Progresses in Utilizing Quantum Dot Nanomaterials for Various Industrial Applications

Neogi, Newton
Nano Research Centre

Kristi Priya Choudhury
Nano Research Centre

https://doi.org/10.5109/7157973

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 9, pp.207-213, 2023-10-19. 九州大学大学院総合理工学府
バージョン：

Progresses in Utilizing Quantum Dot Nanomaterials for Various Industrial Applications

Newton Neogi[1*], Kristi Priya Choudhury[1]
[1]Nano Research Centre, Bangladesh
*Corresponding author email: newtonneogi@gmail.com

Abstract: *Quantum Dot (QD) nanoparticles (NPs) have antibacterial, photocatalytic, biosensing, and bioimaging properties. Because of these features, they have become a subject of interest in a wide range of industrial issues. They have the ability to improve performance, raise safety, and revolutionize synthesis procedures, all of which will have a substantial influence across all industries. QD NPs have applications in a variety of areas, including the pharmaceutical, environmental, biomedical, food, and water treatment sectors. As QD NPs has application in biosensing and bioimaging, these can be utilized in biomedical industries. For the antibacterial activity, these particles can be used in food packaging in food industry. By using the property of photocatalysis these materials can be utilized in water treatment industry. In this study, we highlight the most important applications in various industries of QDs NPs.*

Keywords: QD nanomaterials; photocatalysis; antibacterial property; biosensing; industry

1. INTRODUCTION

Nano sized materials are recently shown efficient in different purposes. NPs are being explored now in photocatalytic applications [1,2]. In recent years, 1D semiconductor nanostructures have drawn great attention. Nanorods, nanowires, nanotubes, QD semiconductors are used in environmental cleanup, solar energy conversion, photodetectors, and photocatalysis. QDs are nanostructures with sizes between 2 and 10 nm and are composed of a semiconducting substance. TiO_2 hetero junction nanostructure photoactivities are augmented by coating nano-metals (Ag, Au, or Pd) or interfering with metallic or non-metallic ingredients. Improved by merging with secondary semiconductors (Co_3O_4, CdS, MoS_2, Ag_2O, ZnO). CdS has been considered at length as a visible-light-responsive photocatalyst due to its inherent perfect bandgap (2.4 eV), matching sunlight's spectra. CdS QDs get a size-dependent band gap, enormous oscillator strengths, and perform best as bulk [3]. Wurtzite zinc oxide has wide band-gap. ZnO is semiconductor oxides that have been addressed to the most research on the nanoscale. It can even be incorporated in laser diodes, LEDs, UV protection films, chemical sensors, and therefore more [4].Quantum confinement effects and size-dependent attributes of ultra-small nanocrystals have only been uncovered very lately. As a result, this methodology is prominent in semiconductor QDs. Multiplex electron-hole formation is realized after absorbing a single photon on semiconductor QDs. Because of the many electron-hole pair generation during QD excitation, their additional conduit did not boost photo-redox efficiency. This was primarily because the photo-excited electrons recombined back into their ground state because there was no proper electron acceptor present. Blending semiconductor QDs with broad band gap nanostructured semiconductor is recommended since it produces better results. They could be made of TiO_2 or ZnO, and they are the ones responsible for catching the numerous excited electrons supplied by the QDs [5]. The photocatalytic expression was enhanced as a result of QDs to the upgraded photocatalyst. QDs can optimize visible light use and restrict charge carrier recombination. In QD self-modified homojunctions, the composition on both sides of the interface may cause band bending. These are therefore considerably more advantageous for charge transport over the interface, which also makes carrier separation much easier. Thermal degradation of TiO_2 QDs yielded a self-modified homojunction. This tweak formed a charge transfer channel on TiO_2 nanosheets. This provides amazing photoactivity [6] [7] [8]. The aim of our work is to explain the utilization of QDs in several industries and the properties behind the applications. The properties are explained in second section. The applications of QDs in water treatment industries and biomedical industries have been included in third and fourth section. In fifth section of the article we have given an overview of application of QDs in cosmetics. The utilization in food industry and in environmental industry of QDs are explained in the sixth and seventh section of this article.

2. PROPERTIES OF QDs

QDs are a recently discovered class of nanomaterials that have zero dimensionality. QDs contain semiconductor nanocrystals featuring high conductivity, thermochemical and optical and electrical stability, and amazing recyclability (see fig. 1). The degradation of organic contaminants and reaction mechanism both have a clear link to semiconductor QD-based nanocomposites, which have critical repercussions [7]. QD nanocomposites' mode of action is regulated by surface functionalization, pH, reaction time, adsorbent capacity and concentration and some other parameters. The principal function for them is in the clearance of a broad diversity of poisonous metal ions and polymeric dyes [8]. QDs reinforced with carbon nitride (gCN QDs) are very analogous to graphene and have recently gained recognition due to the exceptional electrical and optical features they possess. In addition to this, gCN QDs have excellent biocompatibility. Because of these distinguishing characteristics, gCN QDs have the potential to be beneficial in various biological and environmental applications which include applications in sensing, bioimaging, photocatalysis, energy conversion, and biomedical fields of inquiry [9].

