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Review Article

Carbon Quantum Dot-Based Nanocarriers for Precision Drug Delivery and Breast Cancer Theranostics

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ABSTRACT

Carbon dots (CDs) are nanoscale carbon-based materials that have become attractive in biomedical research because their optical behaviour, aqueous compatibility and surface chemistry can be adjusted through precursor selection, synthesis conditions, heteroatom doping and post-synthetic functionalisation. In breast-cancer research, these characteristics support a multifunctional concept in which one nanosystem can contribute to imaging, targeted drug delivery and light-activated therapy. This review presents a structured discussion of CD classification, synthesis, physicochemical properties, surface engineering, drug-loading strategies, tumour targeting, controlled release, fluorescence imaging, photodynamic therapy (PDT), photothermal therapy (PTT), and combination approaches. Particular attention is given to breast-cancer models, including hormone-receptor positive and triple-negative breast-cancer systems, and to representative studies using doxorubicin, folate, transferrin, red/near-infrared emitting dots and hybrid platforms. Figure 1. Graphical representation in breast cancer management.

INTRODUCTION

Breast cancer remains an important therapeutic and diagnostic challenge because the disease is biologically heterogeneous and its clinical behaviour varies with receptor status, molecular subtype, stage and treatment history. Standard management may involve surgery, radiotherapy, systemic chemotherapy, endocrine therapy, targeted agents or combinations of these approaches. Nanomedicine does not replace these established modalities; instead, it is investigated as a means of improving where, when and how a therapeutic payload reaches a tumour.

Carbon dots occupy a distinctive position among nanomaterials because the same particle can potentially provide an optical signal and participate in therapy. Their fluorescence makes them useful as labels or imaging probes, while surface functional groups can be

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used to attach or adsorb drugs, targeting ligands, polymers or other functional components. Their small dimensions also allow researchers to investigate cellular uptake and intracellular trafficking at the nanoscale. Reviews published from 2020–2026 consistently identify bioimaging, drug delivery, PDT, PTT and theragnostic as major areas of CD research.

The breast-cancer application is especially interesting because chemotherapy can suffer from systemic exposure and because some aggressive subtypes, such as triple-negative breast cancer (TNBC), lack the conventional ER/PR/HER2 targets used in endocrine or HER2-directed treatment. CD platforms can be engineered with ligands or stimulus-responsive linkers, but the actual targeting performance depends on the formulation, receptor biology, protein corona, route of administration and tumour microenvironment. Therefore, a rational review must connect material design with biological outcome rather than treating all carbon dots as equivalent.

This review is designed as an academic synthesis rather than a reproduction of any single published review. It combines information from recent reviews and representative primary studies, with emphasis on mechanisms, design logic and translational limitations. The central question is: how can a carbon-dot formulation be deliberately designed so that its structure, optical behaviour, drug-delivery function and biological response support a useful breast-cancer theranostic application?

A. Carbon dots:

Carbon dots are commonly described as small carbon-based nanomaterials, generally in the few-nanometer regime, with a carbon-rich core and a chemically active surface. The literature uses overlapping terms such as carbon quantum dots, carbon nanodots, graphene quantum dots and polymer dots. These categories are related but are not interchangeable in every mechanistic discussion.

Differences in crystallinity, polymeric content, surface states and graphitic domains can influence fluorescence and biological behavior. A practical classification is based on structure and formation. Carbon quantum dots are often discussed in relation to nanoscale confinement and carbon-rich domains; graphene quantum dots contain graphene-like sp2 domains and edge functionalities; carbon nanodots may describe quasi-spherical carbon-rich particles with variable ordering; and functional polymer dots may retain polymer-derived features. Because terminology is inconsistent across the field, a good review should report the actual synthesis route and analytical evidence rather than relying only on the label used by the authors.

At the structural level, the carbon-rich core is only one part of the particle. Surface groups such as hydroxyl, carboxyl, amino and other oxygen- or nitrogen-containing functionalities can dominate interactions with water, proteins, drugs and cell membranes. The surface can also be modified deliberately after synthesis. Consequently, two particles with similar core dimensions may show different biological behaviour if their surface chemistry differs.

Size, shape, core ordering, surface composition, heteroatom content and charge form a connected design space. These parameters affect colloidal stability, protein adsorption, cellular unctionalizati, fluorescence and clearance. The concept of a structure–property–function relationship is therefore central to CD research and is particularly relevant when comparing results across different laboratories.

Table 1: Original Summary of Major CD Design Variables and Their Likely Consequences.

Feature	What it means	Potential effect	Why it matters
Core structure	Carbon-rich / graphitic or polymer-derived domains	Affects electronic and optical states	Helps explain fluorescence
Particle size	Nanoscale physical dimensions	Can influence uptake and biodistribution	Important for delivery and clearance
Surface groups	–COOH, –OH, –NH2 and related groups	Change solubility and biomolecular interactions	Controls functionalization and loading
Heteroatom doping	N, S, P or other atoms introduced during/after synthesis	Can alter electronic states and emission	Useful for tuning optical/therapeutic behaviour

Feature	What it means	Potential effect	Why it matters
Surface charge	Net interfacial charge	Influences protein adsorption and membrane interaction	Relevant to uptake and safety

B. Synthesis strategies

Carbon-dot synthesis is broadly organised into top-down and bottom-up routes. Top-down approaches begin with larger carbon materials and reduce or oxidise them into nanoscale fragments. Examples include electrochemical oxidation, chemical oxidation, laser ablation and related fragmentation methods. Bottom-up approaches build nanoscale carbonaceous structures from small molecules or biomass-derived precursors using hydrothermal, solvothermal, microwave, pyrolytic or other energy-assisted processes.

