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REVIEW ARTICLE

Quantum dots: Application in medical science

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Abstract

Quantum Dots are a group of semiconductors nanomaterials whose size is about less than 10 nm exhibiting unique optical and electric properties which impart different advantages in terms of wide and continuous absorption spectra, narrow emission spectra, high quantum yield, long fluorescence lifetimes, and high photostability. Based on the unique properties of quantum dots have a variety of applications. This review informs about quantum dots structure, properties of quantum dots, surface modification of quantum dots for biocompatible, synthesis process and its important application like labeling cell structure and FRET (Fluorescence resonance energy transfer). Quantum dots as bio-sensors, bio-marker, and bio-imagine are used in many therapeutic systems. Several attractive applications have been observed with supramolecular compounds: Calix-4 arenes derivatives with quantum dots in the field of medical science.

Keywords: *Bioimaging; Calix-4 Arenes; Optical Properties; Quantum Dots; Medical Applications; Synthesis Method.*

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INTRODUCTION

In 1982, Russian Physicists Alexei Ekimov and Onushchenko have observed the quantum size effect on optical spectra of the nanocrystals [1]. They observed that by reducing the size of material optical properties are changed. In 1993, Murray and his group discovered CdSe, CdS, and CdTe colloidal monodispersed quantum dots (QDs) using organometallic precursors [2]. QDs are nanoparticles whose size range is about 2 nm to 10 nm. QDs are a zero-dimension nanostructure. It has unique optical properties with larger absorption spectra and smaller emission spectra [3-4]. It is widely used in optoelectronic devices and bio-imaging [5]. From bulk to nanomaterial properties of material, changes like electric, physical, and chemical properties. e.g., Iron is magnetic material in a bulk state but iron nanoparticle is not magnetic. A few applications of the QDs are shown in Fig. 1. Due to the small size of QDs, energy levels are discrete. With the decrease in particle size, the spacing between energy levels is increasing and the spectrum of QDs shifts from emitting red light to blue light (Fig. 2).

According to their dimension, nanostructures can be divided into three categories. A structure known as a quantum well is created when one dimension is shrunk to the nanoscale while the other two remain big. Quantum wells are often used in diode lasers, such as laser pointers, Digital Versatile Disks, infrared lasers, and fiber optic transmitters. They are also used to create HEMTs (high electron mobility transistors), which are applied in low-noise electronics. Imaging in the infrared range uses infrared photodetectors. When two dimensions are diminished while one stays big, the emerging structure is known as a Quantum wire. Electronics equipment uses quantum wires because of their great tensile strength, high electrical conductivity, low chemical reactivity, smaller diameter, and light in weight. QDs are the

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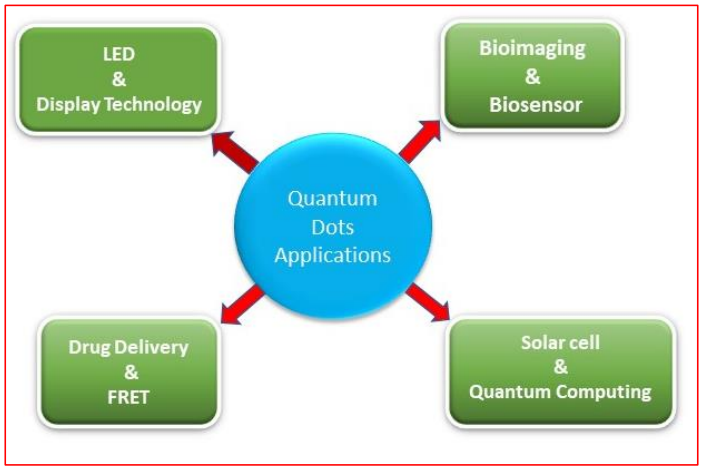

Fig. 1. Application of quantum dots in various field.

extreme case of this size reduction procedure when all three dimensions are low nanometer range. The graphs of different nanostructure densities of states vs energy are shown in Fig. 3 [6-10].

Due to its small size, surface area to volume ratio and confinement of electron is very high in QDs. The optical, electrical, and magnetic properties of QDs change with their size and composition. The construction of the QDs is shown in Fig. 3. The core of QDs is a base part (Fig. 3). Shelling is important for QDs because the high surface-to-volume ratio creates a surface state and these surface states decrease the photoluminescence of QDs [11-14]. Inorganic and organic compounds are used to shell QDs. Solubility is important for QDs to use in bio-applications [15-20]. QDs are coated with amphiphilic polymers or ligand exchange to provide water solubility for bio-conjugation [21-22]. Mercaptopropionic acid (MPA), Dihydrolipoic acid (DHLA), and polyethylene glycol (PEG) are generally used to coat QDs for water solubility. Water-soluble QDs are connected with biomolecules like nucleic acids, carbohydrates, small proteins, and other molecules [23-25]. For biomedical applications, capping agents are used to modify the surface of QDs.

The present study provides key information for the future of QDs-DOX (Quantum dots-Doxorubicin) Nanopolymer some formulations for treatment, image-guided surgery applications, and initial stage breast cancer detection. Aptamer (AS1411) coupled QDs that could bind with human glioblastoma (U87MG) cells and exhibited in vitro molecular imaging with high fluorescence strength and specificity. QDs are used in several industrial applications including the following Information storage, semiconductors, Pharmaceuticals, Microelectromechanical (MEM)

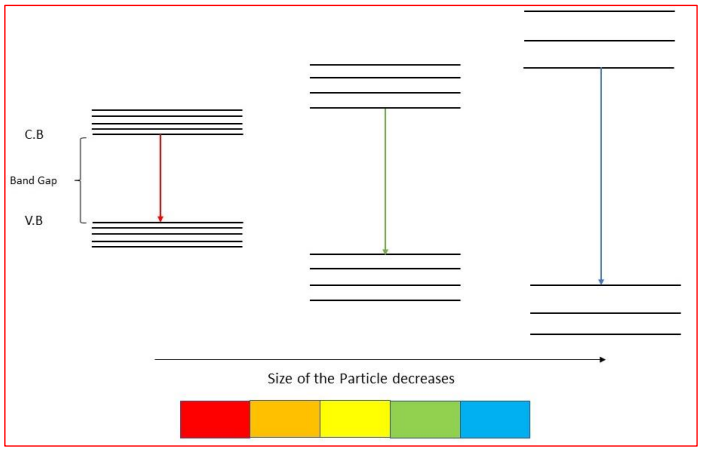

Fig. 2. Bandgap of material Changes with Particle Size of that material.

