

NANOSCIENCE MARVELS: EXPLORING THE FASCINATING WORLD OF QUANTUM DOTS AND THEIR MULTIFACETED APPLICATIONS

Abstract

The text discusses fluorescent carbon quantum dots (CQDTs) and their emerging significance in the field of nanomaterials. CQDTs, known for their unique optical and physicochemical properties, have attracted considerable research interest due to their diverse applications. The text covers CQDTs' synthesis methods, including top-down and bottom-up approaches, and highlights their low toxicity, biocompatibility, and ease of preparation. CQDTs are portrayed as eco-friendly alternatives to toxic semiconductor quantum dots. The applications of CQDTs are explored, emphasizing their use in metal ion sensing, bio-imaging, drug delivery, photocatalysis, and electrocatalysis. Their benefits in metal ion detection and their suitability for bio-imaging, with bright fluorescence and non-toxicity, are particularly noteworthy. The text also touches on their potential in drug delivery, showcasing their unique properties.

Keywords: Quantum Dots, Nanoparticles, Nano sciences, CQDT

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I. INTRODUCTION

Carbon is among the abundant elements, capable to form number of molecules. Nature utilizes it to form various types of substances when it is combined with other elements. It is also well known to form allotropes with variety of properties and structures ranging from sp^3 hybridized diamond to sp^2 hybridized graphite. Diamond is highly stable form of carbon that possesses three-dimensional structure while graphite is known for its thermal stability and consists of a layered two-dimensional structure. In addition to these substances, carbon forms some nano materials. Carbon-based nano materials such as fullerenes, carbon nano tubes, nano wires, nanorings, nano diamond and graphene show some unique optical, electronic, thermal, and chemical properties [1-4]. At nano scale dimension, the properties of carbonaceous nano materials are dependent on their atomic structure and interactions with other materials. Properties and applications of carbonaceous nano materials have made them special and inspired their search community. The potential of carbon-based material has been recognized by prestigious scientific awards such as 1996 noble prize for fullerenes (Chemistry) and 2010 noble prize for graphene (physics). Interest in carbon-based materials and their applications are increasing as material science is growing. Similar to its famous older carbonaceous nano materials, fluorescent carbon nano particles (CNPs) have emerged as a new class of important material in the carbon family. Fluorescent carbon nano particles (CNPs) owing to their physiochemical and optical characteristics have attracted intense interest of the research community.

1. Literature survey: Fluorescent carbon nano particles represent a captivating category of nano carbon materials and have become part of the fluorescent material family [5-22]. These nano particles exhibit discrete, quasi-spherical structures with sizes reaching up to 100 nm. The accidental discovery of carbon nano particles occurred in 2004 during the separation and purification process of single-walled nanotubes [19]. Carbon nanodots (CNDs), on the other hand, refer to carbon nano particles with sizes below 10 nm. In 2006, Sun's group named these fluorescent carbon nano particles "carbon quantum dots" and proposed a synthetic method to enhance their fluorescence emissions significantly [15]. Fluorescent CNPs have demonstrated their potential as versatile nano materials across various applications, including chemical sensing, bio-imaging, drug delivery, photo catalysis, and electro catalysis.

Periodically, advancements in their synthesis, properties, and biomedical applications are reviewed [23]. For many years, semiconductor quantum dots have been extensively studied for their strong and adjustable fluorescence emission properties, enabling their use in bio sensing and bio-imaging. However, semiconductor quantum dots are hindered by limitations such as high toxicity due to the inclusion of heavy metals during their preparation [24-26]. The presence of trace amounts of heavy metal ions severely restricts the applications of these semiconductor quantum dots [27].

Fluorescent carbon nanoparticles, as an alternative to these hazardous inorganic quantum dots, have demonstrated significant potential due to their low or no toxicity, biocompatibility, low cost, ease of preparation, and chemical inertness. Their favorable chemical composition, hydrophilicity, tunable fluorescence emissions, straightforward

fictionalization, and exceptional physicochemical and photochemical stability (non-photo bleaching or non-photo blinking) make them highly promising materials. Some of the carbon-based nano materials are shown in figure1.