The choice of synthesis route affects more than yield. Precursor identity, concentration, reaction temperature, reaction time, pressure, pH, solvent and purification can all influence particle size distribution, surface groups and optical emission. Consequently, synthesis should be considered part of the biological design rather than merely a preparation step. A reproducible nanocarrier requires control of these variables and an analytical strategy that confirms the resulting material.

Hydrothermal and solvothermal methods are particularly common in biomedical CD research because they can process water-compatible organic precursors under relatively contained conditions and can produce surface functionalized particles in a single reaction. Microwave-assisted synthesis can shorten reaction time, while electrochemical methods provide an alternative route for some carbon precursors. Green synthesis approaches use plant material, food residues or other biomass sources, potentially reducing dependence on petroleum-derived starting materials; however, natural feedstocks can introduce batch variability that must be controlled.

After synthesis, purification is essential. Small molecules, oligomers, salts and unreacted precursors can contribute to fluorescence or biological effects and may be mistaken for properties of the CDs themselves. Dialysis, ultrafiltration, chromatography or related purification procedures may therefore be necessary depending on the formulation. For a pharmaceutical-development pathway, purification and residual analysis are not optional details; they are part of product definition.

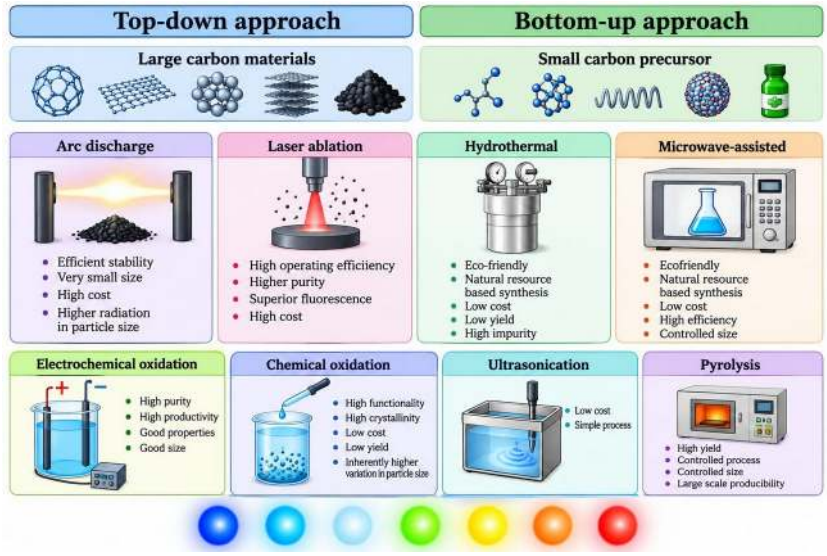


Figure 2: Original Schematic Comparing Top-Down and Bottom-Up Synthesis Route

C. Physicochemical and optical properties

The biomedical appeal of carbon dots is closely linked to their optical behaviour. Many CDs absorb strongly in the ultraviolet or visible region and emit fluorescence whose colour and intensity depend on the particle's core, surface states, heteroatom content and

molecular components. Emission can sometimes be shifted toward longer wavelengths by precursor selection, surface engineering or doping. This tunability is valuable for imaging, although emission in the blue/green region may be less suitable for deep tissue applications than red or near infrared windows.

Photoluminescence mechanisms remain an active area of study because different CD families can exhibit different contributions from quantum confinement, surface states, molecular fluorophores, crosslink-enhanced emission and other pathways. For a review or project, it is safer to present these mechanisms as formulation dependent rather than claiming one universal model. Quantum yield, excitation dependence, lifetime, photostability and resistance to photobleaching are useful measurements for comparing imaging performance.

CDs can also participate in electron-transfer and redox processes. Depending on composition and irradiation conditions, they may generate or quench reactive oxygen species. This dual behaviour can be advantageous for PDT but can also influence oxidative stress and toxicity. Thus, antioxidant and pro-oxidant descriptions should be interpreted in context rather than treated as intrinsic properties of every CD formulation.

Other relevant properties include aqueous dispersibility, colloidal stability, surface charge, hydrodynamic diameter and interaction with serum proteins. These properties determine whether a formulation remains stable in biological fluids and how it interacts with cells. In drug-delivery research, characterisation should therefore connect optical data with physical and colloidal measurements rather than reporting fluorescence alone.

