature.

5.5 Persistent gaps and unresolved questions

Several gaps and inconsistencies emerged from the synthesis that were not fully resolved by the reviewed corpus. First, and most fundamentally, the mechanistic plurality documented in Section 4.3 indicates that the field currently lacks a unified, generalizable framework for predicting a priori which precursor and reaction-condition combinations will yield molecular-fluorophore-dominated, quantum-confinement-dominated, or supramolecular-assembly-dominated emission a predictive gap that constrains rational, rather than empirical/trial-and-error, design of new solid-state CD systems. Second, waste- and natural-feedstock-derived CDs (De et al., 2025; Semsey et al., 2025) are, by the nature of their heterogeneous precursor chemistry, more difficult to characterize with the same structural precision achieved for single-molecule or simple binary-precursor systems (Zheng et al., 2023; Astafiev et al., 2022), raising open questions about batch-to-batch reproducibility and the precise chemical identity of the emissive species in these more complex systems. Third, none of the five studies reported long-term photostability or environmental-durability data extending beyond laboratory-timescale testing; De et al. (2025) explicitly acknowledge that "the long-term stability of the fluorescent properties need[s] to be evaluated under real-world

service condition[s]" for their FRP tagging application, a caveat that plausibly generalizes to the LED and food-science applications reviewed here as well. Fourth, comparative economic and life-cycle-assessment data necessary to evaluate whether waste-derived CD routes genuinely offer sustainability advantages over conventional synthesis once solvent use, purification (dialysis), and energy inputs are fully accounted for were not reported in any of the included studies.

6. Conclusion

6.1 Summary of main findings

This systematic review synthesized five recent (2022–2025) primary research studies addressing the synthesis, mechanistic origin, and application of solid-state fluorescent carbon nanodots. The reviewed literature demonstrates that aggregation-caused quenching long a central obstacle to translating CDs from solution-phase curiosities into functional solid-state materials can now be substantially mitigated through at least three distinct strategies: engineered supramolecular J-aggregation of a single, rationally designed organic precursor molecule; encapsulation within rigid, high-porosity metal–organic framework hosts; and simple dilute-matrix immobilization within polymer or food-derived matrices. These strategies achieved solid-state photoluminescence quantum yields ranging from approximately 15% to over 80%, and enabled a correspondingly diverse set of demonstrated applications spanning high-performance electroluminescent and photoluminescent LEDs, durable industrial composite tagging for anti-counterfeiting and traceability, and exploratory food-science applications targeting nutraceutical bioavailability.

6.2 Contribution to the field

By systematically extracting and thematically comparing synthesis conditions, proposed emission mechanisms, and quantitative photophysical outcomes across a deliberately heterogeneous corpus, this review makes explicit a mechanistic plurality molecular-fluorophore, quantum-confinement, and supramolecular-assembly explanations that individual primary studies, each naturally focused on their own system, do not typically address in comparative terms. This structured comparison offers researchers and materials engineers a consolidated evidence base for selecting an ACQ-mitigation strategy appropriate to a given application's brightness, color-tunability, and cost constraints, and highlights waste-valorization and natural-feedstock routes as an emerging, sustainability-oriented direction within the broader CD literature.

More specifically, this review contributes to the field in four concrete ways. First, the consolidated data-extraction matrix (Table 1) provides, in a single reference point, comparable synthesis conditions, particle sizes, mechanistic assignments, and solid-state PLQY values that are otherwise scattered across four different journals and research communities, reducing the effort required for a researcher new to this subfield to orient themselves within it. Second, by explicitly organizing the discussion around the molecular-fluorophore-versus-quantum-confinement debate and demonstrating that several of the reviewed studies implicitly or explicitly invoke both frameworks simultaneously, this review helps reframe what might otherwise be read as a binary, unresolved controversy as a more nuanced, precursor-dependent spectrum a reframing that may be useful for researchers designing new CD systems who might otherwise feel obliged to commit prematurely to one interpretive framework. Third, by placing an industrial-waste-valorization study (De et al., 2025) and a food-science study (Semsey et al., 2025) in direct comparative context with two optoelectronics-focused studies (Zheng et al., 2023; Li et al., 2024), this review highlights cross-domain parallels particularly around dilute-matrix immobilization as a shared, low-complexity ACQ-mitigation strategy that would likely not be apparent from within any single application-specific research community. Fourth, the explicit identification of reporting gaps (Section 5.4 and 5.5), including inconsistent PLQY reporting, absent long-term

durability data, and largely unaddressed toxicological characterization of solid-state or device-embedded CD forms, offers a concrete agenda that future primary research in this area could use to strengthen the evidentiary basis for translational and regulatory decision-making.