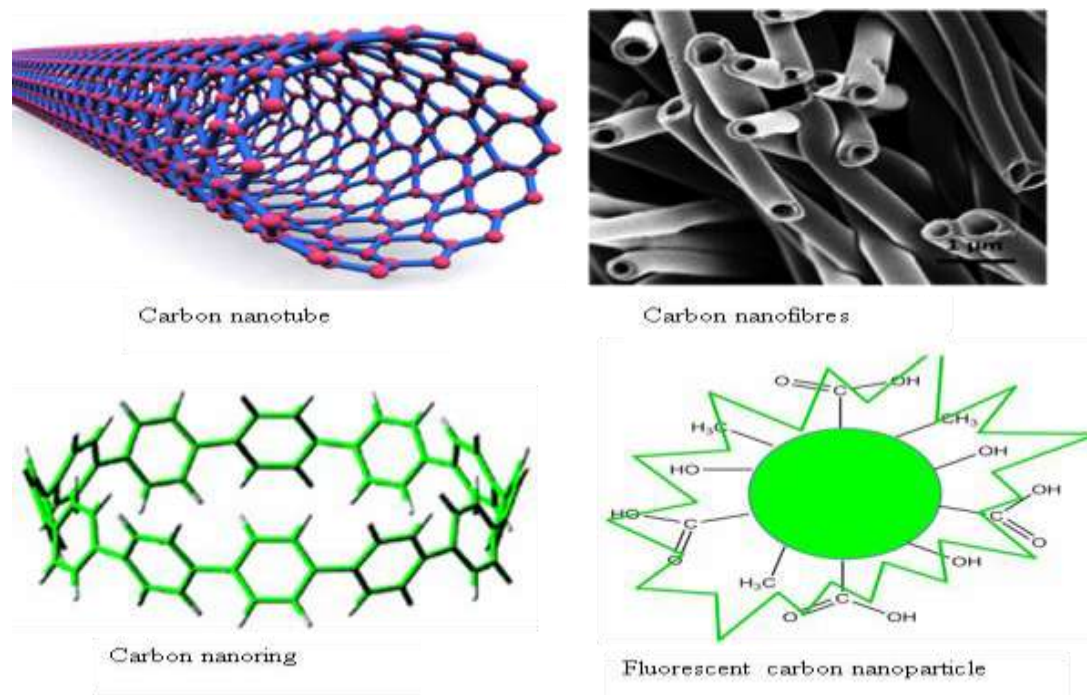


Figure1: Some carbonaceous nonmaterial's

2. **Definition of nano particles:** The term “nanoparticle” was first of all appeared in 1980s [28-31]. The term “nano” is derived from the Greek word for “dwarf”. This etymology and its placement on the metric scale i.e. $1\text{ nm} = 10^{-9}\text{ m}$ make it clear that tiny dimensions are not visible to the bare eye. Objects/materials having dimensions upto 100 nm are commonly considered as nano materials. This classification is somewhat arbitrary, but it is largely established in the scientific literature. Under this dimensions specific properties of materials become size-dependent and differ from those of three-dimensional infinite bulk/solids. Simple models towards understanding of nano dimensions are depicted in figure 2 and 3.

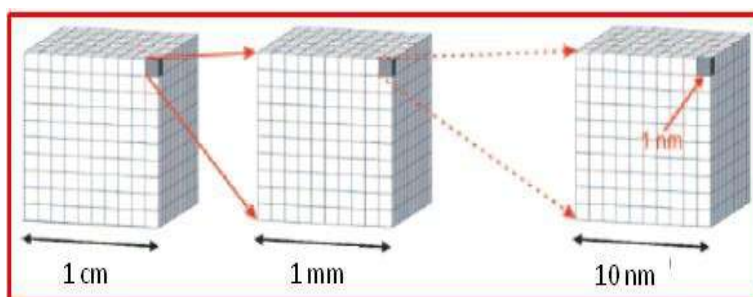


Figure2: A simple model towards understanding of nano dimensions

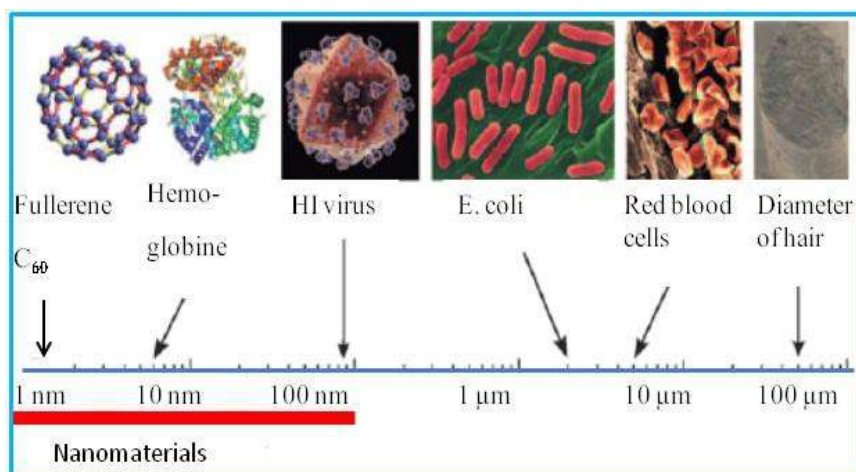


Figure 3: Dimensions of some materials highlighting nano materials

Quantum dots are semiconductor nanoparticles with unique optical and electronic properties. They are typically composed of elements from groups II-VI (such as cadmium selenide) or III-V (such as indium phosphide) of the periodic table. The size of quantum dots is on the nanometer scale, typically ranging from 2 to 10 nanometers in diameter. At this size, quantum dots exhibit quantum confinement effects, which lead to their unique properties.

The optical properties of quantum dots are particularly noteworthy. They have a size-dependent bandgap, which determines the wavelengths of light they can absorb and emit. By controlling the size of the quantum dots during synthesis, their optical properties can be precisely tuned across the entire visible spectrum and into the infrared region. This tunability allows for the generation of quantum dots with specific emission colors, from blue to red and beyond.

