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Perspective

# Quantum dots technologies—On the edge of a boom

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**Abstract:** Quantum dots are unique nanoentities (few nm in size) having a semiconducting structure and promising surface, optical, electronic, electrical, thermal, conductive, mechanical, fluorescence, quantum confinement, and other quantum characteristics. Remarkable features of these zero-dimensional nanoparticles depend upon their types based on core materials and size differences. Quantum dots have been synthesized by various top-down or bottom-up strategies. This perspective article presents comprehensive info about diverse aspects of quantum dots, including their fundamentals, types, synthesis tactics, intrinsic features, practical applications, and potential for real-world industries. With a focus on their promising structure-property-performance profiles, the respective literature is critically analyzed and conversed. Given the promising outcomes, quantum dots depicted technological worth for wide-ranging industrial areas, including semiconducting devices, protective coatings, environmental, medical, and several other fields. However, several stumbling blocks need to be overcome to attain industrial scale success, including optimized synthesis/procedures, reproducibility, economics, non-toxicity, environment, and sustainability.

**Keywords:** quantum dots; fluorescence; quantum confinement; semiconducting; industries

## 1. Introduction

Quantum dots or fluorescent nanoparticles have garnered scientific curiosities as potential competitors to conventional zero-dimensional nanoparticles (fullerene, nanodiamond, metal/metal oxides) [1, 2]. Different types of quantum dots have been developed up till now using inorganic, carbon or polymeric materials via efficient synthetic routes [3]. These nanoparticles have been recognized for advantageous and controlled size/surface, optoelectronic, physicochemical, and quantum characteristics [4]. Moreover, quantum dots revealed nontoxicity, environmental friendliness, and low price benefits, relative to conventional organic/inorganic nanoparticles [5]. Since their discovery, quantum dots have been valuably used in the fields of diodes, solar cells, transistors, lasers, photon sources, quantum computing, catalysis, sensing, biosensing, bioimaging, biomedicine, and innumerable other sectors [6, 7]. Correspondingly, quantum dots have been noticed favorable for achieving unprecedented performance in present and future industries. Besides, several challenges (of controlled design, synthesis, functionalization, quantum yields, geometry, reproduction, structure-characteristics links, etc.) need to be tackled before these nanoparticles can truly outperform their counterparts in technical areas.

Briefly, this groundbreaking perspective article discloses fundamentals, research advancements regarding fabrication/features, and today's technical promises of quantum dots. According to the literature so far, quantum dots appeared as one of the most widely focused types of nanoparticles for energy, environment and biomedical industries. This paper also argues the foremost challenges and possible confines hindering industrial-scale advances and the commercialization of quantum dots. In addition, the future scope of these nanoentities in various industries has been stated. As compared to the past literature reports, it is hoped that this manuscript will offer a comprehensive overview of the existing state of quantum dot technology in order to open new outlooks towards future R&D and industrial scale progressions.

## 2. Quantum dots

**Figure 1** shows different types of zero-dimensional nanoparticles. Out of these, quantum dots are tiny nanoparticles, usually consisting of ~100–1,000 atoms and a few free electrons [8]. Till now, different classes of quantum dots have been discovered **(Figure 2**).

