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Carbon Quantum Dots and Bioinspired Photonic Nanomaterials for Next-Generation Optoelectronics, Nanomedicine, and Photodynamic Applications

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Abstract

Carbon quantum dots (CQDs) and bioinspired photonic nanomaterials have emerged as promising multifunctional platforms for a wide range of applications in optoelectronics, nanomedicine, biosensing, fluorescence imaging, and photodynamic therapy. CQDs are nanoscale carbon-based materials characterized by unique optical and electronic properties, including size-dependent photoluminescence, high photostability, excellent water solubility, low cytotoxicity, and remarkable biocompatibility. These characteristics make them attractive alternatives to conventional semiconductor quantum dots for both technological and biomedical applications. Inspired by natural photonic systems such as photosynthetic light-harvesting complexes, rhodopsin-based photoreceptors, butterfly wings, and bioluminescent organisms, researchers have developed advanced nanostructures capable of efficient photon capture, energy transfer, and photoinduced charge separation. Recent advances in synthesis techniques, including hydrothermal, solvothermal, microwave-assisted, and green synthesis approaches, have enabled precise control over the size, surface chemistry, and optical properties of CQDs. Functionalization and heteroatom doping further enhance their photophysical performance and application versatility. In optoelectronics, CQDs have been incorporated into photodetectors, solar cells, light-emitting diodes, and flexible electronic devices due to their tunable emission characteristics and efficient charge transport properties. In the biomedical field, CQDs are increasingly utilized for targeted drug delivery, bioimaging, biosensing, and photodynamic therapy because of their excellent fluorescence behavior and biological compatibility. Furthermore, bioinspired photonic nanomaterials are being explored for artificial photosynthesis and sustainable energy conversion systems, where efficient light harvesting and electron transfer are critical. This review highlights recent developments in the synthesis, photophysical properties, and multifunctional applications of CQDs and related bioinspired photonic nanomaterials, while discussing current challenges and future opportunities for the development of intelligent nanophotonic and bioelectronic technologies.

Keywords: Carbon quantum dots; bioinspired photonic nanomaterials; optoelectronics; nanomedicine; fluorescence imaging; photodynamic therapy

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INTRODUCTION

Nanotechnology has transformed the field of photonic materials by enabling precise control over optical and electronic properties at the nanoscale. Among emerging nanomaterials, carbon quantum dots (CQDs) represent a unique class of fluorescent carbon-based nanoparticles typically smaller than 10 nm in diameter. Since their discovery, CQDs have attracted widespread interest due to their remarkable photoluminescence, low toxicity, environmental friendliness, and ease of synthesis [1–3].

Unlike traditional semiconductor quantum dots containing heavy metals such as cadmium and lead, CQDs offer safer alternatives for biomedical and environmental applications. Their tunable optical behavior results from quantum confinement effects, surface defects, and functional group modifications.

Nature provides numerous examples of efficient photonic systems. Photosynthetic complexes, microbial rhodopsins, and photoreceptor proteins utilize highly optimized energy transfer pathways to capture and convert solar energy. Inspired by these biological systems, scientists have developed bioinspired photonic nanomaterials capable of mimicking natural light-harvesting mechanisms [4].

The convergence of quantum dot technology, photochemistry, photobiology, and nanomedicine has created exciting opportunities for next-generation optoelectronic devices and therapeutic platforms [5].

Objective of the Review

The objective of this review is to provide a comprehensive overview of recent developments in carbon quantum dots (CQDs) and bioinspired photonic nanomaterials, with particular emphasis on their synthesis methods, structural and optical properties, and emerging applications in optoelectronics, nanomedicine, biosensing, fluorescence imaging, and photodynamic therapy. Furthermore, this review discusses recent technological advancements, current challenges, and future research perspectives toward the development of multifunctional nanophotonic systems for biomedical and energy-related applications [6].