One of the significant advantages of quantum dots is their exceptional brightness and photostability. They can absorb light energy and efficiently convert it into intense fluorescence emissions, making them ideal for various applications that require bright and long-lasting fluorescence. Additionally, quantum dots have broad absorption spectra, allowing for excitation with a range of light sources, including ultraviolet, visible, and near-infrared wavelengths. Quantum dots find applications in diverse fields due to their unique properties:

- 3. Synthesis of Carbon Nano particles:** As per the literature, there are a variety of methods applied for synthesis of fluorescent carbon nanoparticles (CNPs). These methods have been always attempted to be cost-effective, simple and large scale preparation. Variety of carbon sources such as candle soot, papaya peel, banana juice, sweet potato and organic molecules (citric acid, formaldehyde, dopamine etc) have been used to synthesize CNPs. In terms of optical activity, it is always desired that these nanoparticles should exhibit excellent fluorescence characteristics. There are two broad categories for the synthesis of fluorescent CNPs, i.e. top-down and bottom-up. In top-down approach, macroscopic carbon source like carbon powder, graphene, carbon nanotubes, etc get converted to nanoscale materials. All these decomposition processes are non-selective. Further,

this top-down approach could be physical and chemical. Physical method involves treatment of carbon source with temperature and radiation while in chemical method, it is treated with some chemical reagent or derobring the source to nanoscale of final product. Synthetic methods can be optimized to some extent or dero to get particle size of a suitable range [32].

In bottom-up approach, organic precursors are required as seeds to grow CNPs under certain conditions. Microwave, heat and ultrasonic waves are primary approaches used for energy aggregation and molecular structure transition. The presence of precursor shows lower requirements of carbon sources. A diversity of carbon sources are chosen, such as sucrose, citric acid, amino acids, and even waste biomasses. Purification methods include centrifugation, dialysis, electrophoresis, etc. Three cycles of concentration/dilution were implemented by Zhu and group to separate nano particles from the mixture [33]. Li et al. obtained CNPs with different surface modifications by dialyzing against Milli-Q water using different cellulose stermem brane bags. Surface modification of these nanoparticles is always endeavored to get some more interactive sites. Electrochemical, chemical oxidation and laser radiation are three main employed methods that use top-down approach.

II. TOP-DOWN APPROACHES

1. Electro Chemical Methods: These methods are easy to manipulate and cost-effective for the synthesis of CNPs [34-37]. Alcohol, carbon fiber, graphite, MWCNT set care used as carbon source. Electro depreparatio is easy with graphite and nanotubes, hence these are commonly used in these methods. The utilization of graphite and nanotubes in these methods makes the synthesis process straightforward. Zhou et al. devised a technique to transform multi-walled carbon nanotubes (MWCNTs) into nanodots. They applied cyclic potential in a degassed acetonitrile solution containing 0.1 M tetrabutylammonium perchlorate. As the procedure unfolded, the colorless solution transitioned to yellow and eventually dark brown, indicating the formation of carbon dots detached from the nanotubes. Carbon dots were obtained through the electro-oxidation of a graphite column electrode at 3V relative to a saturated calomel electrode (SCE) in a 0.1 M NaH₂PO₄ electrolyte. The solution progressively changed from transparent to yellow and then dark brown during the oxidation process.

To achieve carbon nanoparticles (CNPs) with a narrow size distribution without the need for subsequent separation procedures, Bao et al. developed a tuning system using electrochemical etching of carbon fibers. By adjusting the applied electrode potentials, they obtained CNPs of controlled sizes.

2. Chemical Oxidation: Chemical oxidation, involving treatment of the carbon source with oxidizing agents such as nitric acid or sulfuric acid, is a commonly employed approach for synthesis. It serves as a simple and effective method for large-scale production. Qiao et al. successfully prepared biocompatible CNPs through a direct chemical oxidation route [38]. They used three commercially available activated carbons—coal, wood, and coconut activated carbons—as carbon sources. In the presence of nitric acid, CNPs were easily etched from the amorphous structure of activated carbons. A passivation process using amine-terminated compounds was subsequently conducted. The resulting products

from the three carbon sources exhibited similar narrow size distributions and displayed vibrant luminescence

- 3. Laser Irradiation:** The conventional steps involved in this approach exhibit a certain level of complexity and require stringent reaction conditions. Synthesizing carbon nanoparticles (CNPs) through laser irradiation capitalizes on the generation of high heat and high pressure induced by lasers. Hu et al. devised an innovative one-step protocol for CNP synthesis via laser irradiation [7]. In this method, the research group employed a laser to irradiate graphite powders suspended in an organic solvent. Through their experiments, they deduced that the presence of carboxylic acid (-COOH) groups on the nanoparticle surface imparted the fluorescence characteristics to the CNPs. Notably, this method offers the advantage of simultaneous functionalization of CNPs. Furthermore, it is proposed that by employing various solvents, CNPs with diverse characteristics can be prepared. This is depicted in figure 4.

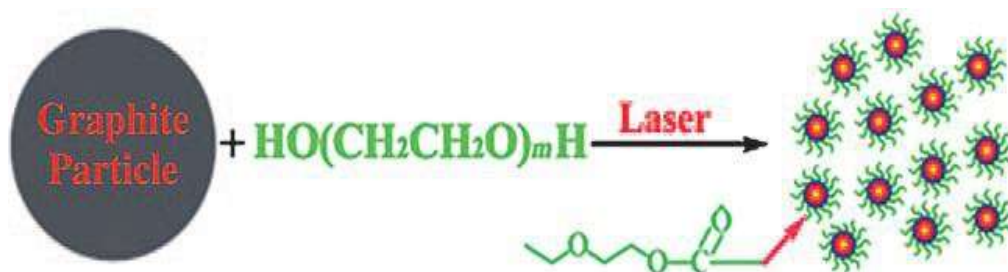


Figure 4: One step laser irradiation method for synthesis of fluorescent carbon nanoparticles

III. BOTTOM-UP APPROACHES

- 1. Microwave Assisted Synthesis:** Microwave irradiation, known for its ability to deliver high-energy radiation, effectively disrupts the chemical bonds within a substrate. Microwaves, classified as electromagnetic waves with wavelengths ranging from 1 mm to 1 m, find common usage in everyday life and scientific research. Notably, microwave-assisted synthesis offers the advantage of significantly reducing the synthesis time. This method typically entails the parolysis and surface functionalization of the substrate [39-40]. A synthetic method of CNPs from egg shell membrane as he were a kind of protein-rich wastes and could be easily obtained at low cost. They were broken into fragments by micro wave, since the electrons rotated and vibrated vigorously under the switching electronic field. After further polymerization, oxidization and surface passive as ion under basic conditions, CNPs were prepared. The PL spectrum of the products indicated that micro wave assisted synthetic route was a cost-effective, eco-friendly and resources aving one.