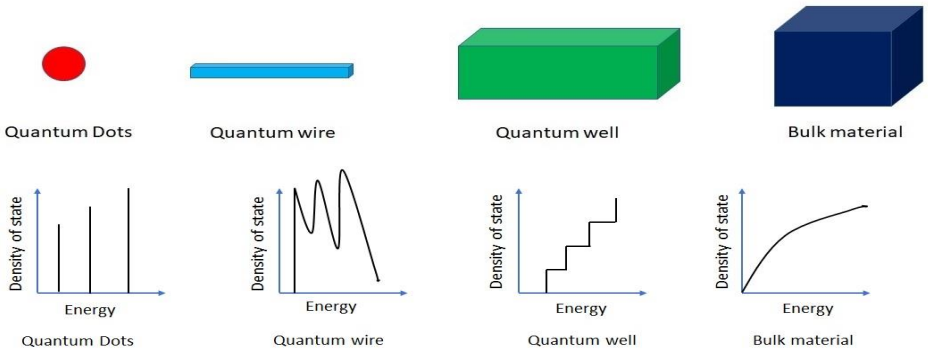

Fig. 3. Density of states vs energy graphs of QDs, quantum wire, quantum well, and bulk material.

devices, Biomedical applications, Sensors, and Microelectronics. Quantum dots have gained much interest in biomedical applications for different types of cancer treatment, bone treatment, drug delivery and development, several medical tools, various diagnostic tests, gene transfection, and medical imaging. The small size of QDs allows them to enter living organisms, translocate within, and cause damage. Their ability to penetrate the physiological barrier allows them to travel within the circulatory systems of biomolecules. In the future, QDs may be capable of detecting and preventing disorders very quickly, thus improving the entire process of treating, diagnosing, and detecting diseases. Polymeric-based QDs have great potential, being able to use in MRI (Magnetic resonance imaging) technology, disease therapy, and delivery systems of drugs by decreasing the severe side effects and being harmless. Many applications, such as increasing the biocompatibility of QDs, can benefit from surface coating polymers such as dextran and polyethylene glycol. There has been an increase in the use of polymeric-based QDs for targeted drug delivery. Biomedical applications may benefit from the utilization of coating techniques, magnetic fields, gene transfer methods, and bioimaging methods. It is possible to enhance the sensitivity and low cytotoxicity of polymeric-based QDs in targeted therapy, cancer imaging, and gene therapy using different types of polymeric QDs [26-30]. Table 1 shows a list of various capping agent which is used in biomedical applications.

OPTICAL PROPERTIES

Multiple Exciton Generation

A single photon falling on a photosensitive semiconductor can cause more than one electron to be excited into the conduction band, a mechanism known as multiple exciton generation (MEG). A single photon can only excite one electron across the semiconductor material bandgap in the concept of photoexcitation of semiconductors, leading to the photocurrent. Although, photons with energy twice as great as the material's bandgap can place more than one electron into a conduction band gap in materials, that can support MEG. As a result, in theory, solar cells made from those materials could be more efficient than cells made from other materials. Such materials which have MEG potential are QDs. Lead selenide was the first material on which the MEG was seen and then also lead sulfide and cadmium selenide were used to demonstrate it. This is a method that holds a lot of promise for improving the photoconversion effectiveness of photovoltaic systems.

Photoluminescence

As a function of size, QD luminescence varies;

Table 1. List of capping agents used in biomedical applications.

Capping agent/surfactants	Application
PVA (Polyvinyl alcohol)	In vivo imaging and drug delivery
Starch	In vivo Imaging
Dextran	In vivo Imaging
PVP (Polyvinyl pyrrolidine)	Drug delivery
Chitosan	Tissue engineering, hyperthermia
PEG (Polyethylene glycol)	Magnetic resonance imaging

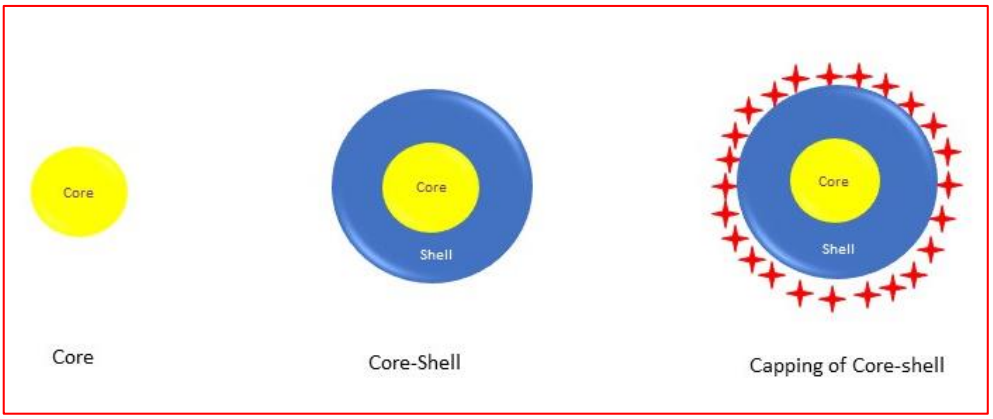

Fig. 4. Structure of quantum dots.

smaller sizes QDs have wider band gaps. As a result, a larger energy photon is released since more energy is needed to excite the electron. Similar large-size QDs have short bandgaps. By controlling their size and chemistry, QDs are synthesized. This allows QDs to be precisely controlled during synthesis to emit any color of light within the same material by modifying the dot size. Luminescence in QDs can occur in various ways. Numerous processes can lead to luminescence in QDs. Band edge emission is the term used to describe the release of a photon when it arises from an electron moving from the lowest conduction band to the highest valence band. This difference in energy between the highest valence band and the lowest conduction band is the energy of the photon that is released. In some circumstances, the excited electron initially dissipates energy in the way of a phonon before relaxing to the ground state and emitting a photon. Localized levels appear in the energy level of the QDs system with added contaminants. After a nonradiative transition from the conduction band to the localized level and a further radiative transition to the valence band, a photon is released.

Tunable Bandgap

QDs have become the ideal material for producing multijunction solar cells. These exciton Bohr radius-sized QDs have finite energy levels similar to those of individual atoms, and that is tunable by changing their size. It is impossible to modify the bandgap of conventional solar cells to infrared frequencies, but PbS QDs can. Due to their capacity, QDs can be used to create effective solar cells that are tuned to collect infrared frequencies, which account for more than half of the solar spectrum, as well as multijunction solar cells that are specifically tuned to make use of the solar spectrum [31-36].

Absorbance & Emission Characteristics:

Observing the absorbance of fluorescent dye, multiplex wavelength sources are not suitable for bio-imaging. Stokes shift (difference between max. emission wavelength and max. absorbance wavelength) of fluorescent dye is not much wider (approx. 15 to 30 nm) than the QDs. The Stokes shift is approximately hundreds of nanometers for QDs and so multiplex wavelength sources are used for bio-imaging. If the size distribution of synthesized QDs is not uniform then the range of emission of wavelength is more. The fluorescent dye shows an asymmetric emission [37-40].

Quantum Yield

The ratio of the number of photons emitted

Table 2. Comparison between Dyes and quantum dots.

Properties	Dyes	QDs
Absorption properties	Narrow	Wide-ranging
Emission properties	Asymmetric	Symmetric with a narrow range
Photo Stability	Low	High
Dimensions	Less than 1 nm	Appr. 2 to 20 nm
Fluorescence lifetimes	Less than 10 ns	Less than 100 ns

to the number of photons absorbed is known as quantum yield. Fluorescent dye has a large quantum yield of approx. nearly 100% but when the fluorescent dye is attached to a biomolecule, quantum yield is reduced [41-43].

Photostability

The fluorescent dye has less photostability than QDs. Even with high-intensity illumination from sources, the effect on the photostability of QDs is less. This property helps with a continuous optical probe for the observation of QDs in Bio-imaging [44-47].