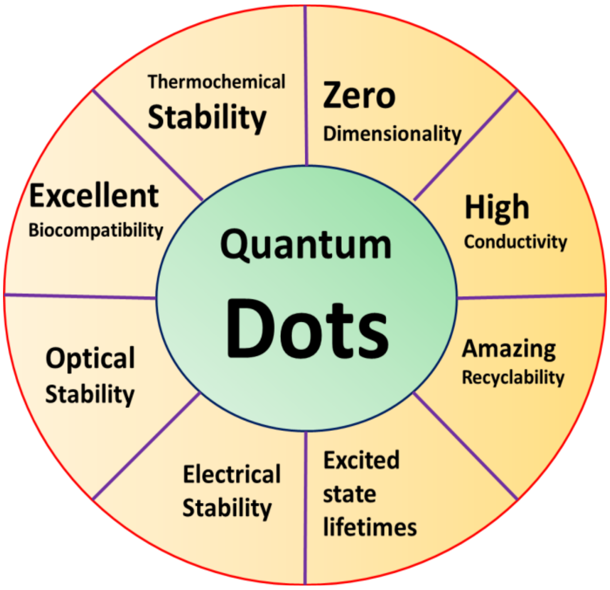

Fig. 1. Various properties of QDs that are reason for the application in industry [5].

QDs are creative and effective kind of Nano photocatalysis that can remove dye contaminants by dye degradation process. Because excited electrons and holes constrain QDs, these have distinctive optical and electrical properties beyond bulk semiconductors. QDs have superior extinction coefficient, quantum yields, limited photo bleaching, broad adsorption and narrow emission. Among the semiconductors, ZnS QDs are all being evaluated. Numerous researchers have successfully produced ZnS QDs with the assistance of capping agents; as a corollary, these QDs display an extensive variety of unique architectures because the growth rate along separate directions can be tuned. In comparison to other II–VI compound semiconductors, ZnS is superior in terms of its chemical stability, nontoxicity, and environmental friendliness, and it exhibits strong confinement effects [10].

3. WATER TREATMENT INDUSTRY

The high concentration of heavy metals is very hazardous and cause accumulation in human bodies. Designing devices that can assess heavy metal ions in real water economically and on-site is crucial. As QDs exhibit desirable luminescence in aqueous solution, QDs can be utilized as prospects for sensing applications for toxins of water. As Pb^{2+}, Cr^{3+}, and Hg^{2+} have the potential to be harmful and are prominent, a lot of emphasis has been focused on them. The study that was put out by the Environmental Protection Agency of the United States stated that the maximum contamination limit (MCL) for lead, chromium, and mercury in drinking water was set at 0.015 mg L^{-1}, 0.1 mg L^{-1}, and 0.001 mg L^{-1}, respectively. Therefore, it is the most important to develop approaches that are promising for heavy metal ion detection and quantification in water. QDs are advantageous for multiplex detection, due to excellent photo stability, narrower emission spectra, and water solubility [11]. There are lots of different kinds of QDs, namely CdS, CdTe, ZnS, and the composites of these elements. Tin oxide (SnO_2) QD is a non-toxic, chemically stable, moderate semiconductor. In order to detect xanthene in water, SnO_2 photoluminescence sensors were developed. Using QDs' fluorescence effect, exact detection of heavy metal ions was observed [12]. As QDs shown better photoluminescence capabilities, it can reduce the concentration of Hg^{2+} and other ions in water [9]. Based to the PANI/PbS composite's elevated photo and electrical activity, an innovative electrode was built to photodegrade dye molecules in water when exposed to a UV lamp. Under visible light environment, researchers implemented PANI/PbS QD composite for rhodamine 6G degradation. This research proven QDs are highly efficient for dye degradation [13]. By the performance of dye degradation these nano compounds can treat waste water which come from several industries [14]. Mainly textile industry use dye to color their textiles. They use vast amount of water and dissolve dye into that. After their uses the water become contaminated and become harmful for environment [15]. Thus the degradation of dye become important for water treatment and QDs are most promising in photocatalytic dye degradation (Figure 2). Mainly QDs has smallest size among nanoparticles and for that these can perform high catalytic property in degradation of dye [16].

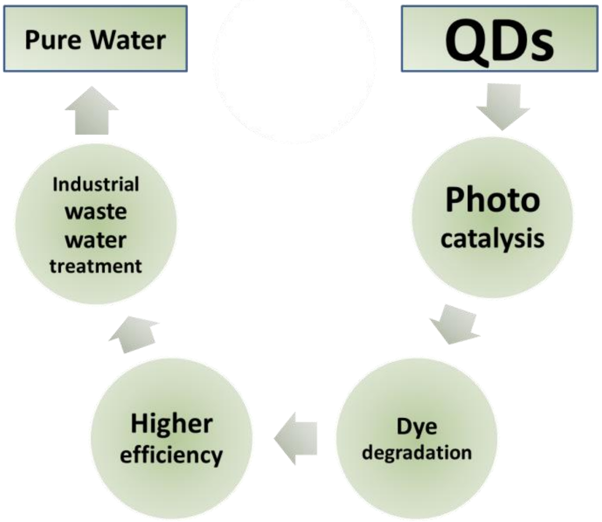

Fig. 2. Waste water treatment by QDs with photocatalysis of dye degradation reaction.

