Hindawi
Journal of Nanomaterials
Volume 2023, Article ID 2832964, 26 pages
https://doi.org/10.1155/2023/2832964

*Review Article*

# Comprehensive Review on Synthesis, Applications, and Challenges of Graphene Quantum Dots (GQDs)

**Pooja Kadyan**,[1] **Rohit Malik**,[2] **Saurabh Bhatia**,[3,4] **Ahmed Al Harrasi**,[4] **Syam Mohan**,[3,5,6] **Mansi Yadav**,[1,7] **Sunita Dalal**,[8] **Seema Ramniwas**,[9] **Sudhir Kumar Kataria**,[1] **and Thillai Arasu**[10]

[1]*Department of Zoology, Maharshi Dayanand University, Rohtak, Haryana, India*
[2]*Gurugram Global College of Pharmacy, Gurugram, India*
[3]*School of Health Sciences, University of Petroleum and Energy Studies, Dehradun, Uttarakhand, India*
[4]*Natural and Medical Sciences Research Centre, University of Nizwa, Birkat Al Mauz, Oman*
[5]*Substance Abuse and Toxicology Research Centre, Jazan University, Jazan, Saudi Arabia*
[6]*Center for Transdisciplinary Research, Department of Pharmacology, Saveetha Dental College, Saveetha Institute of Medical and Technical Science, Saveetha University, Chennai, India*
[7]*Department of Zoology, Ramjas College, University of Delhi, Delhi, India*
[8]*Department of Biotechnology, Kurukshetra University, Kurukshetra, Haryana, India*
[9]*University Centre for Research and Development & Department of Pharmacy, Chandigarh University, Gharuan, Mohali, Punjab, India*
[10]*Department of Chemistry, Wollega University, P.O. Box 395, Nekemte, Ethiopia*

Correspondence should be addressed to Sudhir Kumar Kataria; sudhir.zoology24@mdurohtak.ac.in and Thillai Arasu; thililaiarasu@wollegauniversity.edu.et

Received 4 November 2022; Revised 4 January 2023; Accepted 5 January 2023; Published 26 January 2023

Academic Editor: Valeri P. Tolstoy



Carbon-based nanomaterials are contemporary and are outpacing the technology platform. Graphene quantum dots (GQDs) had a significant impact on the subject of bioengineering, pharmaceuticals, biomedicine, biosensors, fuel, energy, etc. Depending on how quickly this field is developing, it is important to recognize the new difficulties that GQDs have to overcome. This is incredibly significant because many novel applications and innovations that have made GQD synthesis easier recently have not been systematically evaluated in prior studies. Their ability to combine the benefits of quantum dots, $sp^2$ carbon materials (large specific surface area), and have rich functional groups at the edge makes them special. The naturally occurring inert carbon helps to stabilize chemical and physical characteristics and makes significant advancements in the creation of benchmark photocatalysts. Moreover, current challenges and potential of these rapidly developing GQDs are emphasized. The future of GQD research is limitless, according to the assessment in this review, notably if future research focuses on simplicity of purification and ecofriendly synthesis. This feature article offers a realistic summary on recent developments in the synthesis, characteristics, and uses of GQDs. Frequent review articles focusing on the progress of GQDs for specific applications are published but a thorough review article on GQDs for their numerous uses has not yet been published. The recent trends of scientific research based on new optical biosensing applications, including the comprehensive applications of different zero-dimensional nanomaterials, specially GQDs are discussed in this study.

## 1. Introduction

Fullerene, carbon nanofiber, diamond, grapheme, carbon nanotubes, and GO are all carbon nanomaterials that have been thoroughly investigated for a variety of potential applications [1–3]. Nanotechnology is the focus of contemporary scientific and technical research, and it promises to revolutionize industries such as transportation, medicine, environment, information technology, electronics, and solar energy. Nanotechnology's outstanding skills in shaping materials structures at extremely small sizes to achieve the desired qualities, allow us to realize the true promise of this

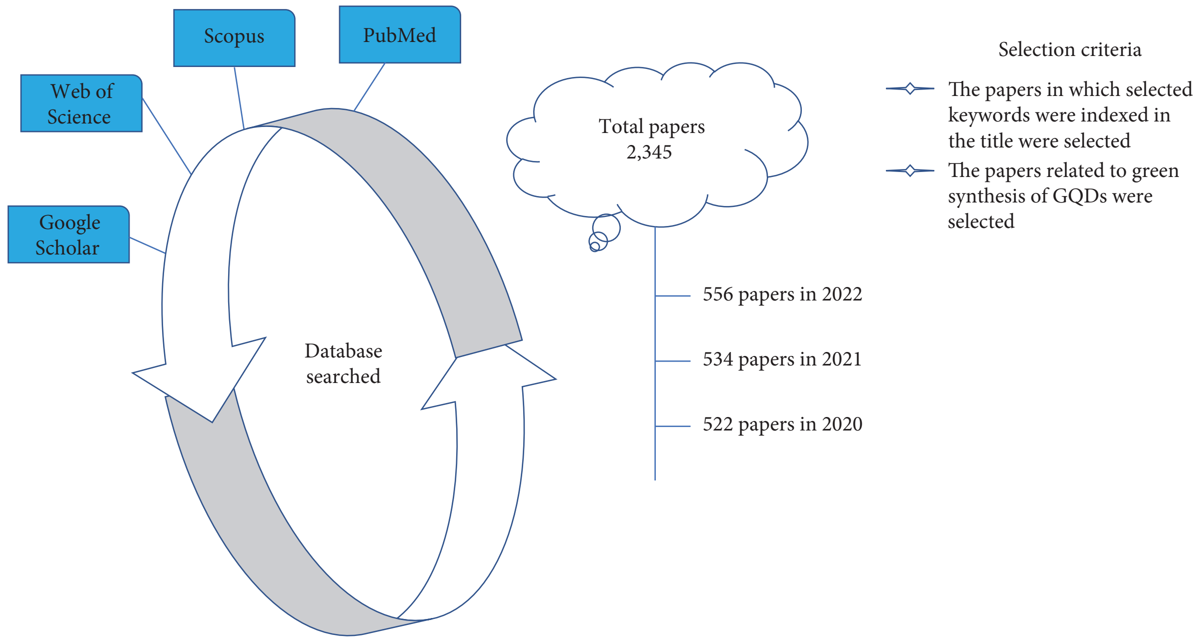


Figure 1: Schematic methodology adapted for review.

technology [4]. Nanomaterials science has advanced rapidly in the last 20 years, resulting in new prospects for materials design in scientific, technological, and industrial applications. Carbon-based materials have sparked the interest of researchers in a variety of potential fields because of their outstanding properties, like tunable structure, large surface area, less toxicity, high conductivity, and long life [5].

Graphene has revolutionized several realms of science and technology from a mysterious chemical to a magnificent legend. This is due to graphene's unique nanoscale properties, which include high current density, chemical stability, high optical permeability, good thermal conductivity, and outstanding hydrophobicity. Graphene has been gaining substantial attention with its two-dimensional, $sp^2$ hybridized extended structure and zero bandgaps, which was purportedly created by mechanical exfoliation in 2004 [6]. Sanchez et al. [7] investigated the facets of graphene-based nanomaterials, such as their toxicity and adequate communication with cells, tissues, and biomolecules as the number of layers increased.

Quantum dots are crystalline materials with diameters ranging from 1 to 10 nm and consist of 100–10,000 atoms that produce light after being excited. In comparison to macrocrystalline materials, their modest size distinguishes them [8]. Quantum dots are notable for their large surface area and optical characteristics, as a result of which they have become a sensor for targeted medication administration and pharmacotherapy. Graphene quantum dots (GQDs) paired with ligands are used to target the cells or tissues in concern. With advancements in the manufacture of biocompatible GQDs, the use of GQDs for *in vivo* studies has recently gained attraction [9]. QDs can have high solubility in plenty of other solvents, such as aqueous buffers when formed as a semiconductor fundamental with a sealant and a cap [10].

Out of 2,345 articles which were available with the above-mentioned keywords only 296 of those articles were chosen using thorough inclusion and exclusion criteria, as shown in Figure 1.

GQDs, which are recent immigrants to the carbon nanomaterials family, are composed of one or few nanometers-size graphene sheets and have extraordinary electrical and optical properties [11]. GQDs are 0D nanomaterials and were initially made from graphene sheets in 2010 using a hydrothermal technique [12]. GQDs have features comparable to graphene, including surface groups like carbonyl, hydroxyl, carboxyl, and epoxy, as well as a crystal structure composed of C, O, and H [13]. GQDs are crystalline and mostly made up of $sp^2$ hybridized carbon. GQDs are luminous due to their quantum confinement, zigzag or armchair edges, and surface defects giving them unique fluorescence features [14–16]. GQDs typically range in size from 3 to 20 nm. However, the largest size being reported is 60 nm [17].

GQDs are accoladed by many researchers due to their intriguing properties, including low cytotoxicity, excellent water solubility, high electrical conductivity, good biocompatibility, chemical stability, photoluminescence, low photobleaching, environmental friendliness, and optoelectronic properties [18]. GQDs have the potential to be used in flash memory devices, solar cells, electronic displays, packaging, LEDs, antibacterial activity, drug delivery, tissue engineering, supercapacitors, batteries, optoelectric detectors, bioimaging, photodynamic therapy photocatalysis, anticancer agent various biosensors, lithium-ion batteries and energy conversion, and theranostic applications [19, 20]. The purpose of this paper is to review the research on the efficacy of green GQDs. The biocompatible, target-specific, and biologically produced GQDs aid in the effective treatment and management of dreadful diseases.

Table 1: Approaches used to synthesize GQDs with its potential applications.

| S. no. | Method | Source | Size (nm) | QY (%) | Applications | References |
|---|---|---|---|---|---|---|
| | | | Process—top-down | | | |
| 1 | Chemical oxidation | CX 72 Carbon black | 15–18 | 2.4–4.0 | Bioimaging and biolabeling | [21] |
| 2 | Hydrothermal | GO | 5–19 | 7.4 | Energy applications | [22] |
| 3 | Solvothermal method | GO | 5.3 | 11.4 | Bioimaging | [23] |
| 4 | Microwave irradiation | GO | ~4.5 | 22.9 | Detection of $Cd^{2+}$ | [24] |
| 5 | Microwave-hydrothermal | Glucose | ~3.4 | 7–11 | Blue and white LED | [25] |
| 6 | Hydrothermal treatment | Graphene sheets | ~2.5 | 19–29 | Bioimaging | [26] |
| 7 | Microwave hydrothermal | GO | 2–6 | 12.5 | Biolabeling and bioimaging | [27] |
| 8 | Microwave irradiation | Graphite | 2–5 | 9 | Bioimaging | [28] |
| 9 | Hydrothermal treatment | 1,3,6-Trinitro-pyrene | ~2.5 | 9.2 | Detection of $Ag^{+}$ ions | [29] |
| 10 | Sonochemical and microwave heating | GO | 2–5 | 23.8 | Metal ions sensing and bioimaging | [30] |
| 11 | Microwave assisted | Glucose and urea | 15 | 11–32 | Removal of triazine | [31] |
| 12 | Hydrothermal treatment | CA | NA | 9% | Photodegradation of methylene blue | [32] |
| 13 | Solvothermal treatment | Graphite | ~35 | 15 | Biomedical applications | [33] |
| 14 | Solvothermal treatment | Graphite | 2.5–50 | 8.8 | Detection of $Tb^{3+}$ and $Eu^{3+}$ | [34] |
| 15 | Solvothermal method | CA | NA | NA | $H_2S$ gas detection | [35] |
| 16 | Electrochemical method | MWCNTs | 3–8.2 | 5.1–6.3 | Nanoelectronic and biomarkers devices | [36] |
| 17 | Electrochemical method | GO | 2.4–4.6 | 7.8 | Biosensor | [37] |
| 18 | Electrochemical | Graphite rod | 5–10 | 14 | Labeling of stem cell | [38] |
| 19 | Electrochemical method | Graphite | ~20 | 18.95 | Bioimaging and detection of $Fe^{+3}$ | [39] |
| | | | Process—bottom-up | | | |
| 20 | Pyrolysis | CA | ~15 | 9.0 | Photovoltaic devices | [40] |
| 21 | Pyrolysis | CA | 5–10 | 22.2 | Biosensing | [41] |
| 22 | Pyrolysis | CA | ~12.7 | 6.91 | Biosensing and bioimaging | [42] |
| 23 | Pyrolysis | L-glutamic acid | ~4.66 | 54.50 | Cell imaging | [43] |
| 24 | Pyrolysis | Trisodium citrate | 1.30 | 3.60 | Cell imaging | [44] |
| 25 | Pyrolysis | Melamine powder | 2–6 | 0.22–0.76 | LED | [45] |
| 26 | Pyrolysis | CA | ~2.0 | 62.8 | Cellular imaging | [46] |

## 2. Synthesis of GQDs

Primarily used methodologies in the synthesis of GQDs are "top-down" and "bottom-up" approaches via diverse synthetic protocols (Table 1). The top-down technique typically employs large $sp^2$ carbon domains like as fullerene, carbon nanofiber, diamond, graphene, carbon nanotubes, and GO. This approach, however, frequently results in a low quantum yield and less photocatalytic activity. The rigid cutting makes controlling the morphologies, dimensions, and the precursors are restricted to bulk carbon materials.

"Bottom-up" synthesis has attracted a lot of interest due to its simple and straightforward preparation process. GQDs are often synthesized from tiny organic molecules including phenyl compounds using a bottom-up approach that involves hydrothermal or solvothermal treatment. Dehydrogenation and carbonization advances are the major reaction processes. This approach can normally produce high-quality GQDs, but the starting ingredients are usually highly toxic, posing a severe environmental risk [47]. To summarize, the bottom-up method is thought to be a suitable choice for synthesizing high-quality GQDs, but the shortcomings of precursors must be overcome.

The science community understood that to achieve the "sustainable green synthesis goals," it is important to manage the plentiful waste biomass that might be used to make graphene-like materials. Fabrication of innovative GQDs with fascinating features from low-cost, renewable plant biomass has been a hot issue [48]. Bioinspired synthesis is more favorable than other traditional approaches to nanomaterial synthesis due to the eco-friendly method and easier availability of biological entities [49]. Plant biomass is primarily constituted of cellulose, hemicellulose, and lignin, the latter of which contributes significantly to structural integrity and chemical resistance [50]. Even though biomass is an eco-friendly, renewable, cost-effective, reliable, and natural source of carbon, it can now be used in the mass production of GQDs [51]. Recently, biomass like rice grain [52], wood charcoal

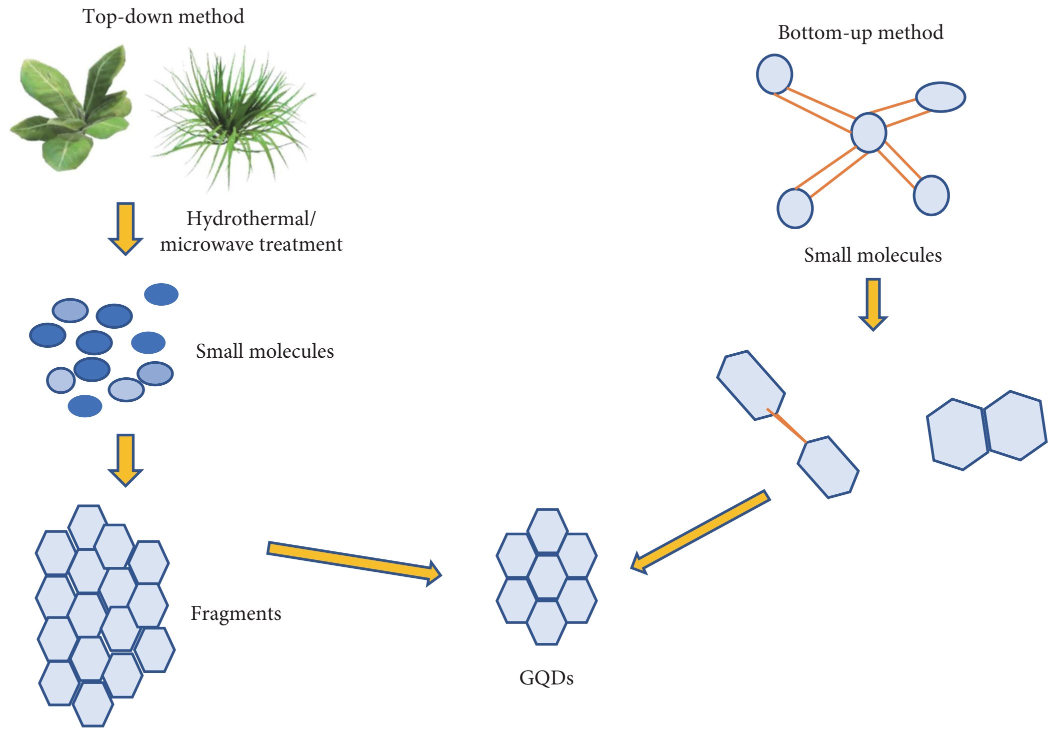


Figure 2: Approaches for synthesis of GQDs.

Table 2: Comparison of synthesis method for GQDs.

| Types | Methods | Advantages | Disadvantages |
|---|---|---|---|
| Top-down | Hydrothermal | Easy, quick, and ecofriendly | It is necessary to use treated carbon material |
| | Electrochemical oxidation | Stable and regular size GQDs formed | Production yield is low |
| | Microwave assisted | Reaction time decreased | It is expensive method |
| | Oxidative cleavage | Large scale production | Oxidizing agent may cause explosion |
| Bottom-up | Controllable synthesis | Stable and regular size GQDs formed | Time consuming process |
| | Carbonization | Facile and ecofriendly method | Polydispersed GQDs may obtained |

[53], tea waste [54], rice husk [55], plant leaves [56], flowers [57], durian, lignin [58], cow milk [59], and molasses [60] have been used as precursors to synthesize GQDs. However, GQDs with high quantum yield is hard to procure directly from biomass material, and investigators enhanced GQD quantum yield by doping of heteroatoms, which complicate the synthesis process. A simple, efficient, environmentally, ecofriendly, and green starting material are desperately needed to produce the best quantum yield GQDs. Figure 2 shows the process of synthesis of GQDs via top-down and bottom-up approaches and Table 2 shows the comparison of both top-down and bottom-up approaches.

GQDs can be synthesized from glucose [61], citric acid [41], and dead neem leaves [62] by pyrolysis; from graphene oxide [63], corn powder [64], cane molasses [65], coconut husk [66] by hydrothermal method; from graphite rod [38], wood charcoal [53] by electrochemical method; from GO [23], guava leaves [67], and dimethylformamide by solvothermal method; from bamboo timber waste [68], neem, fenugreek leaves [69], and cotton cellulose [70] by hydrothermal method, Arjuna Bark [67], *Opuntia* [19], and mango leaf [71] by microwave-assisted method.

*2.1. Green Synthesis.* In recent years, both industrial and academic researchers have turned toward a more broad perspective focused on pollution, sustainable sources, and waste minimization, resulting in the arrival of a new chemistry approach known as green chemistry. The major issues of the modern world include energy scarcity, restricted availability, and overconsumption of nonrenewable resources, as well as increasing degradation of the natural environment [48, 69]. The concerns about global warming and pollution have prompted researchers to look for new functional materials that are clean, sustainable, renewable, and ecologically benign [48, 64].