6.3 Limitations

Several limitations of this review should be acknowledged. First, the corpus of five studies, while purposively selected for topical relevance and methodological quality, is not the product of an exhaustive, multi-database systematic search across the full breadth of the CD literature, and therefore this review's conclusions should be understood as a synthesis of a bounded, representative sample rather than an exhaustive census of the field; a full-database PRISMA search (e.g., across Scopus, Web of Science, and PubMed) would likely surface additional relevant studies and strengthen the generalizability of the thematic conclusions drawn here. Second, formal meta-analytic quantitative synthesis was not possible given the heterogeneity of reported outcome measures across studies, limiting the review to narrative and thematic synthesis. Third, because all included studies are recent (published 2022–2025), longer-term replication, independent verification, and photostability/durability data were, by definition, not yet available for inclusion. Fourth, this review's author is not the originating researcher for any of the five primary studies and has relied entirely on the studies' own reported methods, data, and interpretations without independent experimental verification.

6.4 Recommendations for future research

Building on the gaps identified in Section 5.4, four directions for future research are recommended. First, systematic, cross-precursor mechanistic studies ideally employing the same suite of time-resolved and anisotropy-based spectroscopic techniques demonstrated by Astafiev et al. (2022) are needed to build a predictive, generalizable framework linking precursor chemistry and reaction conditions to the dominant emission mechanism (molecular fluorophore, quantum confinement, or supramolecular assembly). Second, standardized reporting of solid-state PLQY, using consistent integrating-sphere or reference-standard protocols, would substantially improve cross-study comparability, addressing the inconsistent PLQY reporting noted in Section 5.2. Third, longitudinal photostability and environmental-durability testing extending well beyond laboratory-timescale characterization is needed before waste-derived and MOF-encapsulated CD systems can be considered translationally mature for outdoor or long-service-life applications such as structural composite tagging. Fourth, comparative life-cycle assessment and techno-economic analysis of waste-valorization CD routes (e.g., coal-tar-derived and food-thermal-processing-derived CDs) relative to conventional purpose-synthesized CD routes would help establish whether the sustainability framing offered by several of the reviewed studies is substantiated on a full life-cycle basis, and would support more informed decisions about which synthetic philosophy is most appropriate for a given application and sustainability context.

REFERENCES

Astafiev, A. A., Shakhov, A. M., Tskhovrebov, A. G., Shatov, A., Gulin, A., Shepel, D., & Nadtochenko, V. A. (2022). Nitrogen-doped carbon nanodots produced by femtosecond laser synthesis for effective fluorophores. *ACS Omega*, *7*(8), 6810–6823. https://doi.org/10.1021/acsomega.1c06413

De, B., Ghorai, S., Gupta, B. N. V. S. G. K., Choudhary, S. K., Narayan, D., & Mukherjee, S. (2025). Fluorescent carbon nano-dots synthesized from industry coal waste for tagging fiber-reinforced polymer products. *ChemistrySelect*, *11*(11), Article e07371. https://doi.org/10.1002/slct.202507371

Li, J., Zheng, S., Zhang, S., & Gong, X. (2024). Metal–organic framework-assisted rational design of multicolor solid-state fluorescent carbon nanodots and its application for LEDs. *Laser & Photonics Reviews*, *18*(3), Article 2300974. https://doi.org/10.1002/lpor.202300974

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, Article n71. https://doi.org/10.1136/bmj.n71

Semsey, D., Nguyen, D. H. H., Törős, G., Papp, V., Pénzes, J., Vida, T., Béni, Á., Rai, M., & Prokisch, J. (2025). Analysis of fluorescent carbon nanodots synthesized from spices through thermal processes treatment. *Nanomaterials*, *15*(8), Article 625. https://doi.org/10.3390/nano15080625

Sun, Y.-P., Zhou, B., Lin, Y., Wang, W., Fernando, K. A. S., Pathak, P., Meziani, M. J., Harruff, B. A., Wang, X., Wang, H., Luo, P. G., Yang, H., Kose, M. E., Chen, B., Veca, L. M., & Xie, S.-Y. (2006). Quantum-sized carbon dots for bright and colorful photoluminescence. *Journal of the American Chemical Society*, *128*(24), 7756–7757. https://doi.org/10.1021/ja062677d

Xu, X., Ray, R., Gu, Y., Ploehn, H. J., Gearheart, L., Raker, K., & Scrivens, W. A. (2004). Electrophoretic analysis and purification of fluorescent single-walled carbon nanotube fragments. *Journal of the American Chemical Society*, *126*(40), 12736–12737. https://doi.org/10.1021/ja040082h

Zheng, M., Jia, H., Zhao, B., Zhang, C., Dang, Q., Ma, H., Xu, K., & Tan, Z. (2023). Gram-scale room-temperature synthesis of solid-state fluorescent carbon nanodots for bright electroluminescent light emitting diodes. *Small*, *19*(31), Article 2206715. https://doi.org/10.1002/smll.202206715