Fluorescent lifetime

Quantum dots have a longer fluorescence lifetime (approximate 20- 40 ns) than Fluorescent Dye (approximate < 6ns). This property allows us to reduce autofluorescence [48]. Table 2 shows a comparison between the properties of Dyes and QDs.

Structure

There are the following certain terms to understand QDs structure appropriately. The core of the QDs decides the optical properties of QDs [49]. The core of the QDs is mostly hydrophobic. The shell material of QDs is an inorganic material. The core-shell QDs are hydrophobic and soluble in an organic solvent. Water-soluble QDs is important for bio-applications. For this purpose, the core-shell QDs require a coating of hydrophilic Material [50-55]. Core QDs are not used directly for bio-applications because they are poor stability and low quantum yield. Shell is required for highly luminescent and stable QDs. Generally, materials are CdSe, CdS, CdTe, and ZnS are used for a shell to the Core of the QDs. TEM (Transmission electron Microscopy), Size-exclusion chromatography, and Dynamic light scattering (DLS) are used for the measurement of the size of the QDs.

Synthesis method

The synthesis Process is very important to making QDs. We can change the QDs property during the synthesis process. There are two approaches are used for the synthesis of QDs: the top to bottom approach and the bottom-to-top approach (Fig. 5).

Top to down

In this approach, Reduce bulk material dimension to QDs dimension with different techniques like electron beam lithography, ion implantation, Molecular beam epitaxy, and X-ray lithography [56-58]. This method has several disadvantages like surface defects [59-61]. It is a costly approach to make QDs. In earlier days for the synthesis of small size particle material, mechanical milling methods were used. Easy, fast, and straightforward laser ablation methods were also popular for the synthesis of small size materials. Using the laser ablation method (Fig. 6), we can synthesize Gallium nitride QDs [62].

Bottom to up

In this approach, molecules or clusters of atoms are attached stepwise to form QDs. There are widely used because these methods are very simple and get considerable QDs. There are two main methods in the bottom-to-up approach to the synthesis of QDs. (a) Wet chemical methods (WCP) and (b) Vapor phase methods (VPM). Typically, with careful parameter monitoring for

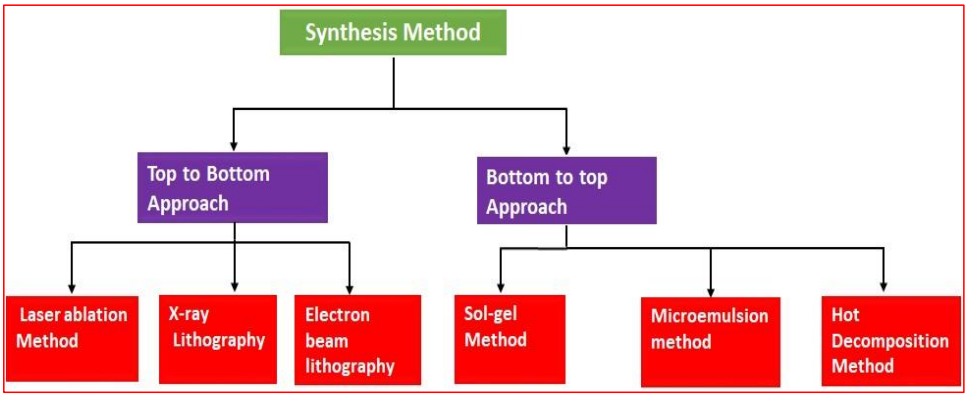

Fig. 5. Flow chart of the synthesis method for QDs.

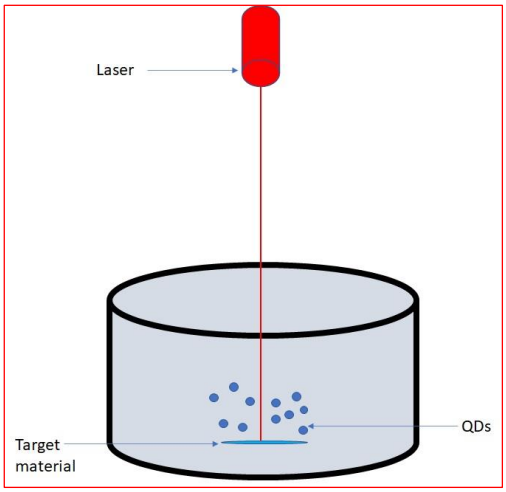

Fig.6. Laser Ablation method sample diagram.

a single solution or mixture of solutions, wet-chemical methods are traditional precipitation methods. It always includes both nucleation and restricted nanoparticle progress. Uniformity, inhomogeneous, or secondary nucleation can happen. When dissolved atoms or molecules merge and reach a critical size without the support of a pre-existing solid interface, homogeneous nucleation occurs. QDs of the desired size, morphology, and composition can be gained by various factors such as temperature, electrostatic double layer thickness, stabilizers or micelle formation, anionic to cationic species ratios, precursor concentrations, and solvent. Wet chemical methods are classified as Microemulsion, hot solution decomposition, and Sol-gel.

Microemulsion Method

At room temperature, the microemulsion system is applicable for QDs production. The methods are categorized as either normal microemulsions (oil-in-water) or opposite microemulsions (water-in-oil). Other polar solvents, such as alcohol, may be used instead of water in some cases. For the production of QDs, the opposite micelle method is used, in which two immiscible liquids (polar water and nonpolar long-chain alkane) are mixed and stirred to form an emulsion. Surfactants such as aerosol OT (AOT), cetyl trimethyl-ammonium bromide (CTAB), sodium dodecyl sulfate (SDS), or Triton-X can be used to disperse nanometer water droplets in alkane solutions. Because the surfactants are terminated on opposite ends by hydrophilic and hydrophobic groups, numerous small droplets known as micelles form in the continuous oil medium. These micelles are thermally stable and also have the capacity to act.

Sol-gel Method

For many long years, sol-gel methods are used to develop nanoparticles such as QDs. A sol (nanoparticles scattered in a solvent by Random motion) is generally prepared in an acidic or basic medium using a metal precursor (normally alkoxides, acetates, or nitrates). Hydrolysis, condensation (Sol formation), and development are the three key steps in this process (gel formation). In brief, the metal precursor hydrolyzes and condenses in the medium to form a sol, which is then polymerized to create a network (gel). This procedure has been used to develop II-VI and IV-VI QDs like CdS, ZnO, and PbS. ZnO QDs, for example, were created by combining solutions of Zn-acetate in alcohol & sodium hydroxide, then aging them in the air. The method is simple, cheap, and scalable. The major drawback of the sol-gel method is its wide size distribution and high concentration of imperfections.

Hot Decomposition Method

Using the hot decomposition approach, trioctylphosphine/tri octyl phosphine oxide (TOP/TOPO) is utilized as the solvent and ligand for the synthesis of CdSe QDs. Wider bandgap semiconductors like zinc sulfide and cadmium sulfide are used to cover the CdSe core. The surface of the QDs is altered by this overactive layer, increasing the photoluminescent yield. In this review article, we explain the synthesis part of cadmium selenium, cadmium sulfide, and carbon QDs by briefly using the wet chemical approach.