4. BIOMEDICAL INDUSTRY

QDs can be utilized for biosensing and bioimaging (Figure 3). Sequencing, immunoassay, fluorescence imaging and drug delivery, biosensing etc. are concerning issue of biomedical industry. QDs can be used as Biosensors that detect DNA, RNA, proteins etc. By in vivo RNA-peptide interactions QD-based biosensors has been established [17]. Single-QD-incorporated DNA nanosensors can significantly reduce background fluorescence from classic molecular probes by adding donor-linked acceptors and it strengthen the targeted signal and boost a donor's acceptors. QD-incorporated nanosensors can create a target signal with a low target over abundance and a considerable probe excess [18]. QD-based nanotechnology can revolutionize biomedical imaging for cancer research [19]. Seamless transition from proof-of-concept studies to clinical applications is vital. In vivo radiolabels and contrast agents are significant. These include PET, CT, SPECT, MRI, sonography, and optical imaging. Nanoscale probes detect, identify, and count molecular biological events in living systems when it was used in connection with different macroscale modalities. Fluorescent semiconductor QDs are a unique class of probes that are ideal for modern fluorescence imaging applications. Multiplexed cellular phenotypic analysis, real-time intracellular process monitoring, and in vivo molecular imaging are several application of these [20]. QDs are often used in Live Cell Imaging, biosensing, fluorescence-based biolabeling, drug delivery, MRI constrant agents and cell separation. Leveraging dextran-functionalized Ag, Fe_3O_4, and CdSe-ZnS QDs has methods that can be deployed to detect glycoprotein concanavalin A. This is attributed to the reason that concanavalin A possesses a unique binding capacity with polysaccharides that are based on glucose and mannose. After this, there is an augmentation of the aggregation of dextran-functionalized NPs. Dextran-functionalized AgNPs and QDs should be used for solution based optical detection of concanavalin A [21].

QDs can perform detection of *V. cholera* [22], DNA [23], glucose [24], xanthine, lactate, chlolesterol [25] etc. biological compound. The reason behind the feasibility of QDs as biosensor is having distinctive photophysical characteristics, which are facilitating the development of durable fluorescent biosensors. The ideal features for biosensing using QDs are high quantum yields, broad absorption spectra, narrow size-tunable photoluminescent emissions, and resistance to photobleaching and chemical degradation [26]

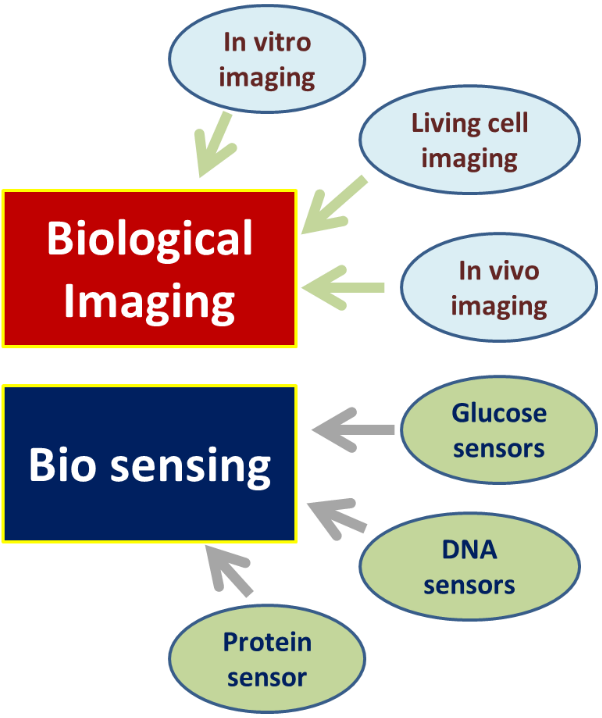

Fig. 3. Biosensing and bioimaging of QDs NPs for making these feasible in biomedical industry [27]

QDs have the ability to examine, and latest innovations in QD-based immunoassays with ultrahigh sensitivity or the power for quick screening have also assisted the development of innovative readout methods. Ultrasensitive western blot assessment relies on QD monoclonal antibody conjugates was used to assess protein expression in cell or tissue with high specificity and throughput. These strategies entail electrochemical detection, barcode, and the microfluidics technique. In some multiplexed DNA detection techniques, some target analytes are not grouped with fluorophore. These conceptual models offer significant potential for ultrasensitive genetic target analysis using QD bioconjugates. The QD barcode can speedily map genes and detect infections [28]. Researchers created fluorescent QDs for glucose sensing. Reversible glucose-CdSe QD interaction for a boronic alkaline organic quencher made QD feasible for glucose detection. Researchers has used an interaction between CdSe/ZnS QDs and dye-modified galactose–dopamine to establish a marketable glucose test[29]. Researchers examined the possibility of loading oil soluble CIS /ZnO QDs with biodegradable FA-FOC micelles and their targeting efficacy tumors utilizing in vitro and in vivo optical imaging [30]. Through the use of bio conjugated QDs in sensing, the transfer of genes and drugs, imaging cellular and biomolecular processes has become ubiquitous in the field of biology. Labeling of cells through the use of bioconjugated QDs can be broken down into two categories: Targeted and nonspecific Bioconjugated. QDs that are conjugates of antibodies, proteins, peptides, aptamers, nucleic acids, and liposomes can identify extracellular proteins and intracellular organelles. Researcher observed CsSe/ZnS QDs coated with AMP can bind HEK cells more than mouse fibroblast cells [31]. Peroxide extinguishes the phosphorescence of TiO_2/SiO_2 nanocomposites and coupling with GOx permits similar glucose serum detection. Direct conjugation of GOx with manganese-doped ZnS QDs has yielded a glucose sensor for clinical samples [32]. When applied as donors though rather than organic dyes, QDs offer a number of benefits, and the fact that their emission spectra are size-tunable and narrow. It means that donor spectral leakage into the acceptor channel is minimized. Due to their broad absorption spectrum, an excitation that fits the acceptor absorption optimum is possible which extends to wavelengths of blue shift in emission. In a wide variety of sensing strategies, it is projected that the use of QDs will significantly increase sensing performances [33].