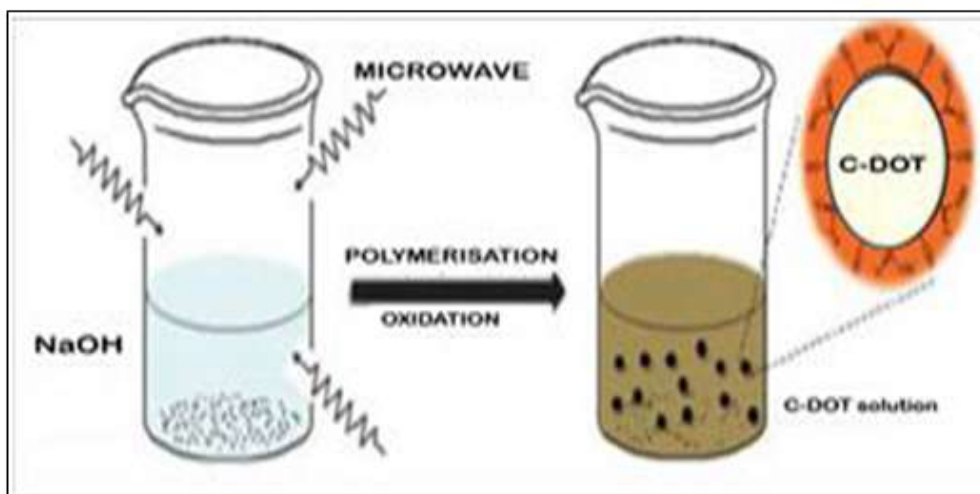


Figure 5: Schematic way of a microwave-assisted process to form carbon dots (CDs)

- 2. Thermal Decomposition:** For a considerable period, thermal decomposition has served as a means to fabricate diverse nanomaterials, including semiconductor and magnetic nanomaterials. Recent investigations have revealed that external heat plays a significant role in the dehydration and carbonization of organic compounds, leading to the formation of carbon nanoparticles (CNPs) [42]. Wang et al. employed hot non-coordinating solvents to inject carbon precursors, such as citric acid, and successfully synthesized carbon dots (CDs) through carbonization. Remarkably, the resulting products exhibited stable performance for a minimum of two months [43].

In another study, Liu et al. presented a combustion oxidation method for CNP synthesis [44]. Soot was subjected to heating by a burning candle and subsequently mixed with an oxidant to facilitate surface oxidation of the particles. Following further cooling, the products underwent purification through centrifugation or dialysis. Zhu and colleagues explored a hydrothermal method involving the condensation of citric acid and ethylenediamine. The resulting polymer was subsequently carbonized to yield CNPs [45]. This synthetic process encompassed ionization, condensation, polymerization, and carbonization stages. Additionally, Chen et al. developed a facile synthetic method to produce gram-scale CNPs by heating sucrose and oleic acid at 215°C under vigorous magnetic stirring and nitrogen protection [46].

- 3. Ultrasonic Synthesis:** Ultrasonic synthesis of CNPs has also been reported in the literature. Ultra sound treatment of carbon source leads to dehydration, polymerization and carbonization and form nucleation for CNPs. In 2011 Li and group introduced single-step synthesis of CNPs through ultrasound treatment [47]. A notable large-scale environmentally friendly method for synthesizing carbon dots (CDs) involves the utilization of waste food as carbon sources [48]. This approach employs ultrasound irradiation at room temperature, which induces sequential processes of dehydration, polymerization, and carbonization. The ultrasound operates at a frequency of 40 kHz, facilitating the formation of nuclei. These nuclei subsequently grow through the diffusion of solutes towards the surface of the carbon nanoparticles.

- 4. Surface Modification:** The mechanisms underlying surface modification approaches for carbon nanoparticles (CNPs) remain incompletely understood, yet they exert a significant influence on the fluorescence properties of the resulting CNPs. Particularly in the context of medical applications, surface passivation is a crucial requirement. The presence of carboxyl groups on the CNP surface confers hydrophilicity, facilitating their application in biological systems. Through the use of various reagents, the solubility of CNPs in non-polar solvents and their fluorescence properties can be adjusted. Additionally, the synthesis of CNPs with different surface groups enables the achievement of diverse designed functions [49].

Biodegradable polymeric substances containing carboxylic and amine groups are also employed for surface modification purposes. The deactivation of CD surfaces can be achieved by incorporating them with polyethylene glycol (PEG) that contains amino groups.