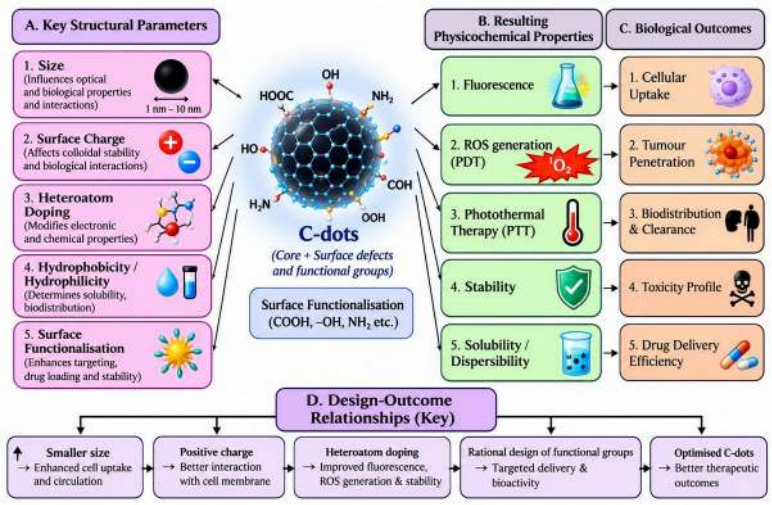


Figure 3: Original Structure–Property–Function Map for Rational CD Design.

D. Surface engineering and functionalisation

Surface engineering converts a relatively generic carbon nanodot into an application-specific nanoplatform. Functional groups can be introduced during synthesis by choosing appropriate precursors or added after synthesis through covalent or non-covalent modification. Hydrophilic groups can improve aqueous dispersibility, while polymers such as polyethylene glycol can be used to alter colloidal behaviour and reduce unwanted interactions. Ligands such as folate or transferrin can be explored when a relevant receptor-mediated uptake mechanism is justified.

Surface charge deserves particular attention. Positively charged particles may interact strongly with negatively charged cell membranes and can show enhanced uptake, but excessive cationic charge can also increase nonspecific interactions and toxicity. Neutral or mildly charged surfaces may circulate differently. The ideal charge is therefore not universal; it depends on the route, target, formulation and desired balance between uptake and safety.

Heteroatom doping is another form of engineering. Nitrogen, sulfur, phosphorus and other dopants can alter electronic states and photoluminescence, while metal-containing hybrid systems may add imaging or

catalytic functions. However, metal doping introduces an additional safety and regulatory dimension because the biological fate of the dopant must be assessed separately from the carbon framework.

Targeting ligands should be selected from a biological hypothesis, not simply attached because they are commonly used. Receptor density, internalisation pathway, receptor accessibility and expression in healthy tissues all influence targeting performance. In breast-cancer studies, folate- and transferrin-related systems illustrate receptor-mediated strategies, while TNBC studies may use alternative surface interactions or multimodal designs.

E. Carbon dots in drug delivery

Drug delivery is one of the most investigated biomedical applications of CDs. Their surface groups provide sites for electrostatic association, hydrogen bonding, π–π interactions or covalent coupling with drug molecules. In other systems, CDs are incorporated into a larger carrier such as a polymeric micelle, hydrogel or lipid structure. The resulting formulation can use the CD as both a functional component and an optical label.

Doxorubicin is a frequently studied model payload in breast-cancer CD research. Representative work has shown that hydrothermally prepared CDs can associate with doxorubicin and improve cellular uptake compared with free drug in MCF-7 cells. More recent systems have investigated pH-responsive porphyrin-derived CDs, folate-decorated CDs and nitrogen-doped CD-labelled polymeric micelles. These studies demonstrate the design principle of combining a therapeutic payload with a nanoscale carrier that also provides an imaging or targeting function.

Drug-loading performance should be described using clearly defined metrics such as loading capacity, encapsulation efficiency or drug-loading efficiency. These terms are sometimes used inconsistently, so the calculation method should be stated. Release studies should also report the medium, pH, temperature, sampling method and cumulative-release calculation. A release curve without experimental context cannot by itself establish tumour selectivity.

An important advantage of CD-based delivery is the possibility of combining delivery with controlled release. Acidic pH, redox conditions, enzymes, light or other triggers can be incorporated into the design. The goal is not simply to load more drug; it is to release an appropriate amount at the intended location while maintaining stability during circulation and storage.

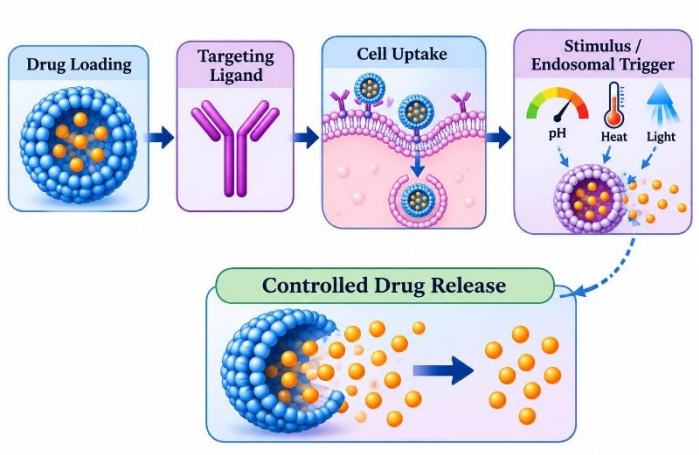


Figure 4: Figure Title: Illustrative Mechanism of a CD-Enabled Targeted Drug Delivery System

F. Tumor targeting and controlled release

Targeting can be passive, active or microenvironment responsive. Passive accumulation is often discussed using the enhanced permeability and retention concept, but its magnitude varies among tumour types and experimental models. It should therefore not be treated as a guaranteed mechanism. Active targeting uses a ligand–receptor interaction, while microenvironment-responsive systems exploit properties such as pH, redox potential, enzymes or light exposure.

