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A multidimensional review of the applications and implications of quantum dots in modern agriculture

Wan Nur Zarifah Wan Azamuddin[1], Janna Ong Abdullah[2], Azzreena Mohamad Azzeme[3], Shafinaz Abd Gani[3], Rosfarizan Mohamad[1,4], Murni Halim[1,4], Helmi Wasoh[1,4] and Zulfazli M. Sobri[1,4*]

*Correspondence:
Zulfazli M. Sobri
zulfazli@upm.edu.my
[1]Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Serdang 43400 UPM, Selangor, Malaysia
[2]Department of Cell and Molecular Biology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Serdang 43400 UPM, Selangor, Malaysia
[3]Department of Biochemistry, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Serdang 43400 UPM, Selangor, Malaysia
[4]Bioprocessing and Biomanufacturing Research Centre, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia, Serdang 43400 UPM, Selangor, Malaysia

Abstract
Quantum dots (QDs) are nanoscale materials exhibiting quantum confinement effects synthesized from various sources, including semiconductors QDs (e.g., CdSe, PbS), carbon-based materials, MXenes, magnetic QDs, metal oxides, chalcogenides, and perovskites that have unique optical and electronic properties, typically ranging from 1 to 10 nanometers. These properties, including tunable fluorescence, high photostability, and size-dependent emission that greatly influenced by the size, shape, and composition of QDs. Due to their small size, QDs exhibit a high surface-to-volume ratio, where quantum confinement dominates and results in a size-dependent bandgap unlike other bulk materials. Its nanosructure composed of core-shell configurations with specific bandgap alignments such asType-I or Type-II, between the valence band critically influence their optical and electronic properties. QDs are synthesized using either top-down or bottom-up approaches, depending on the desired structure and properties. These synthesis techniques allow for precise control over the size, composition, and functionality of QDs. The QDs evolve in agricultural practices especially semiconductor QDs and carbon quantum dot (CQD) that have significant effects, increased crop yields by 15–40%, enhanced photosynthesis by 56%, and boosted nitrogen uptake by 30%. They help plants tolerate stress by improving root health and water efficiency, aiding sustainable crop production. However, their successful application depends on understanding their uptake mechanisms in plants and addressing concerns related to their toxicity and environmental impact. This review explores the synthesis, applications, and potential risks associated with QDs in agriculture, highlighting their role in advancing sustainable agricultural practices.

Keywords Quantum dots (QDs), Modern agriculture, Unique properties, Synthesis methods

1 Introduction

The nanomaterials are classified into different dimensions based on their electronic structure along various axes. These include zero-dimensional forms, such as nanoclusters and metallic nanoparticles, one-dimensional structures like nanotubes and nanowires, two-dimensional materials such as graphene sheets and nanoplates, and three-dimensional configurations, like nanocrystals. Recent advancements in the study of electron confinement in reduced dimensions have led to significant developments in QDs. These zero-dimensional, dot-sized nanomaterials, typically less than 10 nm and comparable to the exciton Bohr radius. QDs are highly luminescent crystalline structures composed of elements from the II-VI (CdSe, ZnS, CdTe), III-V (InP, InAs), and IV-VI (PbSe, PbS) groups [1]. It has unique properties with nanometer-size diameters that are different from bulk materials due to their due to their quantum confinement and limited number of electrons, leads to discrete quantized energy levels in their box model according to Pauli's exclusion principle, thus instigated as artificial atoms [2].

QDs have diverse applications across several fields, including biomedical research, electronics and optoelectronics, environmental sensing and agriculture. In biomedical research, for example, QDs serve as highly effective bioimaging agents due to their precise and stable light emission, thereby enabling advanced imaging, targeted drug delivery, diagnostics, and photodynamic therapy [3, 145]. Moreover, in electronics and optoelectronics, QDs enhance devices such as LEDs and QLED displays by providing improved color control and efficiency, offering higher efficiency and controllable luminescence spectra [145, 146]. In addition, QDs also utilized as highly sensitive and selective biosensors for various analytes, including metal ions and environmental pollutants as photocatalysts for water purification and pollutant removal [146]. Recently, nanotechnology, and particularly QDs, is revolutionizing agriculture by offering innovative solutions to enhance food security, improve crop yields, and promote environmental sustainability. This developments of QDs hold great potential in agriculture with research demonstrating their ability to address challenges like climate change, pests, and diseases, thereby supporting sustainable farming practices under challenging conditions [147].

The evolution and expansion of QDs in agriculture can be seen through several key applications and their underlying mechanisms. QDs represent luminescent materials that act as artificial antennas, by absorbing ultraviolet (UV) and the blue light [148]. It optimized the spectrum and emit the light towards longer wavelength. The QDs not used in photosynthesis, however this process often involving fluorescence resonance energy transfer (FRET), can significantly increase photosynthetic efficiency, enhance electron transport in chloroplasts, and boost chlorophyll synthesis and CO2 assimilation [149]. A relevant study involving fluorescent silica nanoparticles (SiNPs) demonstrated that their ability to enhances photosynthesis by absorbing ultraviolet (UV) radiation and emitting visible blue light that spectrally overlaps with chlorophyll's absorption, enabling FRET from the SiNPs to chlorophyll. This FRET directly accelerates the electron transfer pathway in the light reactions of photosynthesis, leading to an increased rate of the process, improved plant growth and quality, and reduced UV damage [154]. Studies have shown that QDs can improve overall plant growth, root and shoot length, plant weight, and grain yield This has been shown to improve overall plant growth, including root and

