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Reviewing Quantum Dots: Synthesis, Characterization and Applications

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ABSTRACT

Quantum dots (QDs) are nano-sized particles or nanocrystals of a semiconducting material with diameters in the range of 2-10 nanometers. The QD possess some unique optical and electrical properties due to quantum confinement of charge carriers inside it. Also, their fluorescent properties are tunable over a wide range with their size variation and surface functionalization. This delicate tuning in their morphology can be used in optoelectronics, sensing, bio-imaging applications. In present scenario, the QDs have numerous commercial uses in electronics and various kinds of biological applications (such as, fluorescent tagging, cellular detection, tracking, and imaging, genetic engineering) in current scientific research due to their distinctive traits. Here, in this review, we discuss different kinds of synthetic strategies, functionalization methods, different characterization techniques and some major scientific applications in society. Characteristic properties of carbon quantum dots, graphene quantum dots and metal ion quantum dots are also discussed.

KEYWORDS: Quantum dots; Optoelectronics; Fluorescent; Nanocrystals; Semiconductor.

1. INTRODUCTION

In the year 1981, Alexei Ekimov and A. A. Onuschenko published a paper where they described their observation of a range of fluorescence colours of copper chloride nanocrystals in a molten glass matrix. In the next year, Russian physicist Alexandre Efros, published the theory of confinement of electrons in order to explain the behavior of these very tiny crystals. In 1983, an American chemist Louis Brus, first originally produced the colloidal suspension of cadmium sulfide quantum dots. After these early discoveries, quantum dots (QDs) drew the attention of researchers from every corner of the globe for their unique nature and enormous industrial possibility. QDs are special nanometer-dimension particles, typically spanning between 1 and 10 nm, which show delightful properties due to their small size and the outcomes of quantum mechanics. Fluorescent semiconductor nanocrystals, or QDs, are often designed using periodic elements from group IV, III-V, or II-VI. The display's nano-dimension size is significantly different from its bulk constituents, particularly in terms of its optical and electrical characteristics. They are readily synthesized using an array of techniques, and it is simple to modify their characteristics via covalent, electrostatic, or salt bridge methods (Bai et al., 2022). By coating with different functional groups as thiols, amines, alcohols, and carboxylic acids, certain QDs' stability in aqueous solution can be improved (Bai et al., 2022). These functional groups and covalent conjugations can result in a variety of molecules. Additionally, by providing an outer sheath of functionalized silica, linker, and phospholipids, QDs may be made more soluble in water (Bai et al., 2022).

The quantum confinement (QC) of moveable charge carriers is the basis for how QDs materials function. De Broglie wavelength (λ_{deB}) is the measured quantity of QC carrier (Galstyan, 2021). A moving charge carrier (of mass 'm') travelling in unidirectional way within the crystal may behave as a wave, as per the de Broglie theory, as indicated by the following equation,

$$\boldsymbol{\lambda_{deB} = h/\sqrt{mK_BT_l}} \quad \text{.......................... Equation 1}$$

Where, crystal lattice temperature is T_l, Boltzmann constant is K_B, and Planck constant is h.

QD materials may be classified according to the number of directions where the structure's size corresponds to the charge carrier's de Broglie wavelength carrier (Galstyan, 2021). Quantum-confined structures are categorized as 0D (no movement), 1D (one direction of movement), and 2D (two directions of movement) based on the direction of charge carrier movement. Such phenomena cover quantum dots, quantum wires, and quantum wells. Electrons and holes exhibit discrete, atomic density-like states in QDs (Galstyan, 2021). QDs are zero-dimensional (0-D) nanoparticles of semiconductors in which charge carrier movement is restricted in all three directions. Based on the size of QDs particle, the band gap of energy exists between valence band and conduction band. Hence, it is feasible to modulate the particle band gap by varying their size. For smaller particles, the operational band gap is enhanced because of quantum confinement within these. This effectively causes the emission and absorption spectra to shift towards lower wavelengths (blue shift) regions. Excited electrons across the bandgap achieved strong interact with holes. Electrostatic attraction and spin exchange coupling create highly restricted excitons (electron-hole pairs). In such conditions, at elevated excitation levels, QDs occupy multiple excitons. In QD, the electron and hole pair's nearby vicinity conduct to raise the many-body circumstances which operate on their electrical and optoelectronic impacts (Ramiro et al., 2020).

