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# TAILORING GRAPHENE QUANTUM DOTS FOR NEXT-GENERATION TECHNOLOGIES: ENERGY, ENVIRONMENT AND HEALTH

This review examines the design, properties, and applications of graphene quantum dots in energy, environmental, and health sectors. We discuss synthesis methodologies, highlighting the transition from zero-bandgap graphene to luminescent quantum-confined structures. The study details the integration of graphene quantum dots in photovoltaic architectures and lithium-ion batteries to improve stability and efficiency. Environmental sensing capabilities for metal ion detection are explored, emphasizing the safety of carbon-based dots over toxic heavy-metal alternatives. Biomedical applications, including bioimaging and photodynamic therapy, are evaluated with a focus on biocompatibility and renal clearance. Finally, challenges in large-scale production and commercialization are addressed.

*Keywords:* Graphene quantum dots; photovoltaics; bioimaging; environmental sensing; energy storage

## 1. Introduction

The discovery of graphene quantum dots (GQD, GQDs) is closely linked to the rise of graphene, a two-dimensional sheet of $sp^2$-hybridized carbon atoms arranged in a honeycomb lattice. Graphene was first isolated in 2004 by physicists Andre Geim and Konstantin Novoselov at the University of Manchester using a surprisingly simple technique: mechanical exfoliation of graphite with adhesive tape [1]. This revolutionary achievement earned them the Nobel Prize in Physics in 2010 and sparked a global surge of interest in carbon-based nanostructures. Graphene's exceptional properties, including high electrical conductivity [2-6], mechanical strength [7-11] and transparency [12,13] made it a model material for nanoscale innovation [3]. However, its zero bandgap posed challenges for applications requiring light emission or on-off switching, leading scientists to explore ways to modify or miniaturize graphene into quantum-sized derivatives [14-18].

This pursuit gave rise to the field of graphene quantum dots. Around 2008-2010, researchers began developing methods to cut or synthesize graphene fragments small enough to exhibit quantum confinement and edge effects, resulting in GQDs with strong and tunable photoluminescence [19-24]. Unlike bulk graphene, GQDs can emit visible light upon excitation, a property that stems from their discrete energy levels and surface chemistry [25]. **GQDs are an emerging class of carbon nanomaterials that combine quantum mechanical behavior with the physicochemical properties of graphene** [26]. Typically smaller than 20 nanometers, they exhibit size-dependent photoluminescence, high surface area, tunable electronic properties [25], and excellent biocompatibility [27-31]. These features make them ideal candidates for a wide range of applications, including bioimaging [32], drug delivery [33], catalysis [34], and environmental sensing [35]. Unlike traditional semiconductor quantum dots, GQDs are carbonaceous, often nontoxic, and can be synthesized through relatively low-cost and green methods [36]. One of their most fascinating properties is that their emission color can be tuned by adjusting their size: smaller GQDs tend to emit blue light, while larger ones shift toward green, yellow, or even red emissions [37]. This behavior results from quantum confinement and edge effects, which alter the band gap energy and lead to discrete electronic transitions [38]. Their growing importance

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in both scientific research and industrial applications reflects the increasing demand for materials that combine performance, safety, and sustainability.

The presence of oxygen-containing functional groups and the ability to modify edge states further enhance their versatility [39]. As a result, GQDs are not just scaled-down versions of graphene, but they are a distinct and powerful class of nanomaterials with novel behavior and applications. Broadly, GQDs can be synthesized using two main approaches: top-down methods, which involve breaking down larger carbon structures such as graphite, graphene oxide, or carbon fibers into nanoscale dots; and bottom-up methods, which build the dots atom-by-atom or molecule-by-molecule from organic precursors or small carbon compounds [40]. Each approach has advantages and limitations in terms of scalability, precision, purity, and environmental impact. A comprehensive understanding of these synthesis routes is essential for optimizing the properties of GQDs for specific applications and forms the basis of the following sections in this paper.

GQDs have since demonstrated outstanding potential in a broad spectrum of fields. In biomedicine, they offer a safer and more stable alternative to heavy-metal quantum dots for cellular imaging and biosensing [19,26]. In energy technologies, they contribute to LEDs and supercapacitors by enhancing charge transport [41]. Environmental scientists have employed GQDs in the detection of pollutants due to their sensitivity to various analytes and low environmental impact [42]. Such versatility stems largely from the ability to tailor their size, shape, and surface functionalities, factors that are strongly influenced by the method of synthesis.

Furthermore, GQDs applications in solar energy conversion have emerged as a particularly promising field. GQDs have been employed in various photovoltaic architectures, including dye-sensitized solar cells (DSSCs) [43], organic solar cells (OSCs), and perovskite solar cells (PSCs) [44], to enhance light harvesting, improve charge separation, and reduce recombination losses [45]. Their role as electron acceptors/donors, down-conversion materials, and interfacial layers in these systems demonstrates their multifunctionality in improving overall device efficiency. For instance, GQDs can absorb high-energy UV photons and re-emit them as visible light, increasing the utilization of the solar spectrum [46]. Their quantum yield, adjustable energy levels, and solution processability make them suitable for scalable fabrication and integration into emerging solar technologies.

## 2. Methods

### 2.1. Bottom-Up Synthesis

The bottom-up synthesis approach constructs graphene quantum dots from molecular or atomic precursors, offering precise control over their size, shape, and surface chemistry. Unlike top-down methods, which rely on breaking down bulk carbon materials, bottom-up techniques assemble GQDs through chemical reactions that transform small organic molecules into nanostructures with $sp^2$ carbon domains. This strategy allows for improved control over optical properties such as photoluminescence, as well as enhanced purity and structural uniformity [40,47]. These advantages make the bottom-up approach particularly suitable for applications requiring tailored emission wavelengths or biocompatibility. Recent developments in bottom-up synthesis have focused on achieving atomic-level precision and reproducibility. Novel routes inspired by organic synthesis, such as the molecular fusion of aromatic compounds, have enabled researchers to create structurally defined GQDs with consistent properties. Chemical fusion or organic synthesis is the most precise approach, as it involves the stepwise polymerization or condensation of well-defined aromatic molecules such as polycyclic aromatic hydrocarbons (PAHs). Though this method can be time-consuming and requires sophisticated synthesis and purification steps, it allows for atomic-level control of GQD structure and edge configuration, vital for optoelectronic and quantum applications [48].

Moreover, green chemistry approaches using biomass, ethanol, and sugars as carbon sources have emerged as sustainable alternatives to petrochemical-derived precursors [49]. These methods emphasize environmentally friendly conditions, including pyrolysis, hydrothermal, solvothermal, microwave-assisted synthesis, and chemical fusion. One of the most common bottom-up strategies is pyrolysis, where organic molecules such as citric acid, glucose, or urea are thermally decomposed at high temperatures. For example, heating citric acid under controlled conditions induces carbonization and aromatization processes that lead to the formation of small carbon cores with conjugated domains, the precursors of GQDs [19]. **Adjusting the temperature, time, and precursor ratios allows tuning the size and photoluminescence properties of GQDs.**

Another important technique is hydrothermal or solvothermal synthesis, which involves subjecting precursors to high temperature and pressure in a sealed autoclave, often in aqueous or organic solvents. These methods facilitate the nucleation and growth of GQDs under mild conditions and can incorporate heteroatoms like nitrogen or sulfur during synthesis. This heteroatom doping significantly alters the electronic structure and improves properties such as fluorescence, making these GQDs ideal for bioimaging and sensing [48].