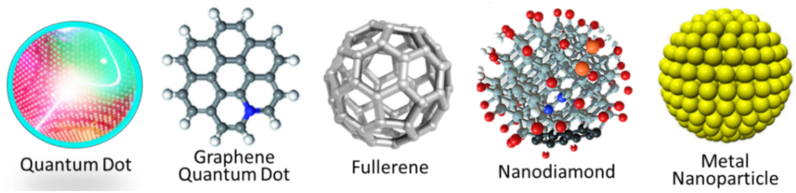


**Figure 1.** Zero-dimensional nanoparticles.

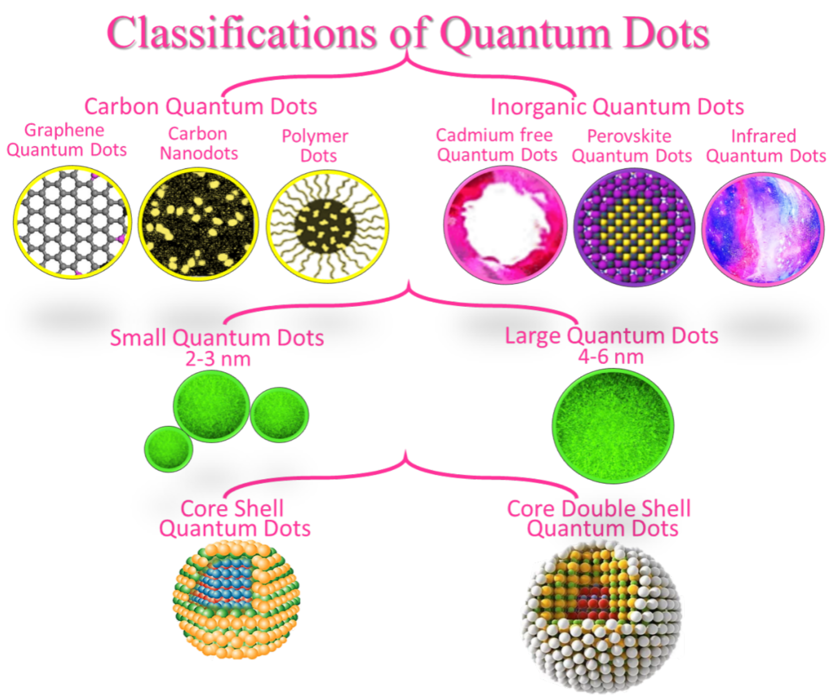


**Figure 2.** Different classifications of quantum dots.

Particularly, quantum dots have been categorized into carbon-based quantum dots (graphene quantum dots, carbon nanodots, polymer dots) and inorganic quantum dots (cadmium-free quantum dots, perovskite quantum dots, infrared quantum dots) on the basis of their core materials [9,10]. Quantum dots have also been classified as smaller quantum dots having sizes of ~2–3 nm and larger quantum dots of ~5–6 nm [11].

Moreover, quantum dots have been referred to as core-shell quantum dots and core double shell quantum dots [12]. In these quantum dots, long-chain hydrocarbons and other capping agents have been used to coat their surface. Varying thickness of such coatings affects the sizes and fluorescent or photoluminescent properties of core-shell or core-double-shell quantum dots.

Different top-down and bottom-up techniques have been adopted to date for the fabrication of quantum dots (**Figure 3**) [13]. For top-down synthesis of quantum dots, nanocutting, mechanical/chemical etching, reactive ion etching, electron/ion beam method, ultrasonication, and other routes have been practiced. Top-down procedures usually result in high purity, yield, and efficiency for quantum dots production. Bottom-up approaches for quantum dots synthesis include chemical vapor deposition, physical vapor deposition, hydrothermal, microwave/plasma, electrochemical, template, and organic synthesis techniques. Herein, control of processing parameters of bottom-up synthesis methods may result in high quality and superior properties of resulting quantum dots.