Some special and interesting characteristics of QDs are (i) quantum confinement owing to nano-dimension size (Mansur, 2010), (ii) size-dependent tunable fluorescence properties that are applicable in optoelectronics, sensing, bio-imaging, *etc.* (Lu et al, 2017; Wang G et al., 2019, Wang Z et al., 2020), (iii) QDs are useful for sensing and long-term photo-imaging applications because of their high photostability as compared to other dyes and typical organic fluorophores (Lee et al., 2022; Michalet et al., 2005), (iv) large surface area respective to their volume leads to unique features that support sensor technologies and catalysis as such conditions surface interaction principal feature (Wang Z et al., 2020, Ghaffarkhah et al., 2022, Cheng et al., 2022; Mondal et al., 2024), (v) Charge carrier dynamics where QDs can confine charge carriers (such as holes and electrons) for extended intervals that can be implemented in quantum computing or photovoltaic cells (Guo et al., 2010; Kumar et al., 2019), (vi) emission boosted by QDs: in certain cases, the light emitted may regulate the "on" and "off" states, which is highly useful for precise molecular dynamics calculations or imaging of single molecules (Lee et al., 2022; Mondal et al., 2024). Light-emitting diodes (LEDs), solar cells (Quantum dot solar cells), and display technology (QLED displays) are merely some of the numerous commercial uses for QDs due to their distinctive traits, which include size-tunable light emission, quantum confinement consequence, and high efficacy (Lee at al., 2022; Ghaffarkhah et al., 2022; Cheng et al., 2022). Fluorescence resonance energy transfer (FRET), fluorescent tagging, cellular detection, tracking, and imaging, genetic engineering, as well as the study of tumors and malignancies, are among the biological applications of QDs (Michalet et al., 2005; Mondal et al., 2024; Panja & Patra, 2023).

Recently, researchers have focused on carbon core shell-based quantum dots (CQDs) synthesis over the metal-based quantum dots (MQDs) due to its various benefits (Wang G et al., 2019; Ghaffarkhah et al., 2022, Cheng et al., 2022; Guo et al., 2010; Dua et al., 2023). Initially, silicon and heavy metals (*s.a.* cadmium or mercury) were thought to be the main ingredients for conventional QDs creation. However, silicon-based QDs are expensive and metal-based QDs are inherently poisonous, particularly those containing heavy metals like mercury and cadmium. According to recent assessments, the breakdown of heavy metal-based QDs in biological environments is causing the release of ions that are exceedingly harmful (Sun et al., 2006). However, because CQDs are less detrimental to biological systems, they are typically higher regarded by the biological community. They are easily disposed of in the environment because they are non-toxic and eco-friendly. Such types of QDs' precursor ingredients are inexpensive, carbon-rich compounds. Some of the additional benefits of CQDs are stable photoluminescence, broad fluorescence tenability by size modulation and doping with other elements, increased water solubility in comparison to other QD types, low surface trap state, and easy fictionalization with different groups for particular applications (Wang G et al., 2019; Ghaffarkhah et al., 2022; Cheng et al., 2022; Mondal et al., 2024). New developments in this field of study frequently accompany several noteworthy breakthroughs that have been dissected during the past few decades. The various dimensional, surface-functionalized carbon-based QDs that have been produced quickly and affordably include graphene quantum dots (GQDs), carbon nanotubes, fullerenes, nano-diamonds, heteroatom-doped carbon dots, and carbonized polymer dots (CPDs) (Lee et al., 2022; Ghaffarkhah et al., 2022, Cheng et al., 2022). Like other metal-based QDs, they can be made using both bottom-up (microwave-assisted synthesis, hydrothermal/solvothermal synthesis, pyrolysis, thermal decomposition) and top-down (laser ablation, electrochemical exfoliation, and arc discharge) techniques (Cheng et al., 2022; Azam et al., 2021). Although, MQDs are still helpful in several catalytic reactions and some electrical devices (Park et al., 2021; Ramiro et al., 2020).

Four primary areas are emphasized in this review: addressing QD synthesis methods and the correlation between chemical optical properties, functionalizing the surface through different chemical modifications, surface silanization, and improving the solubility of amphiphilic combinations of both MQDs and CQDs that can be beneficial for a large domain, such as medical science and biomedical engineering. Furthermore, this article contains analytical characterizations of QDs, including mass spectrometry, spectroscopy, and microscopic and diffraction techniques. Recent research developments and captivating general applications of MQDs and CQDs are also discussed here. In order to meet the high demand of numerous applications, we believe that this review article will inspire and encourage readers to pursue novel study possibilities in the field of QD.

2. SYNTHESIS PROCESSES

The processes of synthesize Q-dots have evolved in due course of time. Like all other type of nanoparticles, Q-dots synthesis techniques can be categorized either as a top-down or bottom-up approach (Ghaffarkhah et al., 2022). Below, we will try to discuss different types of top-down and bottom-up approaches.