Microwave-assisted synthesis is another fast and energy-efficient technique. It relies on the rapid heating of precursor molecules, typically in polar solvents, under microwave radiation. This method has gained popularity due to its shorter reaction times, often under 10 minutes, simplicity, and high yields. Additionally, it can produce GQDs with narrow size distributions and high quantum yields [50].

To address the technical hurdles associated with batch-to-batch variability and restricted scalability in traditional hydrothermal or microwave-assisted methods, recent advancements have focused on continuous-flow microfluidic synthesis. By leveraging the high surface-to-volume ratios and precise thermal management inherent in microreactors, this strategy

ensures uniform nucleation and growth kinetics, leading to highly reproducible optical and electronic properties [51].

Furthermore, template-assisted synthesis utilizing confined environments such as mesoporous silica or molecular frameworks allows for the growth of GQDs with atomic-level precision. This spatial confinement dictates the final dimensions and edge configurations of the graphene fragments, which is a critical factor for high-performance quantum and optoelectronic devices. [47].

Despite its many benefits, the bottom-up approach also faces challenges. The overall yield of GQDs can be relatively low. Resulting crude mixtures often contain residual organic precursors and carbonaceous byproducts that necessitate rigorous post-synthetic refinement. To satisfy the stringent purity requirements for biomedical and sensing applications, advanced purification protocols such as long-term dialysis against deionized water have become indispensable. This technique facilitates the precise fractionation of GQDs based on their hydrodynamic volume, effectively narrowing the size distribution and eliminating molecular impurities that might otherwise induce off-target cytotoxicity or obscure the material's intrinsic photoluminescence, and the purification of products to remove unreacted precursors or byproducts is often required [52]. Moreover, ensuring uniformity across batches remains a technical hurdle, especially for large-scale production. Nevertheless, the method's ability to tailor emission color, size, and surface chemistry has made it a preferred route in contexts where precision and safety are essential [47,53].

Bottom-up synthesized GQDs have demonstrated outstanding performance in bioimaging, particularly for multicolor fluorescence labeling due to their tunable emission and low cytotoxicity. They are also used in fluorescent sensors for detecting heavy metals or biomolecules, and in optoelectronic devices such as white-light LEDs or solar energy harvesters [26]. The ability to engineer GQDs from the ground up allows scientists to match the material's properties with the functional requirements of each application, underscoring the power of the bottom-up strategy in nanomaterials design.

### 2.2. Top-Down Synthesis

Top-down methods involve the synthesis of graphene quantum dots from larger fragments such as graphite, graphene oxide and carbon nanotubes, into smaller ones that exhibit the effects of quantum confinement. **Unlike bottom-up methods, which assemble GQDs from molecular or atomic precursors, top-down approaches utilize physical, chemical, or electrochemical processes to break down bulk carbon**. Such routes of top-down approach are particularly advantageous for large-scale production as they rely majorly on readily available precursors without the need for depending on complex organic synthesis. However, most challenges are related to the level of precision that can be reached, as these techniques often suffer from structural uniformity, controlled surface chemistry, due to inaccurate cutting processes [25,40].

One of the most commonly used top-down synthesis techniques is the oxidative cutting. In this technique strong oxidizing agents like $H_2SO_4/HNO_3$ or $KMnO_4/H_2O_2$ are used for cutting graphene oxide or graphite. During these oxidative reactions, mostly the edges of the carbon lattice is attacked, cleaving $sp^2$ domains into nanosized fragments. Further steps of neutralization, reduction or passivation can yield dispersion of GQDs with oxygen-containing functional groups [54]. Such functional groups not only increase the solubility but also enhance photoluminescence properties of GQDs. Oxidative cutting is also scalable and cost-effective, producing GQDs with heterogeneous sizes (2-20 nm). However, oxidative cutting is prone to structural defects which can potentially quench fluorescence [35].

Another effective top-down technique is the Hydrothermal treatment of Graphene oxide or carbon fibers under a high temperature and pressure, in aqueous or organic solvents. This technique is driven by the breakdown of the large carbon framework with the help of the effects of high temperature and solvent reactivity. One of the first to utilize this technique was Pan et al. [37], who synthesized blue-luminescent GQDs and also achieved emission tunability by varying the production parameters. Compared to the previously discussed oxidative cutting, hydrothermal treatments offer a relatively milder condition, which enables better preservation of conjugate domains and high fluorescence quantum yields. Solvothermal techniques further expand this technique to also enable heteroatom doping to enhance its optical and electronic properties [48].

Electrochemical exfoliation has emerged as one of the prominent techniques to achieve stable control over the GQD size, utilizing environmentally friendly approaches. With an applied **voltage, graphite** is electrochemically exfoliated into nanoscale fragments of GQD. The size of the GQDs can essentially be tuned by varying the electrochemical properties such as applied voltage, electrolyte composition, and reaction time [26]. Electrochemical exfoliation avoids the need for dependency on strong oxidizing agents, and allows for facile doping of the dots by manipulating the electrolyte ions accordingly. However, associated major challenges are related to scalability due to equipment size limitation, and potential contamination from electrode materials [53].

A typical procedure using laser is known as Laser ablation of carbon precursors present inside liquid solutions. In this technique, a high energy laser is focused into a specific area which causes localized heating and ablation, breaking down bulk carbon framework into nanoscale fragments. This allows for narrow size distribution of the GQDs but demands for a more sophisticated experimental set up compared to other techniques. Moreover, precise control over the laser parameters are also required [39]. Similar to laser ablation, another technique utilizes ultrasound to exfoliate graphite or carbon fibers, leading to the nanoscale fabrication of GQDs. Such techniques are usually quite simple and also benefit from higher scalability. **However, ultrasound-assisted exfoliation techniques are typically time-consuming and results in low-concentration GQDs** [47].

Therefore, the pivotal advantages of utilizing top-down methods are its scalability and dependency on direct use of inexpensive carbon precursors like graphene oxide and graphite. The as-synthesized dots generally consist of **oxygen-containing** functional groups which assist in modulating solubility, biocompatibility, and surface modifications [42]. However, formidable drawbacks of such techniques are related to the broad size distribution, variations between batches of production, and limited control over shape. These factors largely affect the optical and electronic properties of the quantum dots. Notably, utilizing strong oxidizing agents may introduce impurities, which can adversely affect the end device performance. Hence, the mentioned advantages and corresponding limitations, position the top-down methods to be suitable for applications where high yields and surface functionality is more desired, such as sensors, catalysis, and bioimaging, but not ideal for quantum devices requiring high level of atomic precision [32].

## 3. Applications

Until now, it has been recognized that graphene quantum dots are a promising class of carbon-based nanomaterials with unique optical and electronic properties, such as tunable bandgaps, high photostability, and excellent biocompatibility. All these qualities make them valuable in diverse fields including photovoltaics, biomedical imaging, and environmental sensing. Particularly, in the solar energy field, GQDs enhance light absorption and charge transport, allowing more efficient, flexible, and even cost-effective photovoltaic devices in comparison to the worldwide used PV cells based on silicon. Overall, this section of the review highlights recent advances in the design and application of functional GQDs, emphasizing their key role in next-generation energy technologies.