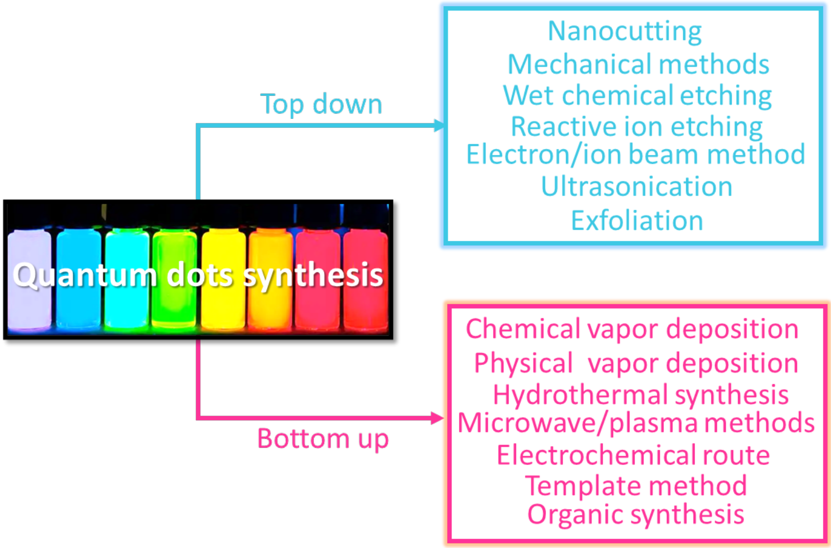


**Figure 3.** Frequently used top-down and bottom-up synthesis strategies for quantum dots.

Consequently, quantum dots obtained by different top down and bottom up fabrication techniques have been investigated for their intrinsic properties [14]. Notably, quantum dots have remarkable size effects, quantum confinement, edge effects, quantum yield, quantum mechanical effects, tunable band gaps, fluorescence, electronic, thermal, and biological characteristics (**Figure 4**). Furthermore, a few literature reports have also been observed for the statistical theory of quantum dots [15]. It is scientifically believed that quantum dots are submicron conducting devices containing several thousand electrons. Accordingly, electron conduction through quantum dots may occur via quantum-coherent processes at low temperatures. As per literature analysis, the statistical properties of quantum dots depend upon electron-electron interactions, quantum interference, and chaotic or diffusive electronic dynamics.

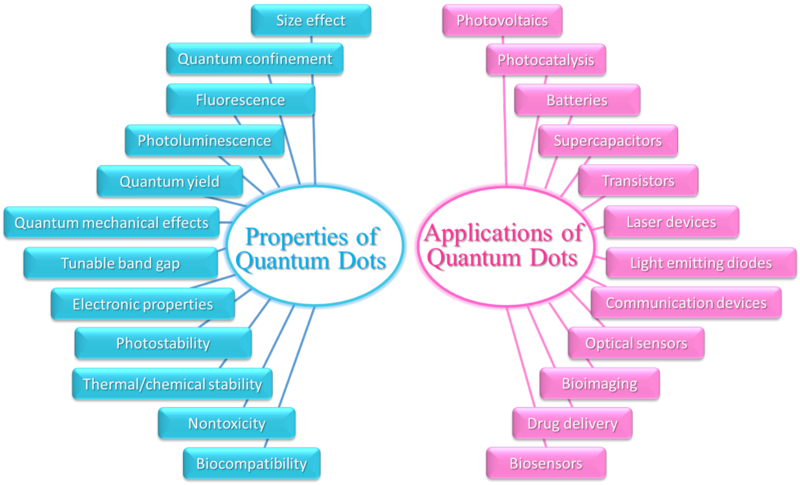


**Figure 4.** Significant properties and applications of quantum dots.

According to a recent study by Gil-Corrales et al. [16], statistically four types of quantum dots have been studied, including cubic quantum dots, ellipsoidal quantum dots, cylindrical quantum dots, and pyramidal quantum dots having fixed dimensions (**Figure 5**). The statistical model analysis revealed that the thermal properties of quantum dots were reliant upon the geometry of the quantum dots. Experimentally, the quantum dots of the same dimensions were designed by using the molecular beam epitaxy method [17]. Accordingly, quantum confinement and optical properties of quantum dots seemed to be dependent upon their shapes.

As stated by literature so far, high-end application areas of quantum dots include semiconducting devices (electronics, sensors, optical sensors), energy devices (photovoltaics, batteries, supercapacitors, transistors), laser devices, light-emitting diodes, communication devices, biosensors, bioimaging, and more [18].