2.1. Top-Down Synthesis Processes

Top-down approaches are those in which a bulk material is broken down into nanosized particle. Generally, the processes which follow top-down approach are described below:

2.1.1. Laser ablation

Laser ablation method is used for manufacturing various kinds of semiconductor QDs (Cheng et al., 2022; Guo et al., 2010). 'Ablation' means the removal of surface atoms, here which is done by the irradiation of laser. In this process the solid 'target' is kept in a liquid or gas media, which is then irradiated with focused laser. As a result, the temperature of that spot of 'target' becomes so high that it evaporates. Now the collision between the vapour and media results forming a laser induced plasma plume. Since the temperature suddenly drops from very high to room temperature, nanoparticles form at the edge of the plasma plum.

2.1.2. Arc Discharge Method

This method is simple, but less sophisticated and less useful method. But it has historical importance. CQDs was prepared accidentally during synthesis of SWCNTs. In this method, very high voltage electrical discharge across two graphite electrodes results in the formation of CDs with other impurities.

2.2. Bottom-up Approach

In bottom up approaches the basic unit assembled together to a larger nanoscale particle by the influence of physical or chemical forces. The bottom-up approach techniques may be broadly subdivided into two categories - wet-chemical methods and vapor-phase methods (Ghaffarkhah et al., 2022).

2.2.1. Wet-Chemical Methods

Wet-chemical methods is actually one special form of conventional precipitation methods where the parameters are controlled very carefully. These are old but still popular processes, because by controlling the parameters it is possible to achieve the QDs of desired size shape and composition. Some common wet chemical methods are described below:

2.2.1.1. Sol-Gel Process

Sol-gel process is a very old and easy chemical process for synthesizing QDs, specially for synthesizing metal oxide QDs. The process consists

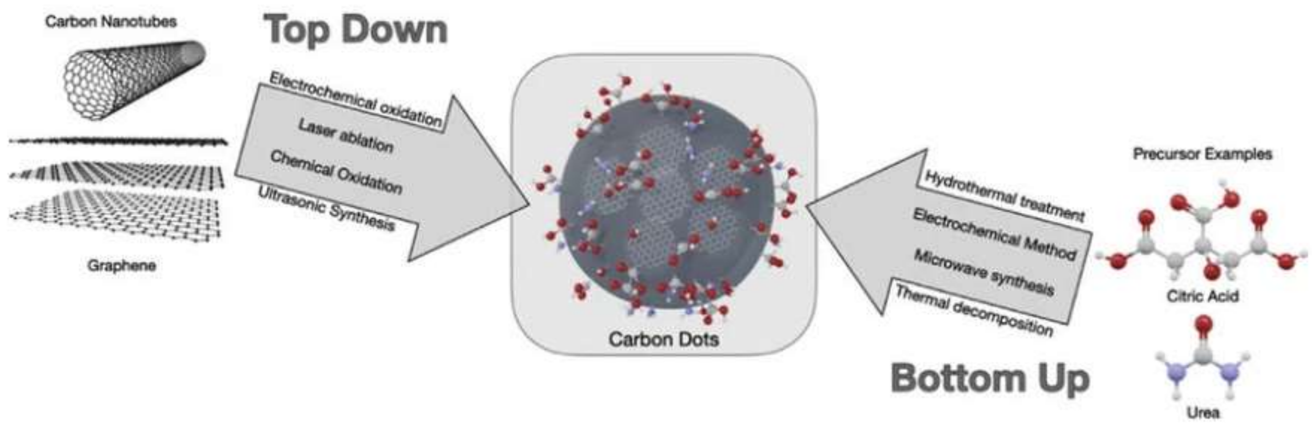

Fig. 1. Top-down and bottom-up approaches for the synthesis of Carbon dots

of three main steps, hydrolysis, condensation and gel formation. This method is generally used to synthesize II-VI & IV-VI Q-dots, such as CdS (Kumar et al., 2019), ZnO (Mondal et al., 2024), PbS (Panja & Patra, 2023). Advantages of this process is its simplicity and low production cost. But it also has some drawback. The main issue with this process is, it is very difficult to get the quantum dot of uniform size.

2.2.1.2. Microemulsion Process:

Microemulsion processes are very easy processes by which QDs can be synthesized at room temperature. The processes can be divided into two types, normal (oil-in-water) (Dua et al., 2023) and reverse microemulsions (water-in-oil) (Sun et al., 2006). Among these two processes, reverse microemulsion has emerged as a more popular method for preparing various core–shell-type QDs (such as silica encapsulated ZnSe (Sun et al., 2006), silica encapsulated CdSe (Lai et al., 2023), *etc.* By this process, the size of the QDs can be tuned by altering molar ratio of water to surfactant. The obtained size distribution is also narrower compared to the sol-gel process. On the other hand, the yield of this process is very low. Moreover, QDs prepared by this method have impurities and defects.