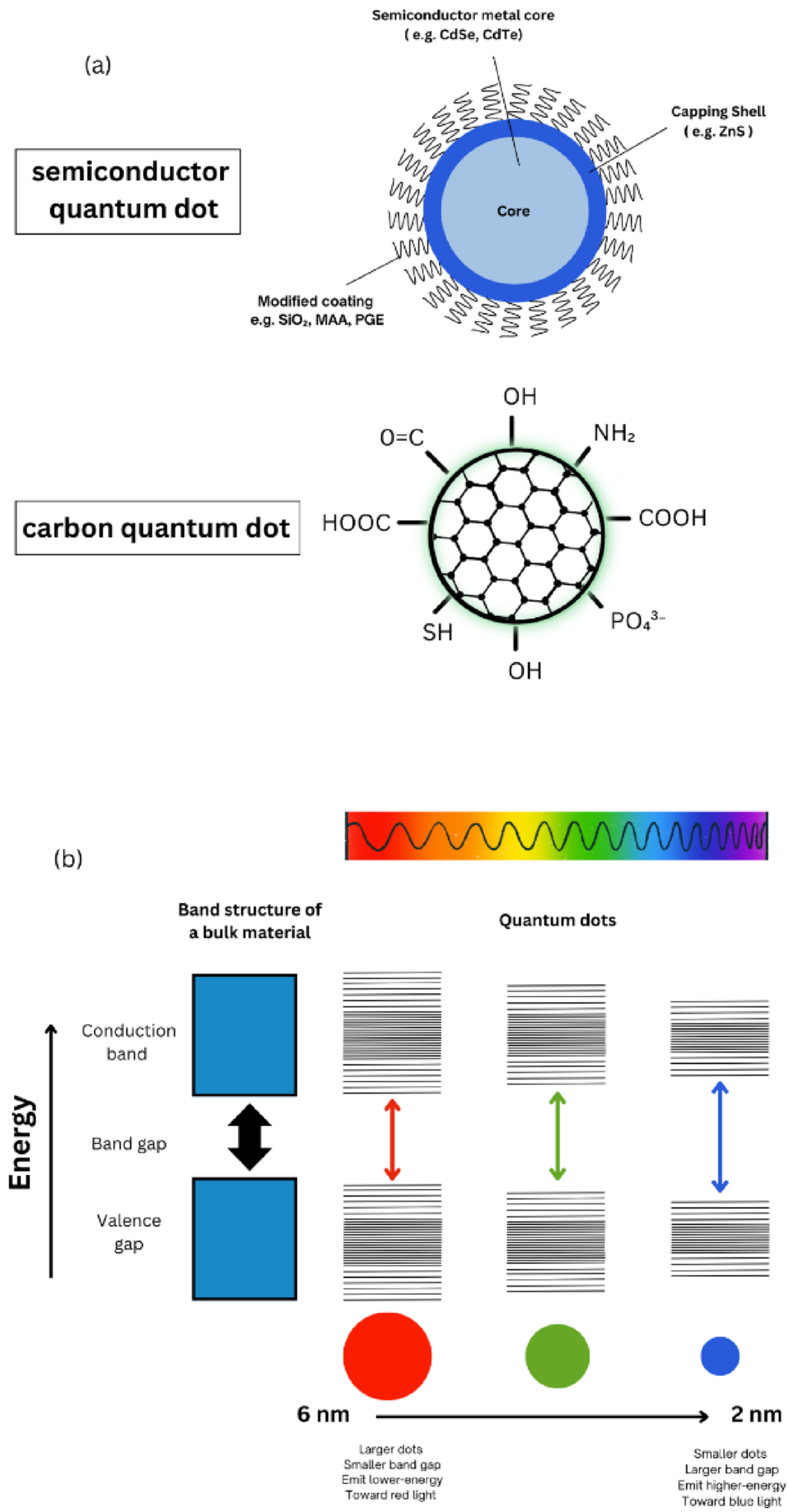

Fig. 1 (See legend on next page.)

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Fig. 1 (**a**) Schematic structure of semiconductor and CQD. CQDs have quasi-spherical core consists of sp^2/sp^3-hybridized carbon with crystalline features, while the shell is formed by various surface functional groups (e.g., –COOH, –OH, $–NH_2$). Structural analyses reveal lattice fringes (~ 0.21 nm), graphite-like (002) planes (~ 3.25 Å), and even diamond-like patterns [164]. (**b**) Illustration of the quantum confinement effect in quantum dots. Red-emitting quantum dots typically have a size of 5–6 nm, whereas blue-emitting quantum dots are generally smaller, with sizes ranging from 2 to 3 nm [18]

shoot length, plant weight, and grain yield. Studies have also indicated a 23% higher light use efficiency and 10% faster vegetative growth rate for plants under QD films [150].

The potential of QDs, particularly CQDs, are revolutionizing modern agriculture due to their tunable and efficient photoluminescence, high light stability, small size, biocompatibility, low toxicity, and water solubility [155]. In seed priming, CQDs significantly enhance germination rates, promoting early plant growth and overall seedling vigor by facilitating efficient water absorption through their hydrophilic surface groups and enhancing nutrient uptake in mung bean sprout [151]. The CQDs as efficient nanocarriers with surface functional groups like hydroxyl and carboxyl can deliver essential metal ions (e.g., K^+, Ca^{2+}, Mg^{2+}, Cu^{2+}, Zn^{2+}, Mn^{2+}, Fe^{3+}) to plants, minimizing nutrient loss and enhancing uptake efficiency [151, 152]. Furthermore, QDs increase plant resistance to environmental stresses, by enhancing plant tolerance to abiotic and biotic stresses, including drought, salinity, heavy metal toxicity, and pathogen infection [153] This stress mitigation is largely attributed to their ability to scavenge reactive oxygen species (ROS) by upregulating antioxidant enzymes such as superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), while also supporting water retention, photosynthetic efficiency, and the activation of plant defense mechanisms [153].

2 Structure of QDs

Quantum dots generally consist of a core-shell structure with a modified coating layer, as illustrated in Fig. 1(a). Significant advances in the field of QDs are achieved due to its size and structures. The shell is typically composed of a wider band gap semiconductor, such as zinc sulfide (ZnS) or cadmium sulfide (CdS) and the core is made of materials like cadmium telluride (CdTe) or cadmium selenide (CdSe) [18, 156]. The primary purpose of this shell is to passivate the active surface of the QD core, that offers protection against oxidation, photobleaching, and blinking, significantly enhancing quantum dot stability and photoluminescence [5, 157, 158] QDs exhibit size-dependent and efficient photoluminescence with narrow emission spectra and high light stability, enabling tunability based on particle size and bandgap [4, 155, 164]. Upon exposure to white light or ultraviolet (UV) radiation, electrons in quantum dots are excited to higher energy states and subsequently return to lower energy levels by emitting light depending on their size and band gap [18, 155]. The emission color and quantum confinement effect is shown in Fig. 1(b), with smaller dots emitting blue light and larger dots exhibiting a red shift [1, 19]. A study observed the effect of photoconversion QD-coated polymer films on the growth of *Solanum lycopersicum* by converting UV light into blue and red emissions, which are considered crucial for plant growth [9, 98]. The result shows that the light conversion by QDs could enhanced the plant biomass compared to the plant grown under white light [10]. Grinberg et al. [9] also mentioned the use of a photoconversion coating made from the fluoropolymer films containing gold nanoparticles and QDs results in larger leaves, most likely because it stimulates photosynthesis, indicated by an increase in CO2 assimilation. Thus, providing a controlled wavelength for each required spectrum is essential for increasing photosynthetic activity and achieving optimal plant yield [8, 11].

Additionally, QDs like conventional semiconductors, can undergo phase transitions under specific conditions such as high pressure. QDs are known to undergo solid-solid phase transitions, where a change in crystal structure such as the transformation of the bulk CdSe from hexagonal wurtzite or a rock salt cubic structure with a direct or indirect band-gap, respectively [3]. This phase transition profoundly influences their optical properties, including emission in the Near Infrared (NIR) spectral region at 0.67 eV (1.8 μm) where the low intensity optical emission from the rock salt form of CdSe is located [159, 160]. Tolbert and Alivisatos [161] used high pressure XRD and optical absorption demonstrated that the wurtzite to rock salt structural change also happened in CdSe Qdots. Relative difference in light-emission efficiency between direct and indirect QDs stayed the same, regardless of the QD size. The ability to tune the optical properties of QDs is highly relevant in agriculture, where QDs could be used to optimize light spectra for intensifying plant photosynthetic rates in greenhouse cultivation, utilizing specific wavelengths for better chloroplast absorption to enhance the photosynthetic efficiency [18] Various modification strategies are crucial for tailoring the performance of QDs, particularly for biological and agricultural applications. Doping involves introducing small amounts of other elements called activators into the QD structure to modify their properties. This process creates new energy levels within the band gap, influencing how the quantum dots absorb and emit light. It allows for the tuning of emission color and fluorescence properties [18, 155]. For instance, nitrogen-doped carbon QDs have been synthesized using a microwave-assisted hydrothermal method for fluorescent detection of alachlor [104]. These red-emitting QDs showed a decrease in fluorescence as alachlor herbicide concentration increased in the soil, thus doped QDs prove to be effective fluorescent probes for monitoring herbicide levels in soil.