5. COSMETICS INDUSTRY

ZnO QDs have been singled out among the many distinct forms of QDs because they are eco-friendly, have a low level of toxicity, and look promising for implementation in light-emitting devices, photovoltaic cells, sensors, photocatalysis, biological markers, and sunscreens (Figure 4) [34]. ZnO QDs/graphene hetero junction nanohybrids are tips for making of UV sensitizer and broad-band transparent conductor. These QDs has some advantages such as low cost, flexibility, and printability for visible-blind UV detection. ZnO QDs with high crystallinity and compact dimensions have greater UV absorbance and carrier lifespan because it's a direct bandgap semiconductor [35]. As ZnO has such a huge band gap, it is able to absorb UV light in a significant manner [36]. Integrating ZnO QDs and GO nanosheets increases UV blocking ability. The UV-blocking effect of the GO sheets on CCF/ZnO-GO-PVA enables some UV rays to be reflected. The down-conversion effect of ZnO QDs provided for another portion of the ultraviolet light to be transformed into visible light. In the outcome, just a small percentage of UV radiation was able to pass through the UV-blocking coating, which resulted in an amazing performance of UV blocking [37]. ZnO QDs is a suitable candidate for use in UV-blocking applications as it has a direct-bandgap of 3.3 eV and absorbs light in the ultraviolet spectrum. ZnO QDs exhibit photoluminescent emission and high quantum yield due to quantum confinement. Interestingly, these are photostable while dispersed in solvents. A size-dependent photoluminescence is one of the defining characteristics of QDs. This photoluminescence generates distinct emission colors for different dot sizes when excited by a wavelength of the same value. Polymer/ZnO nanocomposites for UV-blocking applications rely largely on polymer and nanocomposites [38].

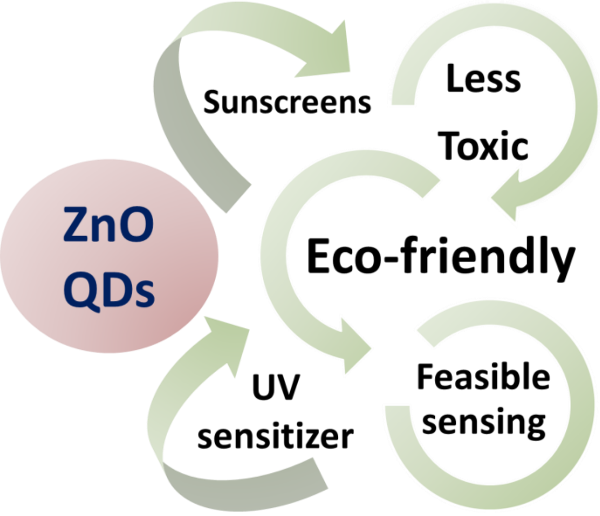

Fig. 4. Utilization of ZnO QDs in cosmetics industry with ecofriendly and less toxic environment.

UV absorption and photoluminescence emission reveal that ZnO QDs maintain their chemical and quantum characteristics during fabrication. These UV-blocking coatings are transparent across the visible spectrum. It is a benefit in comparison with the previously created nanocomposites, which revealed some degree of opacity in their aspect [39]. Due to UV blocking property of these QDs, these can be utilized in sunscreen and other cosmetics products which demands UV blocking properties for the extra ordinary quality of these cosmetics.

6. FOOD INDUSTRY

QDs are important in food industry because of its antibacterial activity, ethylene gas sensing, active packaging utilizations (Figure 5). QDs are an important class of antibacterial agents due to the fact effectiveness against bacteria, fungi, viruses, and parasites. Additionally, these have distinctive intrinsic properties that mediate between single atoms and bulk materials. These characteristics are the resultant of the extremely small size of QDs, which is typically in the vicinity of 2-6 nm [40]. When tested against *S.aureus* and *E .Coli* the antibacterial efficacy of the ZnO QDs@GO-CS hydrogel was effectively urtilized. However, these may not have any light irradiation at 808 nm, which can be connected to the release of Zn^{2+} and the release of ROS from ZnO QDs [41].

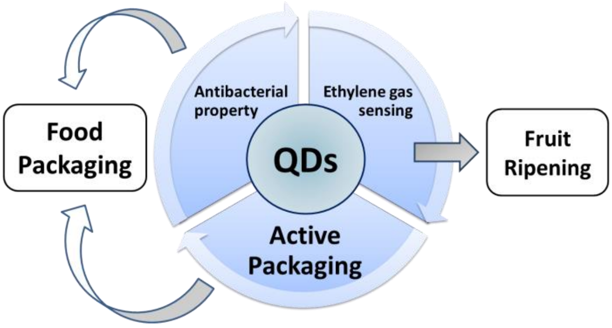

Fig. 5. QDs utilization in food packaging of food industry implying antibacterial activity of these.