### 3.1. Medical applications

Within the biomedical domain, GQDs exhibit several distinct advantages over traditional fluorophores, such as organic dyes and heavy-metal-based quantum dots, thereby establishing them as robust candidates for advanced bioimaging. This application plays a crucial role in both biomedical research and clinical uses, enabling the precise visualization of biological phenomena using different regions of the electromagnetic spectrum. As Abdul Rasheed et al. [55] point out, surface modifications with functional groups like amines or aryl substituents allow emission wavelengths to be tailored across the visible spectrum, and the authors likewise indicated quantum yields reaching up to 40%. As a result, that tunable emission wavelengths allow imaging across the visible and near-infrared (NIR) spectrum, particularly useful in the second NIR window for deep-tissue imaging; the reason for its importance is that NIR-II fluorescence reduces tissue scattering and autofluorescence, substantially enhancing the signal-to-noise ratio in biological environments.

Other significant property of GQDs is their photostability, being this quality what allows them to demonstrate remarkable resistance to photobleaching, enabling the maintenance of stable fluorescence signals during extended imaging sessions. Taking into consideration long term studies such as monitoring of live cells, dynamic biological processes, or therapeutic response, this resistance to photobleaching renders them particularly advantageous, especially in comparison with conventional fluorophores, that often suffer from rapid signal deterioration under continuous light exposure [56]. Building on this property, a recent study introduced a novel "planted GQDs" approach, wherein they were synthesized in situ within the polyethylene glycol (PEG) shell of PEGylated nanoparticles. This innovative configuration significantly has good results: first, it enhanced the bioavailability and imaging performance of GQDs, yielding up to even 8 times higher tumor accumulation, and a fourfold increase in blood circulation time compared to conventional GQD formulations. Second, this system exhibited highly stable fluorescence, facilitating long-term in vivo imaging and precise tracking of nanoparticle pharmacokinetics in tumor-bearing models. Finally, the precise modification of surface ligands allowed for targeted multimodal imaging across multiple tumor types within this diagnostic platform [57].

**Another essential advantage is their inherent carbonaceous composition, which completely eliminates the risks of tissue accumulation and long-term toxicity associated with metallic residues. Furthermore, their aqueous solubility minimizes aggregation-induced cytotoxic responses commonly observed with other nanomaterials.** As reported by the Chung et al. [32], studies have shown that GQDs modified with functional groups such as amino, carboxyl and -CHO-$N(CH_3)_2$, remain non-toxic to cells at concentrations up to 200 μg/mL, while hydroxyl functionalized GQDs only exhibit cytotoxic effects at higher concentrations. Those results are valuable because hydroxyl groups on GQDs tend to cause cytotoxicity at higher doses by generating reactive oxygen species (ROS) upon irradiation, which can damage cells by oxidative stress, leading to cell death or inflammation. In contrast, GQDs with amino, carboxyl, or -CHO-$N(CH_3)_2$ groups generate fewer ROS, making them safer for medical applications that involve exposure to light or radiation. Adding to these results, in vivo studies using carboxylated GQDs have demonstrated efficient clearance from mouse organs within 12 hours, emphasizing no significant differences in blood counts or histological analyses compared to controls, even at relatively high doses.

In a more specific application as cancer diagnostics, imaging is particularly valuable, as its high sensitivity facilitates early tumor detection, as well as the identification of metastases and cancer recurrence. One notable 2025 analysis on glioblastoma emphasizes that sulfur-doped GQDs (S-GQDs) conjugated with targeting peptides (Ang-2) were integrated into a biosensor platform for selective glioma cell detection with a low limit of detection (40 cells/mL) in both buffer and serum; with this configuration, the biosensor relies on changes in electrical impedance when glioma cells bind to the sensor surface, allowing sensitive and specific detection of cancer cells [58].

Further exploring their application in cancer diagnosis, Chen et al. [59] introduced a novel single-molecule hydrophilic pure graphene quantum **dots (HPGQDs)**, as **photosensitizers** for photodynamic therapy (PDT). This therapy is very valuable in the cancer diagnosis area, because it uses an agent that when it is exposed to a specific light wavelength, it activates only cancer cells, clearly minimizing damage to surrounding healthy tissue. **The presented nanostructures successfully** enhance intramolecular charge transfer and promote efficient generation of reactive oxygen species (ROS) upon light irradiation, using a unique donor-acceptor molecular architecture, called D12 A, containing one central electron donor and twelve peripheral electron acceptors. Remarkably, it achieves a singlet oxygen quantum yield as high as 0.85 and exhibits rapid ROS production within just 30 seconds of light exposure, followed by efficient ROS scavenging after just 10 minutes. These results mean rapid kinetics and considering that slow kinetics are one of the primary clinical limitations of traditional PDT, the **HPGQDs** address that restriction by vastly reducing the patient's photosensitivity period. Consequently, the research establishes **HPGQDs** as a highly efficient, next-generation nano-photosensitizer suitable for advanced and clinically advantageous oncological applications.

Also, recent developments have highlighted the potential of nitrogen-doped graphene quantum dots (N-GQDs) in the development of high-performance electrochemical immunosensors for cancer diagnostics. Zhengzheng et al. [60] reported the in situ growth of gold nanoparticles (AuNPs) on N-GQDs anchored onto reduced graphene oxide (rGO) nanosheets, forming a ternary nanocomposite named as AuNPs/N-GQDs@rGO; these nanocomposites provided abundant functional sites, such as amino groups, for efficient antibody immobilization via Au-$NH_2$ interactions. The resulting label-free electrochemical immunosensor demonstrated exceptional sensitivity for carcinoembryonic antigen detection, achieving a low detection limit of 0.13 pg/mL and a broad linear range from 1 pg/mL to 0.5 μg/mL. **Moreover, the platform confirmed its promise for clinical cancer biomarker screening by demonstrating crucial characteristics such as excellent selectivity, reproducibility, anti-fouling capability, and stability in fetal bovine serum samples. Additionally, the incorporation of N-GQDs not only enhanced conductivity through nitrogen doping but also served as a structural spacer to prevent graphene restacking, thus ensuring a high surface area and stability**.

Regarding further diagnostic applications, GQDs have established themselves as prominent candidates for next-generation magnetic resonance imaging (MRI) contrast agents, owing to their ultra-small dimensions, facilitated surface functionalization, and superior biocompatibility. In a recent study, Li et al. [61] developed a T1-weighted nano-contrast agent by conjugating GQDs with gadolinium diethylenetriaminepentaacetic acid, represented by Gd(DTPA), resulting in a Gd(DTPA)-GQDs with a longitudinal relaxivity of 10.90 $mM^{-1}s^{-1}$, more than twice that of the commercial Gd-DTPA, usually of 4.18 $mM^{-1}s^{-1}$, indicating a profound enhancement in MRI signal intensity. In addition to this high relaxivity, Gd(DTPA)-GQDs demonstrated excellent colloidal stability in physiological media, low protein adsorption due to **their PEGylated surface,** and negligible cytotoxicity across multiple human cell lines. Furthermore, enhanced T1 contrast in tumor sites was observed up to 2 hours post-injection, confirming their effective tumor accumulation and imaging capability.

