Graphene Quantum Dots (GQDs) and their Applications

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Graphene quantum dots (GQDs) have been widely studied in recent years due to its unique structure related properties, such as optical, electrical and optoelectrical properties. Furthermore, GQDs are environment friendly due to its non-toxic and biologically inert properties, which have attracted worldwide interests from academic and industry. This review introduces quantum dots (QDs) and explores their applications, delivery systems in biology. QDs are one of the first nanotechnologies to be integrated with the biological sciences and are widely anticipated to eventually find application in a number of commercial consumer and clinical products. The various applications of GQDs in biological imaging, photodynamic therapy, electrochemical sensors and use in drug delivery and medicine are described. GQDs composites, having optimized contents and properties, are also discussed to extend the applications of GQDs.

Keywords: Graphene quantum dots GQDs, Drug delivery, Nanobiotechnology, Biosensors.

1. INTRODUCTION

Since 19 century, carbon is one of the most abundant elements, has been globally researched and has experienced a sudden increase in its studies. From few past years, a new class of fluorescent particles appears as a good candidate for single molecule and single particle tracking (SPT) in living cells and organisms, the semiconductor quantum dots [1]. Quantum dots (QDs), narrate as ‘artificial atoms,’ exhibit discrete energy levels, and their band gap can be accurately modulated by varying the size [2]. Quantum dots (GQDs), a novel type of zero dimensional luminescent nanomaterial, are small graphene fragments varying in size from 1 to 100 nm [3,4]. GQDs not only possess the fascinating properties derived from two-dimensional (2D) graphene but also demonstrate outstanding physicochemical characteristics of the QDs, including edge effects, non-zero band gap, and quantum confinement effects, by which they hold great potential in energy, electronic, and optical industry [5]. QDs exhibit distinctive luminescence characteristics and electronic properties such as vast and continuous absorption spectra, narrow emission spectra, and high light stability [6].

Graphene quantum dots (GQDs) are nanoscale graphene particles typically less than 20 nm in diameter. Their unique features include low toxicity, good solubility, tunable photoluminescence (PL), biocompatibility, and photo-induced electron transfer. GQDs can be produced using methods such as hydrothermal reactions, laser ablation, microwave radiation, and electrochemical oxidation. These production methods involve various chemical reactions like carbonization, oxidation, pyrolysis, and polymerization. Due to their small size, GQDs have strong tunable fluorescent properties and high photoluminescence emissions. They are suitable for various applications, including eliminating pollutants and organic dyes through catalysis, absorbing heavy metals, and purifying microbial contamination through filtration. However, challenges in developing GQDs for environmental applications include producing high-quality QDs and creating large-scale synthetic methods that ensure consistent size distribution. Therefore, there is a need for theoretical and practical research to develop novel methods that achieve high yields and easy purification of GQDs.

Graphene quantum dots (GQDs) are a type of carbon nanomaterial derived from graphene, known for their excellent electronic, optical, and chemical properties. They exhibit quantum confinement and edge effects, which contribute to their unique characteristics. These dots are highly sought after in various scientific and technological fields due to their multifunctionality. GQDs hold significant promise for a wide range of applications due to their unique properties. Advances in synthesis methods and a deeper understanding of their behavior will be key to overcoming current challenges and fully realizing their potential in environmental and biomedical fields.

2. SYNTHESIS METHODS

2.1. Hydrothermal Reactions

This method involves using high-pressure and high-temperature water to break down carbon precursors into GQDs. It is popular due to its simplicity and ability to control the size and properties of GQDs.

2.2. Laser Ablation

In this method, a high-energy laser beam is used to vaporize a carbon source, leading to the formation of GQDs. It allows precise control over the size and shape of the dots.

2.3. Microwave Radiation

This technique uses microwave energy to rapidly heat carbon precursors, producing GQDs in a short time. It is efficient and can be scaled up for large-scale production.

2.4. Electrochemical Oxidation

This involves applying an electrical current to a graphite electrode in an electrolyte solution, causing oxidation and exfoliation of graphene layers into GQDs. It offers good control over the particle size and surface properties.

3. PROPERTIES

3.1. Low Toxicity and Biocompatibility

GQDs are considered safe for biomedical applications, including bioimaging, drug delivery, and biosensing.

3.2. Tunable Photoluminescence (PL)

The emission properties of GQDs can be adjusted by altering their size, shape, and surface chemistry. This makes them suitable for applications in optoelectronics, such as LEDs and solar cells.