CARBON QUANTUM DOTS: STRUCTURE AND PROPERTIES

Structural Characteristics

Carbon quantum dots (CQDs) are quasi-spherical carbon-based nanomaterials typically possessing dimensions below 10 nm. Their structure generally consists of a carbonaceous core surrounded by abundant surface functional groups that strongly influence their physical, chemical, and optical properties [7]. The nanoscale dimensions of CQDs give rise to quantum confinement effects, while their exceptionally high surface-area-to-volume ratio facilitates extensive surface modification and functionalization. Hydroxyl, carboxyl, amino, and carbonyl groups are commonly present on the surface of CQDs and contribute significantly to their water solubility, colloidal stability, fluorescence characteristics, and biological compatibility. The presence of these functional groups also enables further chemical conjugation with biomolecules, polymers, drugs, and inorganic nanomaterials, thereby expanding their applicability in diverse technological and biomedical fields. Owing to their tunable structure and versatile surface chemistry, CQDs have emerged as promising candidates for next generation nanophotonic and bioelectronic applications [8].

Optical Properties

One of the most remarkable characteristics of carbon quantum dots is their unique optical behavior. CQDs exhibit strong photoluminescence, making them highly attractive for fluorescence-based applications. Their optical absorption generally extends over a broad spectral range, while their emission properties can be tuned by controlling particle size, surface states, and chemical composition. Unlike many conventional fluorescent materials, CQDs display excellent photostability and resistance to photobleaching, allowing prolonged operation under continuous illumination. In many cases, their fluorescence emission depends on excitation wavelength, providing additional flexibility for multiplexed imaging and sensing applications [9].

Another important optical property of CQDs is upconversion luminescence, in which lower-energy photons are absorbed and converted into higher-energy emitted light. This phenomenon has generated considerable interest for applications in bioimaging, photocatalysis, and photodynamic therapy because it enables deeper tissue penetration and improved utilization of incident light. The fluorescence efficiency of CQDs can be further enhanced through surface passivation and heteroatom doping. The incorporation of elements such as nitrogen, sulfur, phosphorus, and boron modifies the electronic structure of CQDs, leading to improved charge separation, enhanced quantum yields, and tunable emission properties. These characteristics have established CQDs as versatile photonic nanomaterials with significant potential in both optoelectronic and biomedical technologies [10].

SYNTHESIS OF CARBON QUANTUM DOTS

The synthesis of carbon quantum dots has attracted considerable attention because the preparation method strongly influences particle size, morphology, crystallinity, surface chemistry, and optical properties. Broadly, CQD synthesis strategies are classified into top-down and bottom-up approaches. Each method offers distinct advantages and limitations depending on the desired application and material characteristics [11].

Top-Down Methods

Top-down approaches involve the breakdown of larger carbon structures into nanoscale carbon quantum dots through physical or chemical processes. Techniques such as laser ablation, arc discharge, and electrochemical oxidation are commonly employed to fragment bulk carbon materials into nanoparticles with controlled dimensions. These methods often produce CQDs with relatively high crystallinity and well-defined graphitic domains, which can be beneficial for charge transport and optoelectronic applications. However, top-down approaches frequently require sophisticated instrumentation, high energy consumption, and extensive purification procedures. In addition, achieving uniform particle size distributions and high production yields remains challenging in many cases. Despite these limitations, top-down methods continue to play an important role in the development of highly crystalline CQDs for advanced nanotechnology applications [11–14].

Bottom-Up Methods

Bottom-up synthesis involves the formation of carbon quantum dots from small molecular precursors through controlled carbonization and nucleation processes. Hydrothermal synthesis, microwave-assisted synthesis, pyrolysis, and solvothermal methods are among the most widely used bottom-up techniques [15]. These approaches offer several advantages, including low production costs, scalability, straightforward processing, and excellent control over surface functionality. The ability to tailor precursor composition enables precise tuning of CQD optical and electronic properties. In recent years, increasing emphasis has been placed on the use of renewable and environmentally friendly carbon sources. Biomass-derived precursors such as fruit peels, sugars, amino acids, agricultural waste, and plant extracts have gained substantial attention as sustainable feedstocks for CQD production. These green synthesis strategies align with the principles of sustainable nanotechnology while simultaneously reducing environmental impact and production costs [16].

BIOINSPIRED PHOTONIC NANOMATERIALS

Nature has evolved highly sophisticated photonic systems capable of harvesting, manipulating, and utilizing light with extraordinary efficiency. These biological systems provide valuable inspiration for the development of advanced nanophotonic materials designed to emulate natural energy transfer and photon management processes. Bioinspired photonic nanomaterials integrate concepts derived from biological light-harvesting systems with modern nanotechnology to achieve enhanced optical performance, efficient charge separation, and controlled energy transport [17].