Biological sources are now used as a source of clean, organic, feasible, cheap, and productive carbon source in the optimized fabrication of GQDs (Table 3). Because biomass is plentiful and cost-effective, and there is no publication on the overall cost of GQD components, the cost of biomass precursors is predicted to be lower than the value

Table 3: GQDs synthesized from biological sources and its applications.

| S. no. | Source | Method | Result | References |
|---|---|---|---|---|
| 1 | Dead neem leaves | Pyrolysis | Detection of $Ag^{+}$ ions | [62] |
| 2 | Mango leaf | Microwave assisted | Detection of intracellular temperature | [71] |
| 3 | Cow milk | Microwave | Bioimaging | [59] |
| 4 | Wood charcoal | Electrochemical synthesis | Detection of $200_2$ and glucose | [53] |
| 5 | Corn powder | Hydrothermal | Lower charge recombination while increasing free charge carriers | [72] |
| 6 | Sugarcane molasses | Hydrothermal | Bioimaging | [73] |
| 7 | Cooking palm oil | Double thermal chemical vapor deposition | Carbon source for the fabrication of graphite | [74] |
| 8 | Rice husk | Hydrothermal method | Extraction of Pb(II) and La(III) from real water | [55, 75] |
| 9 | Sugarcane bagasse | Hydrothermal carbonization | Preparation of better value-added biomass materials | [76] |
| 10 | Turmeric powder | Hydrothermal method | Anti inflammatory activity | [77] |
| 11 | Cotton cellulose | Hydrothermal | Low cytotoxicity | [70] |
| 12 | Mango peels | Hydrothermal | Effective removal of Pb(II) | [78] |
| 13 | Marigold petals | Pyrolysis | Detection of $Fe^{3+}$ ions | [79] |
| 14 | Popcorn powder | Hydrothermal | Antibacterial activity | [80] |
| 15 | *Ziziphus mauritiana* seeds | Microwave assisted | Monitoring of ammonia | [81] |
| 16 | Rice grains | Pyrolysis | Bioimaging | [52] |
| 17 | Cane molasses | Hydrothermal treatment | Bioimaging | [73] |
| 18 | *Passiflora edulis* | Hydrothermal treatment | Cell imaging | [82] |
| 19 | Neem leaf | Hydrothermal method | Bioimaging | [83] |
| 20 | Bamboo timber waste | Hydrothermal method | Detection of curcumin | [68] |
| 21 | Corn powder | Hydrothermal | Engineering application | [64] |
| 22 | Coffee grounds | Hydrothermal cutting | Bioimaging | [84] |
| 23 | Grape seed extract | Microwave assisted | Bioimaging | [85] |
| 24 | Sugarcane bagasse | Hydrothermal method | Antibacterial activity | [86] |
| 25 | Miscanthus | Hydrothermal carbonization | Detection of Tri-channel sensitive $Fe^{3+}$ ions | [87] |
| 26 | Miscanthus | Ultrasound assisted | Synthesis of graphene materials | [88] |
| 27 | Cocoa bean | Hydrothermal method | Bioimaging | [89] |
| 28 | Opuntia | Microwave assisted | Detection of phytic acid | [19] |
| 29 | Marigold flower | Hydrothermal method | Synthesis of a sustainable supercapacitor electrode | [57] |
| 30 | Tea waste | Hydrothermal treatment | Detection of $Fe^{3+}$ | [54] |
| 31 | Molasses | Carbonization | Thermal degradation is observed around 140°C | [60] |
| 32 | Pineapple leaf fiber | Hydrothermal | Detection of $Hg^{2+}$ | [90] |
| 33 | Pinto beans | Hydrothermal | Antibacterial activity | [91] |
| 34 | Lemon leaves | Carbonization | Synthesis of GQDs | [92] |
| 35 | Corn straw | Hydrothermal method | Detection of $PO_4^{3-}$ | [93] |
| 36 | Dhruva grass | Solvothermal method | Photoluminescence property | [94] |
| 37 | Paddy straw | Hydrothermal | Enhancement of dielectric property | [95] |
| 38 | Red onion | Hydrothermal | Electrochemical hydrogen storage | [96] |
| 39 | Garlic extract | Pyrolysis | Chelating agents | [97] |
| 40 | Potato amylose | Hydrothermal | Detection of tetracycline | [98] |
| 41 | Orange peel waste | Hydrothermal | Detection of $Fe^{3+}$ | [99] |
| 42 | Watermelon rind waste | Hydrothermal | Detection of $Fe^{3+}$ | [100] |
| 43 | Tamarind shell powder | Hydrothermal | Detection of uric acid | [101] |
| 44 | Leaves of curry tree | Hydrothermal | Detection of aflatoxin B1 | [102] |
| 45 | Pistachio shells | Hydrothermal | Detection of cysteine | [103] |

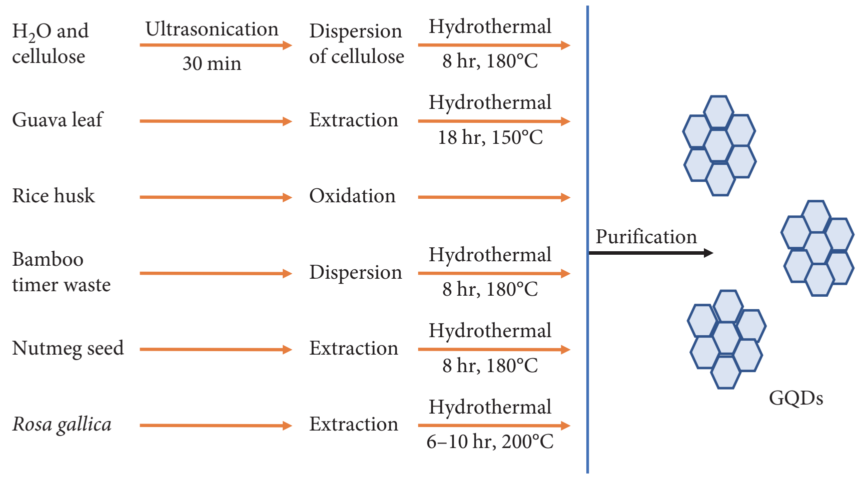


Figure 3: Green synthesis of GQDs from various plant parts [55, 56, 8, 68, 70, 104, 98].

of other precursor chemicals (graphite powder, carbon fiber, glucose, CNTs, and CA). Using various types of biomass, like tea waste [54], plant leaves [56], flowers [57], rice grain [52], coffee grounds [84], miscanthus [88], and wood charcoal [53] GQDs were synthesized, as shown in Figure 3. GQD processing with an extraction yields is more conceivable than the costly graphene-based precursors. GQDs obtained from biomass have a higher quantum yield than graphene and its derivatives. Plant-derived bioinspired GQDs demonstrate promising drug delivery and anticancer activity while posing low cytotoxicity. Plant sources with bioactive compounds as anticancer nanomaterials have various advantages over chemical medications, including the ability to work at lower concentrations, ability to pass the blood–brain barrier, and target specificity. The fundamental benefit of bioinspired nanomaterial is ability to use a wide range of precursors and a variety of technological techniques [64]. Belletti et al. [105] showed cytotoxic effect of curcumin-loaded PLGA nanoparticles with quantum dots on HBL6 and BCBL-1 cell lines. The bioavailability of curcumin and the activity were improved as a result of the loading process. Developing ecofriendly routes to procure GQDs obtained not only from biodegradable materials such as biomass waste, as well as from other natural ingredients found in food or agricultural waste (i.e., lignin, carbohydrates, proteins) without contending with food suppliers without use of any organic solvents, oxidizing, reducing, or passivating agent is a hot topic of research in the twenty-first century.

*2.2. Microwave-Assisted Method.* When compared to other approaches, microwave-assisted nanoparticle production has numerous advantages. The advantage of this method over the hydrothermal method is that it is faster and has a lesser fabrication temperature. Microwave-assisted reactions have a number of advantages, including: (1) low levels of impurities in the products, (2) easy temperature and pressure control, (3) high product efficiency, (4) selective heating (i.e., reduced energy costs), (5) environmental friendliness, (6) high security, (7) reproducibility, and (8) easy control of product size [106, 107]. Microwaves have been proposed by Ayele et al. [9] as bioinspired method for synthesis of CdSe quantum dots [19]. Gu et al. [108] suggested an simple and rapid process for the manufacture of nitrogen-doped GQDs utilizing microwave produced from the root of cedar tree without any surface modification.

*2.3. Electrochemical Oxidation Methods.* Controlling the current–voltage ratio with electrochemical methods allows nanostructures to be adjusted. Electrochemical corrosion methods of carbon reagents occur when a controlled voltage applied to a mass of precursor materials, leading to the formation of nanomaterials. A high temperature does not involve in this process and it can be carried out rapidly on a large scale utilizing any solvents. It is the quickest method to generate graphene sheets [109–111]. Wong et al. [112] proposed using the electrochemical technique to synthesize nitrogen-doped GQDs by the bottom-up approach. This approach is, therefore, simple, clean, and green, which is favorable for larger synthesis having 95% interest rate. The particles have a quantum gain of 0.71 [112].

*2.4. Hydrothermal Method.* The hydrothermal method is a quick and easy way to generate bioactive GQDs, which includes one-step process involving heating a natural precursor to high temperatures and pressures in a teflon line autoclave. The bonds between carbon nanomaterials are disrupted because of high pressure and high temperatures, resulting in bioactive GQDs (Figure 4). Different precursors and temperature optimization can be used to change the electrical–optical characteristics of the particles. To modify the electrical–optical characteristics of the particles, different precursors and temperature optimization can be applied. Using a hydrothermal technique, Liang et al. [113] produced extremely luminous quantum dots from gelatin with ease. Liu et al. [114] created a simple, clean, and cost-effective method for producing luminous quantum dots using hydrothermal processing. They looked into the use of produced quantum dots in $Fe^{3+}$ detection and cell imaging. Wang et al. [93] synthesized GQDs from corn straw to detect phosphate ions.

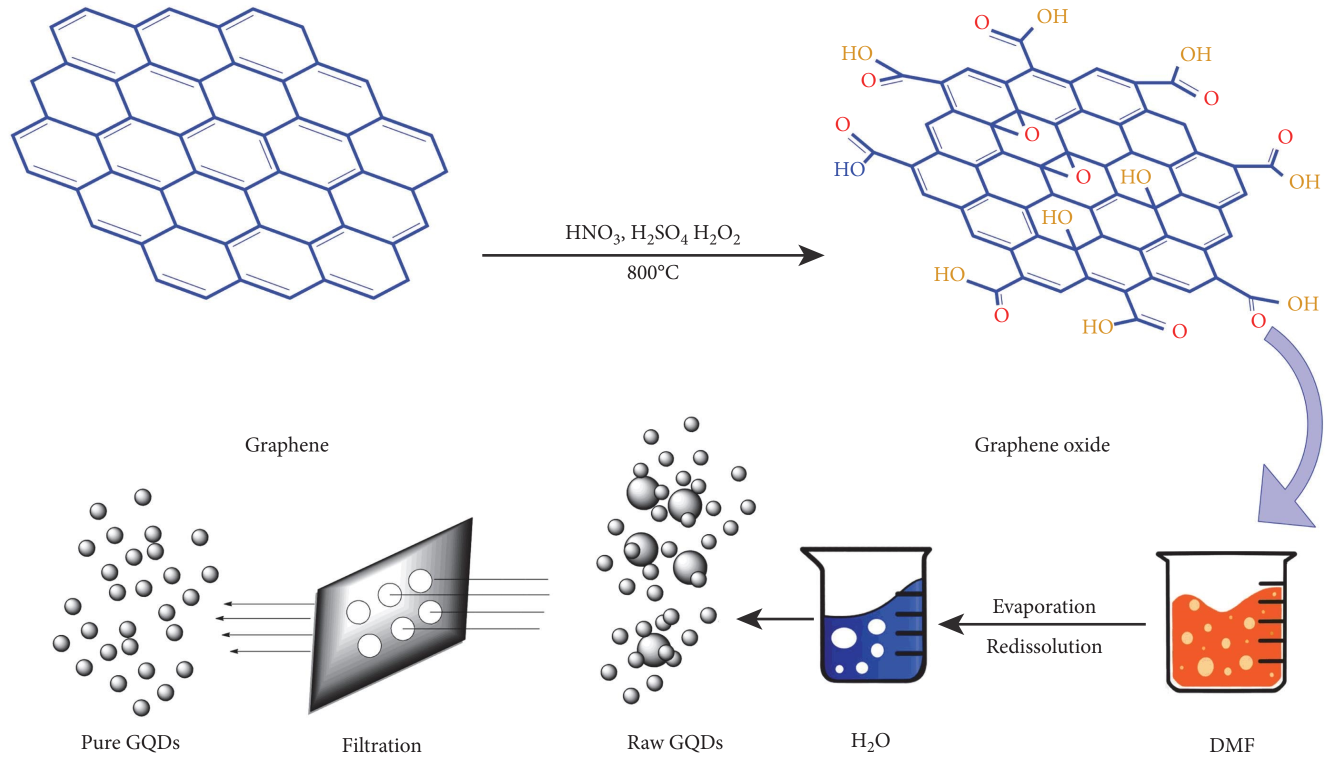


FIGURE 4: Synthesis of GQDs from graphene oxide [33].

*2.5. Ultrasonic Method.* In recent decades, plenty of approaches to develop photocatalyst materials to be used in solar cells have been introduced. Moreover, from the standpoint of green chemistry, the advantages of synthesizing these minerals in unique methods are intriguing. In aspects of science and technology, the concept of producing incredibly effective photocatalytic activity via ultrasound is both exciting and vital, and it holds great potential for developing photocatalysts in the coming future. This method is an encouraging method for controlling material size, structure, and dimension and photocatalytic activity [115]. Zhu et al. [116] used ultrasonic irradiation to produce high GQDs using potassium permanganate and graphene oxide and used them for alkaline phosphate detection test. Kir et al. [92] used lemon as a precursor to create GQDs that were both rapid and ecologically friendly. This method creates nontoxic quantum dots that can be used as optical imaging devices.

*2.6. Liquid Peeling Process.* Liquid peeling (LP) of the 0D materials has a tremendous attention because of their scalability. Additionally, LP is the finest method for producing nanofilms because it offers a number of benefits including easy use, low processing costs, and minimal environmental impact. This procedure converts graphite into graphene sheets, enabling the LP process to produce GQDs with excellent crystallinity. Carbon acetylene powder or graphite powder has also been employed as precursors of low and high flaws in this procedure to create GQDs. Recently, after the intercalation, LP of graphite formed graphene, which has attracted a lot of attention. GQDs were synthesized by using LP probe and by sonication of graphite powder by high-intensity ultrasonic waves. These waves split layers of graphene into ultrafine particles. The process is carried out by the ultra-fine particles, or GQDs, created when these waves separate layers of graphene [117].

*2.7. Method of Soft Template.* In comparison to more conventional synthetic methods, this method was generally an easy and practical way to create nanostructures. The main advantage of using this technology to clarify the properties of any nanoparticles is the ability to efficiently oversee the form, size, and surface texture of graphene nanomaterials. The template system is separated into hard templates and soft templates based on its distinctive form. The soft template method is far more suitable for GQD output in contrast to the hard template method. It may enhance the characteristic nanoscale reaction vacuum smoothly in operations of separation, purification, and mass processing [117].

## 3. Applications

*3.1. Sensors.* QDs are an enthralling collection of materials. It is a class of materials that have unusual fluorescence properties. The ability to fluoresce efficiently is the primary reason why QDs offer so much potential in a variety of sensing applications [118]. GQDs have intriguing optical absorption properties, with a peak ranging from 260 to 380 nm, making them perfect candidates for the production of photodetectors or optoelectronic devices [119]. They have enzymatic activity similar to peroxidase, which makes them ideal for label-free biosensing [120]. Furthermore, biosensors based on GQDs offer a wide range of applications in illness diagnosis, prognosis, and therapy (Table 4). These biosensors are categorized

Table 4: Applications of GQDs in sensors.

| S. no. | Source | Method | Application | Linear range | LOD | References |
|---|---|---|---|---|---|---|
| 1 | L-glutamic acid | Pyrolysis | Rapid detection of $H_2O_2$ | 0.1–10 Mm | 20 mM | [43] |
| 2 | Glycine | Thermolysis | Determination of $Fe^{3+}$ | 0.5–500 $\mu$M. | 100 nM | [121] |
| 3 | SBA-15 template | Vapour cutting method | Determination of $Fe^3$ | 3–60 $\mu$m | 0.3 $\mu$M | [122] |
| 4 | CA | Carbonization | Detection of microRNAs (miRNAs) | 0.1–200 nM | 100 pM | [123] |
| 5 | CA | Pyrolysis | Determination of sunitinib | 0.05–20.00 $\mu$mol $L^{-1}$ | 0.03 $\mu$mol $L^{-1}$ | [124] |
| 6 | GO | Visible-fenton reaction | Detection of lipovitellin | 0.001–1,500 ng/ml | 0.9 pg/ml | [125] |
| 7 | GO | Electrochemical | Detection of glucose | 0.25–50 $\mu$M | 0.1 mM | [126] |
| 8 | Watermelon rind waste | Hydrothermal | Detection of $Fe^{3+}$ | NA | 0.28 $\mu$M | [100] |
| 9 | Tamarind shell powder | Hydrothermal | Detection of uric acid | 10–100 $\mu$M | 401.72 pM | [101] |
| 10 | 1,3,6-Trinitropyrene | Hydrothermal | Fluorescent detection of $Ag^+$ ions | 0.1–130.0 nM | 30 nM | [29] |
| 11 | Glucose | Pyrolysis | Optical sensor for glucose | 4–40 mM | 3.0 mM | [61] |
| 12 | CA | Pyrolysis | Detection of catechins | 0.01–30 $\mu$M | 0.005 $\mu$M | [127] |
| 13 | Wood charcoal | Electrochemical method | Detection of glucose and $H_2O_2$ | 0.01–0.6 mM | 0.006 mM | [53] |
| 14 | CA | Photoelectrochemical synthesis | Zeatin detection | 0.1–100 nM | 0.031 nM | [128] |
| 15 | Glucose powder | Thermal pyrolysis | Determination of cholesterol | 0.08–300 $\mu$mol $L^{-1}$ | 35 nmol $L^{-1}$ | [129] |
| 16 | GO | Sonochemical and microwave heating | Detection of $Fe^{3+}$ | 10–120 $\mu$M | $10 \times 10^{-6}$ M | [30] |
| 17 | CA | Pyrolysis | Hepatitis B virus DNA detection | 10–500 nM | 1 nM | [130] |
| 18 | Graphite rods | Electrochemical synthesis | Detection of tumor cells | 2–64 nM | 1.19 nM | [131] |
| 19 | CA | Pyrolysis | Antibodies detection | 0.16–125 U/ml | 0.11 U/ml | [132] |
| 20 | GO | Sonoe fenton reaction | Detection of CFP-10 protein | 0.0050–500 $\mu$g $ml^{-1}$ | 0.330 ng $ml^{-1}$ | [133] |
| 21 | CA | Pyrolysis | Detection of catecholamine neurotransmitters | 1–120 $\mu$M | 83 nM | [134] |
| 22 | Glucose | Hydrothermal | detection of copper ions | NA | 5.6 nM | [135] |
| 23 | CA | Pyrolysis | Fluorescent detection of microRNA | $1 \times 10^{-18}$–$1 \times 10^{-12}$ M | $1 \times 10^{-18}$–$1 \times 10^{-12}$ M | [136] |
| 24 | CA | Pyrolysis | Topotecan determination | 0.35–100 $\mu$M | 0.1 $\mu$M | [137] |
| 25 | GO | Pyrolysis | Detection of cardiac Troponin I | 0.17–3 ng $ml^{-1}$ | 0.02 ng $ml^{-1}$ | [138] |
| 26 | Graphite flakes | PLA process | Detection of $Fe^{3+}$ | 500 nM–50 $\mu$M | ~5.36 $\mu$M | [139] |
| 27 | CA | Hydrothermal method | Detection of carcinoembryonic antigen | 0.5–1,000 ng $ml^{-1}$ | 0.01 ng $ml^{-1}$ | [140] |
| 28 | Graphene | Electrochemical exfoliation | Detection of $Fe^{3+}$ | Wide range | ≈7.22 $\mu$M | [141] |
| 29 | Coal | Ultrasonic | Detection of $Cu^{2+}$ | 0–8 $\mu$mol $L^{-1}$ | 0.29 $\mu$M | [142] |
| 30 | Leaves of curry tree | Hydrothermal | Detection of aflatoxin B1 | 5–800 ng $ml^{-1}$ | 0.158 ng $ml^{-1}$ | [102] |
| 31 | GO | Hydrothermal | Detection of $Hg^{2+}$ | 0–4.31 $\mu$M | 23 nM | [143] |
| 32 | GO | Hydrothermal | Detection of paraquat | 0.05–2.0 $\mu$g $ml^{-1}$ | 19 $\mu$g $l^{-1}$ | [144] |
| 33 | Marigold petals | Pyrolysis | Detection of $Fe^{3+}$ ions | NA | 41.1 nM | [79] |