Graphene quantum dots represent a transformative platform for **targeted drug delivery. Their unique physicochemical traits and high dispersion stability provide a safe, highly efficient vehicle for intracellular transport without the risk of aggregation-induced toxicity.**

A study by Prabhakar et al. [62] describes an approach for producing GQDs from carbon black through oxidation and a solventless ball-milling method, resulting in nano-sized, water-soluble, and highly fluorescent carriers loaded with the anti-cancer drug B-Lapachone via non-covalent π-π interactions. When evaluated against multiple cell lines (HeLa, MCF-7, PC-12, and LO2), the functionalized GQDs demonstrated high biocompatibility and specific concentration-dependent cellular internalization. In the first case, dialysis tests exhibited a significantly accelerated and targeted drug release profile in simulated acidic cancer environments (pH 5.5) compared to physiological blood pH (7.3), which was uniquely trackable through the quantitative fluorescence recovery of GQDs. For the second case, cytotoxicity assessments showed that the GQD-drug conjugate enhanced cancer cell death relative to the free drug, successfully mitigating the need for excessive drug doses and their related side effects. Overall, the research highlights the potential of scalable, ball-milled GQDs as versatile, biocompatible platforms for enhanced and visually trackable anti-cancer drug delivery.

The work of Vatanparast and Shariatinia [63] provides a comprehensive theoretical evaluation of N-doped GQDs utilizing a combined density functional theory (DFT) and molecular dynamics (MD) approach to understand the role of different nitrogen functionalities in delivering the anti-cancer drug gemcitabine (GC). An investigation into their molecular interactions via MD simulations and DFT calculations demonstrated that GC spontaneously loaded onto all modeled nanocarriers, with center N-GQDs (graphitic, pyridinic, and amido) exhibiting significantly greater binding energies than pristine GQDs or edge N-GQDs. Specifically, simulated release profiles revealed that favorable drug detachment predominantly occurred from these center N-GQDs under the acidic conditions typical of cancer tissues. Regarding cellular internalization, steered molecular dynamics assessments showed that the required force to pull drug-loaded nanocarriers across a lipid bilayer membrane was minimized when penetrating perpendicularly, though N-doped GQDs required slightly more force than pristine variants due to stronger membrane interactions. Ultimately, these findings underscore the critical importance of specific nitrogen-doping positions in designing structurally optimized GQD nanocarriers with superior drug delivery performance.

In a report of Osorio et al. [64] the authors introduced GQDs derived from natural carbon sources and biomass, detailing both

top-down and bottom-up synthesis strategies to create highly biocompatible platforms for drug and gene delivery. An examination of their therapeutic loading capabilities revealed that these naturally sourced GQDs exhibit outstanding efficiency due to their high surface-to-volume ratio and abundant functional groups, which enable the stable binding of chemotherapeutics like doxorubicin via π-π stacking and electrostatic interactions. Notably, the inherent physicochemical properties of GQDs facilitated targeted, pH-responsive drug release directly within the acidic tumor microenvironment, superiorly lowering required therapeutic doses while minimizing systemic toxicity. Beyond their role as carriers, integration studies demonstrated that GQDs synergize with photothermal and photodynamic therapies, generating localized heat and reactive oxygen species under specific light irradiation to further eradicate cancer cells. In essence, this study validates the potential of eco-friendly, natural-source GQDs as multifunctional, targeted vectors capable of revolutionizing combinatorial cancer treatments.

Iannazzo et al. [65] present an innovative targeted drug delivery system by covalently conjugating a biotin (BTN) targeting module to GQDs synthesized via acidic oxidation and exfoliation of multi-walled carbon nanotubes and subsequently loading them with the intercalating drug doxorubicin (DOX). Upon investigating their biocompatibility and cellular interaction using A549 human lung epithelial cancer cells, the synthesized nano-vehicles proved harmless while demonstrating rapid, receptor-mediated endocytosis. Initial cytofluorimetric tracking exhibited a 27% higher and more sustained cellular uptake of the targeted GQD-BTN-DOX complex compared to non-targeted equivalents or the free drug alone. Subsequent confocal microscopy assessments revealed a delayed but marked nuclear internalization of DOX, facilitated by the specific pH-triggered detachment of the drug within the acidic endosomal compartments of the cancer cells. In summary, the findings emphasize the superiority of multimodal, biotin-functionalized GQDs as cell-traceable nanocarriers that improve therapeutic responses and minimize systemic toxicity in targeted cancer chemotherapy.

Li et al. [66] developed a highly efficient smart drug-delivery nanosystem by modifying carboxylated graphene quantum dots (cGQDs) with NH2-poly(ethylene glycol)-NH2 (PEG) and folic acid (FA), resulting in a stable vehicle for the chemotherapeutic agent mitoxantrone (MTN). Comprehensive in vitro and in vivo assessments revealed that the targeted FA-PEG-cGQDs-MTN complexes achieved an unrivaled entrapment efficiency of 97.5% alongside precisely triggered drug release under acidic conditions. Specifically, in vitro assays involving folate receptor-overexpressing HeLa cells exhibited specific, macropinocytosis-dependent cellular uptake that effectively induced apoptosis via the Bcl-2 pathway with minimal macrophage phagocytosis. Furthermore, in vivo investigations involving intravenous administration in cervical tumor-bearing mouse models demonstrated superior targeting capability, leading to massive nanocomplex accumulation at the tumor site and an extraordinary tumor growth inhibition rate of 99.68%, while entirely avoiding off-target damage to major organs. This study shows the immense clinical potential of dual-modified cGQDs as highly biocompatible, immune-evading nanocarriers for safe and precisely targeted in vivo tumor chemotherapy.

### 3.2. Metal Ion detection – environmental monitoring and food safety applications

Emerging strategies based on GQDs have demonstrated their expanding role in optoelectronic sensing applications, particularly for selective metal ion detection. Li et al. [67] synthesized boron-doped orange fluorescent GQDs (o-GQDs) that exhibited strong photoluminescence with an excitation maximum at 480 nm and an emission maximum at 630 nm, producing bright orange fluorescence under UV illumination. The product maintained consistent fluorescence over prolonged periods and under varied pH conditions, in other words, it demonstrated excellent photostability. After doing the respective metal ion sensing tests, the o-GQDs revealed a pronounced fluorescence quenching effect upon exposure to Al ions, attributed to strong chelation between Al and the nitrogen/oxygen-containing functional groups on the o-GQD surface. Also, the authors take in consideration the possible reuse of the material, concluding that the quenching process was reversible by addition of EDTA, confirming potential for reusable sensor design.

Li et al. [68] report the facile synthesis of aminated graphene quantum dots (N-GQDs), using an hydrothermal treatment of nitronaphthalene followed by reduction with hydrazine hydrate, all this resulting in green fluorescent quantum dots with very valuable characteristics such as enhanced photoluminescence performance and stability in both approaches: superior fluorescence stability under varying pH conditions and excellent dispersion stability in aqueous media. **Regarding their application, the N-GQDs showed** selective and sensitive fluorescent quenching responses toward $Cu^{2+}$ and $Co^{2+}$ ions. **This behavior is** attributed to fast and strong chelation kinetics between surface amino and oxygen-containing functional groups and the metal ions. The authors also reported zeta potential values around +10 mV at neutral pH. **This positive surface charge promotes excellent colloidal stability, ensuring that the quantum dots remain well-dispersed in solution without aggregating. Such stability is** crucial for consistent and reliable sensing performance.