Natural Photonic Architectures

Photosynthetic organisms possess some of the most efficient light-harvesting systems found in nature. Within photosynthetic complexes, pigment-protein assemblies containing chlorophylls, carotenoids, and phycobilins capture solar photons and transfer excitation energy with remarkable efficiency toward reaction centers where charge separation occurs. These processes provide fundamental models for the design of artificial energy-conversion systems. Similarly, microbial rhodopsins employ retinal chromophores to perform light-driven proton pumping, ion transport, and sensory functions through highly coordinated photoinduced molecular processes [18–20]. These biological mechanisms have inspired the development of responsive nanomaterials capable of converting optical signals into electrical or chemical outputs. Bioluminescent organisms provide additional examples of efficient photon generation and energy transfer, demonstrating strategies for producing light under mild physiological conditions with minimal energy loss. Collectively, these natural photonic architectures offer powerful design principles for next generation nanophotonic technologies [21].

Biomimetic Nanophotonic Design

Modern biomimetic nanophotonic systems seek to replicate key features of natural light-harvesting architectures, including energy funneling, exciton migration, electron transport pathways, and self-assembly processes. By mimicking these biological mechanisms, researchers have developed nanostructured materials capable of enhanced photon capture and improved charge-separation efficiency. Hierarchical assembly of nanoscale building blocks often facilitates directional energy transfer and minimizes recombination losses. Such approaches have proven particularly valuable in solar energy conversion, optoelectronics, sensing, and bioelectronics. The integration of biological design principles with advanced nanofabrication techniques continues to drive the development of highly efficient photonic materials capable of addressing emerging technological challenges [22].

OPTOELECTRONIC APPLICATIONS

The exceptional optical and electronic properties of carbon quantum dots have established them as important materials for next-generation optoelectronic devices. Their tunable fluorescence, excellent photostability, low toxicity, and solution-processable nature enable integration into a wide variety of electronic and photonic platforms. As research progresses, CQDs are increasingly being incorporated into light-emitting devices, photodetectors, solar energy conversion systems, and flexible electronics [23].

Light-Emitting Diodes

Carbon quantum dot-based light-emitting diodes have attracted substantial interest because of their tunable emission characteristics, high luminescence efficiency, and environmental compatibility. By adjusting particle size, surface chemistry, and dopant composition, CQDs can generate a broad range of emission colors spanning the visible spectrum. Their low toxicity and compatibility with flexible substrates make them particularly attractive for display technologies, wearable electronics, optical communication systems, and next-generation lighting devices. Continued improvements in quantum yield and charge transport properties are expected to further enhance the performance of CQD-based LEDs [24].

Photodetectors

The incorporation of carbon quantum dots into photodetector architectures has led to significant improvements in device sensitivity and spectral response. CQDs exhibit broad optical absorption and rapid photoresponse characteristics, enabling efficient detection of ultraviolet, visible, and near-infrared radiation. Their nanoscale dimensions facilitate effective charge transfer and enhanced carrier mobility when integrated with semiconductor materials. Hybrid CQD-semiconductor systems have demonstrated superior photoelectric conversion performance, making them promising candidates for imaging systems, optical sensing platforms, and advanced communication technologies [25].

Solar Energy Conversion

Carbon quantum dots have emerged as versatile components in solar energy conversion technologies because of their unique ability to absorb light, transfer charge, and participate in photochemical processes. They can function as photosensitizers, charge transport mediators, electron acceptors, or fluorescence converters in various photovoltaic and photoelectrochemical systems. Their incorporation into dye-sensitized solar cells, photoelectrochemical cells, and artificial photosynthetic platforms has resulted in improved light harvesting, enhanced charge separation, and increased energy conversion efficiency. As efforts toward sustainable energy technologies continue, CQDs are expected to play an increasingly important role in the development of efficient and environmentally friendly solar energy conversion systems [26].