- 5. Physical and Chemical Properties:** Carbon nanoparticles (CNPs) predominantly comprise carbon (C) and oxygen (O) elements, with trace amounts of hydrogen (H) and nitrogen (N). The surface of CNPs is typically decorated with various oxygenated functional groups, such as hydroxyl (-OH), carboxyl (-COOH), and ether (-C-O-C-) groups. These functional groups endow CNPs with exceptional water solubility and offer avenues for versatile fictionalization with diverse chemical species. The core structure of CNPs exhibits an amorphous to nanocrystalline nature, characterized by a preponderance of sp^2 hybridized carbon atoms. The lattice spacing's observed in CNPs align closely with graphitic characteristics. In the absence of specific modifications, oxidized CNPs prominently feature oxygenated moieties on their surface, leading to higher overall oxygen content depending on the specific experimental parameters employed. The proposed chemical structure of CNPs is depicted in Figure 6.

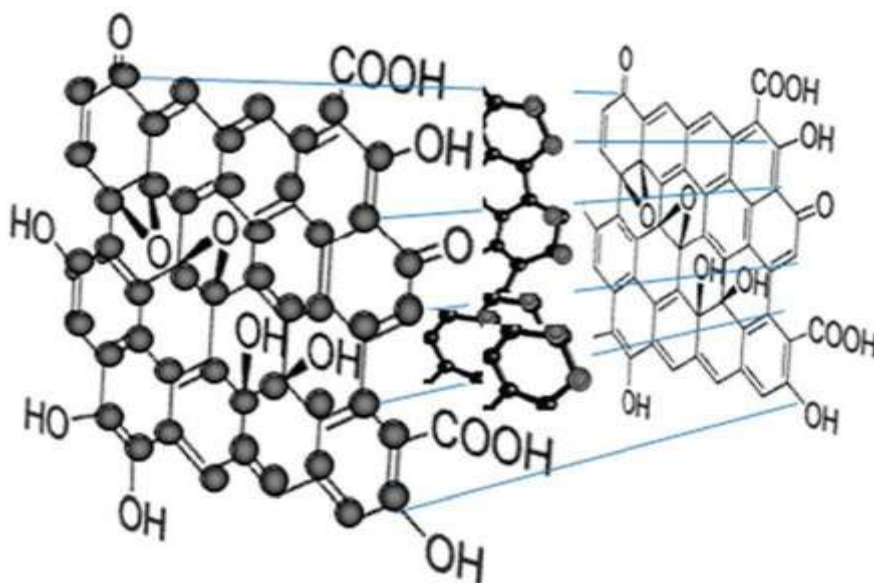


Figure 6: Proposed chemical structure of carbon nanoparticles (ref.50)

- 6. Optical Properties:** Fluorescent carbon nanoparticles (CNPs) typically exhibit UV absorbance with a tail extending into the visible region. However, through surface modification, the absorbance can be extended within the range of 350-500 nm. Upon illumination with UV light, these modified CNPs emit colours such as blue, green, or yellow, which can be perceived by the naked eye. From both a fundamental and application perspective, the most captivating feature of CNPs is their fluorescence nature. Generally, CNPs demonstrate broad emission spectra spanning from the visible to near-infrared (NIR) region. They exhibit various excitation wavelengths (λ_{ex}) that result in emissions at different wavelengths with varying intensities. Bare CNPs have been reported to exhibit multicolour fluorescence emissions. However, the quantum yield of these CNPs is typically quite low [8, 51]. The multicolor emission arises not only from CNPs of different sizes but also from a distribution of emissive trap sites. Particle size variation, as observed in semiconductor nanocrystals, is one factor contributing to tunable performance. Another factor may be the presence of different oxygen-containing groups. To enhance the quantum yield, several approaches have been attempted, including improved purification procedures, doping with other elements, and passivation. CNPs functionalized with diamine-terminated oligomeric PEG (PEG1500N) or poly(propionylethyleneimine-co-ethyleneimine) (PPEI-EI) have shown bright emissions with quantum yields ranging from 4-10% [15]. Through an exploratory synthetic approach, it is possible to achieve CNPs with a visible-to-near-infrared (NIR) spectral range [47]. The NIR emission is particularly advantageous as it enables CNPs to be suitable for imaging biological samples at greater depths within the NIR window. Moreover, the photoluminescence (PL) of CDs can be quenched by electron acceptors or donors, offering opportunities for new applications in energy conversion. Important phenomena such as chemiluminescence (CL) and electrochemical luminescence (ECL) have also been reported with CNPs [52-54].
- 7. Toxicity:** Semiconductor quantum dots containing toxic heavy metal ions, such as Cd, pose a risk of cytotoxicity due to their potential release. These ions may aggregate within biological systems, making their elimination challenging. The accumulation of heavy metals can lead to biological disorders, thereby generating toxicity associated with semiconductor quantum dots. Furthermore, the release of metal-based semiconductor quantum dots into the environment poses an environmental hazard. These biological and environmental risks limit the biomedical applications of semiconductor quantum dots and emphasize the need for non-toxic and environmentally friendly alternatives, such as CNPs. CNPs have emerged as promising candidates for biomedical applications, and their toxicity has been extensively evaluated by various research groups. Ray et al. conducted MTT and Trypan blue assays to assess cell viability following CNP treatment [8]. The results showed that low concentrations of CNPs resulted in a 75% cell survival rate, indicating limited toxic effects. Additionally, Song et al. compared the toxic effects of unmodified CdTe quantum dots, gold nanoparticles, and CNPs on biological systems, including cells and green gram sprouts [55]. The findings clearly demonstrated that CNPs exhibited the highest biocompatibility among the three materials.