3.3. Photo-induced Electron Transfer

This property is valuable in photocatalysis and energy conversion, where GQDs can act as efficient catalysts for various reactions.

4. APPLICATION

4.1. Environmental Applications

4.1.1. Catalysis: GQDs can catalyze the degradation of pollutants and organic dyes in water, making them useful in water purification and treatment processes.

4.1.2. Heavy Metal Absorption: GQDs have a high surface area and functional groups that can bind to heavy metals, aiding in the removal of toxic metals from contaminated water.

4.1.3. Microbial Contamination Filtration: Due to their antimicrobial properties, GQDs can be used in filtration systems to purify water by eliminating bacteria and other microorganisms.

4.2. Application in drug and medications

Nano-sized inorganic particles of either simple or complex nature, display unique, physical and chemical properties and represent progressively important material to buildout the novel nanodevices which helps in various physical, biological, biomedical and pharmaceutical applications [7].With the help of recent studies it is know that GQDs are less toxic, having greater biocompatibility than other nanomaterials, and also have stable and strong fluorescence. All the qualities of graphene quantum dots make these nanomaterials ideal for use in cancer treatment. A compact drug delivery nanosystem with valuable aspects makes an interest for cancer therapy owing to their improved dose tolerance and therapeutic efficacy [8]. GQDs are the more effective carriers or loaders of drug molecules. For instance, a biocompatible and cell traceable drug delivery system based on GQDs, for the targeted delivery of the DNA-intercalating drug doxorubicin (DOX) to cancer cells [9]. GQDs platforms have been studied in gene-based therapies across various breast cell lines. QDs with intense and stable fluorescent properties could enable the detection of tens to hundreds of cancer biomarkers in blood assays, on cancer tissue biopsies, or as contrast agents for medical imaging. Clinical results of cancer diagnosis is highly dependent on the stage at which the malignancy is detected, and that is why early screening has become extremely important in any type of cancer [10]. A schematic diagram showing the drug delivery and release in GQDs based system is shown in Fig. 1 [11]. First, the drugs are delivered to the target cells by EPR (enhanced permeability and retention) effect or the targeting ligand, and then up taken by cells. Similar with other non-degradable nanoparticle drug carriers, drugs released from GQDs via a diffusion process. For example, the adsorbed drugs on GQDs can be released into cytoplasm by desorption and diffusion.

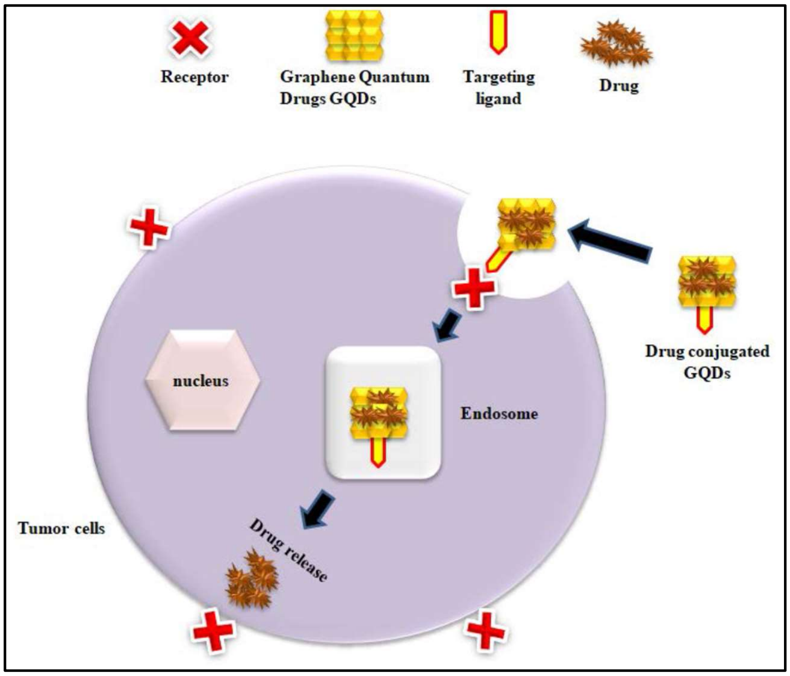

Fig. 1: Illustration of receptor-mediated endocytosis of targeting ligand-conjugated GQDs loaded with an anticancer drug into a tumor cell and drug release inside the cell.