Folate-mediated targeting is frequently explored because folate receptors can be overexpressed in selected cancer cells. Transferrin targeting has also been studied in breast-cancer cell systems. In each case, the presence and accessibility of the receptor should be experimentally confirmed. Increased cellular fluorescence is not automatically proof of receptor-specific targeting; appropriate competition, blocking or receptor-negative controls are needed.

Stimulus-responsive release is attractive because the carrier can remain relatively stable under one condition and release more payload under another. For example, mildly acidic environments can accelerate the release of some pH-sensitive formulations. Redox-responsive designs may use cleavable linkers that respond to intracellular reducing conditions. Light-triggered systems can provide external spatial and temporal control, but penetration depth, dose and phototoxicity must be considered.

Endocytosis is another important stage. Once a particle enters the cell, endosomal trafficking, lysosomal processing, escape and intracellular drug release can determine efficacy. Recent work in TNBC has investigated clathrin-mediated uptake of a casein-protected nitrogen-doped CD platform carrying doxorubicin. Such mechanistic studies are valuable because they connect the material to a defined cellular pathway rather than relying only on a final viability measurement.

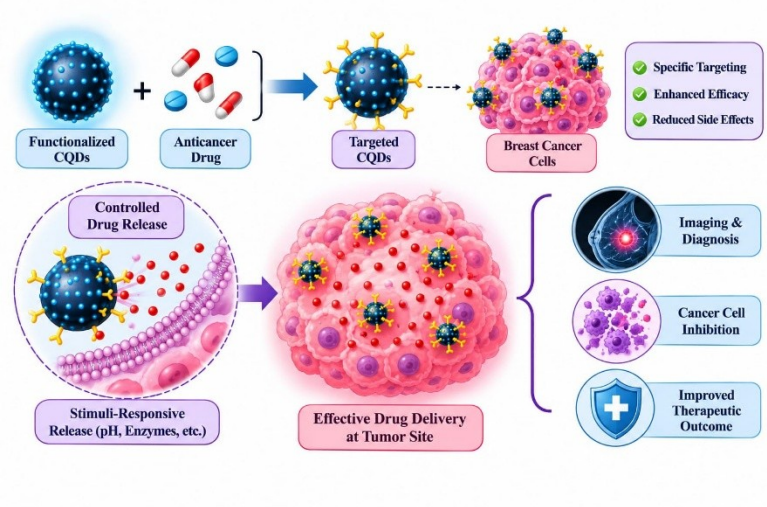


Figure 5: Tumor Targeting and Controlled Release of Functionalized Carbon Quantom Dots (CQDs)

G. Nanocarriers for Targeted Drug Delivery in Breast Cancer

Nanocarriers are nanoscale delivery systems designed to transport anticancer drugs and imaging agents to specific tumor sites. Major types include liposomes, polymeric nanoparticles, metallic nanoparticles, dendrimers and carbon quantum dots (CQDs).

Surface functionalization using targeting ligands such as folic acid, antibodies and peptides helps improve receptor recognition and cellular uptake. These nanocarriers can encapsulate therapeutic agents, protect drugs from degradation and provide controlled release.

Functionalized CQDs are particularly promising due to their fluorescence, surface modification and drug-loading potential. Their multifunctional properties support targeted drug delivery, cancer imaging and combination therapy. Stimuli-responsive nanocarriers can also release drugs under specific conditions, such as acidic pH or enzymatic changes.

Thus, nanocarrier-based systems offer promising opportunities for improving breast cancer diagnosis and targeted treatment while potentially reducing unwanted drug exposure to healthy tissues.

Types of Nanocarriers:

1. Liposomes: Phospholipid-based vesicles capable of carrying hydrophilic and hydrophobic drugs.

2. Polymeric Nanoparticles: Polymer-based carriers that provide drug protection and controlled release.
3. Metallic Nanoparticles: Nanoparticles with potential applications in cancer imaging and photothermal therapy.
4. Dendrimers: Highly branched structures that allow drug attachment and surface modification.
5. Carbon Quantum Dots (CQDs): Fluorescent carbon-based nanomaterials useful for imaging and potential targeted drug delivery.