These optical properties also can be precisely tailored by carefully controlling the amount and placement of the activators. Indeed, Mn-doped ZnS QDs with sizes between 2 and 3 nm and concentrations ranging from 500 ppm to 2000 ppm have been shown to significantly improve the growth and quality of onion crops [13, 14]. Doping manganese (Mn^{2+}) to cadmium sulfide/zinc sulfide (CdS/ZnS) quantum dots exhibited much stronger and sharper yellow photoluminescence (PL), attributed to the $^4T_1$–$^6A_1$ transition of Mn^{2+} ions [12]. These QDs emit strong yellow light because the ZnS shell passivates the CdS core's surface defects, reducing energy losses. This improved nanostructure was confirmed using X-ray Photoelectron Spectroscopy (XPS) and Energy-Dispersive X-ray Spectroscopy (EDS). Beyond solely optical tuning, doping also plays a role in enhancing QD stability and reducing toxicity, with a notable shift towards utilizing transition element-doped QDs instead of heavy metals to mitigate environmental ion leakage and associated toxic effects. Alloying is another modification procedure that combines various semiconductor materials in the QD core, which provides additional control over the band gap and light-emitting properties without necessarily altering the physical size, internal structure, or surface chemistry of the QD [18, 160]. Combining cadmium, mercury, and tellurium to form CdHgTe nanocrystals results in materials that absorb light across a broad spectrum over the wavelength region 400–1200 nm, exhibiting a higher absorbance in this range compared to CdTe QDs [15]. However, combining

CdHgTe nanocrystals with CdTe quantum dots achieves a notably higher energy conversion efficiency of 2.2%, compared to just 1.0% for CdHgTe alone. This enhancement allows the solar cell to harness a greater portion of the available solar energy [15].

The surface structure of QDs is critically important due to their high surface-to-volume ratio as surface defects can reduce light absorption and weaken chemical stabilities, often quenching the intrinsic emission [16]. These defects can act as non-radiative recombination centers for charge carriers and include unoxidized dangling carbon bonds or oxygenated functional groups [16, 17, 23] To overcome this issue, QDs are typically coated with organic or inorganic layers through a process called surface passivation [17]. Proper passivation significantly enhances QDs luminescence and prevents detrimental processes like photo-oxidation [18]. Core/shell quantum dots, such as CdSe/ZnS that have wider bandgap energy improve luminescence and stability by passivating surface defects and reducing nonradiative recombination [162]. For instance, ZnS shells widely used to protect against oxidation and photocorrosion as a blocking barrier against electron transfer back into the electrolyte in photoelectrochemical (PEC) devices [23]. However, excessively thick shells can decrease carrier transfer efficiency, therefore surface coatings with hydrophilic or amphiphilic groups are vital for modulating water solubility, stability and cytotoxicity [18, 163]. For example, mercaptoacetic acid (MAA)-coated CdSe/ZnS QDs passivated with Silwet L-77 efficiently penetrated maize roots tissue with low toxicity and remaining stable for days [20]. These MAA-QDs showed a maximum emission at 585 nm when excited at 400 nm and were observed to be highly dispersed using fluorescence microscopy and characterized by UV-Vis absorption and fluorescence emission spectroscopy.

However, an excessively thick single shell can also sometimes limit carrier transfer efficiency, leading to the development of multiple-shell QDs designed to combine the benefits of different materials and optimize shell thickness for enhanced performance via cascade band alignment [21, 22, 146]. Wang et al. [23] extensively synthesized and characterized heterostructure core/multiple-shell QDs, specifically $CdSe/CdSe_xS_{1-x}/CdS/ZnCd_{1-\gamma}S/ZnS$ multiple-shell QDs, demonstrating that incorporating alloyed interlayers effectively minimizes surface traps and defects, while simultaneously inhibiting exciton recombination [23]. The structural and compositional characteristics of these QDs were confirmed using various techniques including Transmission Electron Microscopy (TEM) and High-Resolution TEM (HR-TEM) revealed their spherical morphology and average sizes such as CdSe cores at ~ 3.4 nm, CdSe/6CdS at 7.4 ± 0.7 nm, CCZ-1 at 7.3 ± 0.8 nm and CCZ-2 at 6.5 ± 0.8 nm, along with crystal planes and boundaries. Their optical properties, including absorption and PL spectra, exhibited characteristic red-shifts, indicating successful epitaxial growth. Fluorescence lifetime measurements confirmed improved carrier separation due to the shell coatings, and a theoretical Schrödinger equation (wave function model) helped understand carrier dynamics and confinement effects within these complex multi-shell structures [23]. The precise control over QD surface structure through passivation, doping, and alloying directly dictates their optical and chemical properties, profoundly impacting their performance and stability in various applications, particularly in sensitive biological and agricultural environments. These structural modifications enable tailored functions, from improved bioimaging and nutrient delivery to highly efficient and stable energy conversion.

3 Unique properties of QDs and comparison with other nanomaterials in agriculture application

QDs possess unique optical and electronic properties that hold significant potential for agricultural applications due to its small size and quantum confinement. One of the most remarkable features is the size-dependent fluorescence. This phenomenon arises from the quantum confinement effect, where the energy levels of electrons within the QD become quantized due to their restricted movement within the nanoscale dimensions [3]. Smaller QDs have higher band gap energy, resulting in a blue shift light emission and the larger QDs exhibit a red shift with lower energy emissions [1, 24]. Kanwal et al. [25] reported that spraying Zn-based QDs (3 nm in size) increased tomato plant height, weight, and yield in soil at concentrations ranging from 500 to 2000 ppm. Additionally, this size-tunable fluorescence allows for the precise selection of emission wavelengths, making the QDs ideal for various applications. In agriculture, this property can be harnessed for imaging and sensing, enabling researchers to track and visualize various processes within plants. For example, QDs can be used as fluorescent probes to monitor the nutrient uptake, water movement, and detection of plant diseases or pests [18]. For instance, the size-dependent fluorescence of QDs also offers potential for developing highly sensitive and selective sensors for detecting pesticides and herbicides in soil and water [26].

Moreover, QDs have tunable emission that could be achieved by manipulating the size and composition. This characteristic is particularly valuable in agriculture, where the QDs may be tailored to emit certain wavelengths that correspond to the ideal absorption ranges of plants, potentially improving photosynthesis and crop productivity [27]. The tunable emission allows for the development of multicolor labeling and imaging techniques, facilitating the simultaneous monitoring of multiple processes within plants [18]. By selecting appropriate materials and controlling synthesis parameters, researchers can control the QDs emitting across a wide spectrum [28]. Additionally, QDs photostability is another key feature that is ideal for long-term agricultural monitoring applications. It enables this carbon nanomaterial to endure extended exposure to intense light, high temperatures, and fluctuations in pH variations without significant degradation of their optical properties. Reports suggested QDs as stable organic materials, while organic dyes degrade rapidly under prolonged light exposure [29]. This durability is particularly beneficial in agricultural applications, where QDs can be employed in sensors for monitoring soil health, detecting pathogens, or tracking nutrient uptake by plants, offering valuable insights for sustainable farming practices. The stable fluorescence of QDs enables researchers and farmers to track processes and changes in the agricultural environment over extended periods, facilitating data collection and analysis for improved crop management strategies.