NANOMEDICINE AND BIOMEDICAL IMAGING

The exceptional biocompatibility, low cytotoxicity, water solubility, and tunable optical properties of carbon quantum dots have established them as highly promising nanomaterials for biomedical applications. Their unique fluorescence behavior, ease of surface functionalization, and ability to interact with biological systems enable their use in diagnostics, therapeutics, and multifunctional biomedical platforms. Unlike many conventional semiconductor quantum dots that contain toxic heavy metals, CQDs exhibit excellent biological compatibility, making them suitable for in vivo and in vitro applications. As a result, they have attracted significant attention in fields such as fluorescence imaging, biosensing, drug delivery, and personalized medicine [27].

Fluorescence Imaging

Fluorescence imaging is one of the most extensively explored biomedical applications of carbon quantum dots. Owing to their strong and tunable photoluminescence, CQDs can function as highly effective fluorescent probes for visualizing biological structures and processes. Their nanoscale dimensions facilitate cellular uptake and intracellular localization, allowing detailed imaging of cells, tissues, and subcellular organelles. In cancer diagnostics, CQDs enable the detection and monitoring of tumor tissues through fluorescence-based contrast enhancement. Furthermore, their excellent photostability minimizes photobleaching during prolonged observation, enabling long-term imaging and real-time monitoring of dynamic biological events. Compared with conventional organic fluorescent dyes, CQDs provide longer imaging durations, higher resistance to photodegradation, and significantly lower toxicity, making them attractive candidates for next-generation biomedical imaging technologies [28].

Biosensing

Carbon quantum dots have emerged as versatile sensing platforms for the detection of a wide range of biological and environmental analytes. Their optical and electronic properties are highly sensitive to changes in the surrounding environment, enabling the development of highly selective and sensitive biosensors. CQD-based sensing systems have been successfully employed for the detection of glucose, nucleic acids, proteins, pathogenic microorganisms, metal ions, and environmental pollutants. Detection mechanisms often involve fluorescence quenching, fluorescence enhancement, Förster resonance energy transfer, charge-transfer interactions, or electrochemical signal generation. Surface modification with recognition molecules such as antibodies, aptamers, enzymes, and peptides further enhances sensing specificity. The combination of rapid response, low detection limits, and excellent biocompatibility positions CQD-based biosensors as valuable tools for clinical diagnostics, environmental monitoring, and point-of-care healthcare applications.

Table 1. Optoelectronic applications of carbon quantum dots.

Application	Function of CQDs	Major advantage
LEDs	Light emission	Tunable fluorescence
Photodetectors	Photon detection	High sensitivity
Solar Cells	Photosensitization	Enhanced charge transfer
Flexible Electronics	Conductive component	Mechanical flexibility
Sensors	Signal transduction	High selectivity

Drug Delivery

The abundant functional groups present on the surface of carbon quantum dots provide numerous opportunities for conjugating therapeutic agents and targeting molecules. As drug delivery vehicles, CQDs offer several advantages, including high loading capacity, controlled release behavior, efficient cellular uptake, and enhanced bioavailability of therapeutic compounds. Their small size allows them to penetrate biological barriers and accumulate in specific tissues when appropriately functionalized. In addition, CQDs can be engineered to respond to environmental stimuli such as pH, temperature, light, or enzymatic activity, enabling controlled and site-specific drug release. A particularly attractive feature of CQD-based drug delivery systems is their intrinsic fluorescence, which allows simultaneous tracking of drug distribution and therapeutic response. This integration of diagnostic imaging and therapy has led to the development of theranostic platforms capable of combining disease detection, monitoring, and treatment within a single multifunctional nanomaterial system.

PHOTODYNAMIC THERAPY

Photodynamic therapy (PDT) is a minimally invasive therapeutic approach that utilizes photoactive compounds, light irradiation, and molecular oxygen to generate reactive oxygen species capable of inducing localized cellular destruction. PDT has gained significant attention as an alternative or complementary treatment strategy for cancer and other diseases because of its high selectivity, minimal systemic toxicity, and reduced side effects compared with conventional therapies. Recent advances in nanotechnology have expanded the capabilities of PDT through the incorporation of carbon quantum dots and other nanophotonic materials as efficient photosensitizing agents.