A flask containing 5 ml of octadecene and 30 mg of selenium was heated to 80°C while being swirled with a magnetic stirrer. To add 0.2 ml of trioctylphosphine (TOP) in order for completely dissolves the selenium. The solution was swirled while being heated and cooled. The solution of octadecene and cadmium oxide was mixed in a flask. The 0.8 ml of oleic acid was added and stirred in the flask. The temperature of the solution was raised to 225°C and mixed with selenium solution, heating it up to 250 to 260°C.

Cadmium chloride, sodium sulfide, and Polyvinyl alcohol are used for cadmium sulfide QDs. To prepare CdCl2 (0.1 M), Na2S (0.1 M), and 10 wt.% PVA solutions in deionized water. To

mix CdCl2 (0.1 M) in 10 wt.% PVA solutions and stirred it and added Na2S solution. The precipitate was filtered, then dried for 20 minutes at 80°C on a hot plate.

Tea can be used to synthesize carbon QDs. The dark green and glossy tea leaves were heated at 200°C for almost 2 hours, then ground into powder form and heated at 200°C again for 8 hours. The black carbonized tea powder was cooled at room temperature and stored. Acetic acid is

Table 3. Different sized QDs using hot-solution decomposition reaction.

QDs	Materials for synthesis	Synthesis Procedure	Dimensions(nm)
Gallium arsenide	Gallium trichloride, trimethyl-silyl Arsenic in Quinoline	250 °C for 3 days; flame anneal at 420 °C	2
Cadmium selenide, Cadmium telluride	$Cd(CH_3)_2$, Silyl chalcogenides, Phosphine chalcogenides; Coordinating solvent: Trioctylphosphine oxide	300–340 °C at 1 atm at Argon (degassing); 220–270 °C (evolution temp.)	1 to 12
Gallium arsenide	Gallium trichloride, diglyme, Arsenic, toluene, Sodium-Potassium alloy	Arsenic, Sodium-Potassium alloy mixture refluxed to 120 °C in Argon for 2 days; Gallium trichloride, diglyme mixture added, heated from 0°C to 110 °C for 2 days	6 to 10
CdSe: ZnS	$Cd(CH_3)_2$, $Zn(CH_3)_2$, selenium Bis(trimethylsilyl)sulfide, Coordinating solvent: Trioctylphosphine oxide, tri-n-octyl-phosphine	Single-step synthesis method Core: 370 °C at 1 atm at Argon, growth: 310 °C Shell: 280 °C	2.5 to 4
CdSe: ZnS	$Cd(CH_3)_2$, $Zn(CH_3)_2$, Selenium, Bis(trimethylsilyl)sulfide, Coordinating solvent: Trioctylphosphine oxide, tri-n-octyl-phosphine	Two-step process (airless) Core evolution: 280–300 °C Shell evolution: 150 °C for 2 nm & 230°C for 6 nm	2 to 6
Zinc selenide	$Zn(CH_3)_2$, Selenium, hexadecyl amine, tri-n-octyl-phosphine	Hexadecyl amine dried & degassed at 150 °C for some hrs in a vacuum and heated to 310°C at 1atm in Argon; core evolution with zinc and selenium precursor at 280 °C.	4 to 6
Cadmium selenide	$Cd(CH_3)_2$, selenium, tri-n-butyl phosphine, Trioctylphosphine oxide, hexyl-phosphonic acid	Trioctylphosphine oxide (+hexyl-phosphonic acid 2 to 3 weight percentage) degassed at 350 °C (or 320 °C, 290 °C); Core evolution: 320°C (or 290 °C or 240 °C)	5 to 6
Zinc selenide: Manganese	$Mn(CH_3)_2$, Diethylzinc, tri-n-octyl-phosphine, Selenium, Hexadecyl amine	Dimethyl Mn, tri-n-octyl-phosphine, Se, Diethyl Zn mixture added to Hexadecyl amine at 320 °C in N_2. Evolution: 250–310 °C	2 to 6
Cadmium telluride	Cadmium Oxide, Trioctylphosphine oxide, hexyl-phosphonic acid/ tetradecyl phosphonic acid, Selenium, Tellurium, tri-n-octyl-phosphine	One-pot: Cadmium oxide, hexyl-phosphonic acid/tetradecyl phosphonic acid heated 270 °C; Core with chalcogenide pioneer: reaction: 260 °C & evolution 260 °C	2 to 8
Lead (II) sulfide	Lead Oxide, oleic acid, Bis(trimethylsilyl)sulfide, tri-n-octyl-phosphine	Lead oxide dissolved in oleic acid at 150 °C in Arsenic; Bis(trimethylsilyl)sulfide & tri-n-octyl-phosphine injected	4 to 5
Lead (II) selenide	Pb-acetate trihydrate, oleic acid, selenium, tri-n-octyl-phosphine	Single Step: Lead acetate + Coordinating solution degassed at 120 to 130 °C at 250 to 450 °C reaction and evolution: 150 °C	4.5 to 5

used as a dispersion medium for carbon QDs. The carbonized tea powder was dispersed in 0.1 M acetic acid and kept for 40 hours. The dispersed medium was centrifuged at 12,000 rpm for 1 hour. The supernatant liquid containing tea carbon QDs was filtered, collected, and stored [63-70]. Table 3 displays QDs that are produced by a hot-solution decomposition procedure.

APPLICATION

The significant role of QDs in biological and medical sciences has been noticed in the last few decades. QDs are one of the materials whose link with biological science [71-75]. With the help of optical properties, electric properties, and magnetic properties of QDs we can use them in different kinds of bio-applications by reducing toxicity [76-80]. The size of QDs is comparable with the biomolecules so interaction allows use in biology. QDs are used in medical science for cell labeling and imaging, gene therapy, virus and bacteria detection, and drug delivery [81-85]. Potential applications of quantum dots in electronics include single-electron transistors, inkjet printing, single-photon sources, Quantum Dot Cellular Automata (QCA), second-harmonic generation, quantum computing, spin-coating, and Langmuir-Blodgett thin films [86-91]. Now discuss a few applications of QDs briefly as follows: In biology, cell labeling is important to study the structure of cells and their properties. QDs track single molecules in living cells and organisms. Earlier instead of QDs, different organic dyes were used for bioimaging. High Photostability, narrow emission spectra, High fluorescent quantum yield, and multiple Bohr exciton pairs are the key parameter for QDs to use in labeling cells better than organic dye. Escherichia coli is a bacterium that can cause bloody diarrhea. Salmonella typhimurium is also a bacterium that can cause typhoid fever that can be detected using the emission wavelength of QDs [92]. Surface passivations QDs are used as labeling cells in vitro and in vivo [93]. Targeted drug delivery and imaging systems functionalized graphene QDs are used for influenza virus detection [94]. Detection of hepatitis B virus DNA is also possible using graphene QDs [95]. GaP, GaAs, InP, and InAs are the most suitable semiconductor QDs for optoelectronic devices. The data in Table 4 shows Bioimaging with QDs.