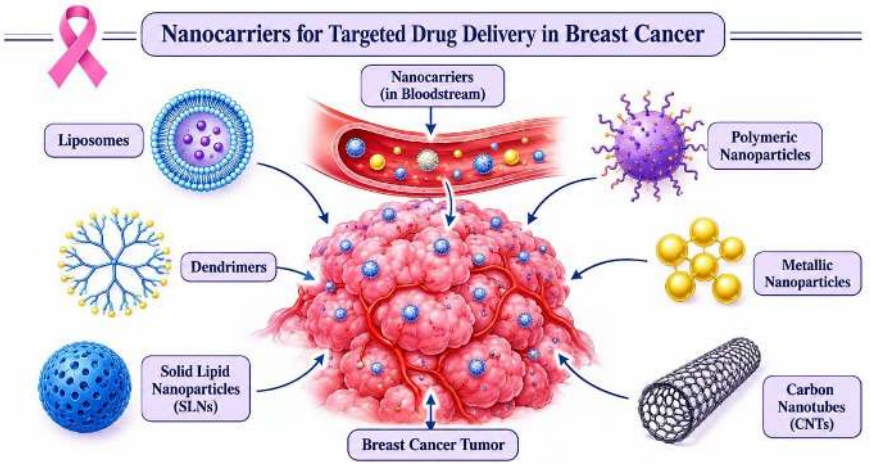


Figure 6: Nanocarriers for Targeted Drug Delivery in Breast Cancer

H. Photodynamic and photothermal therapy

Photodynamic therapy relies on light activation to generate reactive species capable of damaging biological structures. CDs can act directly as photoactive materials or be combined with photosensitising components. The therapeutic effect depends on wavelength, light dose, oxygen availability, particle localisation and the efficiency of reactive-species generation. Tumour hypoxia can limit conventional PDT, so oxygen-independent or oxygen enhancing strategies remain an active research area.

Photothermal therapy converts absorbed light into heat. CDs with suitable absorption can therefore be investigated as photothermal agents. NIR irradiation is commonly explored because it can provide a more useful tissue-penetrating window than ultraviolet light. In experimental systems, temperature elevation can cause cellular stress and damage. Yet photothermal performance must be balanced against normal-tissue heating and the practical penetration limits of light.

Combining PDT and PTT can create complementary mechanisms. Photothermal heating may increase membrane permeability or sensitise cells, while reactive species provide molecular damage. CD systems have also been combined with chemotherapy, producing chemo-photothermal or chemo-photodynamic strategies. Such combinations are promising because they attack cancer through more than one mechanism, but the contribution of each component should be experimentally separated using appropriate controls.

Breast-cancer studies include red-fluorescent carbon dots produced from plant material and lipid-coated to improve aqueous behaviour, as well as NIR-triggered doxorubicin-release systems that combine fluorescence, targeting and photothermal activation. These examples illustrate the broader design principle: one material can be engineered to perform several functions, provided each function is quantitatively validated.

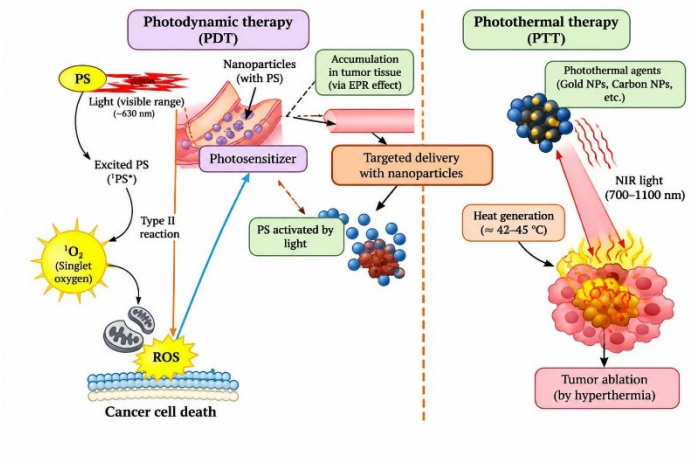


Figure 7: Original Schematic Contrasting the Conceptual PDT and PTT Pathways.

I. Breast-cancer applications

Breast-cancer research provides several useful examples of how CD design can be connected to a biological objective. Early work with doxorubicin-conjugated CDs demonstrated enhanced uptake and antitumour activity in MCF-7 cells compared with free doxorubicin. Later systems added receptor targeting, pH-responsive release, photothermal conversion or combination therapy.

One recent porphyrin-derived CD system used doxorubicin loading and reported high loading efficiency together with pH-responsive release. The formulation was evaluated in MCF-7 and MDA-MB-231 cells and showed stronger cytotoxicity than free doxorubicin under the reported experimental conditions. Such results are encouraging but remain cell-based evidence; they do not establish clinical superiority.

TNBC is a high-interest application area. A casein-protected nitrogen-doped CD platform has been investigated for doxorubicin delivery and cellular imaging in MDA-MB-231 cells, with evidence supporting clathrin-mediated internalisation and pH-dependent release. Other studies have investigated folate-functionalised carriers, transferrin-targeted CDs and plant-derived red-emissive systems. Collectively, these studies show that the field is moving from simple fluorescent labels toward multifunctional and mechanism-informed platforms.

Table 2: Original Comparative Summary of Representative Breast-Cancer CD Studies; Outcomes Are Condensed from the Cited Primary Reports and Should Be Interpreted within Their Experimental Models.