You et al. [69] demonstrated a dual-modal detection method for copper ions, where they synthesized blue-emitting GQDs via a modified citric acid pyrolysis method. The ion detection mechanism relied on a Fenton-like reaction catalyzed by copper ions in the presence of ascorbic acid, generating hydroxyl radicals that irreversibly disrupted the GQDs structure, causing fluorescence quenching. This process allowed for sensitive detection within a linear range of 40 to 2000 nM, with a detection limit as low as 40 nM, showing the method's high sensitivity. Also, the method enabled semi-quantitative visual detection using a portable UV instrument, this being very advantageous because users can quickly assess copper contamination on-site without needing

complex lab equipment. Furthermore, the analytical system demonstrated a minimum detectable concentration of 10 μM, effectively surpassing established regulatory safety thresholds. Consequently, this methodology enables the identification of hazardous copper levels in accordance with public health standards, thereby facilitating prompt and decisive intervention.

Zhang's team [70] developed highly innovative nitrogen-doped graphene quantum dots, synthesized from graphene oxide in the presence of N,N-dimethylformamide (DMF) via a solvothermal process. The resulting nanomaterial exhibits intense cyan emission, which is extremely susceptible to quenching in the presence of $Fe^{3+}$ ions (limit of detection at just 0.00238 μM). The sensor's mechanism is based on the inner filter effect (IFE) combined with the static quenching effect (SQE) induced by the coordination of cations by surface hydroxyl groups. The most significant achievement of this work, however, is the application of N-GQDs in portable hydrogel kits and flexible films, which enabled the visual detection of iron in field conditions. This sensor also acted as an "AND" logic gate – after the signal was quenched by $Fe^{3+}$, the addition of adenosine triphosphate (ATP) restored the original fluorescence.

Following the trend of green chemistry, Ratnesh's team [71] presented a solvent-free, microwave-assisted synthesis of GQDs using biomass waste from mango leaves (*Mangifera indica*). The resulting undoped dots were characterized by a very high quantum yield (45%). They were used to determine iron(II) cations with a detection limit of 4.07 μM, based on the quenching mechanism ("turn-off"). This system was also enriched with molecular logic operations, enabling innovative dual detection of $Fe^{2+}$ and cholesterol molecules in the tested samples.

Another evolution in the determination of the harder-to-chelate iron(II) was presented by the team of Pimsin et al. [72]. They synthesized multi-element doped N,S,I-GQDs using a pyrolysis method in the presence of iodine and sulfur. Exceptionally, garlic extract was used as an auxiliary, fully natural chelating agent in the system. The detection process was carried out via luminescence quenching ("turn-off") and was distinguished by an excellent, consecutive dual linear working range and a limited detection threshold of 1.16 μM, allowing for rapid ion identification without the use of harsh reagents.

The problem of extremely toxic mercury ($Hg^{2+}$) was addressed in the work of Shi et al. [73], who used a one-step ("one-pot") synthesis strategy from citric acid and L-DOPA. This yielded highly charged, oxygen-rich, and nitrogen-doped GQDs. These dots exhibited high photoluminescence dependent on the pH of the environment. The addition of mercury caused the almost immediate formation of strong complexes with oxygen atoms on the dot's surface. This coordination stimulated a rapid, non-radiative transfer of localized electrons from GQDs to the empty *d* orbitals of mercury, reducing the probe's emission proportionally to the amount of metal (LOD: 0.0086 μM, or approx. 8.6 nM).

Multi-target precision was investigated in detail in systems with edge-modified carbon structures dedicated to the determination of lead ($Pb^{2+}$) and hypochlorite anions. Developed by Nandi et al. [74] strategy defined as "hitting multiple targets with one arrow," specific chemical modifications focused exclusively on the outer shells of the dot were introduced. Such functionalization minimized steric hindrances in accessing the active sites for the large lead molecule. This directly translated into measurement reliability *in vivo* and enabled the tracking of toxic $Pb^{2+}$ inside living cells, generating a signal resistant to biological background phenomena.

While most studies focus on toxic metals, Cheng et al. [75] demonstrated the remarkable potential of dopamine-modified GQDs (DA-GQDs) in monitoring physiological calcium ions ($Ca^{2+}$). DA-GQDs stood out for their specific photophysical behavior in the presence of $Ca^{2+}$ – the detection process was not based on quenching, but on a powerful fluorescence enhancement ("turn-on"). The binding of the cation to the dopamine structure on the dot blocked the primary photoinduced electron transfer (PET) in the molecule and stiffened it, leading to the recovery of bright, blue emission with distinguished sensitivity (LOD 50 nM). The ability to precisely image the increase in calcium concentration was proven in living human retinal pigment epithelium cells (ARPE-19), paving the way for advanced physiological diagnostics.

An unprecedented application of a deliberately designed carbon architecture was presented in a paper dedicated to the detection of soluble radioactive elements: uranium and thorium. Through the covalent surface modification of nitrogen dots with phytic acid (PA@N-GQDs), a chemical "trap" was created, highly selective towards actinides at a slightly acidic pH (±5.0). The interaction of heavy, radioactive cations with the electron density of PA@N-GQDs resulted in immediate and highly sensitive photoluminescence quenching. The sensitivity of this solution reached a phenomenal nanomolar level, generating an LOD of 0.00201 μM (2.01 nM) for uranium ($U^{6+}$) and 0.00135 μM (1.35 nM) for thorium ($Th^{4+}$), opening a new, safe chapter in the analytics of contaminated reactor environments [76].

As a final example in this area, Li et al. [77] developed a sustainable and scalable method to make two types of graphene quantum dots: blue (c-GQDs) and yellow (y-GQDs), using nitronaphthalene as a starting material and p-aminobenzoic acid (PABA) as a modulator. Thanks to the electron-withdrawing effect of the carboxyl groups in PABA, they achieved a major red shift in fluorescence, which improved the sensitivity of the yellow GQDs for detecting $Cu^{2+}$ ions. The electron-withdrawing nature of the carboxyl groups in PABA induces a redistribution of electronic density within the GQD structure. This modification shifts internal energy levels to produce a fluorescence red shift, significantly enhancing the sensitivity of the GQDs toward copper ions ($Cu^{2+}$). It is reported that the yellow GQDs showed a high quantum yield of 29.75%, excellent stability, and strong selectivity and sensitivity toward copper ions, outperforming other metal ions tested. The following table summarizes recent breakthroughs in metal ion detection using GQDs and composites (TABLE 1).

TABLE 1

GQD Sensors for metal ion detection: key features

| Metal ion | Detection approach | Key Feature | Source |
|---|---|---|---|
| $Al^{3+}$ | Fluorescence quenching (Orange emission, 630 nm) | Reversible quenching process through the addition of EDTA; exceptional photostability across various pH levels. | [67] |
| $Cu^{2+}$, $Co^{2+}$ | Fluorescence quenching (Green emission) | Use of aminated quantum dots (N-GQDs) with a positive zeta potential (+10 mV), ensuring superior colloidal stability and dispersion. | [68] |
| $Cu^{2+}$ | Fenton-like reaction (Irreversible structural disruption) | Dual-modal detection (fluorescence and visual); allows for semi-quantitative on-site assessment via portable UV instruments. | [69] |
| $Cu^{2+}$ | Fluorescence quenching (Yellow emission) | Significant fluorescence red shift induced by electron-withdrawing carboxyl groups in PABA | [77] |
| $Fe^{2+}$ | Dual On-Off sensing | Solvent-free synthesis from mango leaves; molecular logic operation. | [71] |
| $Fe^{2+}$ | Fluorescence quenching | Multi-doped N,S,I-GQDs using garlic extract as a natural green chelator. | [72] |
| $Fe^{3+}$ | Fluorescence quenching (Cyan emission, IFE and SQE mechanism) | Integration into portable hydrogel kits and flexible films for field detection; functions as an "AND" logic gate with ATP. | [70] |
| $Hg^{2+}$ | Fluorescence quenching (N-OGQDs, one-pot synthesis) | Rapid non-radiative electron transfer to the empty d-orbitals of mercury; high pH-dependent photoluminescence. | [73] |
| $Pb^{2+}$ | Fluorescence quenching (Edge-modified structures) | Minimized steric hindrance for large molecules; enables reliable in vivo tracking and imaging inside living cells. | [74] |
| $Ca^{2+}$ | Fluorescence enhancement ("Turn-on" mechanism) | Detection based on blocking photoinduced electron transfer (PET) and molecular stiffening; applied in ARPE-19 cell imaging. | [75] |
| $U^{6+}$, $Th^{4+}$ | Fluorescence quenching (Phytic acid modified PA@N-GQDs) | High selectivity toward radioactive actinides at slightly acidic pH (±5.0); represents a safe analytical tool for reactor environments. | [76] |