(*continued*)

Table 4: Continued.

| S. no. | Source | Method | Application | Linear range | LOD | References |
|---|---|---|---|---|---|---|
| 34 | Waste toner | Hydrothermal | Detecting of specific DNA sequence | 0.5–30 nM | 0.17 nM | [145] |
| 35 | CA | Hydrothermal | Detection of Cobalt ions | 0–40 mM | 1.25 mM | [146] |
| 36 | CA | Hydrothermal | Detection of $Fe^{3+}$ | 0–85 $\mu$M | 0.26 $\mu$M | [147] |
| 37 | *p*-coumaric acid | Hydrothermal | Detection of $Cu^{2+}$ | 0–10 $\mu$M | 57 nM $L^{-1}$ | [148] |
| 38 | GO | Electrochemical synthesis | Sensing soil moisture with response time of 180 s | NA | NA | [110] |
| 39 | CA | Pyrolysis | Detection of $Hg^{2+}$ and $ClO^{-}$ | 0.25–5.0 $\mu$M | 22.1 nM | [149] |
| 40 | CA | Hydrothermal | Detection of cysteine | 0.5–.5 $\mu$M | 0.1 $\mu$M | [150] |
| 41 | Lactose | Hydrothermal | Detection of $Fe^{3+}$ ions | 2.8–11.2 nM | NA | [151] |
| 42 | CA | Hydrothermal | Detection of neuron-specific enolase | 0.1–1,000 ng $ml^{-1}$ | 0.09 pg $ml^{-1}$ | [152] |
| 43 | CA and thiourea | Solvothermal method | Detection of bisphenol A | 0.12–5 $\mu$M and 5–40 $\mu$M | 0.04 $\mu$M | [153] |
| 44 | Starch | Hydrothermal | Detection of *O. tsutsugamushi* | NA | 0.002 ng/$\mu$l | [154] |
| 45 | Anthracite and bituminous coals | Chemical route | Detection of glutathione | NA | 27 $\mu$M | [155] |
| 46 | CA | Pyrolysis | Detection of glutathione | 0.5–7 $\mu$M | 0.5 $\mu$M | [156] |
| 47 | GO | Hydrothermal | Detection of D-phenylalanine | 0.1–5 $\mu$M | 0.023 $\mu$M | [157] |
| 48 | CA | Microwave irradiation | Detection of isoniazid | 0.19–750 $\mu$M | 10.91 nM | [158] |
| 49 | CA | Hydrothermal | Detection of chloride ion | 8.5–300 $\mu$mol $L^{-1}$ | 0.1 $\mu$mol $L^{-1}$ | [159] |
| 50 | Pistachio shells | Hydrothermal | Detection of cysteine | 0–150 nM | 2.38 nM | [160] |
| 51 | Pistachio shells | Hydrothermal | Detection of homocysteine | 0–100 nM | 1.94 nM | [161] |
| 52 | Xylan | Hydrothermal | Detection of chromium | 3–75 $\mu$M | 0.10 $\mu$M | [162] |
| 53 | CA | Carbonization | Detection of copper ion | 0–2.5 mM | NA | [163] |
| 54 | Starch | Hydrothermal | Detection of clenbuterol | $5 \times 10^{-10}$–$5 \times 10^{-7}$ M | $2.083 \times 10^{-13}$ M | [164] |
| 55 | Lignin | Hydrothermal | Detection of ascorbic acid | NA | 1.62 $\mu$mol/l | [58] |
| 56 | Graphite flakes | Oxidation method | Detection of picric acid | 0–200 $\mu$m | 1.2 $\mu$M | [165] |

into numerous groups based on the type of transducer used like optical, electrochemical, photoelectrochemical, etc. Liu et al. [166] synthesized PEHA-GQD-His, which are often used as fluorescent probes for microRNA fluorescence platforms for biosensors using the compiled molecular beacon double-cycle amplification strategy.

Ananthanarayanan et al. [141] demonstrated first that GQDs could be used for $Fe^{3+}$ detection due to differential fluorescence quenching of $Fe^{3+}$ ions. Gupta et al. [167] created a glucose sensor using a GQD and functionalized graphene composite. Raeyani et al. [168] demonstrated GQDs as a viable optical-based $CO_2$ sensor. Dong et al. [169] reported GQDs sensor for free chlorine detection in drinking water. Sun et al. [170] demonstrated amine functionalized GQDs for the detection of $Cu^{2+}$ ions.

*3.1.1. Electrochemical Sensor.* According to the calculation of the applied electric signal, the various electrochemical sensor types are divided into potentiometry, conductometry, and amperometry or voltammetry. By using pulse differential voltammetry, sensors for electrochemically detecting bisphenol A in water have been developed. Composite electrodes made of polypyrrole (PPy) and GQDs make up this sensor. The sensor demonstrated a good response, with detection limits of 0.01–50 and 0.04 M, respectively [33]. A glucose sensor system based on chemically reduced graphene oxide (CR-GOx) has been reported to have improved amperometric responses for monitoring glucose, with a large linear range (0.01–10 mM) and a 2.0 $\mu$M limit of detection (LOD) [171]. The results of the electrochemical study revealed that the electrode with the GNR/$Co_3O_4$ coating had a good electrocatalytic activity for the oxidation of $H_2O_2$ at 0.925 V. From 10 to 200 M, this sensor responded linearly to $H_2O_2$ oxidation. According to calculations, the LOD is 1.27 M [172]. The use of oxygen plasma treatment, which produces oxygenated functions, edge plane sites, and defects, has improved the performance of graphene-based electrochemical sensors. The treated films showed improved dopamine, ascorbic acid, uric acid, and NADH detection responses [173]. An electrochemical sensor based on Ni/RGO/CCF modified electrode has been reported for uric acid determination with a linear range 10–60 $\mu$M, low limit of detection of 5.083 $\mu$M [174]. Later on, an electrochemical sensor was also developed by using CuO/rGO nanocomposite for determination of ascorbic acid with a linear range from 500 to 2,000 $\mu$M and the limit of detection was 189.053 $\mu$M [175].

*3.2. Bioimaging.* Bioimaging is among the most important fields where GQDs provide numerous advantages in a favorable manner [176, 177]. Bioimaging is a technique for seeing, observing, and detecting desired molecules or tissues in the body avoiding intrusive procedures [178]. It allows for a more thorough insight of the body's biological pathways [179]. In 1896, Wilhelm Roentgen was able to acquire the first X-ray image. A window has opened for bioimaging applications to track and detect ailments and symptoms like tumor imaging [180], carcinoma [181], Parkinson's disease [182], bone fractures [183], and so on. As a result, GQDs have proven to be an effective bioimaging targeting or evaluating candidate for a diverse array of tumor cell lines. HeLa cell lines have frequently been investigated for in vitro imaging [184]. Other cells such as dermal fibroblast cells, A549 cells, T47D, HEK293A cells, MDCK cells, MCF-7 cells, CHOeK1 cells, and MC3T3 cells have all been investigated. GQDs are effective and convenient agents in bioimaging because of their remarkable controllable PL features, chemical inertness, photostability, and high biocompatibility [5], it was observed that because of their crystalline form, GQDs perform better than CNDs in terms of reliability and bleaching activity when exposed to a xenon lamp. During the imaging process, GQDs were found to be sustainable particles that had no effect on the results. Fluorescence imaging of NIR spectra is a common research method [71].

QDs have long been used as imaging technique and are effectively accumulated into bioimaging systems seeing as they overcome the challenges of traditional dying procedures. Nonetheless, their toxicity later became a constraint to biological applications. GQDs are justified for having no or very few properties in living tissue, regardless of the toxicity caused by other semiconductor QDs [184]. These GQDs, on the other hand, could have improved photostability and lighting, as well as size-tunable characteristics [185]. Notably, the initial showing of GQDs (>10 nm) could produce "blue-PL," as compared to graphene nanoribbons, marked the start of a new era. This accelerated research in labeling and optoelectronics, as well as the advancement of GQD-based bioimaging applications. It is essential to know that the extreme luminous emission of GQDs is caused by the closely packed, free zigzag edges shown in small structure arising from the size >10 nm. Furthermore, it has been demonstrated that PL emission is highly sensitive to moderate pH, that is, alkaline mediums can produce strong PL but acidic mediums cannot, implying that PL can be altered when the pH of the medium changed. Because GQDs have superior nontoxicity and bioapplicability when compared to other synthetic QDs, new approaches that use GQDs for bioimaging applications have emerged rapidly [186].

Zhu et al. [187] described a single-step solvothermal strategy for extremely green-PL GQDs with a QY of 11.4% for bioimaging, highlighting that due to their biomedical properties, GQDs are also used as tagging. Conjugations of GQDs with various several other materials enhanced their efficiency and convenience over time. The surface modification of GQDs has been revealed to alter the PL. Although a photochemical reduction approach for boosting QY as well as cell uptakes of GQDs has been proposed [188]. Surface-functionalization of GQDs with tiny organic compounds proved to be an effective technique for PL tuning by changing bandgaps and lowering cellular toxicity [189].

Luo et al. [190] reported a microwave-assisted method to prepare A-GQDs having high fluorescence with QY 21.36%. A-GQDs was found to be a suitable candidate for bioimaging because its high fluorescence quantum yield and their cytotoxicity was examined using MTT viability assay on A549 cell as a test organism. A-GQDs show excellent cell viability and have good biocompatibility at the concentration >2 mg/ml. The cell viability was 94%, even after incubated for 24 hr with A-GQDs at a concentration 2 mg/ml.

For bioimaging purposes, various color emissions of GQDs were generated using various synthetic techniques. Hydrothermal treatment of GO, for instance, led to the formation of N-GQDs with blue luminescence. Biomedical applications of N-GQDs were adequate to illustrate HeLa cells under this study [191]. Ecofriendly luminescent GQDs can be mass-produced from graphite powder using a simple fabrication method for imaging of human liver cancer cells. Afterward, water-soluble, uniformly GQDs with red fluorescence revealed a high bioimaging applicability as a potent biological marker for progenitor or stem cells [192]. Due to their biocompatibility and superior-sized tunable emission properties, it was demonstrated that bioinspired synthesis of GQDs may conquer cytotoxicity. Research using mango leaves for green synthesis of GQDs discovered total cellular absorption and viability for 24 hr after GQD treatment, even at high concentrations, with NIR emissions ranging from 650 to 750 nm. The above NIR excitation-independent fluorescent emissions could meet the demand for *in vivo* administrations requiring deep tissue penetration [71].

Yan et al. [193] presented a method for producing highly biocompatible GQDs using only glucose and no acids or oxidizers in the regard of cytotoxicity. The hydrothermal one-pot approach was used to make HGQDs by sterilizing the solution of glucose at 200°C for 10 hr. HGQDs revealed lower levels of apoptosis than conventionally synthesized GQDs with ~60% less cytotoxicity as well as 2.24% QY, demonstrating greater cytocompatibility than commonly synthesized GQDs. The structure of the as-prepared HGQDs was encountered to be similar to that of glucose, which could improve their cellular uptake. *Ex vivo* experiments demonstrated that HGQDs accumulated in mice's liver, kidney, and brain. Furthermore, sugar-based HGQDs were tested to see if they increased malignant cell survival. When cancer cells were imaged, it was discovered that CGQDs could damage them, whereas HGQDs could provide greater cytocompatibility for bioimaging. *Ex vivo* imaging of isolated organs from rats that had already been handled with HGQDs for 20 days revealed the existence of HGQDs in the brain, liver, and kidney. Their aggregation in the brain, in particular, illustrated that GQDs pass through blood–brain barrier. The above method may describe future brain-related researches for imaging. Chen et al. [194] were able to effectively functionalize the GQDs with sugar moieties, dubbed "sweet GQDs," which were used for monitoring of precisely tagged carbohydrate receptors to examine authentic complexities. GQDs synthesized above exhibited a QY of 31% and had 5.40 nm size. Similarly, mannose receptors were found to be upregulated in breast cancer cell lines, and the synthesized man-GQDs were found to be capable of recognizing mannose receptors in various body areas. Similarly, mannose receptors were discovered to be upregulated in human breast cancer cells, and man-GQDs were able to recognize mannose receptors in various body areas. Furthermore, it included both biosensing and bioimaging tests, above substantial GQDs were effectively internalized by the MCF-7 cancer cell line and demonstrate significant bioimaging potential. The above heterocyclic hydrocarbon-derived GQDs with sizes ranging from 5 to 10 nm have been found to be great bioimaging probes due to their excellent solubility, high PL, low toxicity, and chemical stability [195]. Chen et al. [196] observed that by increasing the concentration of GQDs from 0.078 to 1.250 mg/ml, cell viability remains more than 80%. This finding suggests that GQDs have minimal cytotoxicity and high biocompatibility, making them appropriate for bioimaging applications.

*3.3. Cytotoxicity Studies.* GQDs' cytocompatibility opens up a world of biological possibilities and is already desirable in many circumstances. In terms of biosafety, the potential cytotoxicity of GQDs on living cells is to be considered [126, 178]. Furthermore, researchers are actively researching the maximum-suited therapy and alternate solution techniques [197].

According to Tabish et al., [126] GQDs with small diameters and concentration levels in the microgram and milligram range are found to be lesser toxic to rat and mouse cell lines. However, it should be remarked that various studies have found GQDs to be threatening [126]. Wang et al. [47] first time investigated mechanism of cytotoxicity by N-GQDs. The communication between RBCs and carbonic structures was examined because nonspecific adherence of nanomaterial to the cell membrane increased cytotoxicity. As a result, the N-GQDs were found cytotoxic to RBCs, despite the fact that they had no more harmful effects than GO [198]. However, it was also stressed that the way of communication between the living compartment and GQDs must be carefully investigated to gain a complete understanding of the effect mechanism. PDT applications of GQDs, on the other hand, are still pending for comprehensive cytotoxicity data.

Lee et al. [199] demonstrated that GQDs' excretion pathway is another key component of their toxicity. GQDs were eliminated from mice via the renal system after being degraded by numerous enzymes, such as HRP. Furthermore, human myeloperoxidase and eosinophil peroxidase enzymes were found to degrade GQDs [200]. PEGylation has been proposed as a viable strategy for reducing the toxicity caused by GQDs [201]. Another study using the idea of PEGylation found that PEGylation may really reduce cytotoxicity because GQDs did not trigger considerable cell death in HeLa cells *in vitro* at concentrations of 160 g/ml. In the same report, GO-PEG and GQD-PEG *in vivo* comparisons were performed with the GQD-PEG conjugation demonstrating exceptional biocompatibility. The small size and ease of elimination from their bodies, as well as the high oxygen content, were factors for their desirable biocompatibility [202]. One gene on hematopoietic stem cells have been appear, this is a small number among the 20,800 genes [203]. At the subcellular, cellular, protein and genetic levels, graphene has biological effects. Graphene's toxicity is determined by its absorption in numerous organs as well as chemical and physical interference. The buildup of graphene in these organs has an impact on cellular performance. After entering a cellular system, dispensation, their impeachment and excretion acquire information about their cytotoxicity. Mitochondrial imaging has previously been accomplished using a variety of approaches, such as having GQDs gather mitochondrial and lysosomal sites using a simple alteration of aptamer AS1411 to tag tumor cells. The specific mechanism of uptake of AS1411-GQDs, however, was unknown and was found that it was similar to that of AS1411. Fan et al. [204] glanced into GQDs-TPP as a specific target agent for mitochondria imaging, expecting the lipophilic TPP to accumulate inside mitochondria for targeted imaging. Mitochondrial and nuclear imaging were performed with no adverse effects, as expected [204]. GQDs are undeniably promising in a variety of applications today, as noted; nonetheless, it is necessary to assess the negative consequences of GQDs in order to ensure biosafety before being used in medical applications. In the study of toxicology, SEIRA has proven to be a highly effective instrument for assessing the connection between GQDs and their environment [204]. Table 5 shows cytotoxic studies of GQDs against various cell lines.

*3.4. Antimicrobial Activity.* One of the most persistent risks to humanity's well-being is the growth of antibiotic-resistant microorganisms [46]. Functionalized GQDs have been discovered to be an efficient antibacterial substance (Table 6). The huge $\pi$-conjugated system present in GQDs can interact with the cell wall of bacteria by $e^-$ transfer, exacerbating membrane stress, and the generation of ROS, that eventually causes cell death [226, 205]. Luo et al. [190] reported a microwave-assisted method to prepare A-GQDs and the antimicrobial effect of A-GQDs against *E. coli* was demonstrated using the propidium iodide (PI) stain by white light irradiation [190]. Kashani et al. [46] discovered that the Ag@S-GQDs nanocomposite outperforms AgNPs and S-GQDs in antibacterial activity, with MIC levels as low as 35 and 70 mg/ml, respectively, to resist the growth of *S. aureus* and *P. aeruginosa*.