4.3. Sensors (Electrochemical Sensor)

These materials have been predominantly utilized toward the fabrication of electrochemical and optical biosensors which has been proved by some few past decades [12]. The interaction between GQDs and some substances can cause fluorescent intensity of the GQDs to be reduced. On the authority of this principle, a variety of chemical or biological sensors can be designed to detect heavy metal ions [13], small organic or inorganic molecules [14], and biological molecules [15]. Mimicking metallic nanomaterials, graphene has been reported as a zero-bandgap material. Yet, this zero-bandgap restricts graphene from emitting light and generating an electron–hole pair upon excitation. If we cut graphene into nanometer sized materials, say GQDs, they can have a non-zero variable bandgap according to their size, thereby can emit light upon excitation [16]. Most valuable features of graphene is its lateral conduction in 2D sheets. This property helps in designing electrochemical biosensors for various biomedical applications [17]. Electrochemical biosensors are the analytical devices that provide quantitative information on an analyze by converting a biological signal into a final readable electrical signal [18]. The components of these biosensors include a biorecognition element, an immobilization matrix, and a transducer surface. Latterly, GQDs have best features for the designing of different types of electrochemical biosensors having marvelous properties such as fast transduction, a high electron-transfer rate, inimitable electro catalytic characteristics, higher surface areas, ease of surface fictionalization, and higher biomolecules loading. These GQD-based electrochemical biosensors have been used for the detection of small molecules, nucleic acids, bioflavonoids, amino acids, vitamins, heavy metal ions, and biomarkers with remarkable biosensing characteristics as shown in Table 1 [19].

Table 1: Summary of different GQD-based ECL biosensors along with their sensing characteristics.

Sensing platform	Analyte detected	LOD	Detection range	References
BamHI-GQDs	Hepatitis C virus	0.45 fM	5 fM to 100 pM	25
GQDs-chitosan	Glucose	0.3 pM	1.2–120 pM	26
GQDs–AuNPs	p53 DNA damage	13 nM	25–400 nM	27
PDDA-GO-GQDs	DNA	0.1 pM	1.0 pM to 1000 nM	28
PDA-SIP-N-GQDs	E. coli	8 CFU mL^{-1}	10^1 –10^7 CFU mL^{-1}	29
GQDs and GO	Protein kinase	0.05 U mL^{-1}	0.05–5 U mL^{-1}	30

4.4. Bioimaging

GQDs having a marvelous application in biological imaging for medical diagnostic as they can assist in locating cancerous cells and regulate if drugs have been delivered to targeted cells as well as locating the drugs within cells [20]. They are 0-D member of the carbon family; GQDs hold great promise to actively substitute these fluorophores owing to the tunable and, photo stability, excellent biocompatibility, and effective renal clearance, thus offering unprecedented opportunities for bioimaging [21]. GQDs have a potential application in the field of bio-imaging because of their excellent fluorescence properties and the low cytotoxicity [22]. As we know, there had been no direct effective technology for imaging of stem cells for a long time, due to the particularity of the stem cells. Three different kinds of stem cells, namely neurospheres cells (NSCs), pancreas progenitor cells (PPCs) and cardiac progenitor cells (CPCs), were used in the studied and cultured in different mediums and the results showed that GQDs can smoothly enter into the stem cells. It was found that GQDs were not observed in the nucleus, indicating that it will not cause genetic disruption of the stem cells. It showed that GQDs had relatively low cytotoxicity [23]. This perspective signifies the peculiar advantages of GQDs for direct and efficient stem cell labelling, opening up great opportunities for their biomedical applications.

4.5. Photodynamic therapy

Photodynamic therapy (PDT) has garnered increasing attention in cancer research. PDT is a non-invasive targeted technique employing a photosensitizing drug molecule that gets activated upon irradiation of a light source [24]. Photodynamic therapy (PDT), also known as photo chemotherapy, is a type of phototherapy involving the use of light and a photosensitizing chemical substance that applied in conjunction to induce cell death by molecular oxygen photo toxicity [25]. Latterly, it has been reported that GQDs can also generate singlet oxygen (O_2) upon irradiation, thus GQDs themselves are potential photodynamic therapy (PDT) agents [26]. PDT gives an opportunity for several advantages over conventional cancer therapies. Most principally, it does not require any surgical interventions and it can be localized at the tumor site with laser irradiation, thereby limiting systemic toxicity [27]. Two kinds of mechanisms (type I and II) are involved in the PDT process. In most cases, the type II mechanism needs to transform ground-state triplet oxygen into highly reactive singlet oxygen and is limited by the concentration of O_2. Different from the type II route, the type I process takes place through either electron or hydrogen atom abstraction by exciting PSs from the substrate and performs well even under low O_2 conditions [28].