Fundamental Mechanism

The photodynamic therapy process begins with the administration of a photosensitizer that preferentially accumulates within diseased tissues. Upon exposure to light of an appropriate wavelength, the photosensitizer absorbs photons and undergoes excitation to a higher electronic state. Subsequent energy-transfer processes lead to the generation of reactive oxygen species, including singlet oxygen, superoxide radicals, and hydroxyl radicals. These highly reactive species cause oxidative damage to cellular components such as membranes, proteins, nucleic acids, and mitochondria, ultimately resulting in apoptosis or necrosis of targeted cells. Because reactive oxygen species possess limited diffusion distances and short lifetimes, cellular damage remains localized to the irradiated region, thereby minimizing injury to surrounding healthy tissues.

Carbon Quantum Dots as Photosensitizers

Carbon quantum dots have emerged as promising alternatives to conventional photosensitizers due to their favorable optical and biological properties. Their strong light absorption capabilities, efficient generation of reactive oxygen species, excellent photostability, and low systemic toxicity make them attractive candidates for photodynamic therapy applications. Furthermore, CQDs can be engineered through surface functionalization and heteroatom doping to enhance light-harvesting efficiency and increase reactive oxygen species production. Nitrogen-doped carbon quantum dots have demonstrated particularly promising performance because of their improved electronic structure and enhanced photodynamic activity. These modifications contribute to more effective cellular destruction while maintaining excellent biocompatibility.

Cancer Therapy Applications

The integration of carbon quantum dots into photodynamic therapy has demonstrated considerable potential for cancer treatment. CQD-mediated PDT has shown effectiveness against a variety of malignancies, including breast cancer, lung cancer, skin cancer, and brain tumors. Their ability to selectively accumulate in tumor tissues and generate cytotoxic reactive oxygen species upon illumination allows targeted destruction of cancer cells while minimizing damage to healthy tissues. Additionally, the intrinsic fluorescence properties of CQDs enable simultaneous tumor visualization and therapeutic intervention, providing image-guided treatment capabilities. This dual functionality enhances treatment precision, facilitates monitoring of therapeutic outcomes, and supports the development of personalized cancer therapy strategies.

BIOELECTRONICS AND NEURAL INTERFACES

The rapid advancement of flexible and wearable electronic technologies has created growing demand for biocompatible nanomaterials capable of interfacing with biological systems. Carbon quantum dots have emerged as attractive components for bioelectronic applications because of their optical responsiveness, mechanical flexibility, chemical stability, and excellent compatibility with living tissues. Their integration into wearable sensors, neural interfaces, and tissue-engineering platforms has opened new opportunities for healthcare monitoring, neurotechnology, and regenerative medicine.

Wearable Sensors

Wearable healthcare technologies require lightweight, flexible, and highly sensitive sensing materials capable of continuously monitoring physiological parameters. Carbon quantum dots possess optical and electrochemical properties that make them suitable for incorporation into flexible sensor platforms. CQD-based wearable devices have been developed for monitoring heart rate, blood glucose levels, oxygen saturation, body temperature, and other physiological indicators. Their high sensitivity and rapid response characteristics enable accurate real-time data acquisition, supporting personalized healthcare and remote patient monitoring. Furthermore, their compatibility with flexible substrates facilitates integration into smart textiles, skin-mounted devices, and portable diagnostic systems.

Neural Stimulation

The development of photoresponsive nanomaterials has significantly expanded opportunities for noninvasive neural stimulation and neuromodulation. Carbon quantum dots can interact with light to generate electrical or chemical signals capable of influencing neuronal activity. Their nanoscale dimensions, biocompatibility, and tunable optical properties make them particularly attractive for applications involving optogenetics, neuroprosthetic devices, and brain-machine interfaces. By enabling precise spatial and temporal control of neural activation, CQD-based systems offer potential solutions for studying neural networks, restoring lost sensory functions, and treating neurological disorders. Continued advances in nanophotonics and bioelectronics are expected to further enhance the performance and clinical applicability of these technologies.

Tissue Engineering

Tissue engineering aims to develop biomimetic structures capable of supporting tissue regeneration and functional restoration. Carbon quantum dots have increasingly been incorporated into tissue-engineering scaffolds because of their multifunctional properties and compatibility with biological environments. CQD-containing scaffolds can promote cell adhesion, proliferation, and differentiation while simultaneously providing optical functionality for monitoring tissue development. Their ability to carry therapeutic agents further enables controlled drug release within regenerative environments.