*3.5. Drug Delivery.* GQDs having graphene's nanoscale layered structural motif are rapidly expanding as a prospect for designing and implementing efficient drug delivery systems, which include theragnostic drugs [209]. GQDs have been

TABLE 5: Cytotoxicitystudy of GQDs.

| S. no. | Source | Method | Cell lines | Assay | Cell viability | References |
|---|---|---|---|---|---|---|
| 1 | GO | Solvothermal method | MG-63 MC3T3 | MTT | >80% | [205] |
| 2 | CA and 3-mercaptopropionic acid | Pyrolysis Ag@S-GQDs | HEK 293 | MTT assay | Reduction in cell viability by 21.4%, 1.54%, and 0.35% | [190] |
| 3 | GO | Oxidation method | THP-1 | WST 1 | Cell viabilitry reduced by 20% | [206] |
| 4 | Carbon fiber | Hydrothermal method | KB, MDA-MB231, A549 MDCK | MTT, LDH | >95% | [207] |
| 5 | GO | Photo-Fenton reaction | MGC-803 MCF-7 | MTT | GQDs < GO | [208] |
| 6 | CA | Carbonization | Saos-2 | MTT | 45.4% | [209] |
| 7 | Graphite powder | Oxidative cutting method | HeLa cells and A549 cells | WST-1 | >95 | [210] |
| 8 | GO | Hydrothermal | A549 | MTT | >80% | [211] |
| 9 | Pyrene | Hydrothermal | 4T1 cells | CCK-8 | >90% | [212] |
| 10 | Aspartic acid | Pyrolysis | SW 480 | CCK-8 | Low cytotoxicity | [213] |
| 11 | Rice grains | Pyrolysis | HeLa cells | SRB assay | 90% | [52] |
| 12 | Neem leaf | Hydrothermal method | HeLa, MCF-7, and MCF-10A | MTT | >95% | [89] |
| 13 | GO | Hydrothermal method | HeLa cells | CCK-8 | >90% | [214] |
| 14 | Graphite | Hydrothermal | THP-1 macrophages | MTT | 82.5% | [215] |
| 15 | Graphite rods | Electrochemical oxidation | SH-SY5Y | MTT | NA | [216] |
| 16 | GO | Microwave | HeLa | MTT | 87% | [217] |
| 17 | GO | Solvothermal | RBC | MTT | Low cytotoxicity | [218] |
| 18 | Coffee grounds | Hydrothermal cutting | HeLa cells | MTT | >88% | [88] |
| 19 | Grape seed extract | Microwave assisted | L929 cells | MTT | Sensor applications and nucleus imaging | [90] |
| 20 | Graphite plate | Laser ablation | MCF-7 | MTT | Real time tracking and bioimaging | [219] |
| 21 | Adenine modified | Microwave assisted | A549 | MTT assay | 94% | [203] |
| 22 | GO | Sonochemical and microwave heating | HeLa | MTT | Cell viability ≥ 90% | [220] |
| 23 | CA | Hydrothermal | 4T1 | CCK-8 | >90% | [221] |
| 24 | Trisodium citrate | Pyrolysis | HeLa | MTT | >80% | [222] |
| 25 | Lignin biomass | Hydrothermal | RAW 264.7 | MTT | >85% | [223] |
| 26 | CA | Carbonization | B16F10 and MCF-7 | SRB assay | Photodynamic therapy | [224] |
| 27 | CA | Pyrolysis | ACHN | MTT | Negligible toxicity | [225] |
| 28 | Cocoa bean | Hydrothermal method | MCF-7 | MTT | Low cytotoxicity | [93] |

studied in a variety of applications (Table 7) due to their tuning PL, abundance of peripheral –COOH groups, thermal and chemical stability, and low cytotoxicity nature. GQDs have been used in field of biomedicine and pharmaceuticals applications like phototherapy, drug delivery, biosensors, supercapacitors, and bioimaging. Wang et al. [212] were the first to illustrate GQDs' extraordinary ability not only to deliver the anti-cancer drug DOX but also to contribute to the drug's anticancer activity against breast cancer cells. When compared to pristine pharmaceuticals, the GQDs-DOX combination was seen to utilize substitute cellular and nuclear internationalization mechanisms, which improves drug delivery efficiency [104]. Remarkably, such GQDs-DOX conjugates increased DOX nuclear absorption and cytotoxicity in drug-resistant cancer cells, indicating that combining anticancer drugs with GQDs could be able to improve inadequate anticancer drug chemotherapeutic effectiveness due to drug resistance [104, 210]. Figure 5 illustrates GQDs as nanocarrier in drug delivery.

*3.6. Phototherapy.* It is a noninvasive therapy that employs fluorescent light to treat a wide range of medical conditions. "Photodynamic therapy" and "photothermal therapy" are two types of phototherapies. During diagnostics, the targeted agent is administered to the disease part and the therapeutic agent is then photoexcited at specific wavelengths. Photothermal agent consumes near-infrared light which generate heat, which causes cell ablation [63]. When used against tumors, the main concern with conventional chemo- and radiotherapies

Table 6: Antibacterial study of GQDs.

| S. no. | Source | Method | Microbial strain tested | Result | References |
|---|---|---|---|---|---|
| 1 | CA and 3-mercaptopropionic acid | Pyrolysis | *S. aureus* and *P. aeruginosa* | MIC value of Ag@S-GQDs was 35 mg $ml^{-1}$ for *S. aureus* and 70 mg $ml^{-1}$ for *P. aeruginosa* | [46] |
| 2 | MWCNTs | Hydrothermal | *P. aeruginosa*, *S. aureus*, *E. coli*, and *B. subtilis* | MICs value for *E. coli* and *B. subtilis* were found to be 512 $\mu$g $ml^{-1}$. And the MICs for *S. aureus* and *P. aeruginosa* were ~256 $\mu$g $ml^{-1}$ | [226] |
| 3 | PEG | Pulsed laser | *S. aureus* and *P. aeruginosa* | MIC value for *P. aeruginosa* was 25 $\mu$g ml/1 And the MIC value for *S. aureus* was found to be 50 $\mu$g $ml^{-1}$ | [205] |
| 4 | Graphite | Microwave assisted | *E. coli* | Excellent antibacterial activity against *E. coli* Produced $^1O_2$ destroy cell membrane of *E. coli*. | [190] |
| 5 | Coconut husk | Hydrothermal carbonization | *E. coli* | Antibacterial activity | [190] |
| 6 | CA | Hydrothermal method | *E. coli* | 85% bacterial survival by GQDs alone 50% bacterial survival by ZnO 0% bacterial survival by ZnO-GQDs upon UV irradiation for 5 min | [54] |
| 7 | GO sheet | Ultrasonic shearing reaction | *E. coli* | Inhibits bacterial cells growth | [206] |
| 8 | Nickel oxide | Laser ablation method | *M. luteus* and *E. coli* | *M. luteus* and *E. coli* were inactivated after irradiation of 5 min | [207] |
| 9 | GO | Microwave | *S. aureus* and *E. coli* | Inhibit bacterial cells growth by generating free radical | [208] |

Table 7: Drug delivery applications of GQDs.

| S. no. | Source | Method | Drug | Drug loading | % Drug release (%) | Release time (hr) | Cell viability (%) | Assay | Cell line | References |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | GO | Photo-Fenton reaction | DOX | 50 $\mu$g/ml | 70 | 24 | 35 | MTT | MGC-803 and MCF-7 cells | [211] |
| 2 | CX-72 carbon black | Chemical oxidation | DOX | 68 wt% | NA | 8 | >80 | MTT | A549 and HEK293A cells | [212] |
| 3 | L-glutamic acid | Pyrolysis | DOX | 15 wt% | 70 | 48 | >35 | CCK8 | BT-474 | [213] |
| 4 | GO | Thermally exfoliated | DOX | 54.6 wt% | 40 | 72 | 60.8 | MTT | U251 | [214] |
| 5 | CA | Pyrolysis | DOX | 10 mg/ml | 42.5 | 24 | 17 | MTT | Nucleus | [210] |
| 6 | GO | Solvothermal method | DOX | 101 $\mu$g/mg | 60 | 72 | 45–60 | CCK8 | MC3T3-E1, DU-145, and PC-3 | [215] |
| 7 | Oxidized graphene Sheets | Amino-hydrothermal treatment | DOX | 80 wt% | 12 | 6 | >90 | MTT | HeLa cells | [216] |
| 8 | MWCNTs | microwave-assisted hydrothermal | Methotrexate | 10 mg/ml | 60 | 9 | ~80 | MTT | A549 and MCF-7 cells | [217] |
| 9 | GO | Hydrothermal | DOX | 2.5 mg/ml | 42 | 6 | NA | NA | NA | [66] |
| 10 | CA | Carbonization | Sodium salicylate | 3 mg/ml | 74 | 7 | NA | NA | In vivo | [218] |
| 11 | Cow milk | Microwave | BHC | 0.2 mg/ml | 50 | 24 | 50 | MTT | MDA-MB-231, HeLa, and L929 cells | [59] |

is the increase in side effects. Due to their superior qualities, much more efficient treatment activity, and fewer side effects, nanomaterials produced for PTT and PDT have shown considerable promise [219, 220] (Table 8).

PDT uses photosensitizers that, when it is activated by light, it generates reactive oxygen species that harms cells [220] (Figure 6). With the development of next-generation therapeutic molecules, phototherapy has the potential to

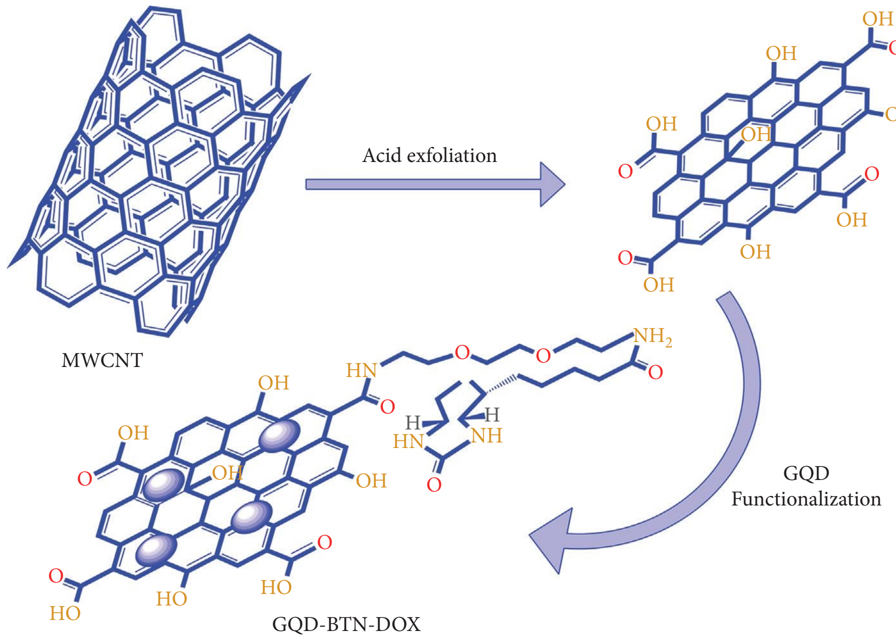


Figure 5: GQDs as agent for drug delivery.

Table 8: Phototherapy study of GQDs.

| S. no. | Source | Method | Model | Finding | References |
|---|---|---|---|---|---|
| 1 | Graphite | Electrochemical | *Staphylococcus aureus* and *Escherichia coli* | When photoexcited at wavelength of 470 nm, it produces reactive oxygen species, and kill harmful methicillin-resistant bacteria, *S. aureus* and *E. coli* | [221] |
| 2 | Graphite | Electrochemical | *Escherichia coli* | Produce single oxygen upon UV illumination increase in photoluminescence quantum yield | [222] |
| 3 | Carbon black | Chemical oxidation | HepG-2, A549, MCF-7, and HeLa | Generates heat from light absorption which leads to death of the cancer cells | [223] |
| 4 | Polythiophene (PT2) | Hydrothermal treatment | HeLa cells | Generate $^1O_2$ via a multistate sensitization process. | [224] |
| 5 | CA | Hydrothermal | 87.9% photothermal conversion efficiency | Upon 808 nm laser irradiation it completely eradicatestumors upon | [225] |
| 6 | GO sheet | Ultrasonic shearing reaction | *E. coli* | $^1O_2$ and $O_2^-$ were effectively generated | [227] |
| 7 | Chemical | Chemical | 4T1 cells | Convert the near-infrared irradiation into the heat | [228] |

become an optimal treatment for malignancies. The phototherapy treatment kills cancer cells and improves the efficacy of other therapeutic modalities such as radiotherapy, chemotherapy, and gene therapy. However, these of photothermal therapy enhances the efficacy of radio and chemotherapies. Furthermore, enhancing the permeability of cell membranes at tumor areas will improve medication cellular uptake and release [14, 63, 219].

*3.7. Photocatalysis.* Photocatalysis is a process in which a catalyst can greatly improve the pace of a chemical reaction in the presence of light. The main issue in photocatalysis is to first produce a catalyst which may efficiently absorb sunlight, resulting in improved chemical reactionsand then to synthesize effective photocatalyst using a cheap approach. GQDs unique features such as high stability, increased surface area, high solubility, nontoxicity, and superior conductivity, make them a viable photocatalysis and electrocatalysis material. For photocatalysis, heteroatoms such as N, S, and P can be used to optimize the characteristics of GQDs toward the sun absorption property, resulting in improved performance. GQDs have been employed in a variety of photocatalysis reactions, including $H_2$ evolution [229–231], organic pollutant degradation [176, 232, 233], $CO_2$ reduction [144, 234], and so on, either alone or in conjunction with other inorganic materials.

Zhuo et al. [235] devised a unique ultrasonic synthesis method for GQDs with excitation-independent up-and-down conversion of photoluminescent properties. They also created GQD composites with the anatase and rutile phases of titanium oxide and used the composites to degrade methylene blue dye in visible light. On illumination with light >420 nm

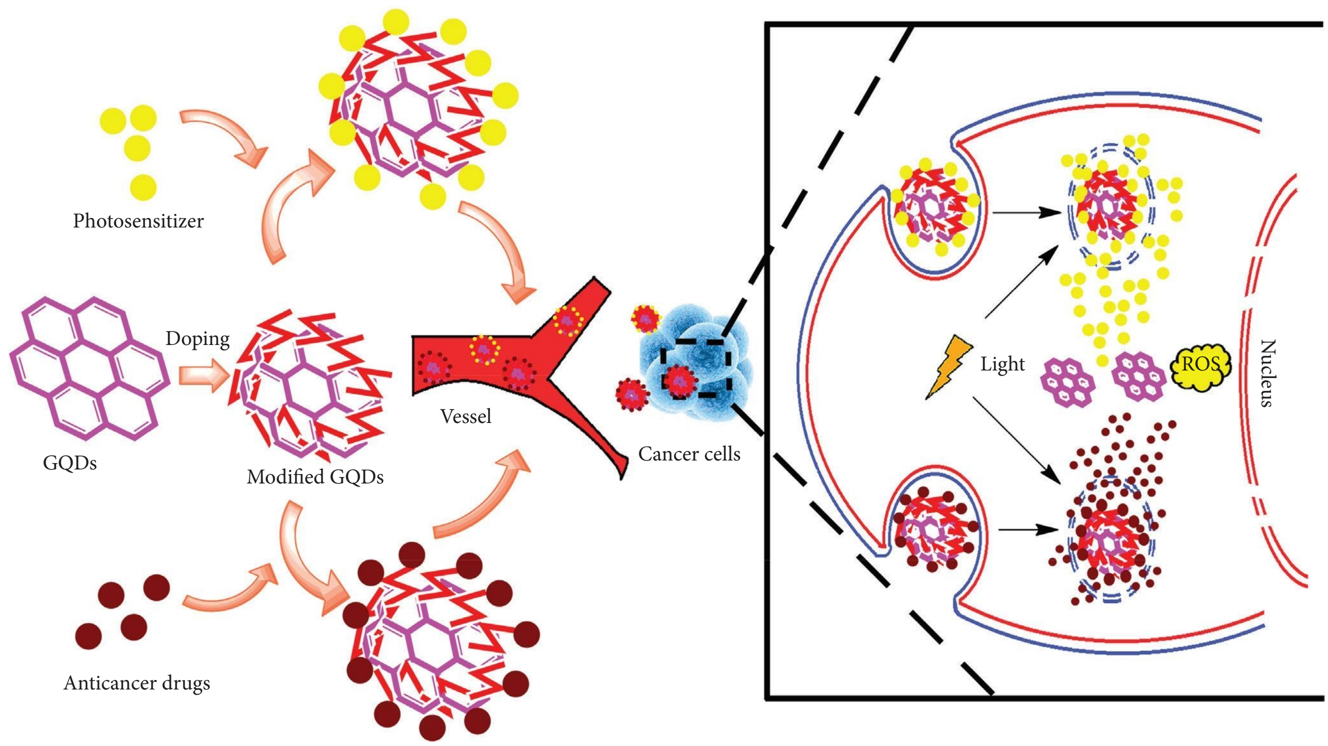


Figure 6: Mechanism of action for photothermal therapy.

wavelength, they observed that composite of rutile $TiO_2$/GQDs has a 9% higher degradation rate than the composite of anatase $TiO_2$/GQDs for degradation of methylene blue [236]. Using the electrostatic interaction approach, Wang et al. [212] illustrated the synthesis of hydroxyl-GQDs and the composite of hydroxyl-GQDs and mesoporous carbon nitride [240]. In the presence of visible light, the composite was found to greatly increase the photodegradation of contaminants such as Rhodamine B and tetracycline hydrochloride. The photocatalysis reaction proceeds by generating $O^{2-}$ species as well as producing holes, according to electron spin resonance spectroscopy data. Wang et al. [237] designed a hydrothermal synthesis technique to obtain GQD-decorated ZnS nanobelts, which they then employed for Rhodamine dye photodegradation.

*3.8. Antibiotics Detection.* Antibiotics can be obtained from both natural and synthetic sources, which are used to avoid bacterial infections and divided into numerous classes of antibiotics penicillins, tetracyclines, fluoroquinolones, sulfonamides cephalosporins, aminoglycosides, phenolics, and macrolides antibiotics [176]. The common detected antibiotics by QDs fluorescent nanosensor include tetracyclines and sulfonamides to minimize accumulation inbody of human by food chain which promote food safety [238]. Antibiotics have been detected using a variety of approaches based on GQDs materials (Table 9). They have been extensively researched as a fluorescence sensor for detecting a variety of compounds, including RNA [251], antibiotics [139], metal ions [252], pesticide [253], DNA [160], vitamin [254], and protein [255].

*3.9. Supercapacitor.* Huge energy consumption as a result of technological improvements and the need for energy storage are two essential concerns. Therefore, there is great potential for the accumulation of electrochemical energy systems, which opens up a brand-new area of research for both the industrial industry and academia. Electrochemical energy storage systems (EESS) which is transferred from chemical energy to electrical power frequently used to store energy. EESS, which has drawn a lot of interest due to its rapid discharge/charge rates and extended life, is a crucial prerequisite for any energy storage unit. The main component of the EESS is supercapacitor, which in the current context solves extreme caution and significant energy sources. It is also referred to as the electrochemical capacitor and offers quick discharge/charge, with long-term and high-power density. These characteristics make EESS one of the best-performing alternative materials for the use in emergency power systems, portable electronics, and electric vehicles [117].

*3.10. Challenges and Future Perspective.* Although there has been considerable success in recent years, GQDs still face significant obstacles in pollutant degradation and industrial production, necessitating further study in the future. Some of challenges faced by GQDs are discussed as follows:

(1) Enhance the synthesis process—the large-scale output cannot be addressed by the present synthesis method
(2) The van der Waals heterostructure should be strengthened

Table 9: Antibiotic detection applications of GQDs.

| S. no. | Source | Method | Application | Linear range | LOD | References |
|---|---|---|---|---|---|---|
| 1 | Graphite | Hydrothermal | Detection of tetracycline | 40–90 ng $ml^{-1}$ | 45 ng $ml^{-1}$ | [239] |
| 2 | CA | Pyrolysis | Detection of norfloxacin | 1.0–100.0 $\mu g\,l^{-1}$ | 0.35 $\mu g\,l^{-1}$ | [240] |
| 3 | CA | Pyrolysis | Detection of ceftazidime | 0.10–10.0 $\mu g\,l^{-1}$ | 0.05 $\mu g\,l^{-1}$ | [241] |
| 4 | CA | Pyrolysis | Cefazolin detection | 0.10–10.0 $\mu g\,l^{-1}$ | 0.10 $\mu g\,l^{-1}$ | [242] |
| 5 | CA | Pyrolysis | Determination of sulfadiazine | 0.04–22.0 $\mu$M | 10 nM | [204] |
| 6 | MWCNTs | Hydrothermal | Detection of the streptomycin antibiotic | 0.1–700 pg $ml^{-1}$ | 0.033 pg $ml^{-1}$ | [243] |
| 7 | Poly (aminophenol) | Electropolymerization | Determination of levofloxacin | 0.05–100 $\mu$M | 10 nM | [244] |
| 8 | Graphene | Acid hydrolysis | Detection of ofloxacin | 500–1,000 ng $ml^{-1}$ | 10.7 ng $ml^{-1}$ | [245] |
| 9 | CA | Hydrothermal | Detection of sulfamethoxazole | 1–100 $\mu$M | 1 $\mu$M | [56] |
| 10 | Citric acid | Pyrolysis | Detection of tetracyclines | 0–20 mM | 8.2 nM | [246] |
| 11 | Passion fruit juice | Microwave treatment | Detection of tetracycline | 0.04–70 $\mu$M | 1 nM | [247] |
| 12 | CA | Microwave | determination of chloramphenicol | 0.00250–0.020 mg $ml^{-1}$ | 0.0018 mg $ml^{-1}$ | [82] |
| 13 | CA | Pyrolysis | Detection of levofloxacin in milk | 0.10–25.0 g $l^{-1}$ | 0.03 g $l^{-1}$ | [248] |
| 14 | Potato amylose | Hydrothermal | Detection of tetracycline | $2.5 \times 10^{-10}$–$5 \times 10^{-6}$ M | $9.735 \times 10^{-13}$ M | [98] |
| 15 | CA | Hydrothermal | Determination of piroxicam | 2.0–35.0 nmol $l^{-1}$ | 0.11 nmol $l^{-1}$ | [249] |
| 16 | GO | Hydrothermal | Detection of tetracycline | 1.0–104 $\mu g \cdot l^{-1}$ | 1 $\mu g \cdot l^{-1}$ | [250] |

(3) Prevent second-hand contamination

(4) Increase the use of GQDs in more contexts

GQDs have garnered a lot of attention in recent decades due to their qualities and use in a variety of environmental and health domains. GQD fabrication, size, repeatability, and limited quantum efficiency are all areas that need improvement in the perspective of their biomedical application. GQDs are also suited for usage in a variety of *in vivo* applications due to their low toxicity. As a result, by addressing the issue of their poor quantum efficiency by creating GQD nanocomposites by surface factorization their prospective applications in diverse domains can be expanded. GQDs as well as their synthesis methods were introduced in this work. Bioimaging, biosensors, drug delivery, gene therapy, photodynamic therapy, detection of antibiotics, and removal of dyes were among the biomedical applications of GQDs considered. The broad surface and functional groups present on GQDs allows mixing of various medicines and ligands. Therefore, GQDs are used as a nanocarrier in targeted drug delivery.