IV. APPLICATIONS

- 1. Sensing:** The exceptional optical properties of carbon nanoparticles (CNPs) have led to their exploration in fluorescence-based analysis of metal ions. This involves the effective fluorescence quenching of CNPs upon the addition of specific metal ions, enabling their application in the selective and sensitive detection of metal ions at low concentrations [56-58]. Notably, Hg^{2+} ions are highly toxic and environmentally hazardous [59]. Qin et al. synthesized CNPs from flour, and their emission was selectively quenched by Hg^{2+} ions, achieving a detection limit of 0.5 nM. Another example is the detection of Sn^{2+} ions, which are heavy metal ions known to be environmental pollutants and harmful to human health. Yazid et al. developed a sensor for Sn^{2+} detection by exploiting the fluorescence quenching of CNPs derived from dehydrated sago starch [41]. Additionally, the detection of Fe^{3+} ions has been explored using CNPs. The presence of Fe^{3+} ions leads to strong fluorescence quenching due to the formation of a complex between CNPs and Fe^{3+} ions [60]. CNPs have also been employed as chemiluminescence probes for Fe^{3+} ions [61].

When it comes to sensing applications, CNPs offer advantages over organic molecular probes, which often involve complex and costly synthesis processes and are limited to organic or mixed organic/aqueous media. Moreover, CNPs are more desirable than semiconductor quantum dots (QDs) due to the absence of heavy metal ions that restrict the applications of QDs [27, 62]. As CNPs are non-toxic, they serve as ideal candidates for a variety of applications, including sensing. Quantum dots have emerged as powerful diagnostic tools due to their bright fluorescence, enabling sensitive detection of analytes in biological samples. Quantum dot-based biosensors have been developed for the detection of biomarkers, pathogens, and genetic sequences. Their unique optical properties, such as broad absorption spectra and narrow emission peaks, allow for multiplexed detection of multiple analytes simultaneously, enhancing the efficiency and accuracy of diagnostic tests. In the field of environmental and chemical sensing, quantum dots find utility in the detection and monitoring of pollutants, heavy metals, and gases. Their exceptional fluorescence properties enable high sensitivity, selectivity, and rapid response times, making them valuable tools for environmental monitoring, food safety analysis, and industrial process control.

- 2. Bio-Imaging:** Fluorescent probes for bio-imaging have garnered significant interest, and the versatility and sensitivity of fluorescence microscopy heavily rely on the properties of the chosen probe. Carbon nanoparticles (CNPs) stand out as deserving candidates for bio-imaging due to their non-toxic and non-side-effect inducing nature. Furthermore, CNPs exhibit excellent fluorescent characteristics, and even low concentrations are sufficient to produce stable and bright fluorescence signals. The water dispersibility of CNPs is particularly advantageous, and CNPs with near-infrared (NIR) emission properties hold promise for imaging deeper tissue samples. Na et al. explored the imaging of human serum proteins on gels using CNPs that emit bright light at 450 nm [63]. By directly incubating the proteins with a diluted CNPs solution after polyacrylamide gel electrophoresis (PAGE), a simple staining method with low background and high resolution was achieved, presenting a qualified protein imaging approach.

Zhu et al. developed a two-photon "turn-on" fluorescent probe based on CNPs, which was employed for imaging hydrogen sulfide (H₂S) in live cells and tissues [33]. This probe exhibited a remarkably low detection limit of 0.7 μM, enabling the "turn-on" two-photon fluorescent imaging of H₂S in live cells and tissues. CNPs were utilized as the fluorophore due to their large two-photon absorption cross-section. Hsu and colleagues reported the utility of CNPs for imaging LLC-PK1 cells, where green fluorescence was observed upon introducing CNPs to the cells [64] (see Figure 7).

Quantum dots have revolutionized biological imaging techniques, offering bright and stable fluorescence properties that make them ideal for cellular and tissue imaging. They can be functionalized with specific ligands or antibodies to target particular cells or biomarkers, enabling precise visualization of cellular processes, molecule tracking, and the study of cellular interactions. Quantum dots have found applications in live-cell imaging, immune his to chemistry, and in vivo imaging, providing superior sensitivity and spatial resolution compared to traditional organic dyes.