There are various distinguishing features between bulk materials and QDs. QDs have quantized energy levels due to charge carrier confinement, which results in unique absorption and emission peaks [30], whereas bulk nanomaterials have a continuous energy spectrum with broad spectral characteristics [31]. Yan et al. [32] indicates that QDs can be excited by various energy sources, emitting light in different colors across the visible to infrared spectrum, while Li et al. [33] state the bulk semiconductors are mainly determined by their chemical composition and lattice structure, resulting in a stable band gap that does not significantly change with size. Furthermore, excitation of the electrons results in production of photons in the form of energy known as fluorescence. It efficiently generates a continuous band gap using QDs compared to bulk materials, which enhances their fluorescence [34]. Singh [154], fluorescence property of silica nanoparticles (SiNPs) enhances the rate of photosynthesis in plants primarily through a mechanism called fluorescence resonance energy transfer (FRET). This process effectively transfers light energy to the plant's photosynthetic machinery, leading to improved plant growth and quality. Specifically, the SiNPs exhibit blue fluorescence with an emission maximum of 454 nm when excited at 370 nm, means this process allows for the utilization of UV light, which green plants generally do not absorb efficiently for photosynthesis [154]. A perfect spectral overlap exists between the SiNPs' emission and chlorophyll's absorption, enabling efficient energy transfer to the plant's photosynthetic machinery [166]. This energy transfer increases the fluorescence intensity at photosystem II (PS II) and directly influences the electron transfer pathway in the light-dependent reactions of photosynthesis [166, 167]. As a result, the overall rate of photosynthesis is accelerated, leading to improved plant growth and quality. Barroso MM [35]. reported that QDs contain high photostability compared to conventional organic dyes used for bioimaging. CdSe/ZnS QDs coated with dihydrolipoic acid maintained their fluorescence for up to 14 h, demonstrating 100 times greater stability and 20 times higher brightness compared to rhodamine 6G dye [36, 37]. Furthermore, compared to other nanomaterial semiconductors, GQDs are not particularly hazardous [38, 62, 63] and study shown that CQDs demonstrate an excellent biocompatibility in vitro and in vivo, with no significant cytotoxic effects observed in various cell types [39, 64]. The toxicity of QDs can vary significantly based on their composition. For instance, QDs containing heavy metals like cadmium or selenium are known to exhibit toxicity, which necessitates to consider this factor [40]. Other nanomaterials, such as metal oxides and carbon nanotubes, exhibit varied biocompatibility and although some metal oxide nanoparticles possess antimicrobial properties, it can also induce oxidative stress in biological systems [41]. QDs offer unique advantages due to their quantum confinement, small size, and broad tunability, which translate into specific benefits for bioimaging, light harvesting, and targeted nutrient delivery. TiO2 is valuable for its stability and photocatalytic activity but requires sensitization for efficient solar light absorption [14, 86]. ZnO nanoparticles are promising as nanofertilizers and for their antimicrobial properties, though their effectiveness is often size and concentration-dependent [14]. The development of core/shell or multi-shell structures and surface modifications for all these nanomaterials is critical to optimize their performance and mitigate potential toxicities in agricultural applications [18]. Table 1 shows the comparison of QDs with other nanomaterials utilized in agriculture including their composition, size range, limitations and toxicity.

4 Synthesis of QDs

There are several techniques for synthesizing graphene quantum dots, with the top-down and bottom-up methods being the primary approaches [42]. The top-down approach commonly involves molecular beam epitaxy, electron beam lithography, ion implantation, and X-ray lithography [18]. These procedures reduce the bulk material chemically or physically to produce quantum-sized particles with unique properties. For instance, wet etching, reactive ion etching, and electron beam lithography are often used to fabricate quantum dots with sizes below 30 nm [43]. This approach encompasses

Table 1 Shows the comparison of QDs with other nanomaterials utilized in agriculture

Nano-material Type	Composition	Size Range (approx.)	Key Agricultural Applications/ Advantages	Limitations/Toxicity	Relevant Source(s)
Quantum Dots (QDs) - General	II-VI (e.g., CdSe, ZnS), III-V (e.g., InP), IV-VI (e.g., PbS); core/shell with surface ligands	< 10 nm (e.g., 1–12 nm)	Bioimaging, enhances photosynthesis and plant yield, antibacterial, smart delivery systems, pesticide detection, greenhouse lighting alternative	Dose-dependent toxicity, interaction with biomolecules, instability of bare core QDs, photobleaching	[146], [14], [23], [20]
Carbon Quantum Dots (CQDs)	Carbon-based; sp^2 core with oxygenated functional groups (COOH, OH, etc.), often plant-derived	< 10 nm (e.g., ~ 2.5–4.1 nm)	Low toxicity, eco-friendly, enhances plant growth, photosynthesis, scavenges radicals, drought stress mitigation, heavy metal adsorption, antimicrobial, fluorescent detection of herbicides	Generally safer, but may inhibit root growth/cell division at high concentrations; lower crystallinity than GQDs	[18]
Graphene Quantum Dots (GQDs)	Derived from graphene; single/multi-layer graphite with functional groups	< 10 nm	High crystallinity, thermal/electrical conductivity, photostable, boosts chlorophyll, improves overall plant growth, soil moisture sensors	Requires specific synthesis methods like CVD or top-down carbon precursor breakdown	[18], [146]
Silicon Quantum Dots (SiQDs)	Silicon confined in Si_3N_4 or SiC	< 4.3 nm	Biodegradable, nontoxic, size-tunable emission, enhances water absorption, light conversion for photosynthesis	Limited optoelectronic performance in bulk form; needs confinement in insulating materials	[18]
Semiconductor QDs (e.g., CdSe, ZnS, CdS)	II-VI elements (e.g., CdSe, ZnS, CdS), core/shell structures	1–12 nm (e.g., ZnS: 2.4 nm)	High luminescence, used in PEC hydrogen generation, nutrient absorption (ZnS QDs), increased chlorophyll	High toxicity (e.g., Cd, Pb), oxidative stress, DNA damage, harsh synthesis methods	[14], [20], [23]
Zinc Oxide (ZnO) NPs/QDs	ZnO	QDs, 20–60 nm	Fertilizer effect, improved growth (tomato, soybean), increased Fe/chlorophyll, antioxidant enzyme activity, antimicrobial properties	High concentrations can reduce chlorophyll; bare particles may cause soil metal accumulation	[14], [154]
Silica Nanoparticles (SiNPs)	SiO_2 (e.g., amine-functionalized from fly ash)	5–100 nm (avg. ~4 nm)	Stable, eco-friendly, enhances photosynthesis (FRET), growth parameters, stress resistance, pathogen protection, insecticidal, synthesized from waste	Weak fluorescence without amine functionalization	[165], [154]
Carbon Nanotubes (CNTs)	Carbon-based; single-walled or multi-walled	Lengths: 2.44–3.44 µm	High mechanical/electronic/thermal properties, biosensors, drug carriers, protein adsorption (e.g., BSA)	Cytotoxicity, membrane disruption, high dependence on size/shape/surface properties, defects act as binding sites, often negatively charged	[16]

techniques such as hydrothermal method,, chemical peeling, microwave-assisted and the electrochemical peeling method [44, 45]. Bottom-up approaches involve pyrolysis of small organic compounds like citric acid, glucose, fructose, and ascorbic acid, which can be utilized alongside other molecules to introduce heteroatom doping elements like nitrogen, boron, and sulfur [46–48]. Wet chemical and vapor phase methods are the commonly used bottom-up approaches for synthesizing QDs [3]. Top-down methods offer significant advantages including the capacity to scale up carbon dot (CD) production while producing well-defined CD structure [49]. It is useful for creating QDs from existing bulk materials, but they are limited due to the potential for defects and require additional purification [18, 44]. However, Kang et al. [50] introduce a novel top-down for fabricating the GQDs by patterned etching of graphene with self-assembled gold (Au) nanoparticles formed via solid-state dewetting, offering precise control over size, optical properties, and oxygen content through thermal reduction. Bottom-up approaches, on the other hand, assembled from smaller units allow for more precise control over QD characteristics, making them more favorable for producing high-quality quantum dots [51]. However, these approaches are not ideal for large-scale production because of their low yield and the complicated purification process [52].