The photoluminescence of GQDs is also being exploited to bioimaging approaches for identifying different biomolecules, which could lead to a variety of new disease diagnosis tools. As a result, new ways for achieving high performance, cost-effective, and simple purification procedures that do not need the removal of raw components are required.

This review detailed recent research developments of GQDs and its composites, with an emphasis on their synthesis and biomedical applications, such as bioimaging, biosensing, drug delivery, gene therapy, photodynamic therapy, removal of dyes, and detection of antibiotics. Finally, the review suggests that further developing GQD and its composites for numerous unresolved therapeutic usages has a bright future. The practical usage of GQDs necessitates careful consideration of chemical and electrochemical stability.

## Abbreviations

GQDs: Graphene quantum dots
GO: Graphene oxide
LEDs: Light-emitting diodes
QDs: Quantum dots
MWCNTs: Multiwalled carbon nanotubes
CNDs: Carbon nanodots
LOD: Limit of detection
LR: Linear range
CA: Citric acid
PEHA-GQDs-His: Pentaethylenehexamine and histidine-functionalized graphene quantum dots
AS1411-GQDs: 26-base guanine-rich short oligonucleotide
MDCK: Madin–Darby canine kidney
MCF-7: Breast cancer cell line
CHOek1: Chinese hamster ovary
A-GQDs: Adenine-modified grapheme quantum dots
Ag@S-GQDs: Silver–sulfur doped graphene quantum dot
MIC: Minimum inhibitory concentration
GQDs-DOX: Doxorubicin conjugated graphene quantum dots
QY: Quantum yield
CNDs: Carbon nanodots
NIR: Near infrared region
MTT: 3-(4,5-Dimethylthiazol-2-yl)-2,5-Diphenyltetrazolium bromide

HGQDs: Highly biocompatible graphene quantum dots
Man-GQDs: Graphene quantum dots conjugated with mannosamine
HRP: Horseradish peroxidises
GQD-PEG: PEGylation of GQD
GO-PEG: PEGylation of graphene oxide
AS1411–GQDs: Aptamer AS1411 conjugates with graphene quantum dots
TPP: (3-carboxyl) phenyl bromide phosphine
SEIRA: Surface-enhanced infrared absorption spectroscopy.

## Data Availability

All the data related to this study are available in the manuscript.

## Additional Points

*Highlights*. Short review on synthesis of GQDs is presented. Precursors like biomass waste, plant extracts, and biomolecules are identified for GQDs production. The cytotoxicity, bioimaging, sensors, and antibiotics detections applications have been explained. Phototherapy and its mechanism of action have been discussed.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Pooja Kadyan and Rohit Malik: writing—original draft; Saurabh Bhatia, Ahmed Al Harrasi, Syam Mohan, Mansi Yadav, and Sunita Dalal: writing–review and editing, literature review; Sudhir Kumar Kataria and Thillai Arasu: conceptualization, writing–review and editing.

## References


[1] K. D. Patel, R. K. Singh, and H.-W. Kim, "Carbon-based nanomaterials as an emerging platform for theranostics," *Materials Horizons*, vol. 6, no. 3, pp. 434–469, 2019.

[2] M. Gaur, C. Misra, A. B. Yadav et al., "Biomedical applications of carbon nanomaterials: fullerenes, quantum dots, nanotubes, nanofibers, and graphene," *Materials*, vol. 14, no. 20, Article ID 5978, 2021.

[3] O. Zaytseva and G. Neumann, "Carbon nanomaterials: production, impact on plant development, agricultural and environmental applications," *Chemical and Biological Technologies in Agriculture*, vol. 3, Article ID 17, 2016.

[4] I. Khan, K. Saeed, and I. Khan, "Nanoparticles: properties, applications and toxicities," *Arabian Journal of Chemistry*, vol. 12, no. 7, pp. 908–931, 2019.

[5] J. Deng, M. Li, and Y. Wang, "Biomass-derived carbon: synthesis and applications in energy storage and conversion," *Green Chemistry*, vol. 18, no. 18, pp. 4824–4854, 2016.

[6] M. J. Allen, V. C. Tung, and R. B. Kaner, "Honeycomb carbon: a review of graphene," *Chemical Reviews*, vol. 110, no. 1, pp. 132–145, 2010.

[7] V. C. Sanchez, A. Jachak, R. H. Hurt, and A. B. Kane, "Biological interactions of graphene-family nanomaterials: an interdisciplinary review," *Chemical Research in Toxicology*, vol. 25, no. 1, pp. 15–34, 2012.

[8] X.-W. Fu, W.-Q. Shi, Q.-J. Zhang et al., "Positive effects of Taxol pretreatment on morphology, distribution and ultrastructure of mitochondria and lipid droplets in vitrification of *in vitro* matured porcine oocytes," *Animal Reproduction Science*, vol. 115, no. 1–4, pp. 158–168, 2009.

[9] D. W. Ayele, H.-M. Chen, W.-N. Su et al., "Controlled synthesis of CdSe quantum dots by a microwave-enhanced process: a green approach for mass production," *Chemistry—A European Journal*, vol. 17, no. 20, pp. 5737–5744, 2011.

[10] V. G. Reshma and P. V. Mohanan, "Quantum dots: applications and safety consequences," *Journal of Luminescence*, vol. 205, pp. 287–298, 2019.

[11] K. Li, J. Chen, Y. Yan et al., "Quasi-homogeneous carbocatalysis for one-pot selective conversion of carbohydrates to 5-hydroxymethylfurfural using sulfonated graphene quantum dots," *Carbon*, vol. 136, pp. 224–233, 2018.

[12] D. Pan, J. Zhang, Z. Li, and M. Wu, "Hydrothermal route for cutting graphene sheets into blue-luminescent graphene quantum dots," *Advanced Materials*, vol. 22, no. 6, pp. 734–738, 2010.

[13] P. Jegannathan, A. Termeh Yousefi, M. S. A. Karim, and N. A. Kadri, "Enhancement of graphene quantum dots based applications via optimum physical chemistry: a review," *Biocybernetics and Biomedical Engineering*, vol. 38, no. 3, pp. 481–497, 2018.

[14] H. Zhu, Y. Fang, Q. Miao et al., "Regulating near-infrared photodynamic properties of semiconducting polymer nanotheranostics for optimized cancer therapy," *ACS Nano*, vol. 11, no. 9, pp. 8998–9009, 2017.

[15] L. A. Ponomarenko, F. Schedin, M. I. Katsnelson et al., "Chaotic Dirac billiard in graphene quantum dots," *Science*, vol. 320, no. 5874, pp. 356–358, 2008.

[16] R. Wang, G. Xia, W. Zhong et al., "Direct transformation of lignin into fluorescence-switchable graphene quantum dots and their application in ultrasensitive profiling of a physiological oxidant," *Green Chemistry*, vol. 21, no. 12, pp. 3343–3352, 2019.

[17] X. T. Zheng, A. Ananthanarayanan, K. Q. Luo, and P. Chen, "Glowing graphene quantum dots and carbon dots: properties, syntheses, and biological applications," *Small*, vol. 11, no. 14, pp. 1620–1636, 2015.

[18] N. A. Travlou, D. A. Giannakoudakis, M. Algarra, A. M. Labella, E. Rodríguez-Castellón, and T. J. Bandosz, "S- and N-doped carbon quantum dots: surface chemistry dependent antibacterial activity," *Carbon*, vol. 135, pp. 104–111, 2018.

[19] L. Centeno, J. Romero-García, C. Alvarado-Canché et al., "Green synthesis of graphene quantum dots from Opuntia sp. extract and their application in phytic acid detection," *Sensing and Bio-Sensing Research*, vol. 32, Article ID 100412, 2021.

[20] P. Kumar, C. Dhand, N. Dwivedi et al., "Graphene quantum dots: a contemporary perspective on scope, opportunities, and sustainability," *Renewable and Sustainable Energy Reviews*, vol. 157, Article ID 111993, 2022.

[21] Y. Dong, C. Chen, X. Zheng et al., "One-step and high yield simultaneous preparation of single- and multi-layer graphene quantum dots from CX-72 carbon black," *Journal of Materials Chemistry*, vol. 22, no. 18, pp. 8764–8766, 2012.

[22] J. Shen, Y. Zhu, C. Chen, X. Yang, and C. Li, "Facile preparation and upconversion luminescence of graphene quantum

dots," *Chemical Communications*, vol. 47, no. 9, pp. 2580–2582, 2011.

[23] S. Zhu, J. Zhang, C. Qiao et al., "Strongly green-photoluminescent graphene quantum dots for bioimaging applications," *Chemical Communications*, vol. 47, no. 24, pp. 6858–6860, 2011.

[24] L.-L. Li, J. Ji, R. Fei et al., "A facile microwave avenue to electrochemiluminescent two-color graphene quantum dots," *Advanced Functional Materials*, vol. 22, no. 14, pp. 2971–2979, 2012.

[25] L. Tang, R. Ji, X. Cao et al., "Deep ultraviolet photoluminescence of water-soluble self-passivated graphene quantum dots," *ACS Nano*, vol. 6, no. 6, pp. 5102–5110, 2012.

[26] H. Tetsuka, R. Asahi, A. Nagoya et al., "Optically tunable amino-functionalized graphene quantum dots," *Advanced Materials*, vol. 24, no. 39, pp. 5333–5338, 2012.

[27] S. Chen, X. Hai, C. Xia, X.-W. Chen, and J.-H. Wang, "Preparation of excitation-independent photoluminescent graphene quantum dots with visible-light excitation/emission for cell imaging," *Chemistry—A European Journal*, vol. 19, no. 47, pp. 15918–15923, 2013.

[28] Y. Shin, J. Lee, J. Yang et al., "Mass production of graphene quantum dots by one-pot synthesis directly from graphite in high yield," *Small*, vol. 10, no. 5, pp. 866–870, 2014.

[29] S. Bian, C. Shen, Y. Qian, J. Liu, F. Xi, and X. Dong, "Facile synthesis of sulfur-doped graphene quantum dots as fluorescent sensing probes for $Ag^+$ ions detection," *Sensors and Actuators B: Chemical*, vol. 242, pp. 231–237, 2017.

[30] R. V. Nair, R. T. Thomas, V. Sankar, H. Muhammad, M. Dong, and S. Pillai, "Rapid, acid-free synthesis of high-quality graphene quantum dots for aggregation induced sensing of metal ions and bioimaging," *ACS Omega*, vol. 2, no. 11, pp. 8051–8061, 2017.

[31] B. Fresco-Cala, M. L. Soriano, A. Sciortino, M. Cannas, F. Messina, and S. Cardenas, "One-pot synthesis of graphene quantum dots and simultaneous nanostructured self-assembly *via* a novel microwave-assisted method: impact on triazine removal and efficiency monitoring," *RSC Advances*, vol. 8, no. 52, pp. 29939–29946, 2018.

[32] M. T. Dejpasand, E. Saievar-Iranizad, A. Bayat, A. Montaghemi, and S. R. Ardekani, "Tuning HOMO and LUMO of three region (UV, Vis and IR) photoluminescent nitrogen doped graphene quantum dots for photodegradation of methylene blue," *Materials Research Bulletin*, vol. 128, Article ID 110886, 2020.

[33] R. Tian, S. Zhong, J. Wu et al., "Solvothermal method to prepare graphene quantum dots by hydrogen peroxide," *Optical Materials*, vol. 60, pp. 204–208, 2016.

[34] B. Liu, J. Xie, H. Ma et al., "From graphite to graphene oxide and graphene oxide quantum dots," *Small*, vol. 13, no. 18, Article ID 1601001, 2017.

[35] T. Chen, J. Sun, N. Xue et al., "Co,N-doped GQDs/$SnO_2$ mesoporous microspheres exhibit synergistically enhanced gas sensing properties for $H_2S$ gas detection," *Journal of Materials Chemistry A*, vol. 10, no. 19, pp. 10759–10767, 2022.

[36] D. B. Shinde and V. K. Pillai, "Electrochemical preparation of luminescent graphene quantum dots from multiwalled carbon nanotubes," *Chemistry—A European Journal*, vol. 18, no. 39, pp. 12522–12528, 2012.

[37] J. Deng, Q. Lu, H. Li, Y. Zhang, and S. Yao, "Large scale preparation of graphene quantum dots from graphite oxide in pure water *via* one-step electrochemical tailoring," *RSC Advances*, vol. 5, no. 38, pp. 29704–29707, 2015.

[38] M. Zhang, L. Bai, W. Shang et al., "Facile synthesis of water-soluble, highly fluorescent graphene quantum dots as a robust biological label for stem cells," *Journal of Materials Chemistry*, vol. 22, no. 15, pp. 7461–7467, 2012.

[39] Y. Fu, G. Gao, and J. Zhi, "Electrochemical synthesis of multicolor fluorescent N-doped graphene quantum dots as a ferric ion sensor and their application in bioimaging," *Journal of Materials Chemistry B*, vol. 7, no. 9, pp. 1494–1502, 2019.

[40] Y. Dong, R. Wang, H. Li et al., "Polyamine-functionalized carbon quantum dots for chemical sensing," *Carbon*, vol. 50, no. 8, pp. 2810–2815, 2012.

[41] S. Gu, C.-T. Hsieh, C.-Y. Yuan et al., "Fluorescence of functionalized graphene quantum dots prepared from infrared-assisted pyrolysis of citric acid and urea," *Journal of Luminescence*, vol. 217, Article ID 116774, 2020.

[42] M. P. More, P. H. Lohar, A. G. Patil, P. O. Patil, and P. K. Deshmukh, "Controlled synthesis of blue luminescent graphene quantum dots from carbonized citric acid: assessment of methodology, stability, and fluorescence in an aqueous environment," *Materials Chemistry and Physics*, vol. 220, pp. 11–22, 2018.

[43] X. Wu, F. Tian, W. Wang, J. Chen, M. Wu, and J. X. Zhao, "Fabrication of highly fluorescent graphene quantum dots using L-glutamic acid for *in vitro*/*in vivo* imaging and sensing," *Journal of Materials Chemistry C*, vol. 1, no. 31, pp. 4676–4684, 2013.

[44] G.-L. Hong, H.-L. Zhao, H.-H. Deng et al., "Fabrication of ultra-small monolayer graphene quantum dots by pyrolysis of trisodium citrate for fluorescent cell imaging," *International Journal of Nanomedicine*, vol. 13, pp. 4807–4815, 2018.

[45] C. Zhu, S. Yang, G. Wang et al., "Negative induction effect of graphite N on graphene quantum dots: tunable band gap photoluminescence," *Journal of Materials Chemistry C*, vol. 3, no. 34, pp. 8810–8816, 2015.

[46] H. M. Kashani, T. Madrakian, A. Afkhami, F. Mahjoubi, and M. A. Moosavi, "Bottom-up and green-synthesis route of amino functionalized graphene quantum dot as a novel biocompatible and label-free fluorescence probe for *in vitro* cellular imaging of human ACHN cell lines," *Materials Science and Engineering: B*, vol. 251, Article ID 114452, 2019.

[47] L. Wang, Y. Wang, T. Xu et al., "Gram-scale synthesis of single-crystalline graphene quantum dots with superior optical properties," *Nature Communications*, vol. 5, Article ID 5357, 2014.

[48] A. Abbas, L. T. Mariana, and A. N. Phan, "Biomass-waste derived graphene quantum dots and their applications," *Carbon*, vol. 140, pp. 77–99, 2018.

[49] A. Irshad, N. Sarwar, H. Sadia et al., "Silver nano-particles: synthesis and characterization by using glucans extracted from *Pleurotus ostreatus*," *Applied Nanoscience*, vol. 10, pp. 3205–3214, 2020.

[50] S. S. Wong, R. Shu, J. Zhang, H. Liu, and N. Yan, "Downstream processing of lignin derived feedstock into end products," *Chemical Society Reviews*, vol. 49, no. 15, pp. 5510–5560, 2020.

[51] C. Xiong, J. Xu, Q. Han, C. Qin, L. Dai, and Y. Ni, "Construction of flexible cellulose nanofiber fiber@graphene quantum dots hybrid film applied in supercapacitor and sensor," *Cellulose*, vol. 28, pp. 10359–10372, 2021.

[52] H. Kalita, J. Mohapatra, L. Pradhan, A. Mitra, D. Bahadur, and M. Aslam, "Efficient synthesis of rice based graphene quantum dots and their fluorescent properties," *RSC Advances*, vol. 6, no. 28, pp. 23518–23524, 2016.