2.2.1.3. Hydrothermal synthesis methods

This is a very simple and interesting process in which first a saturated aqueous solution of inorganic salts is prepared. After that, by lowering the temperature and pressure carefully, the solubility of inorganic compounds decreases. As a result, nanocrystals of the salt are produced. Inorganic nanocrystals of various shapes and sizes can be achieved in this way. Similar to the microwave method this method is also widely used by the researchers for the preparation of CQDs from a wide variety of carbon sources like banana peel waste, cambuci juice, biomass waste, manilkara zapota fruits, broccoli, lemon juice, cherry tomatoes, *etc.*

2.2.1.4. Microwave irradiation methods

This method became very popular within short period of time span because the method is time-saving, energy-efficient and eco-friendly (Azam et al., 2021). Though various types of inorganic QDs have been successfully prepared using this method (*e.g.,* CdSe-CdS) (Park et al., 2021), this method is very popular for CQD preparation. After the first report of the synthesis of CQDs from carbohydrates, a huge number of researchers used this method for QD synthesis from various carbon sources like cotton linter waste, quince fruit, roasted chickpeas, *etc.* CQD synthesis using a domestic microwave oven has also been reported where the carbon source was eutrophic algal blooms.

2.2.2. Vapor-Phase methods

Vapor-phase methods are the methods in which layers are grown in an atom-by-atom process. There are various this type of processes in which QDs are self-assembled on a substrate. Some common vapour phase methods are mentioned in the following:

2.2.2.1 Physical vapor deposition (PVD)

In this process, at first the material is vaporized. After that, this vapour is transported to the substrate where nanoparticles are formed.

2.2.2.2 Chemical vapor deposition (CVD)

In this process, vaporized precursors are transported through a boundary layer by diffusion to the growth surface. In the surface a chemical reaction occurs and the nanoparticles are formed with by-products, which are latter removed from the growth surface.

2.2.3. Very Large-Scale Integration (VLSI technology)

These methods are developed and used form the time before the discovery of QDs to prepare Integrated Chips. After almost 50 years of the first introduction of these technologies, these are sophisticated enough to create the transistor of nano scale level.

2.2.3.1. Molecular beam epitaxy

Epitaxy is a very important type of VLSI technology. The Greek word 'epi' means upon and 'taxy' means orderly or arranged. So, epitaxy is the technique in which a single crystal layer is arranged on single-crystal substrate layer. There are other types of epitaxial processes (Liquid phase Epitaxy, Vapour phase Epitaxy, *etc.*) among which MBE is the most sophisticated and accurate. It has various advantages. It is a purely physical, low-temperature process. No auto-doping or boundary layer problem occurs in this process.

The only flip side of this process is that, this is a very costly and sophisticated process so that there are only a few MBE systems all over the country. This is actually a physical evaporation process. The substance is evaporated in ultra-high-vacuum conditions (10^{-8} torr to 10^{-10} torr). This high vacuum prevents collision and contamination.

In-situ characterization is facilitated by Quadrupole Mass Analyzer (QMA) instrument, which consists of four cylindrical rods, set parallel to each other. This quadrupole is the mass analyzer - the component of the instrument responsible for selecting sample ions based on their mass-to-charge ratio (*m/z*). Another in-situ analysis tool - Reflection High Energy Electron Diffraction (RHEED) is an analytical technique, which is used to characterize the surface structure and monitor the layer-by-layer growth of QDs in order to investigate the growing surface.

2.2.3.2. Ion implantation

The idea of ion implantation process was proposed in the year 1949, but the use of the process in the practical field started from 1970. It is a process in which material surface is modified by implanting ions of a material into another solid material (Sun et al., 2006). This is such a sophisticated low temperature process, which have the capability to embed virtually any ion species into any substrate with a high level of location control (lateral and depth) and elemental composition. So, applying post implantation annealing all types of QD's can be synthesized.

2.2.3.3. Lithography

'Litho' means 'stone' and 'graphy' means 'to draw'. So, lithography is the process where the same type of technique is used which is employed in stone carving, but the only difference is that the nanoscale drawing is done on the substrate by an electron beam or light beam. Based on the nature of the exposure source, lithography can be divided into several categories. Widely used methods include - optical lithography (photolithography), electron beam lithography, X-ray lithography, and ion beam lithography. Among these, the electron beam lithography is a popular process for the preparation of QDs. In this process, the surface is first covered by an electron-sensitive organic layer which is called 'resist'. After the exposure of electron beam the solubility of the resist changes. It is possible to remove the exposed or unexposed part of the resist depending on the nature of the 'resist'. Finally, the pattern is transferred onto the substrate *via* a chemical process called 'etching'.