Study focus	CD design	Breast-cancer model	Main function	Key message
DOX–CD conjugate	Hydrothermal CD; DOX association	MCF-7	Drug delivery + imaging	Higher uptake/antitumour activity than free DOX in vitro
Transferrin-targeted CQD	CQD + transferrin	Breast-cancer cells	Active targeting	Receptor-directed delivery concept
Folate-CD nanomicelle	Folate-functionalised CD carrier	MDA-MB-231	Targeted delivery + imaging	Acidic release and improved in-vitro cytotoxicity
NIR/folate CD system	CD–PEG–folate + DOX	MCF-7, MDA-MB-231	Chemo-photothermal + imaging	Remote NIR-triggered release reported
Porphyrin-derived CD	DOX@CDs	MCF-7, MDA-MB-231	pH-responsive chemotherapy	High loading and enhanced in-vitro cytotoxicity

Study focus	CD design	Breast-cancer model	Main function	Key message
Casein-protected N-CD	N-doped CD + casein + DOX	MDA-MB-231	Imaging + delivery	Clathrin-mediated uptake and pH-responsive release
Red fluorescent plant-derived CD	Plant-derived CD + lipid coating	4T1	Imaging + PTT	Red emission and photothermal activity

J. Safety, toxicity and biological fate

Biocompatibility is often listed as an advantage of CDs, but it is not a universal property. Toxicity depends on dose, particle size, precursor, surface chemistry, purification, heteroatom or metal content, aggregation state, route of administration and exposure duration.

Residual reagents may also contribute to observed effects. Therefore, safety claims should be made for a defined formulation rather than for the entire CD class. In vitro studies commonly assess cell viability using metabolic or membrane-integrity assays. These are useful screening tools but do not fully describe mechanism.

Complementary measurements may include oxidative stress, mitochondrial function, apoptosis, membrane damage and inflammatory responses. It is also important to compare cancer and non-cancer cells where the intended application is selective tumour therapy. IN vivo evaluation should consider pharmacokinetics, biodistribution, clearance, blood compatibility, immune response and organ toxicity.

Fluorescence can assist tracking, but fluorescent signal is not always equivalent to intact-particle concentration because degradation products or surface changes may alter signal. Analytical confirmation of the nanomaterial and its components is therefore valuable.

Metal-doped or hybrid CDs require additional attention. A formulation may perform well because of a metal component, yet the same component can change long-term safety. For clinical translation, the complete product— not just the carbon core—must be characterised. Long-term studies and standardised reporting are particularly important because different laboratories may use different definitions, doses and biological endpoints.

K. Bioimaging and theragnostic monitoring

Fluorescence is the most recognisable diagnostic function of many CDs. A fluorescent carrier can be tracked by microscopy or other optical methods while delivering a therapeutic payload. This creates a practical bridge between imaging and therapy: the signal can help visualise cellular uptake, intracellular localisation or distribution in experimental models.

However, optical imaging has limitations. Shorter-wavelength fluorescence may suffer from tissue scattering and absorption, while autofluorescence can reduce contrast. Red and near-infrared emitters are therefore actively investigated for deeper imaging. NIR-II approaches are especially interesting because longer wavelengths can potentially improve tissue penetration and reduce background, although they introduce demanding requirements for brightness, stability and instrumentation.

Theranostic monitoring should be distinguished from simple fluorescence labelling. A genuine theranostic design aims to connect the diagnostic signal with the therapeutic process. Examples include fluorescence-guided delivery, image-guided phototherapy and externally triggered release monitored through optical changes. Quantitative imaging requires calibration, appropriate controls and attention to signal intensity, photobleaching and tissue attenuation.

For breast cancer, a future goal is image-guided precision treatment in which a CD platform reports its location while simultaneously delivering or activating therapy. This could be especially useful for heterogeneous tumours, but translation requires imaging performance to remain reliable in complex biological environments rather than only in cultured cells

L. Characterisation and quality-control considerations

A robust CD review or development program should link each material property to a biological purpose. Transmission electron microscopy can provide morphology and approximate core size, while dynamic light scattering gives hydrodynamic size in dispersion.

Zeta potential describes interfacial charge. Spectroscopic methods such as UV–visible absorption, fluorescence spectroscopy, FTIR and XPS can help define optical behaviour and surface chemistry. Raman spectroscopy may provide information about carbon structural features, while thermogravimetric analysis can contribute to composition and thermal behaviour.

Drug-delivery formulations require additional tests. Drug-loading capacity and encapsulation efficiency should be calculated using clearly stated equations. Release should be studied under physiologically relevant and stimulus-specific conditions. Colloidal stability should be examined in water and, where appropriate, in buffers or serum-containing media. Sterility and endotoxin considerations become essential for any future parenteral development.

Quality-by-design thinking can be applied to CD formulation. Critical material attributes may include particle size distribution, surface charge, optical emission, residual precursor level, drug content and release profile. Critical process parameters may include precursor ratio, temperature, reaction time, pH, purification conditions and drying/storage conditions. Establishing relationships between these variables can improve reproducibility.

An important problem in the field is that 'carbon dot' is sometimes used as a broad label for materials with substantially different compositions. Reporting a complete analytical fingerprint would improve cross-study comparison. At minimum, studies should provide synthesis details, purification method, particle/hydrodynamic size, surface chemistry, optical properties, concentration basis and relevant biological controls.