[53] N. R. Nirala, G. Khandelwal, B. Kumar, Vinita, R. Prakash, and V. Kumar, "One step electro-oxidative preparation of graphene quantum dots from wood charcoal as a peroxidase mimetic," *Talanta*, vol. 173, pp. 36–43, 2017.
[54] A. Abbas, T. A. Tabish, S. J. Bull, T. M. Lim, and A. N. Phan, "High yield synthesis of graphene quantum dots from biomass waste as a highly selective probe for $Fe^{3+}$ sensing," *Scientific Reports*, vol. 10, Article ID 21262, 2020.
[55] M. E. Mahmoud, N. A. Fekry, and A. M. Abdelfattah, "A novel nanobiosorbent of functionalized graphene quantum dots from rice husk with barium hydroxide for microwave enhanced removal of lead (II) and lanthanum (III)," *Bioresource Technology*, vol. 298, Article ID 122514, 2020.
[56] T. H. Le, H. J. Lee, J. H. Kim, and S. J. Park, "Highly selective fluorescence sensor based on graphene quantum dots for sulfamethoxazole determination," *Materials*, vol. 13, no. 11, Article ID 2521, 2020.
[57] G. K. Gupta, P. Sagar, M. Srivastava et al., "Excellent supercapacitive performance of graphene quantum dots derived from a bio-waste marigold flower (*Tagetes erecta*)," *International Journal of Hydrogen Energy*, vol. 46, no. 77, pp. 38416–38424, 2021.
[58] L. Zhu, D. Li, H. Lu, S. Zhang, and H. Gao, "Lignin-based fluorescence-switchable graphene quantum dots for $Fe^{3+}$ and ascorbic acid detection," *International Journal of Biological Macromolecules*, vol. 194, pp. 254–263, 2022.
[59] M. Thakur, A. Mewada, S. Pandey et al., "Milk-derived multi-fluorescent graphene quantum dot-based cancer theranostic system," *Materials Science and Engineering: C*, vol. 67, pp. 468–477, 2016.
[60] Ş. Kir, İ. Dehri, Y. Önal, R. Esen, and C. A. Başar, "The investigation of structural alteration of raw materials used to attain graphene quantum dots in different prolysis conditions," *Surfaces and Interfaces*, vol. 29, Article ID 101679, 2022.
[61] M. Shehab, S. Ebrahim, and M. Soliman, "Graphene quantum dots prepared from glucose as optical sensor for glucose," *Journal of Luminescence*, vol. 184, pp. 110–116, 2017.
[62] A. Suryawanshi, M. Biswal, D. Mhamane et al., "Large scale synthesis of graphene quantum dots (GQDs) from waste biomass and their use as an efficient and selective photoluminescence *on–off–on* probe for $Ag^{+}$ ions," *Nanoscale*, vol. 6, no. 20, pp. 11664–11670, 2014.
[63] H. Liu, D. Chen, L. Li et al., "Multifunctional gold nanoshells on silica nanorattles: a platform for the combination of photothermal therapy and chemotherapy with low systemic toxicity," *Angewandte Chemie International Edition*, vol. 50, no. 4, pp. 891–895, 2011.
[64] P. Jegannathan, A. T. Yousefi, N. A. Kadri, and W. J. Basirun, "Sustainable GQDs for potential application in engineering using corn powder as green precursor," *Fullerenes, Nanotubes and Carbon Nanostructures*, vol. 28, no. 11, pp. 919–924, 2020.
[65] Y. Lou, J. Ji, A. Qin et al., "Cane molasses graphene quantum dots passivated by PEG functionalization for detection of metal ions," *ACS Omega*, vol. 5, no. 12, pp. 6763–6772, 2020.
[66] Z. Wang, J. Xia, C. Zhou et al., "Synthesis of strongly green-photoluminescent graphene quantum dots for drug carrier," *Colloids and Surfaces B: Biointerfaces*, vol. 112, pp. 192–196, 2013.
[67] R. V. Khose, P. Bangde, M. P. Bondarde et al., "Waste derived approach towards wealthy fluorescent N-doped graphene quantum dots for cell imaging and $H_2O_2$ sensing applications," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 266, Article ID 120453, 2022.
[68] R. S. Tade and P. O. Patil, "Green synthesis of fluorescent graphene quantum dots and its application in selective curcumin detection," *Current Applied Physics*, vol. 20, no. 11, pp. 1226–1236, 2020.
[69] P. Roy, A. P. Periasamy, C. Chuang et al., "Plant leaf-derived graphene quantum dots and applications for white LEDs," *New Journal of Chemistry*, vol. 38, no. 10, pp. 4946–4951, 2014.
[70] W. Chen, J. Shen, G. Lv et al., "Green synthesis of graphene quantum dots from cotton cellulose," *ChemistrySelect*, vol. 4, no. 10, pp. 2898–2902, 2019.
[71] M. K. Kumawat, M. Thakur, R. B. Gurung, and R. Srivastava, "Graphene quantum dots from *Mangifera indica*: application in near-infrared bioimaging and intracellular nanothermometry," *ACS Sustainable Chemistry & Engineering*, vol. 5, no. 2, pp. 1382–1391, 2017.
[72] H. Teymourinia, M. Salavati-Niasari, O. Amiri, and H. Safardoust-Hojaghan, "Synthesis of graphene quantum dots from corn powder and their application in reduce charge recombination and increase free charge carriers," *Journal of Molecular Liquids*, vol. 242, pp. 447–455, 2017.
[73] S. Sangam, A. Gupta, A. Shakeel et al., "Sustainable synthesis of single crystalline sulphur-doped graphene quantum dots for bioimaging and beyond," *Green Chemistry*, vol. 20, no. 18, pp. 4245–4259, 2018.
[74] M. Robaiah, M. A. Mahmud, M. J. Salifairus et al., "Synthesis and characterization of graphene from waste cooking palm oil at different deposition temperatures," *AIP Conference Proceedings*, vol. 2151, no. 1, Article ID 020026, 2019.
[75] Z. Wang, J. Yu, X. Zhang et al., "Large-scale and controllable synthesis of graphene quantum dots from rice husk biomass: a comprehensive utilization strategy," *ACS Applied Materials & Interfaces*, vol. 8, no. 2, pp. 1434–1439, 2016.
[76] X. Chai, H. He, H. Fan, X. Kang, and X. Song, "A hydrothermal-carbonization process for simultaneously production of sugars, graphene quantum dots, and porous carbon from sugarcane bagasse," *Bioresource Technology*, vol. 282, pp. 142–147, 2019.
[77] E. S. Anooj, V. Suganthi, and P. K. Praseetha, "Synthesis and characterization of graphene quantum dots from turmeric powder (Berberisaristata) and its biomedical applications," *Indian Journal of Public Health Research & Development*, vol. 10, no. 7, Article ID 1239, 2019.
[78] M. E. Mahmoud, N. A. Fekry, and S. M. S. Mohamed, "Effective removal of Pb(II)/4-nitroaniline/*E. faecalis* and *E. coli* pollutants from water by a novel unique graphene quantum dots@gemifloxacin@ double-layered Fe/Al nanocomposite," *Journal of Water Process Engineering*, vol. 46, Article ID 102562, 2022.
[79] Y.-P. Zhang, J.-M. Ma, Y.-S. Yang et al., "Synthesis of nitrogen-doped graphene quantum dots (N-GQDs) from marigold for detection of $Fe^{3+}$ ion and bioimaging," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 217, pp. 60–67, 2019.
[80] H. Teymourinia, M. Salavati-Niasari, and O. Amiri, "Simple synthesis of $Cu_2O$/GQDs nanocomposite with different morphologies fabricated by tuning the synthesis parameters as novel antibacterial material," *Composites Part B: Engineering*, vol. 172, pp. 785–794, 2019.
[81] S. Ganesan, R. Kalimuthu, T. Kanagaraj et al., "Microwave-assisted green synthesis of multi-functional carbon quantum dots as efficient fluorescence sensor for ultra-trace level

monitoring of ammonia in environmental water," *Environmental Research*, vol. 206, Article ID 112589, 2022.
[82] H. L. Tran, W. Darmanto, and R.-A. Doong, "Ultrasensitive detection of tetracycline using boron and nitrogen co-doped graphene quantum dots from natural carbon source as the paper-based nanosensing probe in difference matrices," *Nanomaterials*, vol. 10, no. 9, Article ID 1883, 2020.
[83] P. Roy, A. P. Periasamy, C.-Y. Lin et al., "Photoluminescent graphene quantum dots for in vivo imaging of apoptotic cells," *Nanoscale*, vol. 7, no. 6, pp. 2504–2510, 2015.
[84] L. Wang, W. Li, B. Wu et al., "Facile synthesis of fluorescent graphene quantum dots from coffee grounds for bioimaging and sensing," *Chemical Engineering Journal*, vol. 300, pp. 75–82, 2016.
[85] M. K. Kumawat, M. Thakur, R. B. Gurung, and R. Srivastava, "Graphene quantum dots for cell proliferation, nucleus imaging, and photoluminescent sensing applications," *Scientific Reports*, vol. 7, Article ID 15858, 2017.
[86] A. N. Mohan and B. Manoj, "Biowaste derived graphene quantum dots interlaced with $SnO_2$ nanoparticles – a dynamic disinfection agent against *Pseudomonas aeruginosa*," *New Journal of Chemistry*, vol. 43, no. 34, pp. 13681–13689, 2019.
[87] R. Wang, L. Jiao, X. Zhou, Z. Guo, H. Bian, and H. Dai, "Highly fluorescent graphene quantum dots from biorefinery waste for tri-channel sensitive detection of $Fe^{3+}$ ions," *Journal of Hazardous Materials*, vol. 412, Article ID 125096, 2021.
[88] Y. Yan, S. Manickam, E. Lester, T. Wu, and C. H. Pang, "Synthesis of graphene oxide and graphene quantum dots from miscanthus via ultrasound-assisted mechano-chemical cracking method," *Ultrasonics Sonochemistry*, vol. 73, Article ID 105519, 2021.
[89] E. S. Anooj and P. K. Praseetha, "Cocoa bean-extract mediated graphene quantum dots as antimicrobial, anticancer and plant growth regulators," *International Journal of Recent Technology and Engineering (IJRTE)*, vol. 8, no. 3S2, pp. 269–273, 2019.
[90] Z.-H. Xiong, Y.-N. Zou, X.-C. Cao, and Z.-H. Lin, "Color-tunable fluorescent nitrogen-doped graphene quantum dots derived from pineapple leaf fiber biomass to detect $Hg^{2+}$," *Chinese Journal of Analytical Chemistry*, vol. 50, no. 2, pp. 69–76, 2022.
[91] S. Rashki, H. A. Alshamsi, O. Amiri et al., "Eco-friendly green synthesis of ZnO/GQD nanocomposites using *Protoparmeliopsis muralis* extract for their antibacterial and antibiofilm activity," *Journal of Molecular Liquids*, vol. 335, Article ID 161951, 2021.
[92] Ş. Kir, İ. Dehri, Y. Önal, and R. Esen, "Graphene quantum dots prepared from dried lemon leaves and microcrystalline mosaic structure," *Luminescence*, vol. 36, no. 6, pp. 1365–1376, 2021.
[93] Y. Wang, Q. He, X. Zhao et al., "Synthesis of corn straw-based graphene quantum dots (GQDs) and their application in ${PO_4}^{3-}$ detection," *Journal of Environmental Chemical Engineering*, vol. 10, no. 2, Article ID 107150, 2022.
[94] A. R. Pai, B. Silpa Sasi, J. Arya, and K. S. Arjun, "Synthesis of Graphene Quantum dots from the fresh leaves extract of *Cynodon Dactylon* and its Photoluminescence studies," *IOP Conference Series: Materials Science and Engineering*, vol. 1219, Article ID 012005, 2022.
[95] A. K. Chaturvedi, A. Pappu, and M. K. Gupta, "Unraveling the role of agro waste-derived graphene quantum dots on dielectric and mechanical property of the fly ash based polymer nanocomposite," *Journal of Alloys and Compounds*, vol. 903, Article ID 163953, 2022.
[96] M. Ghiyasiyan-Arani and M. Salavati-Niasari, "Decoration of green synthesized S, N-GQDs and $CoFe_2O_4$ on halloysite nanoclay as natural substrate for electrochemical hydrogen storage application," *Scientific Reports*, vol. 12, Article ID 8103, 2022.
[97] N. Pimsin, C. Keawprom, Y. Areerob et al., "Selective Fe(II)-fluorescence sensor with validated two-consecutive working range using N,S,I-GQDs associated with garlic extract as an auxiliary green chelating agent," *RSC Advances*, vol. 12, no. 23, pp. 14356–14367, 2022.
[98] H. Xie, Y. Lu, R. You, W. Qian, and S. Lin, "Green synthetic nitrogen-doped graphene quantum dot fluorescent probe for the highly sensitive and selective detection of tetracycline in food samples," *RSC Advances*, vol. 12, no. 13, pp. 8160–8171, 2022.
[99] S. I. Maalavika and R. Ilangovan, "Biomass-derived porous carbon and colour-tunable graphene quantum dots for high-performance supercapacitor and selective probe for metal ion detection," *International Journal of Energy Research*, vol. 46, no. 8, pp. 10833–10843, 2022.
[100] C. Rodwihok, T. V. Tam, W. M. Choi et al., "Preparation and characterization of photoluminescent graphene quantum dots from watermelon rind waste for the detection of ferric ions and cellular bio-imaging applications," *Nanomaterials*, vol. 12, no. 4, Article ID 702, 2022.
[101] S. Nangare, S. Patil, S. Patil, Z. Khan, A. Patil, and P. Patil, "Design of graphene quantum dots decorated $MnO_2$ nanosheet based fluorescence turn "On-Off-On" nanoprobe for highly sensitive detection of lactoferrin," *Inorganic Chemistry Communications*, vol. 143, Article ID 109751, 2022.
[102] A. K. Singh, S. Sri, L. B. V. S. Garimella, T. K. Dhiman, S. Sen, and P. R. Solanki, "Graphene quantum dot-based optical sensing platform for aflatoxin B1 detection *via* the resonance energy transfer phenomenon," *ACS Applied Bio Materials*, vol. 5, no. 3, pp. 1179–1186, 2022.
[103] Z. G. Khan and P. O. Patil, "Design and synthesis of poly-L-lysine-functionalized graphene quantum dots sensor for specific detection of cysteine and homocysteine," *Materials Chemistry and Physics*, vol. 276, Article ID 125383, 2022.
[104] D. Iannazzo, I. Ziccarelli, and A. Pistone, "Graphene quantum dots: multifunctional nanoplatforms for anticancer therapy," *Journal of Materials Chemistry B*, vol. 5, no. 32, pp. 6471–6489, 2017.
[105] D. Belletti, G. Riva, M. Luppi et al., "Anticancer drug-loaded quantum dots engineered polymeric nanoparticles: diagnosis/therapy combined approach," *European Journal of Pharmaceutical Sciences*, vol. 107, pp. 230–239, 2017.
[106] X. Hou, Y. Li, and C. Zhao, "Microwave-assisted synthesis of nitrogen-doped multi-layer graphene quantum dots with oxygen-rich functional groups," *Australian Journal of Chemistry*, vol. 69, no. 3, pp. 357–360, 2016.
[107] A. K. Alves, A. C. S. Frantz, and F. A. Berutti, "Microwave-assisted oleothermal synthesis of graphene-$TiO_2$ quantum dots for photoelectrochemical oxygen evolution reaction," *FlatChem*, vol. 12, pp. 26–34, 2018.
[108] D. Gu, S. Shang, Q. Yu, and J. Shen, "Green synthesis of nitrogen-doped carbon dots from lotus root for Hg(II) ions detection and cell imaging," *Applied Surface Science*, vol. 390, pp. 38–42, 2016.
[109] Y. Li, S. Li, Y. Wang et al., "Electrochemical synthesis of phosphorus-doped graphene quantum dots for free radical

scavenging," *Physical Chemistry Chemical Physics*, vol. 19, no. 18, pp. 11631–11638, 2017.

[110] H. Kalita, V. S. Palaparthy, M. S. Baghini, and M. Aslam, "Electrochemical synthesis of graphene quantum dots from graphene oxide at room temperature and its soil moisture sensing properties," *Carbon*, vol. 165, pp. 9–17, 2020.

[111] O. Karaman, N. Özcan, C. Karaman, B. B. Yola, N. Atar, and M. L. Yola, "Electrochemical cardiac troponin I immunosensor based on nitrogen and boron-doped graphene quantum dots electrode platform and Ce-doped $SnO_2/SnS_2$ signal amplification," *Materials Today Chemistry*, vol. 23, Article ID 100666, 2022.

[112] K. K. Wong, "Synthesis of nitrogen-doped graphene quantum dots and its antibacterial property," 2018, https://theses.lib.polyu.edu.hk/handle/200/9414.

[113] Q. Liang, W. Ma, Y. Shi, Z. Li, and X. Yang, "Easy synthesis of highly fluorescent carbon quantum dots from gelatin and their luminescent properties and applications," *Carbon*, vol. 60, pp. 421–428, 2013.

[114] W. Liu, H. Diao, H. Chang, H. Wang, T. Li, and W. Wei, "Green synthesis of carbon dots from rose-heart radish and application for $Fe^{3+}$ detection and cell imaging," *Sensors and Actuators B: Chemical*, vol. 241, pp. 190–198, 2017.

[115] M. Kaur, M. Kaur, and V. K. Sharma, "Nitrogen-doped graphene and graphene quantum dots: a review onsynthesis and applications in energy, sensors and environment," *Advances in Colloid and Interface Science*, vol. 259, pp. 44–64, 2018.

[116] Y. Zhu, G. Wang, H. Jiang, L. Chen, and X. Zhang, "One-step ultrasonic synthesis of graphene quantum dots with high quantum yield and their application in sensing alkaline phosphatase," *Chemical Communications*, vol. 51, no. 5, pp. 948–951, 2015.

[117] B. A. Al Jahdaly, M. F. Elsadek, B. M. Ahmed, M. F. Farahat, M. M. Taher, and A. M. Khalil, "Outstanding graphene quantum dots from carbon source for biomedical and corrosion inhibition applications: a review," *Sustainability*, vol. 13, no. 4, Article ID 2127, 2021.

[118] R. Cheng, C. Yu, Z. Zhen, S. Tang, and S. Ou, "Understanding the selective-sensing mechanism of lysine by fluorescent nanosensors based on graphene quantum dots," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 242, Article ID 118732, 2020.

[119] B. D. Mansuriya and Z. Altintas, "Graphene quantum dot-based electrochemical immunosensors for biomedical applications," *Materials*, vol. 13, no. 1, Article ID 96, 2020.

[120] S. Campuzano, P. Yáñez-Sedeño, and J. M. Pingarrón, "Carbon dots and graphene quantum dots in electrochemical biosensing," *Nanomaterials*, vol. 9, no. 4, Article ID 634, 2019.

[121] L. Li, L. Li, C. Wang et al., "Synthesis of nitrogen-doped and amino acid-functionalized graphene quantum dots from glycine, and their application to the fluorometric determination of ferric ion," *Microchimica Acta*, vol. 182, pp. 763–770, 2015.

[122] H. Xu, S. Zhou, L. Xiao et al., "Nanoreactor-confined synthesis and separation of yellow-luminescent graphene quantum dots with a recyclable SBA-15 template and their application for Fe(III) sensing," *Carbon*, vol. 87, pp. 215–225, 2015.

[123] H. Zhang, Y. Wang, D. Zhao et al., "Universal fluorescence biosensor platform based on graphene quantum dots and pyrene-functionalized molecular beacons for detection of microRNAs," *ACS Applied Materials & Interfaces*, vol. 7, no. 30, pp. 16152–16156, 2015.

[124] H. M. Kashani, T. Madrakian, and A. Afkhami, "Highly fluorescent nitrogen-doped graphene quantum dots as a green, economical and facile sensor for the determination of sunitinib in real samples," *New Journal of Chemistry*, vol. 41, no. 14, pp. 6875–6882, 2017.

[125] A. Yang, Y. Su, Z. Zhang et al., "Preparation of graphene quantum dots by visible-fenton reaction and ultrasensitive label-free immunosensor for detecting lipovitellin of paralichthys olivaceus," *Biosensors*, vol. 12, no. 4, Article ID 246, 2022.

[126] T. A. Tabish, C. J. Scotton, D. C. J. Ferguson et al., "Biocompatibility and toxicity of graphene quantum dots for potential application in photodynamic therapy," *Nanomedicine*, vol. 13, no. 15, pp. 1923–1937, 2018.

[127] J. Sun, Y. He, and L. Wang, "Enzyme-free fluorescence sensing of catechins in green tea using bifunctional graphene quantum dots," *Analytical Methods*, vol. 9, no. 23, pp. 3525–3530, 2017.