### 3.3. Energy applications

Considering all the mentioned qualities of GQDs, they are promising candidates for a broad spectrum of energy-related applications. In recent years, they have been successfully integrated into electrodes for batteries and supercapacitors, where they enhance conductivity, facilitate charge transport, and improve electrochemical stability.

The study by Hwang [78] reports the development of a novel composite anode material for lithium-ion batteries, combining GQDs, silicon oxide (SiOx) with varying weight percentages from 0 to 30 wt.% and carbon nanoparticles as a structural stabilizer. It is important to consider that, typically, silicon oxide expands and contracts repeatedly as lithium ions move in and out during battery cycling, and this creates mechanical stress inside the electrode material, which can lead to cracking, pulverization, or loss of electrical contact within the electrode. Such structural fluctuations of the SiOx during charge-discharge cycles causes the deterioration of battery's performance over time. **However, the composite reported by Hwang successfully mitigates this degradation. Addressing the specific nature of this buffering mechanism, the stabilization is primarily mechanical and structural rather than reliant on covalent bonding. The integration of GQDs and carbon nanoparticles creates a highly porous composite with dedicated internal cavities. These cavities share space with the silicon oxide, acting as a physical mechanical buffer that effectively accommodates the immense stress caused by volume changes during continuous charging and discharging. This porous architecture preserves the structural integrity and maintains robust electrical contact within the electrode, all without inducing unwanted structural changes to SiC during synthesis.** Moreover, electrochemical testing revealed that the composite with 15 wt.% SiOx achieves an optimal balance, showing a high initial discharge capacity of 595 mAh/g, good cycle stability and improved initial coulombic efficiency around 77%, where this last parameter indicates how efficiently the battery converts charge during the first cycle, with higher values meaning less energy loss and better overall battery performance.

The use of GQDs as heteroatom-doped or metal-free catalysts has shown great promise in energy conversion processes such as the hydrogen evolution reaction (HER). Regarding its technical significance, HER facilitates the electrochemical generation of hydrogen fuel via water splitting, serving as a foundational process for clean energy technologies such as hydrogen fuel cells. Recent studies have demonstrated that heteroatom-doped GQDs, particularly nitrogen-doped variants, can act as metal-free electrocatalysts for HER, offering a sustainable and cost-effective alternative to noble metal catalysts. Noble metal catalysts like platinum are currently the most effective materials for the hydrogen evolution reaction (HER), but they have a high cost and limited availability; so, considering these two major drawbacks, this application of GQDs is especially advantageous. For example, ethylenediamine-functionalized GQDs have been shown to significantly improve HER activity under alkaline conditions, where functionalization enhances water dissociation at amide-linked sites, resulting in dramatically increased current density and pH-dependent performance that peaks at pH ≈10 [79].

Green energy technologies **have gained immense importance** in recent years. **Consequently, sustainable and cost-effective synthesis routes (particularly those utilizing biomass-**

**derived sources) are becoming increasingly essential for the development of GQD-based devices.** Atanasio et al. [80] presents an innovative approach for producing GQDs from rice husk agricultural waste through a green, one-pot synthesis involving carbon aerogel precursors and solventless ball milling, yielding crystalline GQDs with an average diameter of approximately 20-30 nm and enriched oxygen-functional groups. Analysis of their performance as electrode materials indicated promising electrochemical activity as both supercapacitor electrodes and lithium-ion battery anodes. Specifically, supercapacitor evaluations yielded initial high capacitance values of approx. 100 $Fg^{-1}$ with stable performance around 55 $Fg^{-1}$ over several cycles, outperforming comparable single-component carbon dot electrodes reported in the literature. In contrast, lithium-ion battery testing demonstrated effective lithium intercalation, although capacity retention remained moderate at approximately 38.6% after 100 cycles due to challenges in electrode cohesion and solid electrolyte interphase formation. Conclusively, this work emphasizes the remarkable potential of eco-friendly, biowaste-derived GQDs as functional materials for advanced energy storage.

In this pursuit of sustainable energy solutions, GQDs have garnered attention as efficient charge mediators in photocatalytic systems for solar energy conversion. Yu et al. [81] demonstrated the successful in situ encapsulation of GQDs into a robust PCN-222 MOF, which is a porous, stable framework made with porphyrin units, which are molecules that absorb visible light well. This design was tailored for visible-light-driven $CO_2$ photoreduction, meaning it uses sunlight to convert $CO_2$ into useful chemicals, like CO, efficiently. The hybrid composite, called GQDs@PCN-222, achieved a remarkable CO production rate of 147.8 $\mu mol\ g^{-1}\ h^{-1}$, which is nearly four times higher than that of pristine PCN-222, under simulated sunlight. Outstandingly, the structural integrity and porosity of the MOF framework were preserved after GQD integration, ensuring sustained catalytic activity and material stability.

The integration of graphene quantum dots has also proven effective in addressing the structural and kinetic limitations of sodium-ion (Na-ion) battery anodes, particularly those based on transition metal dichalcogenides. As reported in a study regarding high-performance anode materials [82], researchers developed a composite consisting of porous graphene quantum dot-coated molybdenum disulfide ($MoS_2$) to overcome the low intrinsic conductivity and significant volume expansion typically associated with $MoS_2$ during sodiation and desodiation cycles. The porous GQD coating serves a dual purpose: it constructs a robust conductive network that facilitates rapid electron transport and acts as a mechanical buffer to accommodate the stress of volume changes, thereby preventing the pulverization of the active material. Furthermore, the porous architecture of the GQDs enhances electrochemical kinetics by providing shorter diffusion pathways for $Na^+$ ions, which is critical for high-rate performance. This synergistic design resulted in an anode with high reversible capacity and superior cycling stability compared to pristine $MoS_2$ electrodes.

He [83] presents a comprehensive overview of utilizing graphene quantum dots as highly surface-active modifiers to enhance the energy storage capacity and charge-discharge efficiency of zinc batteries. An appraisal of their electrochemical benefits revealed that GQD-integrated electrodes possess a substantial capacity to inhibit deleterious dendrite formation, optimize large-scale electrolyte performance, and provide a high density of active sites. In the context of electrode architecture, the implementation of GQDs as a functional artificial interfacial layer or their direct incorporation into graphite felt yielded a considerable increase in conductivity, facilitating the development of highly stable static zinc-iodide redox batteries with superior efficiency, notably under high-rate conditions. Parallel evaluations of defect-rich, nitrogen-doped GQD composites, such as N-GH-GQD-1000, demonstrated superior oxygen reduction reaction (ORR) catalytic activity relative to commercial Pt/C catalysts, thereby enhancing the operational efficiency, longevity, and reliability of zinc-air batteries. In summary, these findings demonstrate the profound potential of GQDs as conductive, structurally tunable modifying agents for the fabrication of stable, high-performance next-generation zinc batteries.