The ZnO QDs have a high antibacterial capacity. Yamamoto et al. studied how ZnO nanoparticles' antibacterial activity changed with particle size from 100–800 nm. Antibacterial activity can be improved by using small sized NPs, and this range was found to be effective against a wide range of bacterial growths [42]. QDs are smallest NPs and so these are most efficient against several bacteria such as *E. coli*, [43], *P. aeruginosa* [44], *S. typhimurium* [45], *B subtilis* [46], *B. cereus* [40] etc. PON-based antimicrobial peptide mimics were used to coat CdTe QDs. PONs-CdTe QDs has antibacterial effect due to their high amine density [47]. For these antibacterial effect QDs are feasible for food packaging purposes. Functionalized SnO_2 QDs is highly selective in ethylene gas sensing [48]. Thus it can be utilized to sense the ripening process of fruits. The main purpose it to find if the fruit has ripened naturally or artificially. Active packaging is a type of food wrapping that aims to preserve and enhance the nutritional value, sensory characteristics, and quality of the food it contains. Additionally, it prolongs the shelf life of the food product. CdSe/ZnS QDs are utilized in active food packaging. The color rending index (CRI) of the materials can be improved by expanding the QD emission band, as evidenced by the 21.46 CRI of the single hybrid LED versus the 66.20 CRI of the multi-hybrid LED. Moreover, by increasing the working currents from 1 to 50 mA, this research was capable to boost the CRI of a single hybrid LED from 15.31 to 32.50 [49].

7. ENVIRONMENTAL INDUSTRY

Adopting an in situ solvothermal technique and CeO_2 QDs painted g-C_3N_4 increased the efficiency of organic pollutant degradation by $NaBH_4$. In this research, a two-dimensional hetero junction with strong interfacial contact is produced as a result. XRD data demonstrates a shift in the composite's electrical structure due to less CeO_2 QDs than in the pristine sample. XPS analyzing potential generated carbon vacancies in the C_3N_4 structure and an increased Ce^{4+} ion concentration in g-C_3N_4/CeO_2 QDs. When organic C_3N_4 and inorganic CeO_2 semiconductors was attached, Type-II energy band alignment was produced [50]. The weathering efficiency of FeOOH QDs anchored on g-C_3N_4 is seven times greater than on pure g-C_3N_4, which has great potential in treating organic pollutants [51]. With the help of Sol-Gel process, 0D FeOOH QDs were manufactured in-situ on the surface of 2D Bi_2WO_6 nanosheets in order to achieve a composite material comprising compound for organic pollutant degradation. This composite can be utilized as a photo-Fenton catalyst to degrade or decolorize contaminants such as MB, RhB, and TC-HCl. In comparison of pure Bi_2WO_6 and FeOOH QDs to the catalytic activity, the results reach a high level of catalytic activity. The synergistic effect occurs when FeOOH QDs and Bi_2WO_6 are combined which can provide an insight for the superior photo-Fenton catalytic performance [52]. QDs also feature an over-abundance of functional groups which makes surface functionalization simpler and contributes to their exceptional optical properties. QDs modified g-C_3N_4 ultrathin nanosheet has the ability to increase photoelectron transport and widen the absorption spectrum of solar light. 0D/2D nanostructures can form an exciton dissociation interface and a spatial charge carrier transfer channel which drives interfacial electron transport. This same conjugated electron arrangement can contribute photoactivity. For this reason, 0D/2D hetero junctions are built by QDs with g-C_3N_4 ultrathin nanosheets has high photocatalytic activity [53]. When TiO_2 NPs was combined with CdSe QD-sensitized nanowires, it can boost photoelectrochemical solar hydrogen production. Using green linker-assisted hybridization, CdSe QD-modified TiO_2 was amplified in visible-light photocatalytic activity for pollutant degradation [54]. Because of their superb fluorescence performance and intrinsic biochemical features, semiconductor QDs has been used in optoelectronic devices as well as in biological labeling. Numerous investigations have been done on manufacturing carbon-based QDs, such as carbon nanodots, graphene QDs, and g- C_3N_4QDs. g-C_3N_4 QDs. These have a higher photoluminescence quantum yield than carbon nanodots and graphene QDs. Thus these are more applicable in degradation of organic pollutants [55].

8. CONCLUSION

QDs are semiconductor nanocrystals that are part of inorganic NPs in the range of one to ten nanometers. They are special kinds of semiconductor because of their special features. QDs have become an innovative technology with profound effects across several sectors. Nanomaterials are very beneficial in a variety of fields, including electronics, energy, medical, and environmental research. This is because they have unique and tunable optical, electrical, and chemical properties. QDs have substantially improved medical imaging techniques, enabling earlier and more accurate illness diagnoses. Nanoparticles are extremely ideal for accurate drug delivery due to their favorable properties, such as their compact dimensions and capacity to be customized for certain surface features. This skill makes it possible to reduce negative effects and increase therapeutic effectiveness. QDs have also been used in biosensing applications, making it possible to identify infections and biomolecules quickly and precisely. The advantages of QDs have also benefited the environmental industry. In order to monitor pollutants and toxins in the environment, including air, water, and soil, sensors and detectors have proven crucial. Quantum dot nanoparticles are used in a wide variety of sectors, which demonstrates their substantial impact on technology and innovation. As research continues to concentrate on understanding QDs' characteristics and examining their possible applications, they have the potential to transform a number of industries, including electronics, energy, medicine, and environmental management.