[128] Y. Wang, Y. Zhou, L. Xu, Z. Han, H. Yin, and S. Ai, "Photoelectrochemical apta-biosensor for zeatin detection based on graphene quantum dots improved photoactivity of graphite-like carbon nitride and streptavidin induced signal inhibition," *Sensors and Actuators B: Chemical*, vol. 257, pp. 237–244, 2018.

[129] J. Hassanzadeh and A. Khataee, "Ultrasensitive chemiluminescent biosensor for the detection of cholesterol based on synergetic peroxidase-like activity of $MoS_2$ and graphene quantum dots," *Talanta*, vol. 178, pp. 992–1000, 2018.

[130] Q. Xiang, J. Huang, H. Huang, W. Mao, and Z. Ye, "A label-free electrochemical platform for the highly sensitive detection of hepatitis B virus DNA using graphene quantum dots," *RSC Advances*, vol. 8, no. 4, pp. 1820–1825, 2018.

[131] F. Cui, J. Ji, J. Sun et al., "A novel magnetic fluorescent biosensor based on graphene quantum dots for rapid, efficient, and sensitive separation and detection of circulating tumor cells," *Analytical and Bioanalytical Chemistry*, vol. 411, pp. 985–995, 2019.

[132] M. Hasanzadeh, S. Tagi, E. Solhi et al., "An innovative immunosensor for ultrasensitive detection of breast cancer specific carbohydrate (CA 15-3) in unprocessed human plasma and MCF-7 breast cancer cell lysates using gold nanospear electrochemically assembled onto thiolated graphene quantum dots," *International Journal of Biological Macromolecules*, vol. 114, pp. 1008–1017, 2018.

[133] L. T. Tufa, S. Oh, V. T. Tran et al., "Electrochemical immunosensor using nanotriplex of graphene quantum dots, $Fe_3O_4$, and Ag nanoparticles for tuberculosis," *Electrochimica Acta*, vol. 290, pp. 369–377, 2018.

[134] S. Baluta, A. Lesiak, and J. Cabaj, "Graphene quantum dots-based electrochemical biosensor for catecholamine neurotransmitters detection," *Electroanalysis*, vol. 30, no. 8, pp. 1781–1790, 2018.

[135] T. V. Tam and W. M. Choi, "One-pot synthesis of highly fluorescent amino-functionalized graphene quantum dots for effective detection of copper ions," *Current Applied Physics*, vol. 18, no. 11, pp. 1255–1260, 2018.

[136] N. Li, R. Li, Z. Li, Y. Yang, G. Wang, and Z. Gu, "Pentaethylenehexamine and histidine-functionalized graphene quantum dots for ultrasensitive fluorescence detection of microRNA with target and molecular beacon double cycle amplification strategy," *Sensors and Actuators B: Chemical*, vol. 283, pp. 666–676, 2019.

[137] H. Mahmoudi-Moghaddam, S. Tajik, and H. Beitollahi, "A new electrochemical DNA biosensor based on modified carbon paste electrode using graphene quantum dots and ionic liquid for determination of topotecan," *Microchemical Journal*, vol. 150, Article ID 104085, 2019.

[138] M. Lakshmanakumar, N. Nesakumar, S. Sethuraman, K. S. Rajan, U. M. Krishnan, and J. B. B. Rayappan, "Functionalized graphene quantum dot interfaced electrochemical detection of cardiac troponin I: an antibody free approach," *Scientific Reports*, vol. 9, Article ID 17348, 2019.

[139] S. Kang, H. Han, K. Lee, and K. M. Kim, "Ultrasensitive detection of $Fe^{3+}$ ions using functionalized graphene quantum dots fabricated by a one-step pulsed laser ablation process," *ACS Omega*, vol. 7, no. 2, pp. 2074–2081, 2022.

[140] A. B. Ganganboina and R.-A. Doong, "Graphene quantum dots decorated gold-polyaniline nanowire for impedimetric detection of carcinoembryonic antigen," *Scientific Reports*, vol. 9, Article ID 7214, 2019.

[141] A. Ananthanarayanan, X. Wang, P. Routh et al., "Facile synthesis of graphene quantum dots from 3D graphene and their application for $Fe^{3+}$ sensing," *Advanced Functional Materials*, vol. 24, no. 20, pp. 3021–3026, 2014.

[142] Y. Zhang, K. Li, S. Ren et al., "Coal-derived graphene quantum dots produced by ultrasonic physical tailoring and their capacity for Cu(II) detection," *ACS Sustainable Chemistry & Engineering*, vol. 7, no. 11, pp. 9793–9799, 2019.

[143] F. Du, L. Sun, Q. Zen et al., "A highly sensitive and selective "on-off-on" fluorescent sensor based on nitrogen doped graphene quantum dots for the detection of $Hg^{2+}$ and paraquat," *Sensors and Actuators B: Chemical*, vol. 288, pp. 96–103, 2019.

[144] T.-F. Yeh, C.-Y. Teng, L.-C. Chen, S.-J. Chen, and H. Teng, "Graphene oxide-based nanomaterials for efficient photoenergy conversion," *Journal of Materials Chemistry A*, vol. 4, no. 6, pp. 2014–2048, 2016.

[145] Q. Xu, Y. Gong, Z. Zhang, Y. Miao, D. Li, and G. Yan, "Preparation of graphene oxide quantum dots from waste toner, and their application to a fluorometric DNA hybridization assay," *Microchimica Acta*, vol. 186, Article ID 483, 2019.

[146] W. Boonta, C. Talodthaisong, S. Sattayaporn et al., "The synthesis of nitrogen and sulfur co-doped graphene quantum dots for fluorescence detection of cobalt(II) ions in water," *Materials Chemistry Frontiers*, vol. 4, no. 2, pp. 507–516, 2020.

[147] H. Wang, X. Wu, W. Dong, S.-L. Lee, Q. Yuan, and W. Gan, "One-step preparation of single-layered graphene quantum dots for the detection of $Fe^{3+}$," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 226, Article ID 117626, 2020.

[148] B. Gao, D. Chen, B. Gu et al., "Facile and highly effective synthesis of nitrogen-doped graphene quantum dots as a fluorescent sensing probe for $Cu^{2+}$ detection," *Current Applied Physics*, vol. 20, no. 4, pp. 538–544, 2020.

[149] H. Zhang, Z. Yuan, M. Wang et al., "Application of graphene quantum dots in the detection of $Hg^{2+}$ and $ClO^-$ and analysis of detection mechanism," *Diamond and Related Materials*, vol. 117, Article ID 108454, 2021.

[150] T. H. Le, Y. N. Ahn, and S. J. Park, "An effective method for cysteine determination based on fluorescence resonance energy system between co-doped graphene quantum dots and silver nanoparticles," *Korean Journal of Chemical Engineering*, vol. 39, pp. 1065–1071, 2022.

[151] T. V. Huynh, N. T. N. Anh, W. Darmanto, and R.-A. Doong, "Erbium-doped graphene quantum dots with up- and down-conversion luminescence for effective detection of ferric ions in water and human serum," *Sensors and Actuators B: Chemical*, vol. 328, Article ID 129056, 2021.

[152] A. Kalkal, R. Pradhan, S. Kadian, G. Manik, and G. Packirisamy, "Biofunctionalized graphene quantum dots based fluorescent biosensor toward efficient detection of small cell lung cancer," *ACS Applied Bio Materials*, vol. 3, no. 8, pp. 4922–4932, 2020.

[153] Q. Chen, C. Yuan, Z. He et al., "A label-free photoelectrochemical sensor of S, N co-doped graphene quantum dot (S, N-GQD)-modified electrode for ultrasensitive detection of bisphenol A," *Microchimica Acta*, vol. 189, Article ID 208, 2022.

[154] D. Kala, T. K. Sharma, S. Gupta et al., "Development of paper-based DNA sensor for detection of O. tsutsugamushi using sustainable GQDs@AuNPs nanocomposite," *Chemosphere*, vol. 300, Article ID 134428, 2022.

[155] A. Kundu, B. Maity, and S. Basu, "Coal-derived graphene quantum dots with a $Mn^{2+}/Mn^{7+}$ nanosensor for selective detection of glutathione by a fluorescence switch-off-on assay," *New Journal of Chemistry*, vol. 46, no. 16, pp. 7545–7556, 2022.

[156] R. Kaimal, V. Vinoth, A. S. Salunke et al., "Highly sensitive and selective detection of glutathione using ultrasonic aided synthesis of graphene quantum dots embedded over amine-functionalized silica nanoparticles," *Ultrasonics Sonochemistry*, vol. 82, Article ID 105868, 2022.

[157] Y. Zhao, Y. Zhang, H. Liu, and B. Sun, "A visual chiroptical system with chiral assembly graphene quantum dots for D-phenylalanine detection," *Analytical and Bioanalytical Chemistry*, vol. 414, pp. 4885–4896, 2022.

[158] S. Sivaselvam, C. Viswanathan, and N. Ponpandian, "One-step preparation of N-doped grapheme quantum dots with high quantum yield for bioimaging and highly sensitive electrochemical detection of isoniazid," *Biomaterials Advances*, vol. 135, Article ID 212731, 2022.

[159] X. Fan, S. Wang, Z. Li et al., "A novel fluorescence sensor for the detection of chloride ion in artificial sweat and environmental water with nitrogen-doped graphene quantum dots," *Química Nova*, vol. 45, no. 1, pp. 48–52, 2022.

[160] L. Lan, Y. Yao, J. Ping, and Y. Ying, "Recent advances in nanomaterial-based biosensors for antibiotics detection," *Biosensors and Bioelectronics*, vol. 91, pp. 504–514, 2017.

[161] J. Cai, G. Han, J. Ren, C. Liu, J. Wang, and X. Wang, "Single-layered graphene quantum dots with self-passivated layer from xylan for visual detection of trace chromium(Vl)," *Chemical Engineering Journal*, vol. 435, Part 1, Article ID 131833, 2022.

[162] B. Li, X. Xiao, M. Hu et al., "Mn, B, N co-doped graphene quantum dots for fluorescence sensing and biological imaging," *Arabian Journal of Chemistry*, vol. 15, no. 7, Article ID 103856, 2022.

[163] S. Wongrerkdee and P. Pimpang, "Fluorescence quenching probe based on graphene quantum dots for detection of copper ion in water," *Integrated Ferroelectrics*, vol. 222, no. 1, pp. 56–68, 2022.

[164] H. Xie, C. Chen, J. Lie et al., "Sensitive and selective detection of clenbuterol in meat samples by a graphene quantum dot fluorescent probe based on cationic-etherified starch," *Nanomaterials*, vol. 12, no. 4, Article ID 691, 2022.

[165] D. Mukherjee, P. Das, S. Kundu, and B. Mandal, "Engineering of graphene quantum dots by varying the properties of graphene oxide for fluorescence detection of picric acid," *Chemosphere*, vol. 300, Article ID 134432, 2022.

[166] Q. Liu, J. Fan, C. Zhou et al., "Quantitative detection of miRNA-21 expression in tumor cells and tissues based on molecular beacon," *International Journal of Analytical Chemistry*, vol. 2018, Article ID 3625823, 7 pages, 2018.

[167] S. Gupta, T. Smith, A. Banaszak, and J. Boeckl, "Graphene quantum dots electrochemistry and sensitive electrocatalytic

glucose sensor development," *Nanomaterials*, vol. 7, no. 10, Article ID 301, 2017.

[168] D. Raeyani, S. Shojaei, and S. Ahmadi-Kandjani, "Optical graphene quantum dots gas sensors: experimental study," *Materials Research Express*, vol. 7, no. 1, Article ID 015608, 2020.

[169] Y. Dong, G. Li, N. Zhou, R. Wang, Y. Chi, and G. Chen, "Graphene quantum dot as a green and facile sensor for free chlorine in drinking water," *Analytical Chemistry*, vol. 84, no. 19, pp. 8378–8382, 2012.

[170] H. Sun, N. Gao, L. Wu, J. Ren, W. Wei, and X. Qu, "Highly photoluminescent amino-functionalized graphene quantum dots used for sensing copper ions," *Chemistry A European Journal*, vol. 19, no. 40, pp. 13362–13368, 2013.

[171] A. Singh, A. Ahmed, A. Sharma, and S. Arya, "Graphene and its derivatives: synthesis and application in the electrochemical detection of analytes in sweat," *Biosensors*, vol. 12, no. 10, Article ID 910, 2022.

[172] P. Murugan, A. K. Sundramoorthy, R. D. Nagarajan et al., "Electrochemical detection of $H_2O_2$ on graphene nanoribbons/cobalt oxide nanorods-modified electrode," *Journal of Nanomaterials*, vol. 2022, Article ID 9866111, 10 pages, 2022.

[173] R. Kour, S. Arya, S.-J. Young, V. Gupta, P. Bandhoria, and A. Khosla, "Review—recent advances in carbon nanomaterials as electrochemical biosensors," *Journal of The Electrochemical Society*, vol. 167, no. 3, Article ID 037555, 2020.

[174] A. Singh, A. Sharma, and S. Arya, "Deposition of Ni/RGO nanocomposite on conductive cotton fabric as non-enzymatic wearable electrode for electrochemical sensing of uric acid in sweat," *Diamond and Related Materials*, vol. 130, Article ID 109518, 2022.

[175] A. Singh, A. Sharma, A. Ahmed, and S. Arya, "Highly selective and efficient electrochemical sensing of ascorbic acid via CuO/rGO nanocomposites deposited on conductive fabric," *Applied Physics A*, vol. 128, Article ID 262, 2022.

[176] J. Qian, C. Shen, J. Yan, F. Xi, X. Dong, and J. Liu, "Tailoring the electronic properties of graphene quantum dots by P doping and their enhanced performance in metal-free composite photocatalyst," *The Journal of Physical Chemistry C*, vol. 122, no. 1, pp. 349–358, 2018.

[177] C. Zhang, Y. Cui, L. Song, X. Liu, and Z. Hu, "Microwave assisted one-pot synthesis of graphene quantum dots as highly sensitive fluorescent probes for detection of iron ions and pH value," *Talanta*, vol. 150, pp. 54–60, 2016.

[178] M. Kortel, B. D. Mansuriya, N. V. Santana, and Z. Altintas, "Graphene quantum dots as flourishing nanomaterials for bio-imaging, therapy development, and micro-supercapacitors," *Micromachines*, vol. 11, no. 9, Article ID 866, 2020.

[179] K. Kikuchi, "Design, synthesis and biological application of chemical probes for bio-imaging," *Chemical Society Reviews*, vol. 39, no. 6, pp. 2048–2053, 2010.

[180] C. K. Kuhl, S. Schrading, H. B. Bieling et al., "MRI for diagnosis of pure ductal carcinoma in situ: a prospective observational study," *The Lancet*, vol. 370, no. 9586, pp. 485–492, 2007.

[181] T. D. T. Nguyen, A. Pitchaimani, C. Ferrel, R. Thakkar, and S. Aryal, "Nano-confinement-driven enhanced magnetic relaxivity of SPIONs for targeted tumor bioimaging," *Nanoscale*, vol. 10, no. 1, pp. 284–294, 2018.

[182] P. Mahlknecht, A. Hotter, A. Hussl, R. Esterhammer, M. Schocke, and K. Seppi, "Significance of MRI in diagnosis and differential diagnosis of Parkinson's disease," *Neurodegenerative Diseases*, vol. 7, no. 5, pp. 300–318, 2010.

[183] P. F. Rizzo, E. S. Gould, J. P. Lyden, and S. E. Asnis, "Diagnosis of occult fractures about the hip. Magnetic resonance imaging compared with bone-scanning," *The Journal of Bone & Joint Surgery*, vol. 75, no. 3, pp. 395–401, 1993.

[184] L. Liang, Z. Kong, Z. Kang, H. Wang, L. Zhang, and J.-W. Shen, "Theoretical evaluation on potential cytotoxicity of graphene quantum dots," *ACS Biomaterials Science & Engineering*, vol. 2, no. 11, pp. 1983–1991, 2016.

[185] X. Gao, L. Yang, J. A. Petros, F. F. Marshall, J. W. Simons, and S. Nie, "*In vivo* molecular and cellular imaging with quantum dots," *Current Opinion in Biotechnology*, vol. 16, no. 1, pp. 63–72, 2005.

[186] Y. Liu, S. Zhou, L. Fan, and H. Fan, "Synthesis of red fluorescent graphene quantum dot-europium complex composites as a viable bioimaging platform," *Microchimica Acta*, vol. 183, pp. 2605–2613, 2016.

[187] S. Zhu, J. Zhang, S. Tang et al., "Surface chemistry routes to modulate the photoluminescence of graphene quantum dots: from fluorescence mechanism to up-conversion bioimaging applications," *Advanced Functional Materials*, vol. 22, no. 22, pp. 4732–4740, 2012.

[188] H. Sun, L. Wu, N. Gao, J. Ren, and X. Qu, "Improvement of photoluminescence of graphene quantum dots with a biocompatible photochemical reduction pathway and its bioimaging application," *ACS Applied Materials & Interfaces*, vol. 5, no. 3, pp. 1174–1179, 2013.

[189] Z. Qian, J. Ma, X. Shan et al., "Surface functionalization of graphene quantum dots with small organic molecules from photoluminescence modulation to bioimaging applications: an experimental and theoretical investigation," *RSC Advances*, vol. 3, no. 34, pp. 14571–14579, 2013.

[190] Z. Luo, D. Yang, C. Yang et al., "Graphene quantum dots modified with adenine for efficient two-photon bioimaging and white light-activated antibacteria," *Applied Surface Science*, vol. 434, pp. 155–162, 2018.

[191] C. Hu, Y. Liu, Y. Yang et al., "One-step preparation of nitrogen-doped graphenequantum dots from oxidized debris of graphene oxide," *Journal of Materials Chemistry B*, vol. 1, no. 1, pp. 39–42, 2013.

[192] X. Tan, Y. Li, X. Li, S. Zhou, L. Fan, and S. Yang, "Electrochemical synthesis of small-sized red fluorescent graphene quantum dots as a bioimaging platform," *Chemical Communications*, vol. 51, no. 13, pp. 2544–2546, 2015.

[193] C. Yan, X. Hu, P. Guan et al., "Highly biocompatible graphene quantum dots: green synthesis, toxicity comparison and fluorescence imaging," *Journal of Materials Science*, vol. 55, pp. 1198–1215, 2020.

[194] J. Chen, A. Than, N. Li et al., "Sweet graphene quantum dots for imaging carbohydrate receptors in live cells," *FlatChem*, vol. 5, pp. 25–32, 2017.

[195] L. Zhou, J. Geng, and B. Liu, "Graphene quantum dots from polycyclic aromatic hydrocarbon for bioimaging and sensing of $Fe^{3+}$ and hydrogen peroxide," *Particle & Particle Systems Characterization*, vol. 30, no. 12, pp. 1086–1092, 2013.

[196] W. Chen, D. Li, L. Tian et al., "Synthesis of graphene quantum dots from natural polymer starch for cell imaging," *Green Chemistry*, vol. 20, no. 19, pp. 4438–4442, 2018.

[197] T. A. Tabish, L. Lin, M. Ali et al., "Investigating the bioavailability of graphene quantum dots in lung tissues via Fourier transform infrared spectroscopy," *Interface Focus*, vol. 8, no. 3, Article ID 20170054, 2018.

[198] T. Wang, S. Zhu, and X. Jiang, "Toxicity mechanism of graphene oxide and nitrogen-doped graphene quantum dots in RBCs

revealed by surface-enhanced infrared absorption spectroscopy," *Toxicology Research*, vol. 4, no. 4, pp. 885–894, 2015.

[199] B.-C. Lee, J. Y. Lee, J. Kim et al., "Graphene quantum dots as anti-inflammatory therapy for colitis," *Science Advances*, vol. 6, no. 18, Article ID eaaz2630, 2020.