Beyond electrochemical storage, GQDs have demonstrated superior potential in enhancing the structural integrity and gas impermeability of high-pressure hydrogen storage systems. As discussed in recent literature regarding functionalized carbon nanostructures [84], the primary mechanism for improving barrier properties is the creation of a “tortuous path” that obstructs the diffusion of extremely small hydrogen molecules through the polymer matrix. By integrating functionalized GQDs into materials such as epoxy resins, these nanostructures effectively fill interstitial molecular spaces, greatly reducing the free volume available for gas transport. The efficacy of these barriers relies heavily on surface functionalization with groups such as amines, hydroxyls, or carboxyls, which prevent nanoparticle agglomeration and ensure robust interfacial adhesion. This chemical bonding eliminates micro-voids at the interface that would otherwise serve as high-speed leakage pathways for hydrogen. Additionally, in metallic or hybrid systems, GQD-based coatings provide a secondary defense by blocking the entry of atomic hydrogen into the metal lattice, thereby mitigating the risk of hydrogen embrittlement. These advancements are particularly relevant for the development of Type IV and V storage tanks, where GQD-reinforced liners can maintain mechanical integrity under high-pressure cycling (up to 700 bar) while significantly reducing permeation rates below regulatory standards.

Having already reviewed several general examples of recent applications in the energy sector, it is worth highlighting that in recent years, special attention has been given to the potential of graphene quantum dots in solar energy conversion, using them to improve next-generation photovoltaic devices due to their ability to optimize light absorption, facilitate charge separation, and integrate seamlessly with lightweight materials, thus offering interesting opportunities for the development of flexible film solar cells and other emerging solar technologies.

### 3.4. Photovoltaic applications

First- and second-generation photovoltaic technologies based on mono/polycrystalline silicon and thin-film materials such as amorphous silicon or gallium arsenide, respectively have demonstrated high efficiency. Nevertheless, their large-scale deployment has been constrained by the high manufacturing and processing costs associated with these semiconductor materials. This challenge has driven predominant research over recent decades into the development of versatile photovoltaic alternatives suitable for emerging applications such as flexible devices and building-integrated photovoltaics (BIPV), while ensuring its low-cost in comparison to current technologies. Within this framework, third-generation solar cells have gained attention; these include organic solar cells, dye-sensitized solar cells (DSSCs), perovskite solar cells (PSCs), and quantum dot-based devices. Fig 1. summarizes the current classification of photovoltaic cells.

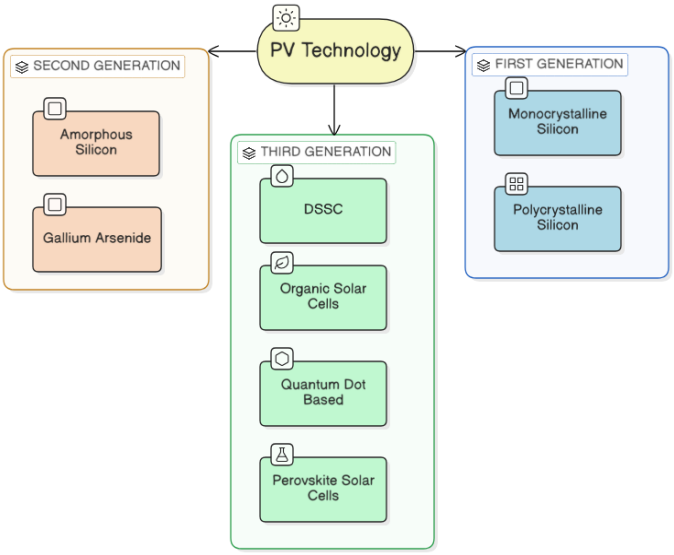


Fig. 1. Generations of photovoltaic technology

The development of photovoltaic technologies and its increase in power conversion efficiencies is illustrated in the Best Research-Cell Efficiency Chart published by the National Renewable Energy Laboratory (NREL) [85], which serves as a key benchmark for tracking improvements across various solar cell types. As it can be seen in the following image, quantum dot (QD)-based solar cells have shown remarkable growth in recent years, evolving from efficiencies below 3% to exceeding 18%. Just the inclusion of QD solar cells in the NREL chart highlights their growing relevance as a competitive alternative to traditional technologies and their potential for improve the current devices with flexible, lightweight, and semitransparent characteristics, areas where graphene quantum dots are particularly promising, as demonstrated in Fig. 2.

Silicon has been the foundational semiconductor for solar photovoltaics since the 1950s. In April 25, 1954, researchers at Bell Labs demonstrated the first practical silicon solar cell (≈6% efficiency) by replacing earlier selenium designs and powering a small toy Ferris wheel, marking the beginning of widespread photovoltaic development. Silicon quickly became dominant for various reasons: its abundance, non-toxic characteristics, it is relatively inexpensive, has been benefited from the extensive manufacturing infrastructure inherited from the microelectronics industry, and well-established processing techniques are available. Moreover, it had a near-optimal bandgap of about 1.1 eV, which balances light absorption with energy conversion [86]. Due to these advantageous characteristics, today, crystalline silicon (c-Si) accounts for approximately 95% of global solar module production [87].

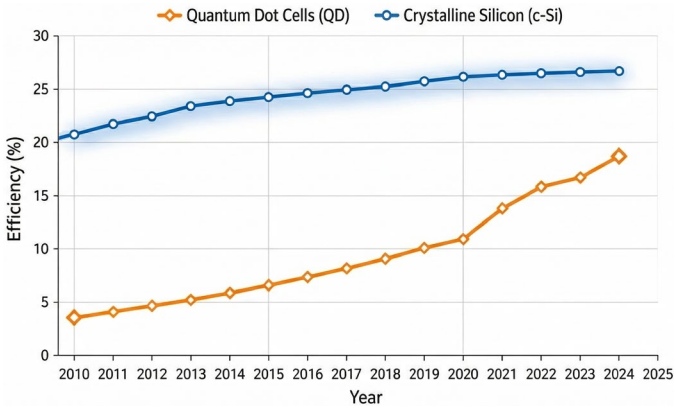


Fig. 2. Comparative efficiency growth of quantum dot solar cells versus crystalline silicon from 2010 to 2025

However, when comparing both technologies within the photovoltaic field, silicon-based solar cells exhibit intrinsic limitations that can be addressed by the use of graphene quantum dots. As a first example, the phenomenon of light-induced degradation (LID) primarily affects boron-doped p-type silicon cells, where upon initial light exposure, boron-oxygen complexes form within the silicon lattice. Those Boron-oxygen complexes are small defect structures created when boron atoms, added during doping, chemically bind with oxygen atoms inside the silicon, considering that oxygen can be present as an impurity from the manufacturing process. As a result, they act as non-radiative recombination centers that reduce the device's energy conversion efficiency. In contrast, GQD-based technologies do not require boron doping, thus completely avoiding the formation of those complexes. In other words, GQD based PV do not exhibit significant LID, offering a distinct advantage in terms of operational stability over conventional silicon-based photovoltaic technologies [88,89].