3. FUNCTIONALIZATION

In contrast to conventional fluorescent organic dyes (fluorophores), QDs demonstrate superior optical performance owing to their tunable broad excitation and narrow emission bandwidths, signal brightness, high quantum yield and photostability. However, uncoated or exposed QDs cannot be used directly for biological applications. Uncoated QDs can form surface defects as they are associated with high surface energy. As a result, the QDs fluorescence properties can be quenched. In addition, uncoated QDs can undergo photochemical degradation, surface oxidation and leaching of metal ions from the QD core can also occur on long-term exposure of QDs to cellular media or ionic media resulting in metal ion toxicity in biomedical applications. To solve this problem surface passivation of QDs is necessary. Another purpose of surface passivation is making the surface hydrophilic to make them soluble in water and biologically relevant media.

The common strategies used for surface modification of QDs are following:

- Small molecule substitution or ligand exchange - In this process, native hydrophobic ligands (such as trioctylphosphine (TOP), trioctylphosphine oxide (TOPO), hexadecylamine (HDA), oleic acid) on the QD surface are substituted with hydrophilic ligands (containing bifunctional groups like thiols (–SH), carboxyls (–COOH), amines ($-NH_2$) or hydroxyls (–OH), *etc.*).
- Surface silanization - In this process the surface of QDs is capped with a thin continuous layer of silanes that can be crosslinked. This is very effective for increasing chemical and thermal stability, reducing the toxicity of QDs.
- Polymer Encapsulation/Coating - In this achieved solubility in aqueous solution is provided through the hydrophilic groups of the amphiphilic block copolymers while preserving the native hydrophobic layer.
- Bio-Conjugation - The surface of QDs is often functionalized with biomolecules (namely proteins, antibodies, peptides or DNA strands, *etc.*) or by biotin-streptavidin coupling.

4. CHARACTERIZATION

The characteristics of quantum dots are strongly influenced by their size, dimensions, shape, chemical makeup, and structural aspects. Therefore, numerous efforts have been made for the characterization of QDs. The characterization techniques used can be classified using the following schematic diagram.

4.1. Microscopic and Diffraction Techniques

These techniques are used for morphology and size determination of QDs. The commonly used such techniques are atomic force microscopy (AFM), transmission electron microscopy (TEM), scanning electron microscopy (SEM), and X-ray diffraction (XRD).

4.1.1. Scanning (SEM) and Transmission Electron Microscopy (TEM)

SEM and TEM are highly effective electron microscopy techniques for collecting valuable information from various nanomaterials. SEM constructs images by examining the QDs sample surface with a focused electron beam that interacts with the atoms of the QDs, generating signals to create the image. In contrast, a high-energy electrons beam is utilized in TEM, which constructs image of a study sample. TEM provided substantially greater resolution ability (about 0.2 nm) compared to SEM (1-20 nm). Image obtained from both the techniques are applied to determine the size, shape, morphology, agglomeration and dispersion state. But the drawback of electron microscopy is that this method requires complicated sample preparation. Moreover, acquiring good quality high-resolution images using this technique is really challenging and the image obtained is only two-dimensional (2D).

4.1.2. Atomic Force Microscopy (AFM)

Another microscopic technique known as AFM, produces high-resolution multidimensional surface images with a resolution of less than 1 nm. AFM provides both two-dimensional and three-dimensional (3D) characteristic surface morphology of QDs. This microscopy-based technique is highly accurate and reliable.

4.1.3. X-Ray Diffraction (XRD)

XRD is a versatile non-destructive analytical technique used to analyze structural properties such as phase composition, crystal structure, and orientation of powder and solid samples. Constructive interference occurs when X-rays interact with a crystalline QD sample. The signal generated from the experiment is used to detect and uncover the average structure of QDs. Each different sample of QDs furnishes different types of diffraction patterns. Additionally, it also provides detailed information about the purity of synthesized QD materials.

4.2. Spectroscopic Techniques

There are various spectroscopic techniques, which are frequently used for the characterization of QDs. The most common among them are photoluminescence (PL), ultraviolet-visible (UV-Vis) spectroscopy, Raman spectroscopy (RS), Fourier-transform infrared (FT-IR) spectroscopy, X-ray photoelectron spectroscopy (XPS), transient absorption (TA) spectroscopy, energy dispersive spectroscopy (EDS) and nuclear magnetic resonance (NMR) spectroscopy.