4.1 Top-down approach

Top-down synthesis approaches are widely employed for the fabrication of GQDs, primarily through the breakdown of larger carbon-based materials into nanoscale structures. The Liquid Peeling (LP) process has emerged as a prominent method due to its scalability, low cost, operational simplicity, and minimal environmental impact [53]. In this method, graphite is exfoliated into graphene sheets, which serve as precursors for GQDs with strong crystallinity. Both low- and high-defect carbon sources, such as graphite powder and acetylene carbon powder, can be utilized, enabling the production of GQDs with varied structural properties [54]. A recent advancement in this method involves the use of high-intensity ultrasonic waves to further disintegrate graphene into ultra-fine particles, followed by extraction using solvents such as water or N, N-dimethylformamide (DMF) [55]. GQDs obtained from water typically exhibit smaller sizes, averaging around 4.1 nm, whereas those from DMF are relatively larger [56]. A key advantage of the LP method is that it does not require additional carbon sources, and its parameters can be adjusted to tailor the physicochemical characteristics of the GQDs, making it a highly adaptable and efficient synthesis route [55].

The hydrothermal and electrochemical methods are also extensively used in top-down synthesis. The hydrothermal technique involves the decomposition of carbon precursors, such as graphite oxide, using strong oxidants including HNO_3, H_2SO_4, and H_2O_2 under high temperature and pressure conditions [57]. By varying the reaction temperature, the size of GQDs can be controlled, with higher temperatures generally yielding smaller particles [56]. This method has also enabled the synthesis of blue-luminescent GQDs with high quantum yields and functionalized derivatives such as PEG-coated GQDs [58, 59]. The electrochemical method employs graphite-based electrodes and electrolytes to generate reactive radicals under an electric field, facilitating the oxidative cutting of graphene into GQDs [60, 61]. Different electrolyte compositions and carbon sources influence the yield and size of the resulting GQDs, with weak electrolytes typically offering higher efficiency [65]. Although this method allows for the production of GQDs with tunable surface functionalities and good optical properties [66], it presents challenges in raw material handling and scalability due to complex processing steps and relatively lower yields.

4.2 Bottom-up approaches

Bottom-up approaches for synthesizing GQDs involve constructing nanostructures from molecular or atomic precursors, offering precise control over size, shape, and functionalization. One commonly used technique is the microwave-assisted hydrothermal (MAH) method, which addresses the lengthy reaction times typical of traditional hydrothermal synthesis [67]. This method integrates the benefits of hydrothermal and microwave heating, using microwave irradiation to provide rapid, uniform heating, thereby accelerating the reaction and enhancing product uniformity. Glucose is frequently employed as a carbon precursor to synthesize water-soluble GQDs, with uniform size and morphology [56]. The GQDs produced by MAH have shown maximum radiation energies of 4.1 eV and the shortest emission wavelengths compared to other quantum dots [68, 69]. In one study, glucose underwent dehydration and nucleation, leading to pyrolytic transformation into GQDs with surface-bound functional groups [70]. Additionally, microwave irradiation of graphene oxide (GO) at temperatures above 190 °C for 5 min has been demonstrated to yield monodisperse GQDs, followed by neutralization and centrifugation to isolate the product [56]. This technique has proven effective for fast, scalable synthesis of high-quality GQDs with desirable optoelectronic properties.

The soft template and carbonization pyrolysis methods also offer effective bottom-up pathways for GQD fabrication. The soft template method enables controlled synthesis of nanostructures by utilizing soft molecular assemblies to direct the formation of GQDs, providing better control over particle size, shape, and surface texture [71, 72]. Yang and co-workers synthesized GQDs using 1,3,5-Tri-amino-2,4,6-trinitrobenzene (TATB) as both the carbon source and soft template, where thermal decomposition produced gases such as NO, NO_2, and H_2O, which expanded the structure into graphite-like sheets [73, 74]. Another study utilized Hexa-peri-hexabenzocoronene (HBC) as a precursor to create 60 nm disc-shaped GQDs through pyrolysis, exfoliation, and reduction processes [75, 76]. The carbonization pyrolysis method, also referred to as small-molecule carbonization, is another widely used technique due to its simplicity and versatility. It involves heating organic precursors like glucose, ethanolamine, and citric acid above their melting points, causing them to condense and form GQDs [77, 78]. Glucose-derived GQDs have shown sizes between 7 and 10 nm, high crystallinity, and abundant carboxyl groups on their edges [79]. Other precursors such as thiourea and hexaphenylbenzene have been used to produce doped or structurally defined GQDs with varying dimensions and optical properties [80, 81]. These bottom-up methods not only facilitate high-quality GQD synthesis but also offer pathways for producing application-specific nanomaterials. In broader terms, the synthesis approach significantly influences QD properties, which affect their functionality in diverse fields such as electronics, biomedicine, agriculture, and pharmaceuticals. While physical methods are commonly used for surface integration of QDs, they often suffer from high cost and poor stability [82, 83]. Chemical synthesis remains prevalent despite its associated toxicity, whereas biological methods present safer alternatives with improved biocompatibility and environmental sustainability [84].

4.3 QDs approaches applied in agriculture

Both top-down and bottom-up approaches are utilized for synthesizing QDs, including graphene quantum dots (GQDs) and CQDs, for agricultural applications [146]. However, refer to the most studies, the bottom-up approach appears to be the most prevalent and preferred method, particularly for plant-derived and biomass-based CQDs in agriculture [146, 152]. The bottom-up approach is widely adopted for synthesizing plant-derived CQDs, primarily due to its high yield. This approach constructs QDs from small molecular precursors [146], offering generally good control over GQD properties and often proving simpler and more efficient [152]. This method strongly aligns with green synthesis strategies, which are highly preferred over chemical methods in agriculture because they are environmentally friendly, utilizing eco-friendly reagents like natural extracts and waste biomass to produce biocompatible QDs [146, 156]. Plant parts such as roots, stems, leaves, fruits, flowers, and seeds serve as cheap, safer, highly abundant, and environmentally friendly precursors for green synthesis of CQDs, eliminating the need for separate reactants for doping or surface passivation due to their inherent biomolecules [146, 152]. The hydrothermal method is highlighted as the most dominant method for synthesizing biomass-based CQDs, known for being simple, affordable, and environmentally beneficial [146, 152]. Other prominent bottom-up techniques include microwave pyrolysis/assisted hydrothermal (MAH) and pyrolysis/carbonization [168]. These methods enable the creation of QDs from various agricultural waste materials like groundnuts, sweet corn, lemon peel, cashew gum, *Calotropis gigantea* leaves, Mexican mint leaves, watermelon peels, lychee seeds, and peanut shells for applications such as bioimaging, enhancing plant growth, and improving stress tolerance [146].

The top-down approach involves breaking down bulk carbon materials into nanoscale dots, but it often requires significant energy input, costly equipment, and harsh conditions, which can lead to structural imperfections or impurities [145]. Common top-down methods include chemical oxidation, ultrasonic synthesis, and electrochemical carbonization. Chemical oxidation, for example, uses strong oxidants to exfoliate large carbon chunks into smaller CQDs while adding hydrophilic groups to improve water dispersion and fluorescence [146]. Ultrasonic synthesis has been used to produce CQDs from biomass waste materials like sugarcane bagasse, garlic skin, and taro scalp [152]. Although one source states that oxidative cleavage is used extensively in the synthesis of GQDs due to its simplicity and efficiency [156], the broader context of agricultural applications, particularly with the emphasis on plant-derived and biomass-based QDs, consistently points to the bottom-up approaches, especially hydrothermal synthesis, as the more widely adopted and dominant methods for sustainable agricultural development [146].