From the standpoint of flexibility and power-to-weight ratio, conventional crystalline silicon solar panels exhibit major limitations, one of the most notable being that the modules are inherently rigid and heavy, averaging 18-20 kg/m$^2$, which confines their deployment to flat, structurally reinforced surfaces. Also, their stiffness makes them unsuitable for curved or mobile applications without additional support infrastructure. On the contrary, quantum dot based solar cells can be fabricated on ultrathin and flexible substrates, with thicknesses below 2 μm

and weights as low as approx. 6.5 g/m$^2$. For instance, a recent study reported colloidal quantum dot (CQD) solar cells with nearly 10% power conversion efficiency, very remarkable considering QDs are an emerging technology, and an impressive power-to-weight ratio of approx. 15.2 W/g, maintaining robust performance after repeated mechanical deformations [90].

Another intrinsic limitation of silicon solar cells, as pointed out by Ghasemi et al. [91], is that they are fundamentally constrained by the Shockley-Queisser limit, which defines a maximum theoretical efficiency of approx. 33.7% for single-junction devices under standard AM1.5 solar conditions, which is a common reference that represents sunlight reaching the Earth's surface with the sun at a 48° angle. These limitations stem from the inability to absorb sub-bandgap photons and the thermalization losses of high-energy photons, which are not fully harnessed by the fixed-bandgap absorber [92]. In contrast, due to the tunable bandgap of GQD, it is possible a broader spectral absorption and the potential for multiple exciton generation (MEG), a very noteworthy process in this field because it can significantly increase the number of charge carriers generated per photon, leading to a potential increase in the solar cell's efficiency because more electrical current can be extracted from the same amount of sunlight. Furthermore, this is highly advantageous considering that, despite advanced device architectures, practical silicon cells reach efficiencies close only to 29-30%, bounded by their fixed 1.1 eV bandgap [93].

Moreover, N. Parvathala Reddy et al. [94] noted that hydrogenated amorphous silicon solar cells exhibit a marked decline in performance, usually between 10% and 30%, within the first few hundred hours or months of illumination. This phenomenon is attributed to the Staebler Wronski Effect (SWE), in which prolonged light exposure induces the formation of metastable defect states, primarily silicon dangling bonds, that enhance non-radiative recombination and reduce both photoconductivity and carrier lifetimes [95]. Also, according to the authors Wetzler et al. [96], most of this degradation occurs during the initial 100 to 400 hours of continuous light exposure, after which device performance typically stabilizes. Conversely, GQD based solar cells are inherently immune to the SWE, as their photoactive mechanisms originate from quantum confinement and surface-state dynamics rather than from extended disordered silicon networks.

In solar cell research, high efficiency alone is not enough; it is critical to consider that the technology must also be scalable and cost-effective for commercial adoption. Referring to silicon-based solar cells, El Khamisy et al. [97] point out that passivation layers and light-trapping strategies help mitigate some efficiency losses, quite important considering that efficiency is an aspect that is still currently considered weak in solar cells, by reducing surface recombination and enhancing photon absorption within the silicon wafer, but these techniques introduce additional complexity and cost to module production. This occurs because the passivation layers require precise deposition of high-quality dielectric films, such as silicon nitride or aluminum oxide, to effectively reduce dangling bonds and surface defects that otherwise serve as recombination centers. Along with this, advanced light-trapping schemes involve textured wafer surfaces or optical coatings designed to increase the optical path length of incident light, thereby boosting absorption but often necessitating more intricate fabrication steps. The integration of these methods demands strict process control, increasing manufacturing time and materials usage, which collectively contribute to higher overall production costs. TABLE 2 summarizes the fundamental differences and comparative advantages of GQDs versus traditional silicon-based photovoltaic technologies.

TABLE 2

GQDs vs. silicon in photovoltaic applications

| Feature | Silicon-based PV Cells | Graphene Quantum Dot (GQD)-based PV Cells |
|---|---|---|
| **Photogeneration Mechanism** | Fixed-bandgap absorption (1.1 eV in crystalline Si); indirect bandgap in a-Si:H | Size- and surface-dependent quantum confinement; bandgap tunability through size, shape, and doping |
| **Light-Induced Degradation (LID)** | Present in B-doped p-type Si; caused by boron-oxygen complexes | Not observed; GQDs do not contain boron or form such complexes |
| **Staebler–Wronski Effect (SWE)** | Significant in a-Si:H (10-30% drop i n efficiency during initial exposure) | Not susceptible; no extended disordered bonding network; stable photoluminescence under prolonged UV-visible exposure |
| **Flexibility & Thickness** | Rigid modules; approx. 18-20 kg/m$^2$; unsuitable for flexible or curved surfaces | Can be integrated into ultra-thin flexible substrates (<2 μm); lightweight (6.5 g/m$^2$); adaptable to non-planar geometries |
| **Power-to-Weight Ratio** | Low; limited by structural and encapsulation mass | High; e.g., CQD-based devices report 15.2 W/g |
| **Efficiency Limits** | Shockley-Queisser limited (approx. 33.7%); practical devices reach 27-29.4% depending on architecture | Potential for MEG (Multiple Exciton Generation); theoretical limits exceed single-junction Si; still under active development |
| **Spectral Absorption Range** | Fixed, limited by bandgap; losses due to sub-bandgap transmission and thermalization | Broad absorption; tunable bandgap allows better matching with solar spectrum |
| **Commercial Maturity** | Established, dominant in the global PV market | Emerging; under development in research and early-stage prototypes |
| **Environmental Stability** | Crystalline Si: high stability; a-Si:H: susceptible to SWE | Reported high photostability under continuous UV-visible exposure |

## 4. Conclusion

Graphene Quantum Dots have demonstrated unprecedented properties, establishing them as an important force across renewable energy, environmental monitoring, and healthcare. This versatility necessitates major investment in their practical applications to move beyond academic research. In the energy sector, GQDs have significantly enhanced solar energy conversion by optimizing light absorption and charge separation while minimizing recombination losses. Simultaneously, they have proven to be a pivotal point for advanced energy storage, improving the electrochemical stability and capacity of next-generation batteries and supercapacitors. Beyond energy generation, GQDs have redefined environmental safety through highly selective and sensitive metal ion detection, providing a sustainable alternative for monitoring water and food quality. In the field of health, their excellent biocompatibility and tunable photoluminescence have enabled breakthroughs in high-resolution bioimaging and targeted therapies. However, to fully capitalize on these unique properties, **future research must address key technological challenges, primarily concerning the standardization of synthesis protocols and large-scale manufacturing. Currently, bottom-up synthesis methods (particularly continuous-flow microfluidic approaches) show the most promise for reaching industrial-scale production. Unlike top-down methods that often struggle with batch-to-batch size homogeneity, advanced bottom-up techniques can maintain the necessary atomic-level precision and structural uniformity required for high-performance optoelectronic and quantum devices. Moving forward, key future research directions should focus on standardizing purification processes, fully elucidating the long-term in vivo degradation pathways of GQDs, and integrating them into commercially viable, flexible device architectures. Advancing toward the widespread commercial integration of GQDs will require interdisciplinary collaboration and strategic resource allocation.** By placing GQDs at the forefront of innovation, we can revolutionize the global landscape with an efficient, sustainable, and cost-effective approach to modern technological challenges.

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