QDs are also used in the display. Today QLED (QDs-based light-emitting diodes) is used instead of OLED (Organic light-emitting diodes) because longer life display, high thermal stability, and high-quality image. Resistant to oxygen and moisture, size-tunable bandgap so multi-junction device is possible using same QDs, the large number of electron-hole pair generated with a single photon are the features of QDs so they are used in next generation of the solar cell [96]. Surface-functionalized carbon in association with triazole and its derivative, carbon QDs can improve the antiviral response to a human coronavirus infection [97-98]. Electrical batteries and the manufacture of explosives need also picric acid. Picric acid is recognized by photoluminescent Zinc Oxide QDs [99]. As per a WHO (World health organization) report published on March 26, 2021, there were 2.3 million women treated for cancer in 2020 and 685,000 deaths globally. Cadmium selenide QDs stabilized with mercaptopropionic acid were developed for breast cancer bioimaging [100]. The leading cause of death globally is heart disease, according to a WHO report released on June 11, 2021. According to studies, 17.9 million deaths worldwide in 2019 were related to CVDs

Table 4. The application of bioimaging using QDs.

QDs	Determine	Spectroscopic method	Vitro/Vivo	Emission wavelength or Size of QDs
CdSe: ZnS	Biological detection & Sensing	Fluorescence	Vitro	1.5 to 4 nm
CdSe: ZnS: SiO2	Biological Imaging	Fluorescence	Vitro	550 nm & 630 nm
CdSe: ZnS	Abnormal growth of body tissue Imaging	Fluorescence	Vivo and Vitro	Less than 12 nm
CdTe: CdSe	Cancer cell Imaging	Fluorescence	Vivo	Near-infrared
CdSe: ZnS	Bonding of glucose molecules	Fluorescence resonance energy transfer	Vitro	540 to 560 nm
CdSe: CdS: SiO_2	Imaging of Mouse fibroblast cell	Fluorescence	Vitro	500 nm & 650 nm

(Cardiovascular disease), or 32% of all fatalities. 85 % of these casualties were caused by heart attack and stroke. FRET is an important application of QDs (Fluorescence resonance energy transfer). Energy is transmitted from one fluorophore to another fluorophore through the FRET method. FRET is a technique for evaluating molecule-to-molecule interactions. Fluorescence resonance energy transfer (FRET) based devices for early heart attack detection in humans have been created [101]. Environmental and health risks are caused by metal ions including mercury, lead, and cadmium globally. Therefore, graphene QDs and carbon nanodots for the FRET-based sensor are used for the detection of heavy metal ions [102]. Calix[4]arene capped QDs & nanoparticles are also used in bio-applications. Vitamin K3 is a synthetic fat-soluble vitamin that aids in bone mineralization and blood clotting. It has attracted a great deal of interest because of its extraordinary anti-cancer effects. Detection and quantification of menadione with excellent sensitivity and selectivity that is coated with p-sulfonato calix[4] arene [103-106] on ZnS quantum dots [107]. A novel, sophisticated, straightforward method for the colorimetric measurement of glucose based on Au nanoparticles functionalized with calix[4]arene phenylboronic acid (CX-PBA) has been developed [108]. Creatinine concentration in blood serum increases as a result of kidney issues, thyroid issues, and muscular diseases; as a result, diagnosing these conditions involves detecting creatinine concentration in blood serum or urine. For the "on place" colorimetric detections of creatinine, a new technique based on calix[4]arene functionalized gold nanoparticles (AuNPs) has been published, with excellent separation in the presence of other biomolecules [109].

CONCLUSION

The Extraordinary characteristics of QDs; such as stability against photobleaching, high quantum yield, larger excitation coefficient, smaller emission spectra, size, and composition-dependent emission wavelength of light give wide a variety of applications in many fields. Single-photon absorption is the key to multi-imaging. In the future, the tremendous applications of QDs will observe in each field of science and technology, but especially in medical science. The high surface area of QDs is useful to biomolecules such as proteins, lipids, enzymes, nucleic acids, and small-molecule ligands for bonding.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Ekimov A. I., Onushchenko A. A., (1982), Quantum size effect in the optical-spectra of semiconductor micro-crystals. *Soviet Phys. Semiconduc.* 16: 775-778.
2. Murray C. B., Norris D. J., Bawendi M. G., (1993), Synthesis and characterization of nearly monodisperse CdE (E=sulfur, selenium, tellurium) semiconductor nanocrystallites. *J. Am. Chem. Soc.* 115: 8706-8715.
3. Woggon U., (1997), Optical properties of semiconductor quantum dots. *Springer Book.* 136: 103-157.
4. Zhang Z. Z., Chang K., Peeters F. M., (2008), Tuning of energy levels and optical properties of graphene quantum dots. *Phys. Rev. B.* 77: 235411-235418.
5. Gao X., Dave Sh. R., (2007), QDs for cancer molecular imaging. In bio-applications of nanoparticles; Springer-Verlag Berlin: *Berlin.* 620: 57-73.
6. Liu H. C., Song C. Y., Thorpe A. J., Cao J. C., (2004), Terahertz quantum-well photodetector. *Appl. Phys. Lett.* 84: 4068-4070.
7. Shrekenhamer D., Rout S., Strikwerda A. C., Bingham C., Averitt R. D., Sonkusale S., Padilla W. J., (2011), High speed terahertz modulation from metamaterials with embedded high electron mobility transistors. *Optics express*. 19: 9968-9975.
8. Chu Z., Zhou Y., Zhou J., Chen P., Li Z., Lu W., Chen X., (2021), Quantum well infrared detectors enhanced by faceted plasmonic cavities. *Infra. Phys. Technol.* 116: 103746-103750.
9. Ridene S., (2017), Novel T-shaped GaSb/InAsN quantum wire for mid-infrared laser applications. *Phys. Lett. A*. 381: 3324-3331.
10. Meehan X. Y., Kathleen M., Guido L., Lu G., Wyatt Ch., Love N., (2005), Synthesis and characterization of silica coated CdSe/CdS core/Shell quantum dots. *PhD Thesis.*
11. Shoujun Zhu., Yubin S., Joy W., Hao W., Zhang Y., Ning Y., Yang B., (2017), Photoluminescence mechanism in graphene QDs: Quantum confinement effect and surface/edge state. *Nano Today.* 13: 10-14.
12. Katsaba A. V., Ambrozevich S. A., Vitukhnovsky A. G., Fedyanin V. V., Lobanov A. N., Krivobok V. S., Vasiliev R. B., Samatov I. G., (2013), Surface states effect on photoluminescence of CdS colloidal nanocrystals. *J. Appl. Phys.* 113: 184306-184311.
13. Huang L., Yang J., Wang X., Han J., Hana H., Li C., (2013), Effects of surface modification on photocatalytic activity of CdS nanocrystals studied by photoluminescence spectroscopy. *Phys. Chem. Chem. Phys.* 15: 553-560.