Various properties and applications of GQDs are shown in Figure 2.

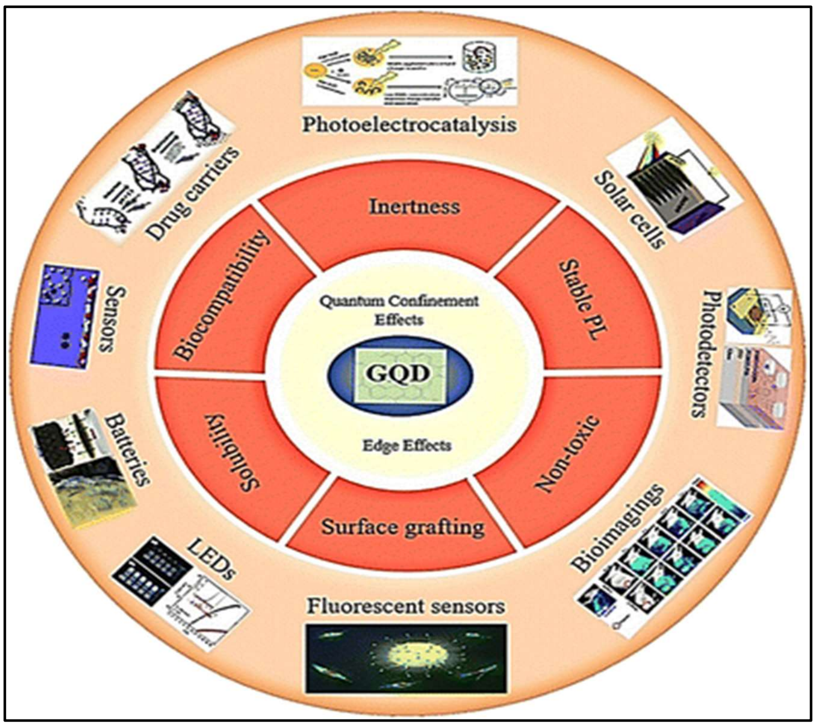

Fig. 2: Properties and applications of GQDs.

5. CHALLENGES AND FUTURE DIRECTIONS

5.1. Quality Control

Producing GQDs with consistent size and properties remains a challenge, affecting their performance in various applications.

5.2. Scalability

Developing large-scale synthesis methods that maintain high quality and yield is crucial for the commercial application of GQDs.

5.3. Research Needs

There is a need for more theoretical and practical research to explore novel synthesis methods, improve yield, and simplify the purification process. This includes investigating the fundamental mechanisms behind the properties of GQDs and their interactions with different environments.

GQDs preparation methods developed in recent years can be classified into two categories, top-down and bottom-up. Top-down synthesis; in this method, Starting from larger molecule, which deteriorate into smaller units and these units are converted into NPs. Examples are grinding/milling, CVD, physical vapor deposition (PVD) and decomposition techniques [29]. In bottom-up synthesis, grapheme like smaller polycyclic aromatic hydrocarbons (PAHs) molecular precursors such as benzene [30], hexa perihexabenzocoronene [31], glucose [32] and fullerene [33] etc. are converted to GQDs with the help of chemical reactions. These two methods were reviewed critically in my previous paper [34].

6. CONCLUSION

In this paper, the history of the GQDs is introduced. Most of the study so far indicates that the applications of GQDs are still at the early stage of development and have been progressing rapidly. Numerous methods in fabricating the GQDs have been reviewed. We believe that this timely rigorous account offers an in-depth understanding, which will promote more exciting and innovative developments in the future, leading to shift in the GQDs from bench to bedside. Nevertheless, this area of research has received much attention by researchers due to the enormous benefits of the GQDs can bring in the different applications. Though NPs are useful for many applications, but still there are some health hazard concerns due to their uncontrollable use and discharge to natural environment, which should be consider for make the use of NPs more convenient and environmental friendly.

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