4.2.1. Ultraviolet-Visible Spectroscopy

This technique is a very common, relatively inexpensive, and extensively applied spectroscopic technique that has been utilized to characterize the

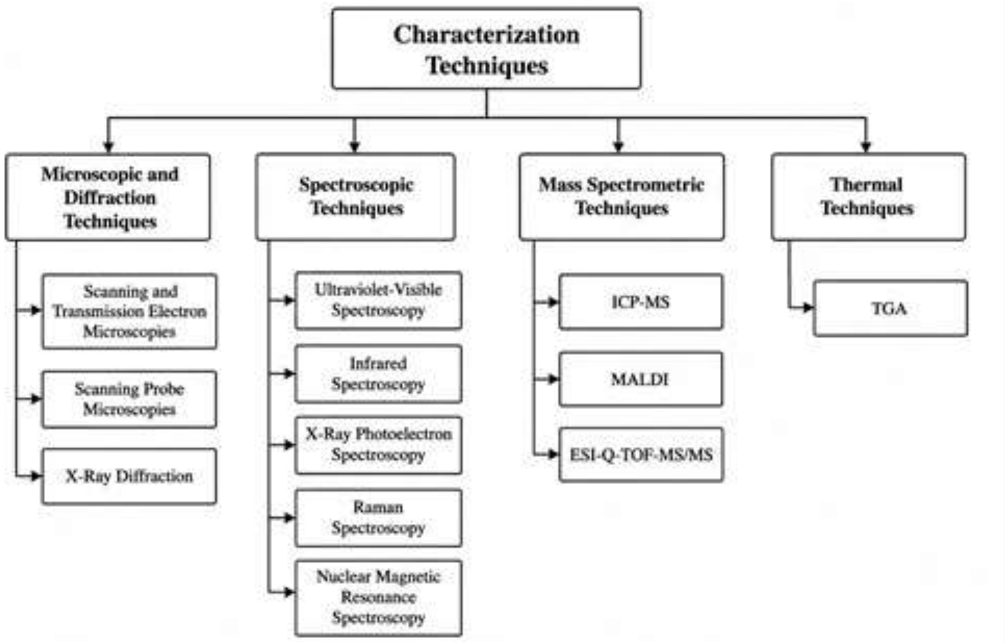

Fig. 2. Different types of characterization techniques for the synthesis of Carbon dots

QDs' optical properties. It is used to determine the concentration of any QD solution by developing a Beer-Lambert law-based linear plot of absorbance versus concentration. Apart from the quantitative data mentioned above, it is possible to derive significant qualitative information from UV-vis spectra. A very sharp first excitonic absorption peak is generally observed if the resultant QD sample has a very narrow distribution of size. Using UV-vis spectroscopy, qualitatively, it is also possible to differentiate between spherical-shaped QDs and non-spherical particles.

4.2.2. Raman Spectroscopy

Raman spectroscopy is a highly effective technique for the characterization of various crystals, as it provides information on molecular vibrations, microscopic disorder, material crystallinity, *etc.* It is a non-destructive and non-invasive spectroscopic technique. It may also be used to determine the carbon structure in a particular C-dot sample. The disordered D band and crystalline G band (D/G) intensity ratio specifies the integrity (degree of disorder or graphitization) of a C-dot sample. It is well established that the amorphous C-dots samples has a high D/G ratio. On the other hand, it was noticed that a relatively lower D/G ratio is observed from a C-dots sample that has a very high degree of graphitization. While using this technique, it should be remembered that sometimes, owing to the brighter fluorescence of C-dots, it becomes very difficult or impossible to acquire a high-quality Raman spectrum of C-dot materials.

4.2.3. X-Ray Photoelectron Spectroscopy

In XPS spectroscopy, the surface of the sample materials is characterized using the principle of the photoelectric effect, which reveals details of elemental composition, surface composition and properties, and electronic states. The sample is irradiated with a beam of X-rays, and the number of emitted electrons and their kinetic energies are simultaneously measured to obtain an XPS spectrum. XPS is highly sensitive to very thin layers and can provide important information about organic layers. A drawback of XPS is that it typically lacks the spatial resolution needed to analyze individual nanoparticles.

4.2.4. Nuclear Magnetic Resonance Spectroscopy.

NMR spectroscopic technique is widely used for the characterization of C-dots because it provides insights into surface chemistry, elemental environments and bonding interactions. The NMR technique is a powerful tool for establishing the chemical alterations that occur in the surface modifiers during carbonization. On the other hand, the ^{13}CNMR spectroscopy is particularly useful for identifying the carbon species in C-dots samples in the liquid state. This technique is non-destructive in nature and preparation of sample is very easy. But the main disadvantages are - this technique is very expensive, time-consuming, and a less sensitive technique compared to mass spectrometric techniques.

4.3. Mass Spectrometric Techniques

Mass spectrometry (MS) is an effective tool for analyzing the chemical composition and structural features of nanoparticles. In QD research, mainly two types of mass spectrometric techniques have been applied to characterize QDs.

4.3.1. Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)

ICP-MS is extensively used for the determination and quantitative analysis of inorganic nanomaterials. This technique enables the accurate determination of QD concentrations and elemental composition in a QD-antibody bioconjugate. Also, there is a linear relationship between the mass of cadmium, selenium and zinc detected by ICP-MS and the concentration of unconjugated QDs. HPLC-ICP-MS and CE-ICP-MS has become a very important method to examine the intracellular behaviour of QDs.