14. Kobayashi Y., Nishimura T., Yamaguchi H., Tamai N., (2011), Effect of surface defects on auger recombination in colloidal CdS quantum dots. *J. Phys. Chem. Lett.* 2: 1051-1055.
15. Yu W. W., Chang E., Drezek R., Colvin V. L., (2006), Water-soluble QDs for biomedical applications. *Biochem. Biophys. Res. Communic.* 348: 781-786.
16. Larson D. R., Zipfel W. R., Williams R. M., Clark S. W., Bruchez M. P., Wise F. W., Webb W. W., (2003), Water-soluble quantum dots for multiphoton fluorescence imaging in vivo. *Science.* 300: 1434-1436.
17. Liu T. C., Huang Z. L., Wang H. Q., Wang J. H., Li X. Q., Zhao Y. D., Luo Q. M., (2006), Temperature-dependent photoluminescence of water-soluble QDs for a bioprobe. *Analyt. Chim. Acta.* 559: 120-123.
18. Zhang M., Bai L., Shang W., Xie W., Ma H., Fu Y., Fang D., Sun H., Fan L., Han M., Liu C., YangS. J., (2012), Facile synthesis of water-soluble, highly fluorescent graphene quantum dots as a robust biological label for stem cells. *Mater. Chem.* **22**: 7461-7467.
19. Liu L., Guo X., Li Y., Zhong X., (2010), Bifunctional multidentate ligand modified highly stable water-soluble quantum dots. *Inorg. Chem.* 49: 3768-3775.
20. Akin M., Bongartz R., Walter J. G., Demirkol D. O., Stahl F., Timur S., Scheper T., (2012), PAMAM-functionalized water soluble quantum dots for cancer cell targeting. *J. Mater. Chem.* 22: 11529-11536.
21. Hezinger A. F. E., Teßmar J., Göpferich A., (2008), Polymer coating of QDs–A powerful tool toward diagnostics and sensorics. *Europ. J. Pharmac. Biopharmac.* 68: 138-152.
22. Jańczewski D., Tomczak N., Han M. Y., (2011), Synthesis of functionalized amphiphilic polymers for coating QDs. *Nat. Protocols.* 6: 1546–1553.
23. Foubert A., Beloglazova N. V., Rajkovic A., Sas B., Madder A., Goryacheva Y. I., Saeger S. D., (2016), Bioconjugation of QDs: Review & impact on future application. *TrAC Trends in Analyt. Chem.* 83: 31-48.
24. Blanco-Canosa J. B., Wu M., Susumu K., Petryayeva E., Jennings T. L., Dawson P. E., Algar W. R., Medintz I. L., (2014), Recent progress in the bioconjugation of QDs. *Coordin. Chem. Rev.* 263–264: 101-137.
25. Boeneman K., Deschamps J. R., Buckhout-White S., Prasuhn D. E., Blanco-Canosa J. B., Dawson P. E., Stewart M. H., Susumu K., Goldman E. R., Ancona M., Medintz I. L., (2010), Quantum dot DNA bioconjugates: Attachment chemistry strongly influences the resulting composite architecture. *ACS Nano.* 4: 7253-7266.
26. Alibolandi M., Abnous Kh., Sadeghi F., Hosseinkhani H., Ramezani M., Hadizadeh F., (2014), Folate receptor-targeted multimodal polymersomes for delivery of quantum dots and doxorubicin to breast adenocarcinoma: In vitro and in vivo evaluation. *Int. J. Pharmac.* 500: 162-178.
27. Alibolandi M., Abnous K., Ramezani M., Hosseinkhani H., Hadizadeh F., (2014), Synthesis of AS1411-aptamer-conjugated CdTe quantum dots with high fluorescence strength for probe labeling tumor cells. *J. Fluoresc.* 24: 1519-1529.
28. Hosseinkhani H., (August 2019), Nanomaterials in advanced medicine. *John Wiley & Sons.* ISBN: 9783527345496.
29. Abraham J. D., Sharifzadeh Gh., Victoria N., Hosseinkhani, H., (2021), Safety evaluation of nanotechnology products. *Pharmaceutics*. 13: 13101615.
30. Wenjie H., Hosseinkhani H., Mohammadinejad R., Roveimiab Z., Hueng Du. Y., Liang K., Domb A. J., (2014), Polymeric nanoparticles for therapy and imaging. *Polym. Adv. Technol.* 25: 1216-1225.
31. Kowalski P., Machnikowski P., (2008), Multiple exciton generation in InAs nanocrystals. *Acta Phys. Pol. A.* 114: 1187–1192.
32. Beard M. C., (2011), Multiple exciton generation in semiconductor quantum dots. *J. Phys. Chem. Lett.* 2: 1282–1288
33. Shockley W., Queisser H. J., (1961), Detailed balance limit of efficiency of p-n junction solar cells. *J. Appl. Phys.* 32: 510-516.
34. Klem E. J. D., MacNeil D. D., Cyr P. W., Levina L., Sargent E. H., (2007), Efficient solution-processed infrared photovoltaic cells: Planarized all-inorganic bulk heterojunction devices via interquantum-dot bridging during growth from solution. *Appl. Phys. Lett*. 90: 10–12.
35. McDonald S. A., Konstantatos G., Zhang S., Cyr P. W., Klem E. J. D., Levina L., (2005), Solutionprocessed PbS quantum dot infrared photodetectors and photovoltaics. *Nat. Mater.* 4: 138–142.
36. Kumar D., Sumanth B., Mahesh M., (2018), Quantum nanostructures (QDs): An Overview. *In book: Synthesis of Inorganic Nanomaterials.*
37. Li J., Zhu J., (2013), QDs for fluorescent biosensing and bio-imaging applications. *Analyst*. 138: 2506-2515.
38. Hutter E., Maysinger D., (2011), Gold nanoparticles and QDs for bioimaging. *Microscopy Res. Techniq*. 74: 592-604.
39. Huo F., Liang W., Tang Y., (2019), Full-color carbon dots with multiple red-emission tuning: on/off sensors, in vitro and in vivo multicolor bioimaging. *J. Mater. Sci.* 54: 6815-6825.
40. Sellers I. R., Liu H. Y., Badcock T. J., Groom K. M., Mowbray D. J., Gutiérrez M., Hopkinson M., Skolnick M. S., (2005), Lasing and spontaneous emission characteristics of 1.3μm In(Ga)As quantum-dot lasers. *Phys. E: Low-dimens. Sys. Nanostruc.* 26: 382-385.
41. Linkov P., Krivenkov V., Nabiev I., Samokhvalov P., (2016), High Quantum yield CdSe/ZnS/CdS/ZnS multishell QDs for biosensing and optoelectronic applications. *Mater. Today: Proceed.* 3: 104-108.
42. Wei Y., Chen L., Zhao S., (2021), Green-emissive carbon QDs with high fluorescence quantum yield: Preparation and cell imaging. *Front. Mater. Sci.* 15: 253-265.
43. Grabolle M., Spieles M., Lesnyak V., Gaponik N., Eychmüller A., Resch-Genger U., (2009), Determination of the fluorescence quantum yield of quantum dots: Suitable procedures and achievable uncertainties. *Analyt. Chem.* 81: 6285-6294.
44. Resch-Genger U., Grabolle M., Cavaliere-Jaricot S., (2008), QDs versus organic dyes as fluorescent labels. *Nat. Meth.* 5: 763-775.
45. Bruchez M. P., (2011), QDs find their stride in single molecule tracking. *Current Opin. Chem. Biol.* 15: 775-780.
46. Zhang L. J., Xia L., Xie H. Y., Zhang Z. L., Pang D. W., (2019), Quantum dot based biotracking and biodetection. *Analyt. Chem.* 91: 532-547.
47. Peng H., Zhang L., Soeller Ch., Travas-Sejdic J., (2007), Preparation of water-soluble CdTe/CdS core/shell QDs with enhanced photostability. *J. Lumines.* 127: 721-726.
48. Hotz C. Z., Bruchez M., (2007), QDs: Applications in biology (Methods in Molecular Biology, 374), ISBN-10:3540140077.