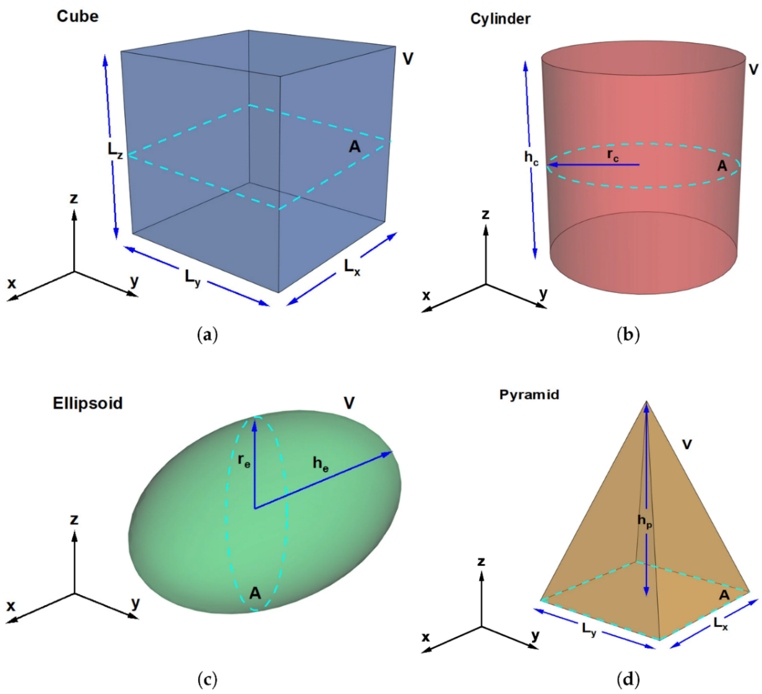


**Figure 5.** Quantum dots types based on statistical analysis: **(a)** Cubic; **(b)** cylindrical; **(c)** ellipsoidal; **(d)** pyramidal, (length $Lx = Ly = Lz = 10$ nm; $A = 10^2$ nm$^2$; volume $V = 10^3$ nm$^3$) [16].

## 3. Quantum dots and today's industries

Quantum dots have gained budding scientific interests in a myriad of technological industries, ranging from next-generation semiconducting devices to high resolution quantum dot systems [19]. Particularly, quantum dots have extremely small sizes, light absorption/emission effects, and quantum effects, thereby rendering them essential building blocks for large-scale applications. Regarding today's real world industrial deployments, quantum dots have been successfully applied for semiconductor industries (energy devices, electronics, sensing devices) [20–22], Internet of Things (IoT) [23], oil and gas industries [24], corrosion/wear protective coatings and lubricants [25,26], water pollution remediation [27], biomedical [28] (**Figure 6**).