9. REFERENCES

[1] O. Falyouna, I. Maamoun, K. Bensaida, Mohd Faizul Idham, Y. Sugihara, O. Eljamal, Mini Review on Recent Applications of Nanotechnology in Nutrient and Heavy Metals Removal from Contaminated Water, Proc. Int. Exch. Innov. Conf. Eng. Sci., 7 (2021) 161–169.

[2] T. Yanagida, Material Design of Metal Oxide Nanowires and Their Promises, Proc. Int. Exch. Innov. Conf. Eng. Sci., 3 (2017) 17–18.

[3] J. Zhang, F.X. Xiao, G. Xiao, B. Liu, Assembly of a CdS quantum dot-TiO2 nanobelt heterostructure for photocatalytic application: Towards an efficient visible light photocatalyst via facile surface charge tuning, New J. Chem., 39 (2015) 279–286.

[4] S. Mallakpour, V. Behranvand, Recycled PET/MWCNT-ZnO quantum dot nanocomposites: Adsorption of Cd(II) ion, morphology, thermal and electrical conductivity properties, Chem. Eng. J., 313 (2017) 873–881.

[5] N.M. Mahmoodi, B. Karimi, M. Mazarji, H. Moghtaderi, Cadmium selenide quantum dot-zinc oxide composite: Synthesis, characterization, dye removal ability with UV irradiation, and antibacterial activity as a safe and high-performance photocatalyst, J. Photochem. Photobiol. B Biol., 188 (2018) 19–27.

[6] Y. Qin, H. Li, J. Lu, H. Dong, C. Ma, X. Liu, Z. Liu, Y. Yan, Synthesis of QDs self-modified Bi2MoO6/Bi4Ti3O12 photocatalysts via controlling charge unidirectional flow for effective degradation of organic pollutants, J. Mol. Liq., 286 (2019) 110919.

[7] R. Koutavarapu, M.R. Tamtam, M.C. Rao, S.G. Peera, J. Shim, Recent progress in transition metal oxide/sulfide quantum dots-based nanocomposites for the removal of toxic organic pollutants, Chemosphere, 272 (2021) 129849.

[8] M. Babaei, P.A. Azar, M.S. Tehrani, M. Farjaminezhad, S.W. Hussain, Green and simple synthesized graphene/MnO2 quantum dot nanocomposite: characterization and application as an efficient adsorbent for solid-phase extraction of heavy metals, J. Nanostructure Chem., 12 (2022) 249–261.

[9] M. Shorie, H. Kaur, G. Chadha, K. Singh, P. Sabherwal, Graphitic carbon nitride QDs impregnated biocompatible agarose cartridge for removal of heavy metals from contaminated water samples, J. Hazard. Mater., 367 (2019) 629–638.

[10] H.R. Rajabi, M. Farsi, Effect of transition metal ion doping on the photocatalytic activity of ZnS quantum dots: Synthesis, characterization, and application for dye decolorization, J. Mol. Catal. A Chem., 399 (2015) 53–61.

[11] J. Liu, G. Lv, W. Gu, Z. Li, A. Tang, L. Mei, A novel luminescence probe based on layered double hydroxides loaded with quantum dots for simultaneous detection of heavy metal ions in water, J. Mater. Chem. C, 5 (2017) 5024–5030.

[12] J. Liu, Q. Zhang, W. Xue, H. Zhang, Y. Bai, L. Wu,

Z. Zhai, G. Jin, Fluorescence characteristics of aqueous synthesized tin oxide quantum dots for the detection of heavy metal ions in contaminated water, Nanomaterials, 9 (2019) 1294.

[13] V.A. Chhabra, R. Kaur, M.S. Walia, K.H. Kim, A. Deep, PANI/PbS QD nanocomposite structure for visible light driven photocatalytic degradation of rhodamine 6G, Environ. Res., 186 (2020) 109615.

[14] K. Bhuvaneswari, G. Palanisamy, T. Pazhanivel, G. Bharathi, D. Nataraj, Photocatalytic Performance on Visible Light Induced ZnS QDs-MgAl Layered Double Hydroxides Hybrids for Methylene Blue Dye Degradation, ChemistrySelect, 3 (2018) 13419–13426.

[15] B. Lellis, C.Z. Fávaro-Polonio, J.A. Pamphile, J.C. Polonio, Effects of textile dyes on health and the environment and bioremediation potential of living organisms, Biotechnol. Res. Innov., 3 (2019) 275–290.

[16] H. Kumari, Sonia, Suman, R. Ranga, S. Chahal, S. Devi, S. Sharma, S. Kumar, P. Kumar, S. Kumar, A. Kumar, R. Parmar, A Review on Photocatalysis Used For Wastewater Treatment: Dye Degradation, Water, Air, Soil Pollut. 234 (2023) 346.

[17] C.Y. Zhang, L.W. Johnson, Quantum-dot-based nanosensor for RRE IIB RNA-Rev peptide interaction assay, J. Am. Chem. Soc., 128 (2006) 5324–5325.

[18] C.Y. Zhang, H.C. Yeh, M.T. Kuroki, T.H. Wang, Single-quantum-dot-based DNA nanosensor, Nat. Mater., 4 (2005) 826–831.