49. Reimann S. M., Matti M., (2002), Electronic structure of quantum dots. *Rev. Mod. Phys.* 74: 1283-1342.
50. Vasudevan D., Ranganathan Gaddam R., Trinchi A., ColeI., (2015), Core-shell QDs: Properties and applications. *J. Alloys Comp*. 636: 395-404.
51. Zhang B., Cheng J., Li D., Liu X., Ma G., Chang J., (2008), A novel method to make hydrophilic QDs and its application on biodetection. *Mater. Sci. Eng: B.* 149: 87-92.
52. Xu J., Ruchala P., Ebenstain Y., Jack Li J., Weiss S., (2012), Stable, compact, bright biofunctional quantum dots with improved peptide coating. *J. Phys. Chem. B.* 116: 11370-11378.
53. Ma L., Tu C., Le P., Chitoor S., Jun Lim S., Zahid M. U., Teng K. W., Ge P., Selvin P. R., Smith A. M., (2016), Multidentate polymer coatings for compact and homogeneous quantum dots with efficient bioconjugation. *J. Am. Chem. Soc.* 138: 3382-3394.
54. Gao W., Zhou Y., Xu C., Guo M., Qi Z., Peng X., Gao B., (2019), Bright hydrophilic and organophilic fluorescence carbon dots: One-pot fabrication and multi-functional applications at visualized Au^{3+} detection in cell and white light-emitting devices. *Sens. Actuat. B: Chem.* 281: 905-911.
55. Hotz C. Z., (2005), Applications of quantum dots in biology. *Methods Mol. Biol.* 303: 1-17.
56. Singh M. K., Mathpal M. C., Agarwal A., (2012), Optical properties of SnO_2 QDs synthesized by laser ablation in liquid. *Chem. Phys. Lett.* 536: 87-91.
57. Dieleman C. D., Ding W., Wu L., Thakur N., Bespalov I., Daiber B., Ekinci Y., Castellanos S., Ehrler B., (2020), Universal direct patterning of colloidal quantum dots by (extreme) ultraviolet and electron beam lithography. *Nanoscale.* 12: 11306-11316.
58. Massimo F. B., Gadipalli R. R., Martin L. A., Rich L. E., Yamilov A., Heckman B. R., Leventis N., Guha S., Katsoudas J., Divan R., Mancini D. C., (2007), Quantum dots by ultraviolet and x-ray lithography. *Nanotechnology*. 18: 31/315603.
59. Kuruma, K., Ota Y., Kakudam M., Iwamoto S., Arakawa Y., (2020), Surface-passivated high-Q GaAs photonic crystal nanocavity with QDs. *APL Photonics.* 5: 5144959.
60. Birindelli S., Felici M., Wildmann J. S., Polimeni A., Capizzi M., Gerardino A., Rubini S., Martelli F., Rastelli A., Trotta R., (2014), Single photons on demand from novel site-controlled GaAsN/GaAsN : H quantum dots. *Nano Lett.* 3: 1275-1280.
61. Kundu S., Pillat V. K., (2020), Synthesis and characterization of graphene QDs. From the book *Volume 2 Multifunctional Materials.* Vol.2, Sec. 5.
62. Timothy J. G., Valerie J. L., Subhash H. R., Ian M. K., Howard W. H., (1997), Synthesis of gallium nitride QDs through reactive laser ablation. *Appl. Phys. Lett.* 70: 3122-3124.
63. Mazumder S., Dey R., Mitra M. K., Mukherjee S., Das G. C., (2009), Review: Biofunctionalized quantum dots in biology and medicine. *J. Nanomater.* 2009: 815734.
64. Nozik A. J., (2008), Multiple exciton generation in semiconductor quantum dots. *Chem. Phys. Lett.* 457: 3-11.
65. Bera D., Qian L., Tseng T. K., Holloway P. H., (2010), Quantum dots and their multimodal applications: A review. *Material.* 3: 2260-2345.
66. Mansur A., Mansur H., González J., (2011), Enzyme-polymers conjugated to quantum-dots for sensing applications. *Sensors.* 11: 9951-9972.
67. Ayela D. W., Su W. N., Wu C. C., Shiau C. Y., Hwang B. J., (2014), Amorphous precursor compounds for $CuInSe_2$ particles prepared by a microwave-enhanced aqueous synthesis and its electrophoretic deposition. *Cryst. Eng. Comm.* 16: 3121-3127.
68. Kuldeep D., (2014), Synthesis and characterization of PVA capped CdS nanocrystals. *Res. J. Phys. Sci.* 2: 1-3.
69. Pu Y., Cai F., Wang D., Wang J. X., Chen J. F., (2018), Colloidal synthesis of semiconductor quantum dots toward large-scale production: A review. *Indus. Eng. Chem. Res.* 57: 1790-1802.
70. Baruah U., Gogoi N., Konwar A., Deka M. J., Chowdhury D., Majumdar G., (2014), Carbon dot based sensing of dopamine and ascorbic acid. *J. Nanopart.* 2014: 178518.
71. Bonilla J. C., Bozkurt F., Ansari Sh., Sozer N., Kokini J. L., (2016), Applications of QDs in food science and biology. *Trends in Food Sci. Technol.* 53: 75-89.
72. Smith A., Nie S., (2009), Next-generation QDs. *Nat. Biotechnol.* 27: 732-736.
73. Gao X., Chan W. C. W., Nie Sh., (2002), Quantum-dot nanocrystals for ultrasensitive biological labeling and multicolor optical encoding. *J. Biomed. Opt.* 7: 532-537.
74. Ballou B., Christoffer Lagerholm B., Ernst L. A., Bruchez M. P., Waggoner A. S., (2004), Noninvasive imaging of quantum dots in mice. *Bioconjug. Chem.* 15: 79-86.
75. Byers R. J., Hitchman E. R., (2011), QDs brighten biological imaging. *Prog. Histochem. Cytochem.* 45: 201-237.
76. Gidwani B., Sahu V., Shukla S. S., Pandey R., Joshi V., Kumar Jain V., Vyas A., (2021), QDs: Prospectives, toxicity, advances and applications. *J. Drug Deliv. Sci. Technol.* 61: 102308-102312.
77. Filali S., Pirot F., Miossec P., (2020), Biological applications and toxicity minimization of semiconductor QDs. *Trends in Biotechnol.* 38: 163-177.
78. Wang Y., Hu R., Lin G., Roy I., Yong K. T., (2013), Functionalized quantum dots for biosensing and bioimaging and concerns on toxicity. *ACS Appl. Mater. Interf.* 5: 2786-2799.
79. Wang Z., Tang M., (2021), The cytotoxicity of core-shell or non-shell structure QDs and reflection on environmentally friendly: A review. *Env. Res.* 194: 110593-110597.
80. BajwaN., Mehra N. K., Jain K., Jain N. K., (2016), Pharmaceutical and biomedical applications of QDs. *Artific. Cells, Nanomedic. Biotechnol.* 44: 758-768.
81. Atchudan R., Jebakumar T. N., Edison I., Shanmugam M., Perumal S., Somanathan T., Lee Y. R., (2021), Sustainable synthesis of carbon QDs from banana peel waste using hydrothermal process for in vivo bioimaging. *Phys. E: Low-dimens. Sys. Nanostruc.* 126: 114417-114421.
82. Shi C., Qi H., Ma R., Sun Z., Xiao L., Wei G., Huang Z., Liu S., Li J., Dong M., Fan J., Guo Z., (2019), N and S-self-doped carbon QDs from fungus fibers for sensing tetracyclines and for bioimaging cancer cells. *Mater. Sci. Eng: C.* 105: 110132-11136.
83. Reshma V. G., Mohanan P. V., (2019), QDs: Applications and safety consequences. *J. Luminesc.* 205: 287-298.
84. Sayed N., Allawadhi P., Khurana A., Singh V., Navik U., Pasumarthi S. K., Khurana I., Banothu A. K., Weiskirchen R., Bharani K. K., (2022), Gene therapy: Comprehensive overview and therapeutic applications. *Life Sci.* 294: 120375-120379.
85. Hernando P. J., Dedola S., Marín M. J., Field R. A., (2021), Recent developments in the use of glyconanoparticles and