Table 3: Suggested Characterisation Package for a CD-based Drug-Delivery Study.

Test	What it answers	Relevance to CD drug delivery
TEM/AFM	Core morphology and approximate size	Confirms nanoscale structure
DLS	Hydrodynamic diameter in dispersion	Useful for colloidal behaviour
Zeta potential	Surface/interfacial charge	Helps interpret stability and uptake
FTIR/XPS	Surface functional groups and elemental states	Supports functionalisation claims
UV–Vis/PL	Absorption and emission behaviour	Defines imaging/phototherapy function
Raman	Carbon structural features	Supports core-structure assessment
HPLC/UV–Vis assay	Drug content and release	Quantifies payload
Serum stability	Behaviour in biological medium	Supports translational relevance

M. Translational barriers and future directions

The major gap in CD research is the distance between promising laboratory experiments and a reproducible clinical product. Many studies use different precursors, purification methods, particle definitions and biological models. A formulation can therefore appear highly effective in one report while another formulation described with the same general term behaves differently. Standardised reporting and reference materials would help address this problem.

Scale-up is another challenge. A synthesis route that works at milligram scale may not preserve the same heat and mass transfer conditions when increased to gram or kilogram scale. Changes in reaction environment can alter nucleation, carbonisation and surface chemistry. Pharmaceutical development therefore requires process understanding rather than simple multiplication of laboratory quantities.

Biological fate must also be clarified. The field needs better data on absorption, distribution, metabolism or degradation, excretion, protein-corona formation and long-term tissue retention. This is particularly important for multifunctional particles that contain polymers, drugs, targeting ligands or metals in addition to the carbon component.

Future research should prioritise red/NIR and NIR-II emitters for deeper imaging, stimulus-responsive release, multimodal PDT/PTT/chemotherapy, green synthesis with controlled feedstock quality, and hybrid systems with clearly justified components. Data-driven methods and AI may also help map synthesis parameters to optical and biological outcomes. Such models will be most useful when trained on standardised datasets that include negative results and complete material characterisation.

Clinical translation should proceed stepwise: reproducible synthesis, physicochemical specification, in-vitro mechanism, 3D or organoid models where appropriate, animal pharmacology and toxicology, manufacturing controls, and regulatory evaluation. A strong preclinical result is an important milestone, not a substitute for these stages.

N. Proposed development workflow for a breast-cancer CD theranostic

A practical development strategy begins with a defined clinical problem. For example, the goal may be to improve doxorubicin delivery, create image-guided therapy, or provide a combination of chemotherapy and photothermal treatment. The problem should determine the required CD functions rather than starting from a material and searching for an application afterward.

Step 1 — Define the target: choose the breast-cancer subtype/model and identify a validated receptor or microenvironmental feature if active targeting is intended.

Step 2 — Select the precursor and synthesis route: choose a reproducible carbon source and document all critical process variables.

Step 3 — Purify and characterise: establish size, surface chemistry, optical properties, charge and residual content.

Step 4 — Add the therapeutic payload and measure loading/release.

Step 5 — Validate mechanism in cells: compare free drug, empty CD, CD–drug, targeting-deficient control and relevant non-cancer cells.

Step 6 — Test imaging and therapy separately before claiming a multifunctional effect.

Step 7 — Evaluate combination therapy using factorial or mechanistic controls so that synergy is not assumed from a lower viability value alone.

Step 8 — Progress to more physiologically relevant models and then in vivo studies only after formulation and mechanism are adequately defined.

Step 9 — Build a quality profile: identify critical material attributes and process parameters, establish stability and batch reproducibility, and define acceptance criteria.

Step 10 — Plan translation: address scale-up, sterilisation, storage, pharmacokinetics, biodistribution, toxicology and regulatory requirements.

Table 4: Key Stages in CQD-Based Drug Development

Stage	Question	Key evidence	Go/no-go criterion
1. Clinical need	What problem is being solved?	Subtype + therapeutic objective	Clear unmet need
2. Material design	What CD structure is required?	Size, surface, emission	Defined material target
3. Formulation	How is drug/ligand incorporated?	Loading, stability, release	Reproducible formulation
4. Mechanism	Why should it work?	Uptake, receptor, ROS/heat, apoptosis	Mechanism supported by controls
5. Preclinical	Does it work in relevant models?	3D/in-vivo efficacy + safety	Benefit with acceptable exposure
6. Translation	Can it be manufactured and controlled?	Scale-up, QC, stability, toxicology	Consistent product profile