[200] C. Martín, G. Jun, R. Schurhammer et al., "Enzymatic degradation of graphene quantum dots by human peroxidases," *Small*, vol. 15, no. 52, Article ID 1905405, 2019.

[201] A. Chandra, S. Deshpande, D. B. Shinde, V. K. Pillai, and N. Singh, "Mitigating the cytotoxicity of graphene quantum dots and enhancing their applications in bioimaging and drug delivery," *ACS Macro Letters*, vol. 3, no. 10, pp. 1064–1068, 2014.

[202] Y. Chong, Y. Ma, H. Shen et al., "The *in vitro* and *in vivo* toxicity of graphene quantum dots," *Biomaterials*, vol. 35, no. 19, pp. 5041–5048, 2014.

[203] S. Fasbender, L. Zimmermann, R.-P. Cadeddu et al., "The low toxicity of graphene quantum dots is reflected by marginal gene expression changes of primary human hematopoietic stem cells," *Scientific Reports*, vol. 9, Article ID 12028, 2019.

[204] Z. Fan, Y. Nie, Y. Wei, J. Zhao, X. Liao, and J. Zhang, "Facile and large-scale synthesis of graphene quantum dots for selective targeting and imaging of cell nucleus and mitochondria," *Materials Science and Engineering: C*, vol. 103, Article ID 109824, 2019.

[205] A. Biswas, P. Khandelwal, R. Das et al., "Oxidant mediated one-step complete conversion of multi-walled carbon nanotubes to graphene quantum dots and their bioactivity against mammalian and bacterial cells," *Journal of Materials Chemistry B*, vol. 5, no. 4, pp. 785–796, 2017.

[206] J. Liu, M. D. Rojas-Andrade, G. Chata et al., "Photo-enhanced antibacterial activity of ZnO/graphene quantum dot nanocomposites," *Nanoscale*, vol. 10, no. 1, pp. 158–166, 2018.

[207] W.-S. Kuo, H.-H. Chen, S.-Y. Chen et al., "Graphene quantum dots with nitrogen-doped content dependence for highly efficient dual-modality photodynamic antimicrobial therapy and bioimaging," *Biomaterials*, vol. 120, pp. 185–194, 2017.

[208] H. Teymourinia, M. Salavati-Niasari, O. Amiri, and F. Yazdian, "Application of green synthesized $TiO_2/Sb_2S_3$/GQDs nanocomposite as high efficient antibacterial agent against *E. coli* and *Staphylococcus aureus*," *Materials Science and Engineering C*, vol. 99, pp. 296–303, 2019.

[209] H. Sun, N. Gao, K. Dong, J. Ren, and X. Qu, "Graphene quantum dots-band-aids used for wound disinfection," *ACS Nano*, vol. 8, no. 6, pp. 6202–6210, 2014.

[210] J. Dong, K. Wang, L. Sun et al., "Application of graphene quantum dots for simultaneous fluorescence imaging and tumor-targeted drug delivery," *Sensors and Actuators B: Chemical*, vol. 256, pp. 616–623, 2018.

[211] X. Sui, C. Luo, C. Wang, F. Zhang, J. Zhang, and S. Guo, "Graphene quantum dots enhance anticancer activity of cisplatin *via* increasing its cellular and nuclear uptake," *Nanomedicine: Nanotechnology, Biology and Medicine*, vol. 12, no. 7, pp. 1997–2006, 2016.

[212] C. Wang, C. Wu, X. Zhou et al., "Enhancing cell nucleus accumulation and DNA cleavage activity of anti-cancer drug via graphene quantum dots," *Scientific Reports*, vol. 3, Article ID 2852, 2013.

[213] X. Wang, X. Sun, J. Lao et al., "Multifunctional graphene quantum dots for simultaneous targeted cellular imaging and drug delivery," *Colloids and Surfaces B: Biointerfaces*, vol. 122, pp. 638–644, 2014.

[214] N. R. Ko, M. Nafiujjaman, J. S. Lee, H.-N. Lim, Y.-K. Lee, and I. K. Kwon, "Graphene quantum dot-based theranostic agents for active targeting of breast cancer," *RSC Advances*, vol. 7, no. 19, pp. 11420–11427, 2017.

[215] J. Ju, S. Regmi, A. Fu, S. Lim, and Q. Liu, "Graphene quantum dot based charge-reversal nanomaterial for nucleus-targeted drug delivery and efficiency controllable photodynamic therapy," *Journal of Biophotonics*, vol. 12, no. 6, Article ID e201800367, 2019.

[216] J. Qiu, R. Zhang, J. Li et al., "Fluorescent graphene quantum dots as traceable, pH-sensitive drug delivery systems," *International Journal of Nanomedicine*, vol. 10, no. 1, pp. 6709–6724, 2015.

[217] C.-L. Huang, C.-C. Huang, F.-D. Mai et al., "Application of paramagnetic graphene quantum dots as a platform for simultaneous dual-modality bioimaging and tumor-targeted drug delivery," *Journal of Materials Chemistry B*, vol. 3, no. 4, pp. 651–664, 2015.

[218] Y. Yang, S. Chen, L. Liu et al., "Increasing cancer therapy efficiency through targeting and localized light activation," *ACS Applied Materials & Interfaces*, vol. 9, no. 28, pp. 23400–23408, 2017.

[219] O. Lv, Y. Tao, Y. Qin et al., "Highly fluorescent and morphology-controllable graphene quantum dots-chitosan hybrid xerogels for *in vivo* imaging and pH-sensitive drug carrier," *Materials Science and Engineering: C*, vol. 67, pp. 478–485, 2016.

[220] H. Zhu, J. Li, X. Qi, P. Chen, and K. Pu, "Oxygenic hybrid semiconducting nanoparticles for enhanced photodynamic therapy," *Nano Letters*, vol. 18, no. 1, pp. 586–594, 2018.

[221] P. Agostinis, K. Berg, K. A. Cengel et al., "Photodynamic therapy of cancer: an update," *CA: A Cancer Journal for Clinicians*, vol. 61, no. 4, pp. 250–281, 2011.

[222] B. Z. Ristic, M. M. Milenkovic, I. R. Dakic et al., "Photodynamic antibacterial effect of graphene quantum dots," *Biomaterials*, vol. 35, no. 15, pp. 4428–4435, 2014.

[223] S. P. Jovanović, Z. Syrgiannis, Z. M. Marković et al., "Modification of structural and luminescence properties of graphene quantum dots by gamma irradiation and their application in a photodynamic therapy," *ACS Applied Materials & Interfaces*, vol. 7, no. 46, pp. 25865–25874, 2015.

[224] X. Wang, X. Sun, H. He et al., "A two-component active targeting theranostic agent based on graphene quantum dots," *Journal of Materials Chemistry B*, vol. 3, no. 17, pp. 3583–3590, 2015.

[225] J. Ge, M. Lan, B. Zhou et al., "A graphene quantum dot photodynamic therapy agent with high singlet oxygen generation," *Nature Communications*, vol. 5, Article ID 4596, 2014.

[226] S. Kadian, G. Manik, N. Das, P. Nehra, R. P. Chauhan, and P. Roy, "Synthesis, characterization and investigation of synergistic antibacterial activity and cell viability of silver-sulfur doped graphene quantum dot (Ag@ S-GQDs) nanocomposites," *Journal of Materials Chemistry B*, vol. 8, no. 15, pp. 3028–3037, 2020.

[227] S. Li, S. Zhou, Y. Li et al., "Exceptionally high payload of the IR780 iodide on folic acid-functionalized graphene quantum dots for targeted photothermal therapy," *ACS Applied Materials & Interfaces*, vol. 9, no. 27, pp. 22332–22341, 2017.

[228] M. Thakur, M. K. Kumawat, and R. Srivastava, "Multifunctional graphene quantum dots for combined photothermal

and photodynamic therapy coupled with cancer cell tracking applications," *RSC Advances*, vol. 7, no. 9, pp. 5251–5261, 2017.

[229] Z. Tian, X. Yao, K. Ma et al., "Metal–organic framework/ graphene quantum dot nanoparticles used for synergistic chemo- and photothermal therapy," *ACS Omega*, vol. 2, no. 3, pp. 1249–1258, 2017.

[230] D. Qu, Z. Sun, M. Zheng et al., "Three colors emission from S, N Co-doped graphene quantum dots for visible light $H_2$ production and bioimaging," *Advanced Optical Materials*, vol. 3, no. 3, pp. 360–367, 2015.

[231] L.-C. Chen, C.-Y. Teng, C.-Y. Lin, H.-Y. Chang, S.-J. Chen, and H. Teng, "Architecting nitrogen functionalities on graphene oxide photocatalysts for boosting hydrogen production in water decomposition process," *Advanced Energy Materials*, vol. 6, no. 22, Article ID 1600719, 2016.

[232] M. Yan, Y. Hua, F. Zhu, L. Sun, W. Gu, and W. Shi, "Constructing nitrogen doped graphene quantum dots-$ZnNb_2O_6$/ g-$C_3N_4$ catalysts for hydrogen production under visible light," *Applied Catalysis B: Environmental*, vol. 206, pp. 531–537, 2017.

[233] B. K. Gupta, G. Kedawat, Y. Agrawal, P. Kumar, J. Dwivedi, and S. K. Dhawan, "A novel strategy to enhance ultraviolet light driven photocatalysis from graphene quantum dots infilled $TiO_2$ nanotube arrays," *RSC Advances*, vol. 5, no. 14, pp. 10623–10631, 2015.

[234] D. Pan, C. Xi, Z. Li et al., "Electrophoretic fabrication of highly robust, efficient, and benign heterojunction photoelectrocatalysts based on graphene-quantum-dot sensitized $TiO_2$ nanotube arrays," *Journal of Materials Chemistry A*, vol. 1, no. 11, pp. 3551–3555, 2013.

[235] S. Zhuo, M. Shao, and S.-T. Lee, "Upconversion and downconversion fluorescent graphene quantum dots: ultrasonic preparation and photocatalysis," *ACS Nano*, vol. 6, no. 2, pp. 1059–1064, 2012.

[236] T.-F. Yeh, C.-Y. Teng, S.-J. Chen, and H. Teng, "Nitrogen-doped graphene oxide quantum dots as photocatalysts for overall water-splitting under visible light Illumination," *Advanced Materials*, vol. 26, no. 20, pp. 3297–3303, 2014.

[237] Y. Wang, F. Wang, Y. Feng et al., "Facile synthesis of carbon quantum dots loaded with mesoporous g-$C_3$ $N_4$ for synergistic absorption and visible light photodegradation of fluoroquinolone antibiotics," *Dalton Transactions*, vol. 47, no. 4, pp. 1284–1293, 2018.

[238] S. Ham, Y. Kim, M. J. Park, B. H. Hong, and D.-J. Jang, "Graphene quantum dots-decorated ZnS nanobelts with highly efficient photocatalytic performances," *RSC Advances*, vol. 6, no. 29, pp. 24115–24120, 2016.

[239] C. Wang, R. Xiao, S. Wang et al., "Magnetic quantum dot based lateral flow assay biosensor for multiplex and sensitive detection of protein toxins in food samples," *Biosensors and Bioelectronics*, vol. 146, Article ID 111754, 2019.

[240] S. R. Ahmed, S. Kumar, G. A. Ortega, S. Srinivasan, and A. R. Rajabzadeh, "Target specific aptamer-induced self-assembly of fluorescent graphene quantum dots on palladium nanoparticles for sensitive detection of tetracycline in raw milk," *Food Chemistry*, vol. 346, Article ID 128893, 2021.

[241] O. Bunkoed, P. Donkhampa, and P. Nurerk, "A nanocomposite optosensor of hydroxyapatite and graphene quantum dots embedded within highly specific polymer for norfloxacin detection," *Microchemical Journal*, vol. 158, Article ID 105127, 2020.

[242] O. Bunkoed, P. Raksawong, R. Chaowana, and P. Nurerk, "A nanocomposite probe of graphene quantum dots and magnetite nanoparticles embedded in a selective polymer for the enrichment and detection of ceftazidime," *Talanta*, vol. 218, Article ID 121168, 2020.

[243] R. Afsharipour, A. M. Haji Shabani, S. Dadfarnia, and E. Kazemi, "Selective fluorometric determination of sulfadiazine based on the growth of silver nanoparticles on graphene quantum dots," *Microchimica Acta*, vol. 187, Article ID 54, 2020.

[244] K. Ghanbari and M. Roushani, "A novel electrochemical aptasensor for highly sensitive and quantitative detection of the streptomycin antibiotic," *Bioelectrochemistry*, vol. 120, pp. 43–48, 2018.

[245] J.-Y. Huang, T. Bao, T.-X. Hu, W. Wen, X.-H. Zhang, and S.-F. Wang, "Voltammetric determination of levofloxacin using a glassy carbon electrode modified with poly(o-aminophenol) and graphene quantum dots," *Microchimica Acta*, vol. 184, pp. 127–135, 2017.

[246] S. Lahouidak, M. L. Soriano, R. Salghi, M. Zougagh, and Á. Ríos, "Graphene quantum dots for enhancement of fluorimetric detection coupled to capillary electrophoresis for detection of ofloxacin," *Electrophoresis*, vol. 40, no. 18-19, pp. 2336–2341, 2019.

[247] W. Li, J. Zhu, G. Xie, Y. Ren, and Y.-Q. Zheng, "Ratiometric system based on graphene quantum dots and $Eu^{3+}$ for selective detection of tetracyclines," *Analytica Chimica Acta*, vol. 1022, pp. 131–137, 2018.

[248] H. Tsai, H.-C. Hu, C.-C. Hsieh, Y.-H. Lu, C.-H. Chen, and C.-B. Fuh, "Fluorescence studies of the interaction between chloramphenicol and nitrogen-doped graphene quantum dots and determination of chloramphenicol in chicken feed," *Journal of the Chinese Chemical Society*, vol. 67, no. 1, pp. 152–159, 2020.

[249] M. Moallemi Bahmani, A. M. Haji Shabani, S. Dadfarnia, and R. Afsharipour, "Selective and sensitive fluorometric determination of piroxicam based on nitrogen-doped graphene quantum dots and gold nanoparticles coated with phenylalanine," *Journal of Fluorescence*, vol. 32, pp. 1337–1346, 2022.

[250] T. Zhou, A. Halder, and Y. Sun, "Fluorescent nanosensor based on molecularly imprinted polymers coated on graphene quantum dots for fast detection of antibiotics," *Biosensors*, vol. 8, no. 3, Article ID 82, 2018.

[251] X.-X. Chen, Z.-Z. Lin, Q.-H. Yao, and Z.-Y. Huang, "A practical aptaprobe for sulfadimethoxine residue detection in water and fish based on the fluorescence quenching of CdTe QDs by poly (diallyldimethylammonium chloride)," *Journal of Food Composition and Analysis*, vol. 91, Article ID 103526, 2020.

[252] O. Adegoke, M. Morita, T. Kato, M. Ito, T. Suzuki, and E. Y. Park, "Localized surface plasmon resonance-mediated fluorescence signals in plasmonic nanoparticle-quantum dot hybrids for ultrasensitive Zika virus RNA detection via hairpin hybridization assays," *Biosensors and Bioelectronics*, vol. 94, pp. 513–522, 2017.

[253] K. Radhakrishnan, S. Sivanesan, and P. Panneerselvam, "Turn-on fluorescence sensor based detection of heavy metal ion using carbon dots@graphitic-carbon nitride nanocomposite probe," *Journal of Photochemistry and Photobiology A: Chemistry*, vol. 389, Article ID 112204, 2020.

[254] H. Chen, O. Hu, Y. Fan et al., "Fluorescence paper-based sensor for visual detection of carbamate pesticides in food

based on CdTe quantum dot and nano ZnTPyP," *Food Chemistry*, vol. 327, Article ID 127075, 2020.

[255] D. Wang, X. P. Mei, S. Wang, J. Li, and C. Dong, "A one-pot synthesis of fluorescent N,P-codoped carbon dots for vitamin $B_{12}$ determination and bioimaging application," *New Journal of Chemistry*, vol. 45, no. 7, pp. 3508–3514, 2021.

[256] R. El-Hnayn, L. Canabady-Rochelle, C. Desmarets et al., "One-step synthesis of diamine-functionalized graphene quantum dots from graphene oxide and their chelating and antioxidant activities," *Nanomaterials*, vol. 10, no. 1, Article ID 104, 2020.

[257] M. Nurunnabi, Z. Khatun, K. M. Huh et al., "*In Vivo* biodistribution and toxicology of carboxylated graphene quantum dots," *ACS Nano*, vol. 7, no. 8, pp. 6858–6867, 2013.

[258] C. Wu, C. Wang, T. Han, X. Zhou, S. Guo, and J. Zhang, "Insight into the cellular internalization and cytotoxicity of graphene quantum dots," *Advanced Healthcare Materials*, vol. 2, no. 12, pp. 1613–1619, 2013.

[259] M. Davardoostmanesh, H. Ahmadzadeh, E. K. Goharshadi, A. Meshkini, and E. Sistanipour, "Electrophoretic extraction of highly monodispersed graphene quantum dots from widely polydispersed bulk and its cytotoxicity effect against cancer cells," *Microchemical Journal*, vol. 159, Article ID 105391, 2020.

[260] Z. Fan, S. Li, F. Yuan, and L. Fan, "Fluorescent graphene quantum dots for biosensing and bioimaging," *RSC Advances*, vol. 5, no. 25, pp. 19773–19789, 2015.

[261] D. Jiang, Y. Chen, N. Li et al., "Synthesis of luminescent graphene quantum dots with high quantum yield and their toxicity study," *PLOS ONE*, vol. 10, no. 12, Article ID e0144906, 2015.

[262] Y. Qin, Z.-W. Zhou, S.-T. Pan et al., "Graphene quantum dots induce apoptosis, autophagy, and inflammatory response via p38 mitogen-activated protein kinase and nuclear factor-$\kappa$B mediated signaling pathways in activated THP-1 macrophages," *Toxicology*, vol. 327, pp. 62–76, 2015.

[263] M. Krunić, B. Ristić, M. Bošnjak et al., "Graphene quantum dot antioxidant and proautophagic actions protect SH-SY5Y neuroblastoma cells from oxidative stress-mediated apoptotic death," *Free Radical Biology and Medicine*, vol. 177, pp. 167–180, 2021.

[264] X. Hai, Q.-X. Mao, W.-J. Wang, X.-F. Wang, X.-W. Chen, and J.-H. Wang, "An acid-free microwave approach to prepare highly luminescent boron-doped graphene quantum dots for cell imaging," *Journal of Materials Chemistry B*, vol. 3, no. 47, pp. 9109–9114, 2015.

[265] A. K. Narasimhan, S. Lakshmi B, T. S. Santra, M. S. R. Rao, and G. Krishnamurthi, "Oxygenated graphene quantum dots (GQDs) synthesized using laser ablation for long-term real-time tracking and imaging," *RSC Advances*, vol. 7, no. 85, pp. 53822–53829, 2017.

[266] D. Zhang, L. Wen, R. Huang, H. Wang, X. Hu, and D. Xing, "Mitochondrial specific photodynamic therapy by rare-earth nanoparticles mediated near-infrared graphene quantum dots," *Biomaterials*, vol. 153, pp. 14–26, 2018.

[267] Z. Ding, F. Li, J. Wen, X. Wang, and R. Sun, "Gram-scale synthesis of single-crystalline graphene quantum dots derived from lignin biomass," *Green Chemistry*, vol. 20, no. 6, pp. 1383–1390, 2018.

[268] S. Ahirwar, S. Mallick, and D. Bahadur, "Photodynamic therapy using graphene quantum dot derivatives," *Journal of Solid State Chemistry*, vol. 282, Article ID 121107, 2020.