related QDs for the detection of lectins, viruses, bacteria, and cancer cells. *Front. Chem.* 9: 668509.
86. Peter L., Sahand M., Søren S., (2015), Interfacing single photons and single quantum dots with photonic nanostructures. *Rev. Modern Phys.* 87: 347–400.
87. Daniel L., Vincenzo D., David P., (1998), Quantum computation with quantum dots. *Phys. Rev. A.* 57: 120–126.
88. Ramírez H. Y., Flórez J., Camacho A. S., (2015), Efficient control of coulomb enhanced second harmonic generation from excitonic transitions in quantum dot ensembles. *Phys. Chem. Chem. Phys.* 17: 23938–23946.
89. Coe-Sullivan S., Steckel J. S., Woo W.-K., Bawendi M. G., Bulović V., (2005), Large-area ordered quantum-dot monolayers via phase separation during spin-casting. *Adv. Func. Mater.* 15: 1117–1124.
90. Hu Z., Yin Y., Ali M. U., Peng W., Zhang S., Li D., Zhou H., (2020), Inkjet printed uniform quantum dots as color conversion layers for full-color OLED displays. *Nanoscale*. 12: 2103-2110.
91. Mohammadi M., Mohammadi M., Gorgin S., (2016), An efficient design of full adder in quantum-dot cellular automata (QCA) technology. *Microelect. J.* 50: 35-43.
92. Kurt H., Yüce M., Hussain B., Budak H., (2016), Dual-excitation upconverting nanoparticle and quantum ot aptasensor for multiplexed food pathogen detection. *Biosens. Bioelectronics*. 81: 280-286.
93. Chinnathambi Sh., Shirahata N., (2019), Recent advances on fluorescent biomarkers of near-infrared QDs for in vitro and in vivo imaging. *Sci. Technol. Adv. Mater.* 20: 337-355.
94. Achadu O. J., Takemura K., Khoris I. M., Park E. Y., (2020), Plasmonic/magnetic molybdenum trioxide and graphitic carbon nitride QDs-based fluoroimmunosensing system for influenza virus. *Sens. Actuat. B: Chem*. 321: 128494-128498.
95. Xiang Q., Huang J., Huang H., Mao W., Ye Z., (2018), A label-free electrochemical platform for the highly sensitive detection of hepatitis B virus DNA using graphene quantum dots. *RSC Adv.* 8: 1820-1825.
96. Jelinek R., (2017), Bioimaging applications of carbon-dots. *Springer Book.* 61-70
97. Markna J. H., Rathod P. K., (2022), Review on the efficiency of quantum dot sensitized solar cell: Insights into photoanodes and QD sensitizers. *Dyes and Pigments.* 199: 110094.
98. Garg P., Sangam S., Kochhar D., Pahari S., Kar C., Mukherjee M., (2020), Exploring the role of triazole functionalized heteroatom co-doped carbon quantum dots against human coronaviruses. *Nano Today.* 35: 101001.
99. Singh K., Chaudhary G. R., Singh S., Mehta S. K., (2014), Synthesis of highly luminescent water stable ZnO quantum dots as photoluminescent sensor for picric acid. *J. Luminesc.* 154: 148-154.
100. Parveen K., Akash D., Sukesh Sh., Lalit B., (2012), Synthesis of mercaptopropionic acid stabilized CdS quantum dots for bioimaging in breast cancer. *Adv. Mat. Lett.* 3: 471-475.
101. Bhatnagar D., Kumar V., Kumar A., Kaur I., (2016), Graphene quantum dots FRET based sensor for early detection of heart attack in human. *Biosens. Bioelect.*79: 495-499.
102. Chini M. K., Kumar V., Javed A., Satapathi S., (2019), Graphene quantum dots and carbon nano dots for the FRET based detection of heavy metal ions. *Nano-Struct. Nano-Objects*. 19: 100347.
103. Sutariya P., Soni H., Gandhi S. A., Pandya A., (2019), Single step fluorescent recognition of As^{3+}, Nd^{3+} and Br- consuming pyrene-allied calix[4]arene : Their application to real samples, computational modelling and paper based device. *New J. Chem.* 43: 737-747.
104. Sutariya P., Soni H., Gandhi S. A., Pandya A., (2019), Novel luminescent paper based calix[4]arene chelation enhanced fluorescence photo induced electron transfer probe for Mn^{2+}, Cr^{3+} and F^-. *J. Luminesc.* 208: 6-17.
105. Sutariya P., Soni H., Gandhi S. A., Pandya A., (2019), Novel tritopic calix[4]arene CHEF-PET fluorescence paper based probe for La^{3+}, Cu^{2+}, and Br^-: Its computational investigation and application to real samples. *J. Luminesc.* 212: 171-179.
106. Sutariya P., Soni H., Gandhi S. A., Pandya A., (2019), Luminescent behavior of pyrene-allied calix[4]arene for highly pH selective recognition and determination of Zn^{2+}, Hg^{2+} and I^- via CHEF-PET mechanism: Computational experiment and paper based device. *New J. Chem.* 43: 9855-9864.
107. Joshi K. V., Joshi B. K., Pandya A., Sutariya P. G., Menon, S. K., (2012), Calixarene capped ZnS quantum dots as an optical nanoprobe for detection and determination of menadione. *Analyst.* 137: 4647-4650.
108. Pandya A., Sutariya P. G., Menon S. K., (2013), Fluorescence switch on–off–on receptor constructed of quinoline allied calix[4]arene for selective recognition of Cu^{2+} from blood serum and F^- from industrial waste water. *Analyst.* 138: 2531-2535.
109. Sutariya P. G., Pandya A., Lodha A., Menon S. K., (2016), A simple and rapid creatinine sensing via DLS selectivity, using calix[4]arene thiol functionalized gold nanoparticles. *Talanta.* 147: 590-597.