2. NEED OF INVESTIGATIONS

1. To develop novel carbon quantum dots (CQDs) for effective breast cancer treatment.
2. To improve the targeting efficiency of anticancer drugs.
3. To study the physicochemical properties of functionalized CQDs.
4. To investigate the effect of CQD size, shape and surface modification on drug delivery.
5. To improve the therapeutic efficiency of anticancer agents.
6. To evaluate the fluorescence properties of CQDs for cancer cell imaging.
7. To study the interaction between CQDs and cancer cells.
8. To investigate the role of AI in designing and optimizing CQD nanocarriers.
9. To predict drug-loading capacity using AI-based approaches.
10. To improve the stability of CQD-based formulations.
11. To study the release profile of drugs from CQD nanocarriers.
12. To investigate the cellular uptake mechanism of CQDs.
13. To evaluate the selectivity of CQDs towards breast cancer cells.
14. To study the effect of surface functional groups on biological activity.
15. To assess the long-term safety of CQD-based drug delivery systems.
16. To investigate the potential of CQDs in combined cancer diagnosis and therapy (Theranostics).
17. To explore the application of CQDs in personalized medicine.
18. To identify suitable functionalization methods for improved drug delivery.
19. To investigate the potential of CQDs in overcoming limitations of conventional chemotherapy.
20. To explore future applications of AI-assisted CQDs in targeted breast cancer therapy

3. IMPORTANCE

1. Targeted Drug Delivery: Functionalized Carbon Quantum Dots (CQDs) offer potential for targeted drug delivery, helping improve drug accumulation at breast cancer cells.
2. Improved Therapeutic Efficiency: CQDs may enhance drug delivery, improve therapeutic effectiveness and reduce unwanted exposure to healthy tissues.
3. Role of Artificial Intelligence: AI helps predict CQD properties, optimize surface functionalization and identify suitable drug-carrier combinations.
4. Early Cancer Detection: Fluorescent properties of CQDs provide opportunities for cancer imaging and diagnostic applications.
5. Controlled Drug Release: Functionalized CQDs can be designed to support controlled and stimuli-responsive drug release.
6. Multifunctional Applications: CQDs offer potential for combining cancer imaging, targeted drug delivery and therapeutic monitoring in a single platform.
7. Personalized Cancer Therapy: AI-assisted approaches may support the development of more precise and patient-specific drug delivery strategies.
8. Reduced Side Effects: Target-specific delivery may help minimize drug exposure to normal tissues and reduce treatment-related adverse effects.
9. Future Research Opportunities: This review highlights challenges related to biocompatibility, toxicity, stability, targeting efficiency and clinical translation.
10. Advancement in Nanomedicine: Integration of AI and CQD-based nanotechnology may contribute to the development of innovative approaches for breast cancer treatment.

CONCLUSION

Carbon dots represent a versatile class of carbon-based nanomaterials whose value in breast-cancer research comes from the possibility of combining several functions within one engineered platform. Their optical properties support imaging, while their surface chemistry provides opportunities for drug association, targeting and stimulus-responsive release. When designed with suitable photophysical behaviour, they can also participate in photodynamic or photothermal therapy. These functions create a logical foundation for theranostic systems that aim to connect diagnosis with treatment.

Evidence from breast-cancer models demonstrates several promising directions. Doxorubicin-loaded CDs can improve cellular uptake in selected systems; folate or transferrin functionalization can support receptor-directed delivery; pH- or redox-responsive designs can alter release behaviour; and NIR-responsive formulations can combine optical imaging with photothermal effects. TNBC is an especially relevant research area because it motivates strategies that do not depend on conventional hormone or HER2 targeting.

Nevertheless, carbon dots should not be described as inherently safe, universally tumour-selective or clinically established. Their properties depend strongly on synthesis, purification, surface chemistry and composition. Differences in nomenclature and analytical reporting make comparison difficult. Long-term toxicity, pharmacokinetics, biodistribution, batch reproducibility, scale-up and regulatory readiness remain major challenges.

The most promising future is therefore not simply 'more carbon dots' but better-defined carbon dots. Rational structure–property–function design, rigorous controls, standardised characterisation, greener yet reproducible synthesis, red/NIR-II imaging, controlled drug release and carefully validated combination therapy could move the field toward clinically meaningful applications

5. FUTURE PERSPECTIVES

1. Targeted Drug Delivery: Carbon dots can be further developed as targeted drug delivery carriers to deliver anticancer drugs specifically to breast cancer cells.
2. Early Cancer Detection: Development of highly sensitive carbon-dot-based fluorescent biosensors for early detection of breast cancer biomarkers.
3. Personalized Cancer Therapy: Carbon dots may support personalized treatment by enabling patient-specific diagnosis and therapeutic monitoring.
4. Photodynamic Therapy (PDT): Further research can improve the use of carbon dots in generating reactive oxygen species to destroy cancer cells using light.
5. Photothermal Therapy (PTT): Development of carbon dots with improved light-to-heat conversion efficiency for localized destruction of breast cancer cells.
6. Multifunctional Theranostic Systems: Integration of diagnosis, imaging, drug delivery, and therapy into a single carbon-dot-based platform.
7. Improved Biocompatibility: Further modification of carbon dots to improve their biodegradability, reduce toxicity, and enhance their safety.
8. AI-Based Nanotechnology: Integration of artificial intelligence for optimizing carbon dot synthesis, predicting their properties, and improving treatment strategies.
9. Clinical Applications: More preclinical and clinical studies are required to establish their effectiveness, safety, pharmacokinetics, and suitability for human use.
10. Large-Scale Production: Development of standardized, cost-effective, reproducible, and GMP-compliant manufacturing methods.

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