5 Application of QDs in agriculture

Agriculture involves the cultivation of natural resources to sustain human life, offering essential food for survival and supporting the livelihoods of people globally. Over the past two decades, advancements in agricultural technologies have significantly reduced the number of malnourished individuals. Nonetheless, problems such as insufficient crop yields, pesticide and herbicide accumulation, deteriorating soil quality, reduced nutritional value, lower moisture content, and the pervasiveness of plant-related diseases still exist [85]. Nanomaterials (NMs) such as TiO2, ZnO, Mg, Ag, Cu, Al, and Zn, are commonly used to enhance plant productivity and expected to offer solutions for future food supply challenges [86, 87]. However, these metal and metal oxide NMs exhibit several drawbacks, particularly their toxicity [88]. In the agricultural application of nanomaterials, biocompatibility is crucial, ensuring that the materials do not harm plants, the environment, or ultimately, human consumers [146]. In recent years, CQDs with their exceptional properties such as remarkable photoluminescence, high biocompatibility, photo-induced electron transfer, low cost, and low toxicity, safely exiting without causing significant pathology, unlike some metal-based NMs, offering the potential to enhance plant growth and yield [22, 89]. QDs biocompatibility ensure their application does not significantly alter the pathology or normal physiological processes of the plant like enhanced growth or photosynthesis without causing cellular damage or stress [6, 146]. For instance, CQDs are capable of dispersing in all biological media, which stabilizes them for labeling and imaging biological samples without additional modifications [89]. Complementing this, functionalization plays a vital role by tailoring NM properties for specific agricultural benefits which involve elemental doping and surface passivation [40, 146]. For instance, X-ray Photoelectron Spectroscopy (XPS) analysis of CQDs has confirmed the presence of oxygen-containing functional groups such as hydroxyl, carboxyl, and carbonyl (C–O, C = O, and O–C = O bonds), which are responsible for their hydrophilic nature and improved photoluminescence quantum efficiency and stability in water, crucial for dispersion in biological media [92]. Analytical results from corn plants treated with N-CDs demonstrate remarkable improvements with foliar application of 5 mg L − 1 N-CDs increased the net photosynthesis rate by 21.51%, carbohydrate content by 66.43% in roots and 42.03% in shoots, and led to significant increases in fresh and dry weights compared to undoped CQDs [94]. Summarize of QDs application in agricultural practice shown in Fig. 2.

5.1 QDs as artificial light harvesters

Photosynthesis involves the process of plants converting the light energy to produce the glucose and oxygen based on Fig. 2(a). However, in conditions of light constraint such as erratic weather or cold winters, plants are unable to perform photosynthesis effieciently. The ability to harvest energy from light is crucial in optimizing photosynthetic processes in plants. Photoluminescent QDs can be utilized as artificial antennas to absorb light

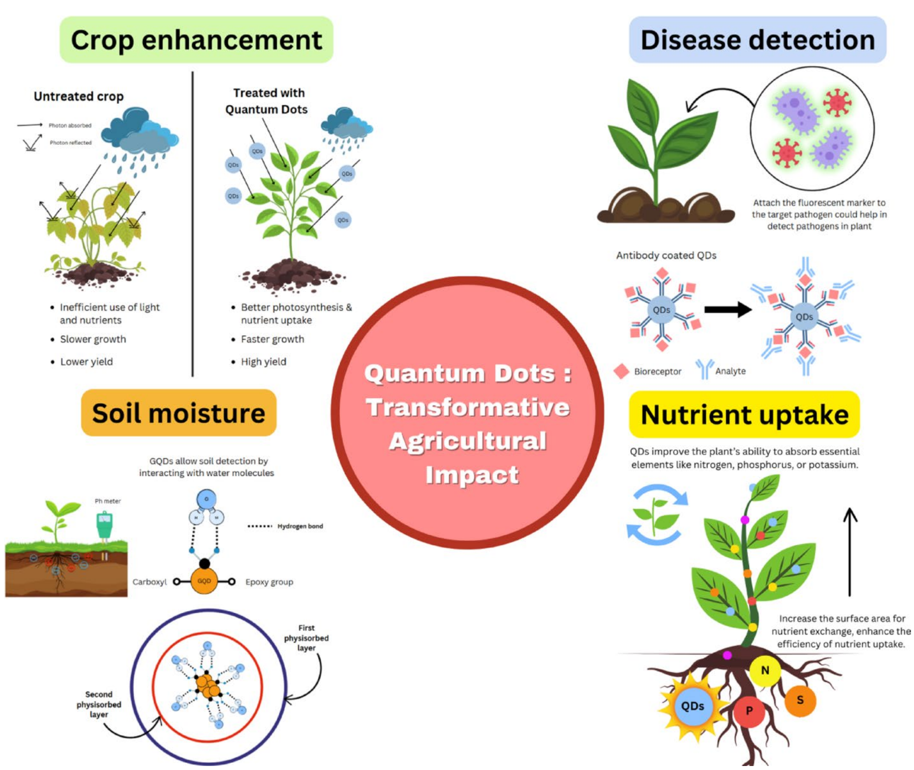

Fig. 2 Impact of quantum Dots (QDs) in agriculture

efficiently across a wide range of photon energies in the solar spectrum. QDs, carbon-based nanomaterials significantly enhance photosynthesis efficiency, thereby boosting plant growth and yield [90]. CQDs helped utilize the photosynthetic parameters such as stomatal conductance, rubisco activity, carbohydrate content, and chlorophyll concentration [89]. For instance, CQD treatment resulted in a 22% increase in glucose content in mung beans, indicating improved photosynthetic efficiency and growth [91]. CQDs in maize resulted in significant increases in both fresh and dry biomass, indicating better overall plant productivity [89, 92]. The treatment of garlic plants with GQDs also showed significantly enhanced root growth, as evidenced by the increased root length observed in GQD-treated plants, which could lead to improved nutrient uptake and overall plant health [93]. The potential of N-CQDs to optimize photosynthesis was highlighted by their significant 206.8% increase in the net photosynthesis rate in maize when compared to controls [94]. These improvements in photosynthesis directly translate into higher carbohydrate production, which is essential for plant growth and yield.

The mechanism involves QDs acting as artificial antennae that absorb light across a broader spectrum, including UV, visible, and near-infrared, and then transfer this energy to the chloroplasts within plant cells [92]. This enhanced light absorption capacity allows QDs to modulate and accelerate the electron transfer process in Photosystem II (PSII) and Photosystem I (PSI), thereby boosting the overall electron transport chain in photosynthesis. The unique fluorescent properties of QDs, often with blue emission, can overlap with chloroplast absorption, facilitating resonance energy transfer and improving light energy utilization efficiency. Furthermore, QDs can serve as electron donors, which directly supplies electrons to accelerate light-dependent reactions and water decomposition in PSII [94]. Foliar spraying of CQDs derived from empty fruit bunch (EFB) biochar significantly enhanced photosynthesis in both rice (C3) and corn (C4) crops [92]. It increased the CO2 assimilation rate by 56% in rice and 16% in corn, and stomatal conductance by 56% in rice and 18% in corn compared to control plants. The maximum rate of electron transport (Jmax) also saw a notable increase of 57.3% in rice and 65.5% in corn. These photosynthetic improvements resulted in enhanced growth and yield, with rice height increasing by approximately 20.9% and significant increases observed in corn ear weight and the average weight per 1000 rice grains. Nitrogen-doped Carbon Dots (N-CDs) demonstrated even stronger promotional effects due to optimized structure for light conversion and electron supply [94]. Foliar application of N-CDs (5 mg·L − 1) on corn increased light conversion efficiency by 121%, net photosynthesis rate by 21.51%, and electron transport rate (ETR) by 122.80%. This led to increases in root carbohydrate content by 66.43%, shoot fresh weight by 34.56%, and root dry weight by 72.30%. Corn yield increased by 24.50%, and the 1000-grain weight by 15.03%. Thus, QDs play a key role in improving photosynthetic efficiency by optimizing light absorption and promoting chlorophyll activity, consequently enhancing crop yields.