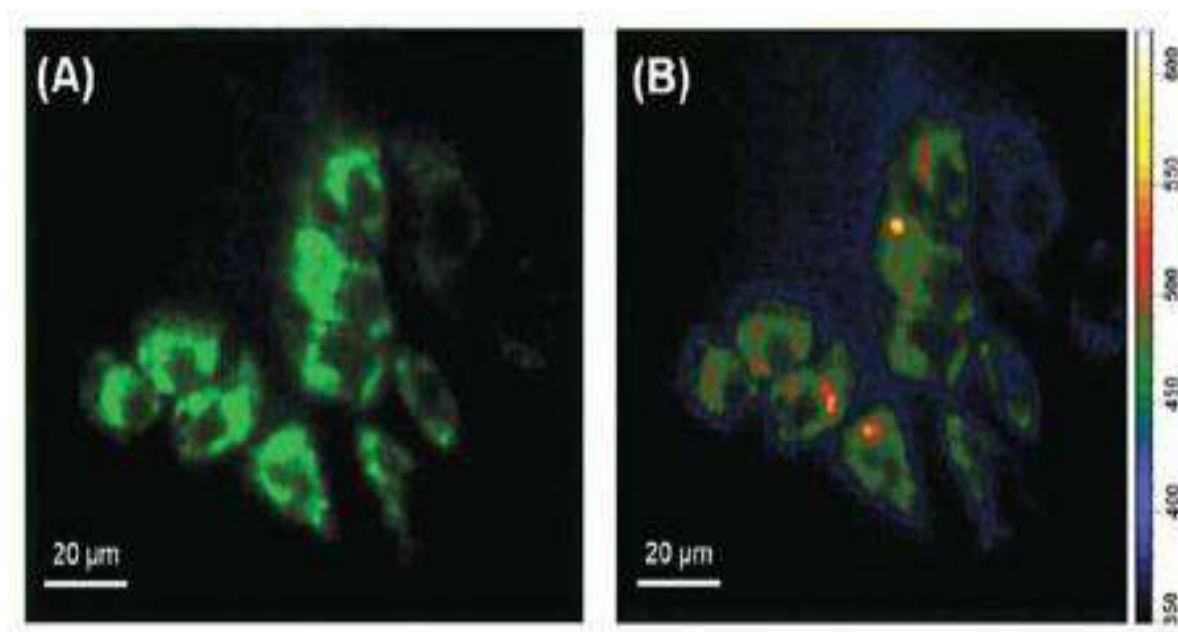


Figure 7: Confocal photoluminescence images of LLC-PK1 cells after CNPs incubation (Ref. 64) Significant efforts have been devoted to targeted imaging approaches. Song et al. conjugated folic acid with carbon dots (CDs) to distinguish folate-receptor-positive cancer cells from normal cells [65]. The receptor-mediated endocytosis of CDs holds promise for more accurate and selective cancer diagnostic approaches.

Diagnostics and Bio sensing: Quantum dots have made remarkable contributions to diagnostics and bio sensing. They have been extensively utilized in the field of display technologies, particularly in the development of high-quality and energy-efficient displays. Quantum dot displays (QLEDs) offer a wider color gamut, improved colour accuracy, and enhanced brightness compared to conventional liquid crystal displays (LCDs). By incorporating quantum dots as colour converters, QLEDs can generate vivid and lifelike colours, enabling more immersive visual experiences in televisions, monitors, and mobile devices. **Photovoltaics:** Quantum dots hold promise in the field of

photovoltaic's for solar energy conversion. Their tunable bandgap allows for the absorption of a broad range of sunlight wavelengths. Quantum dots can be integrated into solar cells to enhance light absorption and improve the efficiency of solar energy conversion. Additionally, their solution-processable nature enables the fabrication of low-cost and flexible solar cell devices.

Optoelectronic Devices: Quantum dots find applications in optoelectronic devices, including light-emitting diodes (LEDs) and lasers. Their narrow emission peaks, high color purity, and efficient energy conversion make them attractive alternatives to traditional light-emitting materials. Quantum dot-based LEDs exhibit improved energy efficiency and color quality. Quantum dot lasers offer advantages such as low threshold currents, high-temperature stability, and narrow line widths, making them promising candidates for various applications, including telecommunications and medical diagnostics.

- 3. Drug Delivery:** Fluorescent carbon nanoparticles (CNPs) have demonstrated their potential as versatile vehicles for drug loading and release in various studies [66-68]. The utilization of CNPs in this context offers several advantages, including rapid cellular uptake, stable fluorescence, biocompatibility, and minimal impact on drug activity [69]. Notably, successful encapsulation of CNPs within zeoliticimidazolate frameworks, a subclass of metal-organic frameworks, has been reported in the literature [70]. By varying the concentration of CNPs and precursors, the fluorescence and size of the resulting nano-composites were optimized. These nano-composites served as carriers for a pH-responsive drug, 5-fluorouracil, targeting cancer cells. Variations in release efficiency were observed at different pH conditions. Importantly, the biological activity of the drug remained unaltered, highlighting the excellent potential of these nano-materials in the field of drug delivery [71]. Using fluorescence resonance energy transfer (FRET), Tang et al. developed a direct CNPs-based drug delivery system [72]. CNPs served as the donors in FRET pairs, while also carrying the drugs. The FRET signals were significantly influenced by the distance between the donor and acceptor, enabling sensitive real-time monitoring of drug release, such as doxorubicin, from CNPs [73].
- 4. Quantum Confinement:** The unique properties of quantum dots arise from quantum confinement effects. When the size of a material is reduced to the nanoscale, the confinement of electrons within a small volume leads to quantization of their energy levels. In quantum dots, the size confinement restricts the motion of electrons in all three dimensions, resulting in discrete energy levels. The energy bandgap of the quantum dot is determined by the size, shape, and composition of the nanocrystal, allowing precise control over its optical and electronic properties.
- 5. Band Structure:** The electronic band structure of quantum dots plays a crucial role in their properties. Unlike bulk materials, quantum dots exhibit discrete energy levels or "electron shells" due to their size-dependent quantization. The confinement of electrons within the nanocrystal creates a discrete set of allowed energy states, separated by energy gaps. The energy gap between the valence and conduction bands determines the absorption and emission wavelengths of the quantum dot. By manipulating the size and composition of the quantum dot, the bandgap can be engineered to achieve specific optical properties.