[19] M. Fang, C. Peng, D. Pang, Y. Li, Quantum Dots for Cancer Research : Current Status , Remaining Issues , and Future Perspectives Characteristics of QDs for Biomedical, Cancer Biol Med, 9 (2012) 151–163.

[20] P. Zrazhevskiy, M. Sena, X. Gao, Designing multifunctional quantum dots for bioimaging, detection, and drug delivery, Chem. Soc. Rev., 39 (2010) 4326–4354.

[21] S.T. Selvan, T.T. Yang Tan, D. Kee Yi, N.R. Jana, Functional and multifunctional nanoparticles for bioimaging and biosensing, Langmuir, 26 (2010) 11631–11641.

[22] D. Vijian, S. V. Chinni, L.S. Yin, B. Lertanantawong, W. Surareungchai, Non-protein coding RNA-based genosensor with quantum dots as electrochemical labels for attomolar detection of multiple pathogens, Biosens. Bioelectron., 77 (2016) 805–811.

[23] E. Golub, A. Niazov, R. Freeman, M. Zatsepin, I. Willner, Photoelectrochemical biosensors without external irradiation: Probing enzyme activities and DNA sensing using Hemin/G-quadruplex-stimulated chemiluminescence resonance energy transfer (CRET) generation of photocurrents, J. Phys. Chem. C, 116 (2012) 13827–13834.

[24] D.B. Cordes, S. Gamsey, B. Singaram, Fluorescent Quantum Dots with Boronic Acid Substituted Viologens To Sense Glucose in Aqueous Solution, Angew. Chemie Int. Ed., 45 (2006) 3829–3832.

[25] L. Saa, V. Pavlov, Enzymatic Growth of Quantum Dots: Applications to Probe Glucose Oxidase and Horseradish Peroxidase and Sense Glucose, Small, 8 (2012) 3449–3455.

[26] K.E. Sapsford, T. Pons, I.L. Medintz, H. Mattoussi, Biosensing with Luminescent Semiconductor Quantum Dots, Sensors, 6 (2006) 925–953.

[27] J. Drbohlavova, V. Adam, R. Kizek, J. Hubalek, Quantum dots - characterization, preparation and usage in biological systems, Int. J. Mol. Sci., 10 (2009) 656–673.

[28] Y. Wang, R. Hu, G. Lin, I. Roy, K.T. Yong, Functionalized quantum dots for biosensing and bioimaging and concerns on toxicity, ACS Appl. Mater. Interfaces, 5 (2013) 2786–2799.

[29] W. Wu, T. Zhou, A. Berliner, P. Banerjee, S. Zhou, Glucose-mediated assembly of phenylboronic acid modified CdTe/ZnTe/ZnS quantum dots for intracellular glucose probing, Angew. Chemie - Int. Ed., 49 (2010) 6554–6558.

[30] D. Deng, Y. Chen, J. Cao, J. Tian, Z. Qian, S. Achilefu, Y. Gu, High-quality CuInS 2/ZnS quantum dots for in vitro and in vivo bioimaging, Chem. Mater., 24 (2012) 3029–3037.

[31] R. Liang, M. Wei, D.G. Evans, X. Duan, Inorganic nanomaterials for bioimaging, targeted drug delivery and therapeutics, Chem. Commun., 50 (2014) 14071–14081.

[32] K.J. Cash, H.A. Clark, Nanosensors and nanomaterials for monitoring glucose in diabetes, Trends Mol. Med., 16 (2010) 584–593.

[33] A.C. Vinayaka, M.S. Thakur, Photoabsorption and resonance energy transfer phenomenon in CdTe-protein bioconjugates: An insight into QD-biomolecular interactions, Bioconjug. Chem., 22 (2011) 968–975.

[34] F. Schmitz, M.B. Silva de Albuquerque, M.D. Alberton, I.C. Riegel-Vidotti, L.M. Zimmermann, Zein films with ZnO and ZnO:Mg quantum dots as functional nanofillers: New nanocomposites for food package with UV-blocker and antimicrobial properties, Polym. Test., 91 (2020) 106709.

[35] M. Gong, Q. Liu, B. Cook, B. Kattel, T. Wang, W.L. Chan, D. Ewing, M. Casper, A. Stramel, J.Z. Wu, All-Printable ZnO Quantum Dots/Graphene van der Waals Heterostructures for Ultrasensitive Detection of Ultraviolet Light, ACS Nano, 11 (2017) 4114–4123.

[36] R. Li, J. Che, H. Zhang, J. He, A. Bahi, F. Ko, Study on synthesis of ZnO nanorods and its UV-blocking properties on cotton fabrics coated with the ZnO quantum dot, J. Nanoparticle Res., 16 (2014) 1-12.

[37] D. Zuo, G. Li, Y. Ling, S. Cheng, J. Xu, H. Zhang, Durable UV-blocking Property of Cotton Fabrics with Nanocomposite Coating Based on Graphene Oxide/ZnO Quantum Dot via Water-based Self-assembly, Fibers Polym., 22 (2021) 1837–1843.

[38] M. Eita, R. El Sayed, M. Muhammed, Optical properties of thin films of zinc oxide quantum dots and polydimethylsiloxane: UV-blocking and the effect of cross-linking, J. Colloid Interface Sci., 387 (2012) 135–140.