5.2 QDs for disease and pathogen detection

QD-based biomarkers have gained significant attention for their potential in biosensing, which allow for detection of specific diseases or conditions as well as the identification of disease subsets using QD-based diagnostic markers [95]. For instance, Polyethyleneimine-coated MXene Quantum Dots (PEI-MQDs), improved cotton tolerance to *Verticillium dahliae*, a significant fungal pathogen that promotes infection by inducing reactive oxygen species (ROS) [96]. PEI-MQDs are specifically designed to scavenge and alleviate the excessive ROS. In vitro, PEI-MQDs retained their ability to scavenge H2O2 and exhibited peroxidase-like activity. Upon application to cotton, pretreated plants exhibited fewer disease symptoms and increased tolerance to *V. dahliae*. This was supported by a reduced disease index, decreased fungal recovery, and less vascular tissue browning, the treated leaves also showed significantly lower malondialdehyde (MDA) and H2O2 content, along with increased activities of antioxidant enzymes such as catalase (CAT), glutathione peroxidase (GSH-PX), and peroxidase (POD) [95]. This demonstrates that PEI-MQDs effectively maintain ROS homeostasis to protect plants from disease without inhibiting the development of the pathogen.

CDs exhibit broad-spectrum antibacterial and antifungal activity, which makes them potentially useful in crop disease prevention and resistance enhancement [7, 99]. In biological application, degradable CDs synthesized from vitamin C have demonstrated strong broad-spectrum antibacterial activity against both Gram-positive and Gram-negative bacteria, offering a promising solution to infectious diseases, without the issues of potential biological toxicity and poor degradation associated with other nanomaterials [100, 101]. CDs exhibited concentration-dependent antibacterial activity, fully inhibiting *Bacillus subtilis* and *Bacillus* sp. WL-6 at 50 $\mu g \cdot mL^{-1}$, and *Staphylococcus aureus* and *Escherichia coli*, including antibiotic-resistant strains, at 100 $\mu g \cdot mL^{-1}$. In all tested strains, bacterial viability dropped from 100% to 0% as CD concentration increased, confirming their strong bactericidal effect. The CDs act by adsorbing onto and entering bacteria via diffusion, disrupting cell walls and membranes as seen by microscopy, and binding to DNA and RNA to interfere with gene expression, ultimately killing the bacteria [100]. Importantly, these vitamin C-derived CDs are low in cytotoxicity, maintaining about 90% human cell viability at 800 $\mu g \cdot mL^{-1}$, and are fully degradable into CO_2, CO, and H_2O within 20 days under visible light or mild heat, as well as in biological media like PBS, LB, and FBS. Their research showed that chemical composition of CQDs contributes to their lower toxicity by reducing the potential for harmful ion release, making them a safer alternative in various applications. These findings show that customized QDs can be a sustainable, non-toxic, and highly efficient substitute for treating plant diseases, making them a promising approach for increasing crop health and resilience.

5.3 QD-based nanosensors in soil health monitoring

Kalita et al. [102] states that GQDs-based sensors demonstrated higher sensitivity compared to existing soil moisture sensors at higher moisture content, which can be attributed to the Grotthuss chain reaction and ionic conductivity. The Grotthuss chain reaction enables effective proton hopping between adjacent water molecules (H2O + H3O+ → H3O + + H2O) under the influence of an applied electric field [169]. This process is facilitated by the high concentration of oxygen functional groups on the GQDs surface, leading to a significant increase in conductivity at higher moisture levels. Water is known to enhance conductivity in pristine graphene by inducing p-type doping, thereby increasing the concentration of holes and enhancing hole transport in the quantum dot system [170]. Additionally, at higher moisture values, physiosorbed water can penetrate the GQD film network, promoting the hydrolysis of functional groups like carboxyl and hydroxyl groups on the GQDs, and the resulting ions contribute to ionic conductivity [169]. These GQD sensors have been successfully tested in different soil environments, showing conductance changes from 0.06 × 10 − 6 1/Ω to 0.68 × 10 − 6 1/Ω in white clay as moisture increased from 4% to 45%, and from 0.06 × 10 − 6 1/Ω to 0.48 × 10 − 6 1/Ω in bentonite clay for moisture ranges of 11% to 90% [102]. They exhibit impressive stability for approximately 4 months and a rapid response time of 2–3 min, the lowest reported for resistive soil moisture sensors.

Beyond moisture sensing, fluorescent CQDs demonstrated potential for detecting herbicide residues in soil, such as trifluralin and alachlor [104, 105]. Red-emissive N-CQDs were synthesized through microwave-assisted hydrothermal treatment, have been used for highly selective and sensitive fluorescence detection of alachlor herbicide, showing a linear decline in fluorescence with increasing alachlor concentration and achieving a low limit of detection (LOD) of 0.2 nM with satisfactory recoveries in soil samples [105]. Similarly, CQDs green-synthesized from cherry tomatoes have demonstrated potential for detecting trifluralin herbicide [105]. This sensing system exhibited a linear relationship for trifluralin concentrations from 0.050 to 200 μM with a very low LOD of 0.5 nM, high selectivity, and excellent stability across various pH levels, UV exposure, and storage times. The quenching mechanism for trifluralin detection was identified as a static quenching process. Furthermore, fluorescent N-CQDs derived from natural biomass like orange and watermelon peels have been effectively used for the sensitive detection of oxytetracycline (OTC) antibiotics in soil samples [106]. Their detection mechanism involves fluorescence quenching due to FRET between the -NH_2 groups in N-CQDs and electron-deficient aromatic rings in the OTC structure. These N-CQDs achieved detection limits as low as 0.077 μmol L − 1 and satisfactory recoveries in pre-treated soil samples. Figure 3 (a) and (b) summarize the uptake QDs in plant tissue.

6 Mechanisms and interaction QDs with plants

The interaction of QDs with plants such as CQDs, enhances photosynthesis and supports plant growth through several mechanisms as shown in Fig. 4. QDs can absorb light across a broader spectrum, including UV, visible, and near-infrared light, which is important since plant chloroplasts mainly absorb light in the visible range. CQDs, for instance, absorb UV light and convert it into blue light, which is more efficiently absorbed by chloroplasts, improving photosynthetic efficiency by enhancing the performance of photosystem II (PSII) and photosystem I (PSI) [107, 108]. In plants, various mechanisms that QDs can be transported through symplastic and apoplastic pathways including endocytosis, pore formation, transport proteins, and plasmodesmata [109]. Nanoparticles can enter cells by diffusion, endocytosis, or direct uptake via ion channels and transporters because of their small size, which allows them to be absorbed by plant roots or leaves [110]. Plants require essential nutrients such as macronutrients (e.g., nitrogen, phosphorus, and potassium) and micronutrients (e.g., iron, zinc, and copper), which are absorbed from the soil through their roots using passive and active transport [111, 112] Smaller ions often reach root cells via passive diffusion, driven by concentration gradients such as diffusion, endocytosis, or direct uptake through ion channels and transporters [113, 114]. Endocytosis is an active transport mechanism that allows the plasma membrane to engulf materials into vesicles, which are then transported into the cytoplasm [115]. QDs utilize this pathway for cellular entry due to their small size and interact with the lipid bilayer of plant cell membranes [116]. However, nutrients present in low concentrations require an active transport, the energy-dependent