4.3.2. Matrix-Assisted Laser Desorption/Ionization Time-of Flight Mass Spectrometry

MALDI is used for the structural characterization of QDs. It can also be used as an alternative technique to TEM in estimating the size of QDs. In TOF analysis, all of the ions are given the same amount of energy and that set of ions is accelerated to a detector and the mass-to-charge ratios of ions are determined from the flight times of the ions. The MALDI-TOF MS analysis is a very accurate method for structural characterization of QDs. The use of this technique successfully tracks the evolution of clusters and the formation of QDs throughout the synthesis. The main disadvantage of this technique is that it is accurate only for smaller nanoparticles, with increasing particle size sensitivity of the technique decreases.

4.4. Thermal Techniques

Thermogravimetric analysis (TGA) is one of the most commonly used thermal techniques for characterizing QDs. This technique is mainly used to characterize certain types of QDs which undergo changes in mass during measurements.

It is performed by heating a solid sample using a known temperature profile and measuring the change in mass as the temperature profile progresses. The instrument continuously weighs a QD sample by coupling with FTIR or MS for gas analysis. TGA data is typically presented as a plot of mass *versus* temperature which provides information about the thermal stability of QDs. The method is fast and a very small amount of sample is required.

5. APPLICATIONS

5.1. Electroluminescence Device Fabrication

Q-dot-based light-emitting diodes (QLEDs) have various advantages over organic material-based light-emitting diodes (OLEDs). These are as follows:

i. Full-width at half maximum (FWHM) of the emission peak of Q-dots is only 20-30 nm, whereas that of OLEDs it is greater than 50 nm.
ii. Inorganic QD materials are thermally more stable than organic materials.
iii. The RGB colours in OLEDs are provided by different materials. Thus, they have different lifetimes. So, the display colour of OLEDs generally changes with time. But we can obtain the RGB colours from Q-dots with the same composition but different particle sizes. So, the display colour does not change with time.
iv. The organic emitters in OLEDs usually emit at wavelengths shorter than 1 μm, whereas QLED devices can produce IR emissions.
v. The spin-statistics are not restrictive for Q-dots, *i.e.,* external quantum efficiency (EQE) of 100% can be achieved (in principle).

All these unique properties have led scientists to consider about the possibility of developing flexible QLEDs, which may significantly transform display technology in the coming decade. In the near future we will be able to see people using the devices like smart glasses, smartwatches with wearable biosensors, fabric display, *etc.* ((Agarwal et al., 2023; Cotta, 2020)). However, despite these possibilities and advantages of QDs in this field there are some barriers that must be overcome before the widespread adoption of QDs. These are the following:

i. Temperature quenching.
ii. Intensity dependence: multi exciton generation.
iii. Intensity dependence: photobleaching.
iv. Reliability at high temperatures and intensities**.**

Table 1 Important biomedical applications of different metal oxides.

NPs	Application areas
ZnO	Cytotoxic against various bacterial pathogens, fungal spores and viruses, lung fibroplast cell as well as adherent epithelial cells originating from human lung tissue.
CuO	Increase the antimicrobial activity of copper, can be employed as nanocarriers for the targeted delivery of therapeutics used in rheumatoid arthritis treatment, phyto-synthesized CuO nanoparticle exhibit appreciable anticancer activity,
TiO_2	Cytotoxic towards numerous cancer cells.
MgO	Potential biomedical applications include cancer therapy, nano cryosurgical procedures, hyperthermia treatment and antimicrobial activity. It also has antidiabetic property.
Fe_3O_4	Used for drug delivery, biosensor and diagnostic medical devices

5.2. Solar Cell Device Fabrication

The production of energy without the emission of CO_2 is a great challenge for modern civilization. Only until the end of this century, the fossil fuels could provide the estimated total global energy requirement. Furthermore, the availability of secure supplies of oil and natural gas is decreasing and costs are increasing. For this we have to use the sources of energy other than fossil fuels. The solar energy is most popular among these sources. But still now it is not so popular so that it can replace the sources like thermal power. The reasons for which solar cells can't fulfil the expectations are the high cost, low conversion rate and less efficiency in low intensity (Agarwal et al., 2023; Cotta, 2020).