- 6. Size-Dependent Optical Properties:** The size of a quantum dot directly affects its optical properties. As the size of the nanocrystal decreases, the energy levels become more closely spaced, resulting in a blue shift in the absorption and emission spectra. This size-dependent tunability allows researchers to synthesize quantum dots with precise emission colors spanning the visible and near-infrared regions. Additionally, quantum dots exhibit a high quantum yield, which refers to the efficiency of light emission. The combination of tunable emission colors and high quantum yields makes quantum dots highly attractive for applications in biological imaging and optoelectronic devices.
- 7. Photoluminescence Mechanism:** The photoluminescence of quantum dots involves a two-step process: absorption of photons and subsequent emission of light. When a quantum dot absorbs a photon with energy greater than its bandgap, an electron is excited from the valence band to the conduction band. The excited electron can then relax back to the valence band, releasing energy in the form of a photon. The energy of the emitted photon corresponds to the bandgap energy, resulting in the characteristic emission color of the quantum dot. The efficient conversion of absorbed energy to emitted light contributes to the intense fluorescence exhibited by quantum dots.
- 8. Surface Effects and Ligand Exchange:** The surface of quantum dots plays a crucial role in their stability, solubility, and functionalization. Quantum dots are typically synthesized with a capping layer of organic molecules, known as ligands, which provide stability and solubility in various solvents. However, the presence of these ligands can impact the quantum dot's optical and electronic properties. Ligand exchange processes involve replacing the original ligands with new functional ligands to modify the surface properties of the quantum dot. This surface engineering enables the attachment of targeting ligands, biomolecules, or polymers, expanding the versatility and applications of quantum dots in biological sensing and imaging.
- 9. Quantum Dot Excitons:** Excitons are fundamental quasiparticles that play a significant role in the optical properties of quantum dots. An exciton is formed when an electron is excited to the conduction band, leaving behind a positively charged "hole" in the valence band. The electron and hole are bound together by the Coulomb attraction, creating an exciton with distinct energy levels. Excitons in quantum dots exhibit size-dependent energy spacing, resulting in discrete excitonic energy levels. The radiative recombination of excitons gives rise to the strong and tunable photoluminescence properties of quantum dots.

V. RECENT UPGRADATION FEEL

- 1. Enhanced Synthesis Methods:** Researchers have been exploring novel synthesis methods to improve the efficiency, yield, and control over CNP production. For instance, a one-step hydrothermal method has been developed by Wu et al. to synthesize CNPs using glucose as the carbon source. The addition of small organic molecules, such as ethylene glycol, during the hydrothermal process resulted in CNPs with improved photoluminescence properties and higher quantum yields. (74) In another study by Li et al. a facile microwave-assisted synthesis approach was employed to prepare nitrogen-doped CNPs using glucose and ethylenediamine as precursors. The microwave irradiation allowed for rapid and efficient synthesis of CNPs with enhanced fluorescence emissions.

This method offers a promising strategy for large-scale production of nitrogen-doped CNPs with tunable properties. (75)

- 2. Tailoring Optical and Surface Properties:** Recent research has focused on tailoring the optical and surface properties of CNPs to expand their applications. Surface modification techniques have been employed to introduce specific functional groups, enhance water solubility, and improve stability. For example, Li et al. reported the synthesis of carboxyl-functionalized CNPs by surface oxidation using nitric acid. The carboxyl groups on the CNPs' surface facilitated further functionalization and enabled their application as pH-responsive drug delivery carriers. (76)

Moreover, efforts have been made to engineer CNPs with specific emission wavelengths and enhanced quantum yields. Zhang et al. demonstrated a strategy to synthesize blue-emitting CNPs through a microwave-assisted pyrolysis method using citric acid and polyethyleneimine as precursors. (77) The resulting CNPs exhibited high fluorescence quantum yields and excellent photostability, making them suitable for bio-imaging applications. **Biomedical Applications:** In the biomedical field, CNPs have shown great potential as versatile platforms for sensing, imaging, and drug delivery. Researchers have explored their applications in targeted drug delivery systems, such as cancer therapy. Liu et al. developed folate-functionalized CNPs for targeted delivery of anticancer drugs to folate receptor-overexpressing cancer cells. The CNPs exhibited efficient cellular uptake and triggered drug release within the cancer cells, leading to enhanced therapeutic efficacy. Furthermore, CNPs have been investigated for their potential in bio-imaging and biosensing applications. (78) Liu et al. reported the synthesis of red-emitting CNPs with aggregation-induced emission (AIE) properties for real-time imaging of lysosomal pH changes. The AIE CNPs exhibited bright fluorescence upon accumulation in the lysosomes, enabling precise monitoring of pH variations in cellular compartments. (79)

- 3. Environmental Sensing:** In addition to biomedical applications, CNPs have garnered attention for their potential in environmental sensing and monitoring. Recent studies have focused on using CNPs for the detection of heavy metal ions and environmental pollutants. For instance, Wang et al. developed a sensitive and selective CNP-based sensor for mercury ions (Hg^{2+}). The CNPs exhibited fluorescence quenching in the presence of Hg^{2+} ions, enabling their use as a rapid and cost-effective detection platform for water quality assessment. Furthermore, CNPs have been explored for the detection of volatile organic compounds (VOCs) and gases. (80) Zhang et al. synthesized nitrogen-doped CNPs and demonstrated their potential as fluorescent sensors for the detection of explosive vapors. The nitrogen-doped CNPs exhibited significant fluorescence quenching in the presence of target explosive vapors, offering a promising approach for real-time monitoring of environmental hazards. (82)

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