[39] M. Eita, L. Wågberg, M. Muhammed, Spin-assisted multilayers of poly(methyl methacrylate) and zinc oxide quantum dots for ultraviolet-blocking applications, ACS Appl. Mater. Interfaces, 4 (2012) 2920–2925.

[40] M. Alavi, E. Jabari, E. Jabbari, Functionalized carbon-based nanomaterials and quantum dots with

antibacterial activity: a review, Expert Rev. Anti. Infect. Ther., 19 (2021) 35–44.
[41] Y. Liang, M. Wang, Z. Zhang, G. Ren, Y. Liu, S. Wu, J. Shen, Facile synthesis of ZnO QDs@GO-CS hydrogel for synergetic antibacterial applications and enhanced wound healing, Chem. Eng. J., 378 (2019) 122043.
[42] P. Joshi, S. Chakraborti, P. Chakrabarti, D. Haranath, V. Shanker, Z.A. Ansari, S.P. Singh, V. Gupta, Role of surface adsorbed anionic species in antibacterial activity of ZnO quantum dots against Escherichia coli, J. Nanosci. Nanotechnol., 9 (2009) 6427–6433.
[43] C. Mi, Y. Wang, J. Zhang, H. Huang, L. Xu, S. Wang, X. Fang, J. Fang, C. Mao, S. Xu, Biosynthesis and characterization of CdS quantum dots in genetically engineered Escherichia coli, J. Biotechnol., 153 (2011) 125–132.
[44] J.B. Morrow, C.A. P., R.D. Holbrook, Association of Quantum Dot Nanoparticles with Pseudomonas aeruginosa Biofilm, J. Environ. Qual., 39 (2010) 1934–1941.
[45] L. Yang, Y. Li, Simultaneous detection of Escherichia coli O157∶H7 and Salmonella Typhimurium using quantum dots as fluorescence labels, Analyst, 131 (2006) 394–401.
[46] S. Pramanik, S.K.E. Hill, B. Zhi, N. V. Hudson-Smith, J.J. Wu, J.N. White, E.A. McIntire, V.S.S.K. Kondeti, A.L. Lee, P.J. Bruggeman, U.R. Kortshagen, C.L. Haynes, Comparative toxicity assessment of novel Si quantum dots and their traditional Cd-based counterparts using bacteria models Shewanella oneidensis and Bacillus subtilis, Environ. Sci. Nano, 5 (2018) 1890–1901.
[47] D.N. Williams, J.S. Saar, V. Bleicher, S. Rau, K. Lienkamp, Z. Rosenzweig, Poly(oxanorbornene)-Coated CdTe Quantum Dots as Antibacterial Agents, ACS Appl. Bio Mater., 2 (2020) 1097-1104.
[48] W. Jin, H. Wang, Y. Liu, S. Yang, J. Zhou, W. Chen, SnO2Quantum Dots-Functionalized MoO3Nanobelts for High-Selectivity Ethylene Sensing, ACS Appl. Nano Mater., 5 (2022) 10485–10494.
[49] H. Wang, K.S. Lee, J.H. Ryu, C.H. Hong, Y.H. Cho, White light emitting diodes realized by using an active packaging method with CdSe/ZnSquantum dots dispersed in photosensitive epoxy resins, Nanotechnology, 19 (2008) 145202.
[50] T.V.M. Sreekanth, P.C. Nagajyothi, G.R. Dillip, Y.R. Lee, Determination of Band Alignment in the Synergistic Catalyst of Electronic Structure-Modified Graphitic Carbon Nitride-Integrated Ceria Quantum-Dot Heterojunctions for Rapid Degradation of Organic Pollutants, J. Phys. Chem. C, 121 (2017) 25229–25242.
[51] X. Qian, Y. Wu, M. Kan, M. Fang, D. Yue, J. Zeng, Y. Zhao, FeOOH quantum dots coupled g-C3N4 for visible light driving photo- Fenton degradation of organic pollutants, Appl. Catal. B Environ., 237 (2018) 513–520.
[52] L. Guo, K. Zhang, X. Han, Q. Zhao, D. Wang, F. Fu, Y. Liang, Highly efficient visible-light-driven photo-Fenton catalytic performance over FeOOH/Bi2WO6 composite for organic pollutant degradation, J. Alloys Compd., 816 (2020) 152560.
[53] M. Zhang, C. Lai, B. Li, F. Xu, D. Huang, S. Liu, L. Qin, Y. Fu, X. Liu, H. Yi, Y. Zhang, J. He, L. Chen, Unravelling the role of dual quantum dots cocatalyst in 0D/2D heterojunction photocatalyst for promoting photocatalytic organic pollutant degradation, Chem. Eng. J., 396 (2020) 125343.
[54] X. Ma, Q. Xiang, Y. Liao, T. Wen, H. Zhang, Visible-light-driven CdSe quantum dots/graphene/TiO 2 nanosheets composite with excellent photocatalytic activity for E coli disinfection and organic pollutant degradation, Appl. Surf. Sci., 457 (2018) 846–855.
[55] T. Wang, C. Nie, Z. Ao, S. Wang, T. An, Recent progress in g-C3N4 quantum dots: Synthesis, properties and applications in photocatalytic degradation of organic pollutants, J. Mater. Chem. A, 8 (2020) 485–502.