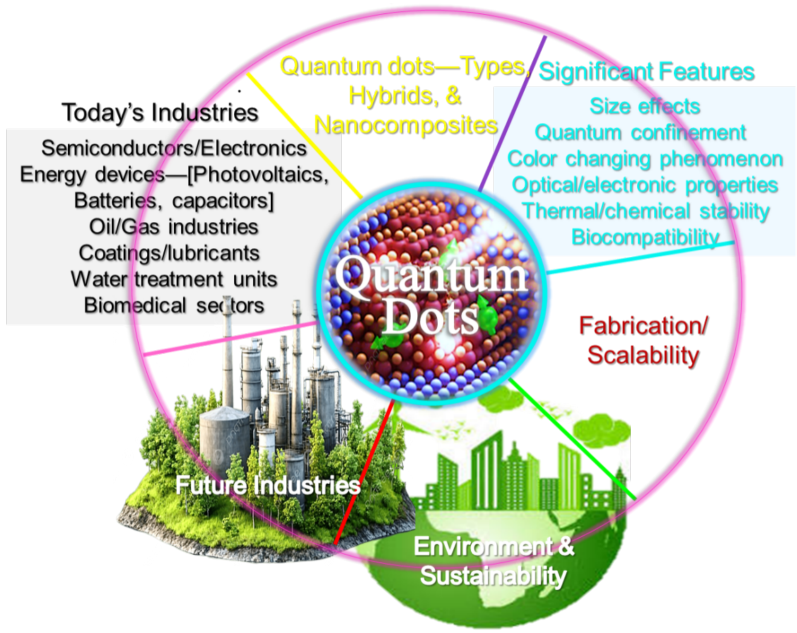


**Figure 6.** Existing and future industrial scenarios of quantum dots.

Particularly, talking about the discovery of carbon-based quantum dots, such as graphene quantum dots, has further expanded the industrial scope of these nanoentities. One of the important types of carbon-based quantum dots is zero-dimensional graphene quantum dots [29]. These quantum dots have distinct structural, microstructural, optoelectronic, electrical/thermally conducting, mechanical/heat stability, and physical features; and so, are widely investigated as competent nanoreinforcements for polymeric matrices (in spite of traditional carbon nanofillers) [30]. Consequently, including graphene quantum dots in polymers depicted applications in the fields of advanced optics, photovoltaics, drug delivery, and pharmaceutics [31,32].

## 4. Quantum dots—Future

Quantum dots are revolutionizing industries owing to their unique quantum properties, tunable emissions, energy efficiency, and other valuable characteristics, as discussed in preceding sections of this article. Consequently, these marvelous nanoentities are transforming innovative ways for electronics/energy—to—healthcare industries and unlocking new market opportunities. Particularly, these nanoscale materials have quickly changed the future of high definition light-emitting displays and devices, quantum computing, high efficiency solar cells, batteries, and related devices, next-generation bio-imaging, and advancements across several other sectors. Moreover, a shift towards cadmium-free quantum dots has changed the picture of future industries for attaining desirable sustainability and reducing environmental impact by maintaining upgraded performance [33]. In this way, key innovations have been observed for sustainable energy modules (like photovoltaics), cadmium-free next-gen displays, and micro light-emitting diode-based reality displays.

Looking at the emerging technological relevance of quantum dots, recent and future forecasts have been analyzed for global industries [34]. As per Compound Annual Growth Rate (CAGR) analysis, the global quantum dots market is expected to grow from USD ~10–13 billion (2025–2026) to USD > 24 billion (2031) [35]. Thus, CAGR predicts ~84 % increase in the global quantum dots market growth (in terms of investments & products) after every five years. Specifically, in the case of graphene quantum dots, a CAGR of ~19 % is expected till 2030. This increase in the global quantum dots market seemed to be linked to rapid uptake of quantum dots by China, the US, European countries, Asia-Pacific, and Middle Eastern countries [36]. Commercial scale maturity is definitely desirable for accelerating lab-scale technologies to mass production for next-generation industrial platforms.

Further progressions in this field seemed to be dependent upon life cycle assessment (LCA) of quantum dots-based nanomaterials to evaluate environmental and sustainability impact. Especially, LCA scenarios involve the assessment of carbon emissions from sourced materials during quantum dots manufacturing and related environmental impacts. In addition to ecological impact, costs and energy consumption need to be analyzed for the conversion of laboratory-scale modules to large-scale designs. Focused scientific investigations along these lines seemed to be indispensable to unlock key insights for quantum dots advancements.

Despite the wide-ranging applied traits of quantum dots, several challenges have been investigated hindering the commercial-scale production and use of these nanomaterials. Hence, future technical implications of quantum dots face challenges of reproducibility, precise synthesis techniques/parameters, controlled luminescence, size-dependent band gap, photostability, toxicity of metal-based quantum dots, material/processing costs, complexity of core-shell nanostructures, limited validation in water conditions, heat/electrical conductivity and stability, and more. As per analysis, these zero-dimensional nanoparticles need to be surface modified to attain controlled surface and physical properties, low toxicity, and better compatibility for different technical applications.

## 5. Conclusion

Since the discovery of quantum dots, continuous scientific interests and advancements have been noticed to unfold their structural, properties, and applied promises. As compared to traditional zero-dimensional nanoparticles, quantum dots have advantages of ultrasmall nanosizes, symmetry, unique surface properties, fluorescence, and quantum effects. Owing to innumerable valuable features, growing technical demands of quantum dots have been noticed for real-world industries, including electronics/energy devices, to—environment and medical sectors. Nevertheless, a number of encounters need to be addressed before industrial-scale applications of quantum dots. Hence, this manuscript is designed to highlight the competences of next-generation quantum dots and also to address their underlying barriers for large scale industrial deployments.

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