The first-generation solar cells are based on crystalline silicon wafers, including single-crystal and polycrystalline silicon, with typical solar conversion efficiencies between 12% and 16%. In contrast, the second-generation solar cells employ thin film technologies using different materials like cadmium indium selenide (CIS), amorphous silicon (a-Si), or thin silicon films on indium tin oxide achieving solar conversion efficiencies ~ 20%. Though the second-generation solar cells draw the attention in reducing the production cost and increasing the efficiency, yet they were less popular due to technological problems and module stability. The use of QDs is showing hope to solve these problems. It was observed that, the QDs have the potential to increase the photon conversion efficiencies through multiple exciton generation (MEG) by producing multiple excitons from a single photon. The next aim is to prepare three-dimensional grids of QDs, which are expected to have higher solar conversion rate. This will have the potential to become a cost-effective alternative power source to compete with coal or gas. In recent days, scientists have been working successfully on quantum dot sensitized solar cells (QDSCs), where they are using QDs instead of organic dyes. These QDs have various advantages over organic dyes. The most important advantages are, the QDs have a tunable band gap depending on the QD size, which makes the dye capable of absorbing photons in the full sunlight spectral range. QDs have a larger extinction coefficient which makes the solar cell efficient even with low intensity light. Also compared to organic dyes, the QDs have higher stability toward water and oxygen, which increases the cell lifetime. The most important observation for improving QD efficiency is the MEG with single-photon absorption, which shows the possibility of much better efficiency. The incorporation of QDs into QDSC photoelectrodes is typically achieved either by growing the nanocrystals directly on the substrate from precursor solutions or by immobilizing pre-synthesized QDs onto the surface. In the latter approach, bifunctional linker molecules may be utilized to enhance the interaction between the QDs and the photoelectrode.

5.3. Bioimaging Applications

Bioimaging is a non-invasive method of visualizing biological processes in real time with minimum interference of associated life processes. It is also used to gather detailed information on the 3-D structure of the observed specimen from the outside. Partridge Hall in 1983 first introduced this method where he used a transmission electron microscope. After that, various instruments were invented for imaging. Common imaging approaches rely on optical, fluorescent, electron-based, ultrasonic, X-ray, magnetic resonance and positron-emission signals. Recently, QDs are emerging as a new promising category of nano-sized probes for bioimaging (Abdellatif et al., 2022). In previous decades, researchers faced various serious problems in developing QD probes. The smaller QDs are bright, but they tend to adhere to proteins and cellular membranes non-specifically. To reduce the nonspecific binding, we can coat them with neutral hydrophilic polymers like polyethylene glycol (PEG), but the brightness of QDs diminishes when crystalline core size is diminished. But hopefully monodispersed QDs encapsulated in stable polymers which are brightly fluorescent suitable for the use as imaging probes. Now-a-days, carbon dots have attracted significant attention as promising nanomaterials for bioimaging applications (particularly for cellular imaging) (Abdellatif et al., 2022). These are biocompatible, less toxic, water-soluble, and offer diverse functionalization routes. Some innovative strategies such as Forster resonance energy transfer (FRET) (instead of conventional excitation and recording fluorescence emission) have been reported recently. In this method carbon dots function as energy donors, whereas the drug molecules serve as energy acceptors. The advantage of this process is that both microscopic visualization and illuminating drug distribution and delivery are enabled here.

5.4. Pharmaceutical applications

Owing to their unique physicochemical properties, nanoparticles are regarded as key components of next-generation medical technologies. Nevertheless, their practical application in biological systems depends on factors such as minimal toxicity, long-term stability, biocompatibility, bioactivity and efficient bioavailability. Many metal nanoparticles, especially heavy metal sulphide nanoparticles, are devoid of these properties. Moreover, the toxic effect of the same nanoparticle is different depending on the synthetic approaches. However, many metal oxide nanoparticles like magnesium oxide (MgO), titanium dioxide (TiO_2), zinc oxide (ZnO), copper oxide (CuO) and iron oxide (Fe_3O_4) nanomaterials are very stable and have been proven to be usable in living human body particularly when they are synthesized by biological methods. Here we can summarize the biomedical applications of the above metal oxides in the following table. After the discovery of biocompatible QDs like CQDs, researchers reported various successful applications as antimicrobial agents.

6. CONCLUSION

In this review, most important aspects of the properties, synthesis, applications of QDs have been discussed. This 0-D nanostructures, among different branches in nano-chemistry, have paved the way for many new advances in both fundamental and applied sciences. This is due to the fact that the QDs exhibit significantly different optical, electronic and physical properties as compared to other common bulk materials. With respect to synthesis of QDs, procedures ranging from simple wet chemical methods to very sophisticated and equipment-intensive atomic layer deposition techniques are being used to synthesize QDs. The ‘bottom-up’ approaches are being widely explored resulting in a wider variety of methods to generate QDs. Despite the large amount of recent scientific research, there is still a lot to understand about the use of QDs in large scale biological and solid-state optical applications, as we discussed throughout the article. Although preliminary experiments at the laboratory level have been successful, scaling up the production and retaining the properties of QDs is not trivial. Continued research and development on QDs will provide further improvements in quantum efficiency, better device fabrication and new materials which extend the emission into the near IR region (García de Arquer et al., 2021).

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