The integration of structural support, bioactivity, imaging capability, and therapeutic functionality within a single platform represents a significant advancement in regenerative medicine. Consequently, CQD-based tissue-engineering systems are expected to play an important role in future biomedical and healthcare technologies.

Table 2. Biomedical applications of CQDs and bioinspired nanomaterials.

Application	Mechanism	Clinical Potential
Fluorescence Imaging	Light emission	Disease diagnosis
Biosensing	Signal generation	Early detection
Drug Delivery	Targeted transport	Precision therapy
Photodynamic Therapy	ROS production	Cancer treatment
Neural Stimulation	Photoactivation	Neuroengineering
Tissue Engineering	Cellular support	Regenerative medicine

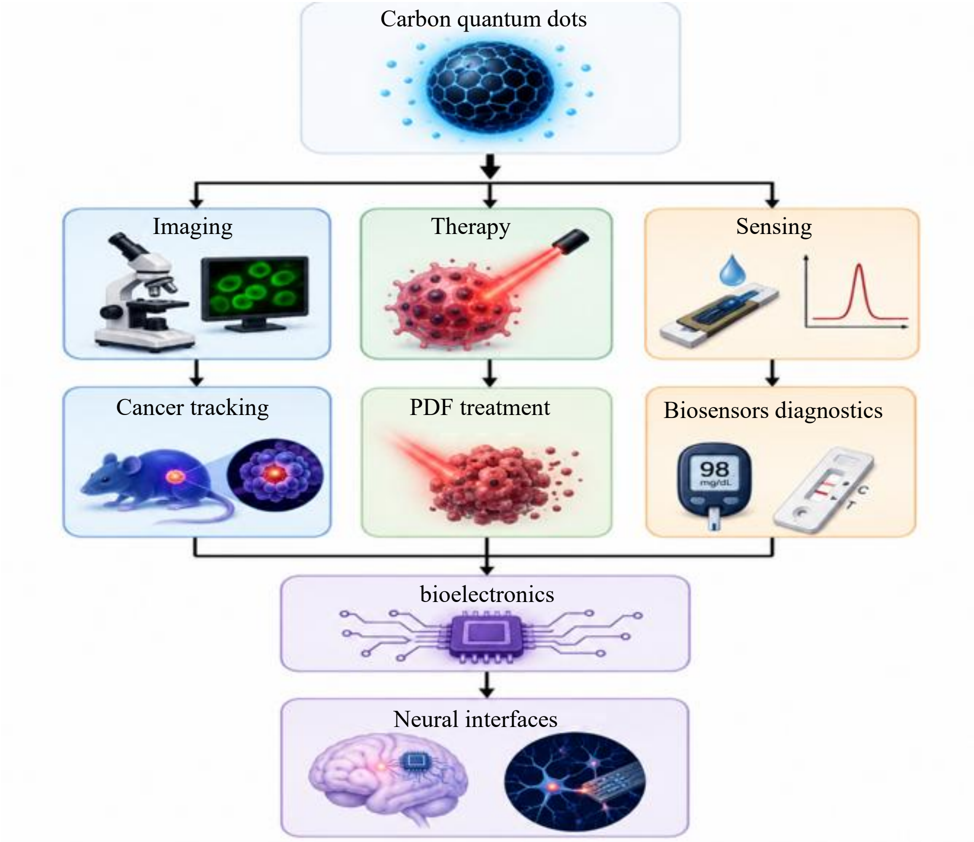

Figure 1. Multifunctional biomedical applications of CQDs.

CONCLUSIONS

Carbon quantum dots and bioinspired photonic nanomaterials have emerged as transformative technologies at the intersection of photochemistry, nanotechnology, optoelectronics, and medicine. Their unique optical properties, low toxicity, and structural versatility make them ideal candidates for applications ranging from solar energy conversion and photodetectors to fluorescence imaging and photodynamic therapy. Inspired by natural light-harvesting systems, researchers continue to develop advanced nanophotonic architectures capable of efficient energy transfer and multifunctional performance. Future integration with artificial intelligence, flexible electronics, and precision medicine is expected to expand the capabilities of these materials significantly. Continued interdisciplinary research will play a critical role in realizing their full technological and clinical potential.

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