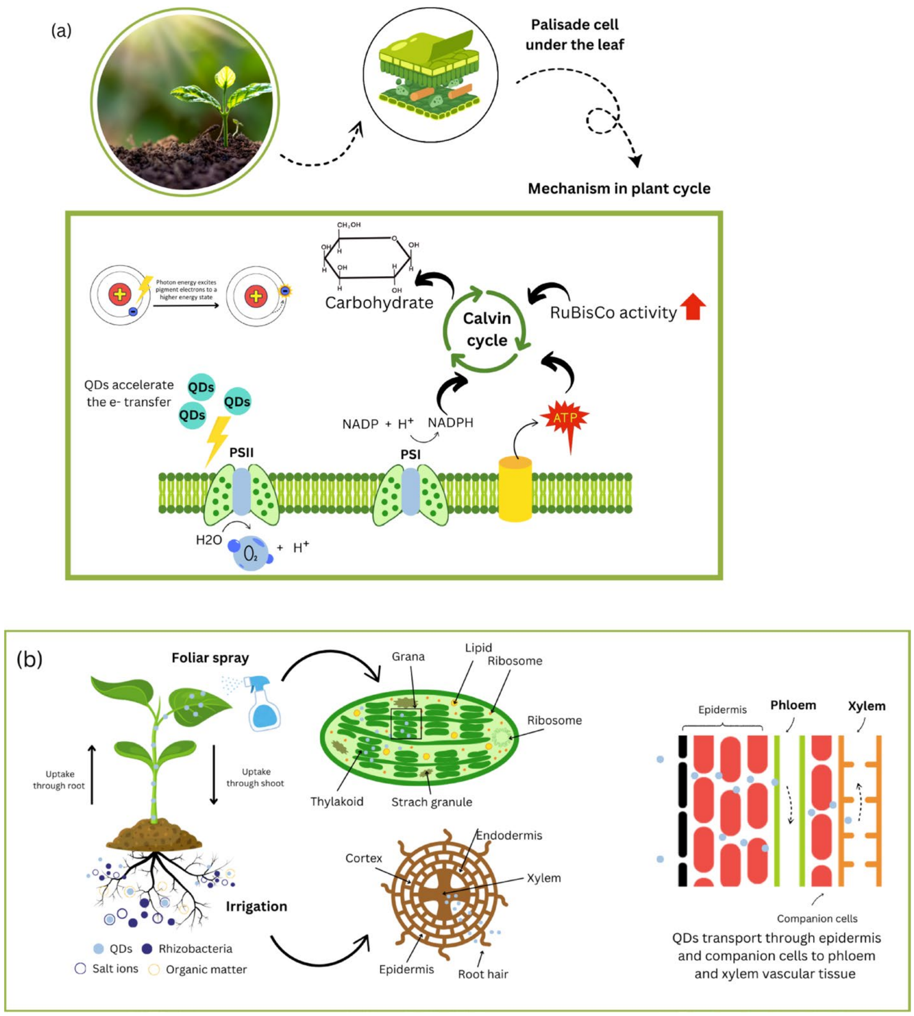

Fig. 3 (**a**) Mechanism of QDs uptake through leaves and their role in enhancing photosynthesis, and (**b**) Mechanism of QDs uptake through roots and their function in improving nutrient absorption

process mediated by root cell transport proteins such as K + transporters and channels like OsGORK, OsAKT1, OsHAK1, OsHAK5, and OsHAK21 [172]. QDs exhibit varying persistence and degradation kinetics in soil and water environments, largely dependent on their composition and environmental factors. CQDs, including GQDs, are generally characterized by high biocompatibility, low toxicity, and environmental friendliness, maintaining stable optical properties and showing less photobleaching and degradation under physiological conditions and even in soil moisture sensors for approximately four months [146]. However, in natural environments, CQDs are expected to agglomerate and lose photostability over time, with some studies showing degradation under visible light, releasing organic compounds, carbon monoxide (CO), and carbon dioxide (CO2) [100]. Similarly, nitrogen-doped CQDs (N-CQDs) and CQDs derived from cherry tomatoes exhibited stable fluorescence performance and good fluorescence stability for up to six weeks at room temperature, even after 60 min of continuous UV irradiation [105].

CQDs, including nitrogen-doped variants (N-CQDs or N-CDs), have demonstrated a significant ability to enhance photosynthesis in various plants by improving several key physiological parameters [92]. For instance, CQDs applied at 150 ppm via foliar spraying

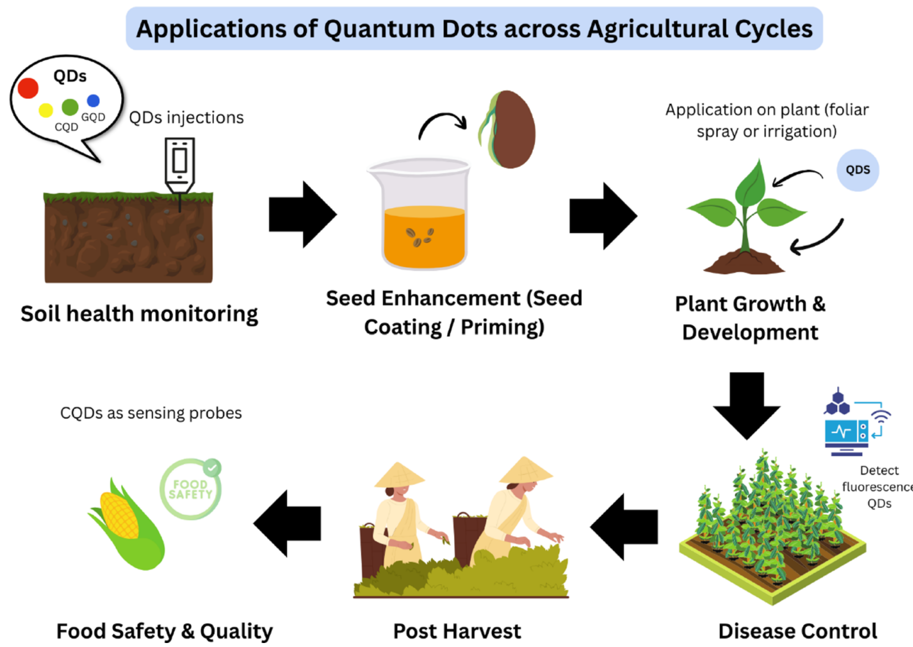

Fig. 4 Schematic QDs applications across agricultural cycles

Table 2 Several types of interaction mechanism of QDs

Interaction Mechanism	Molecular Pathway	Cellular Response	Quantitative Outcome	Citations
Photonic Energy Conversion	UV to visible light transformation	Chloroplast excitation	206.8% enhanced light absorption	[107], [8]
Electron Transport Modulation	Quantum-mediated electron transfer	Photosystem enzyme activation	Increased RuBisCO activity	[126], [127], [93]
Nutrient Translocation	Symplastic/Apoplastic pathway enhancement	Root cell membrane permeability	74.6% improved water uptake	[109], [18]
Stress Molecular Signaling	Reactive oxygen species regulation	Antioxidant system modulation	Disease resistance enhancement	[96]; [97]

led to a substantial increase in the CO2 assimilation rate of rice by 56% and corn by 16% compared to untreated controls. Similarly, N-CDs at 5 mg·L – 1 boosted the net photosynthesis rate in corn by 21.51%, outperforming conventional CDs which increased it by 12.47%. In a full life-cycle study, foliar-sprayed N-CDs increased corn photosynthesis by 44.48% during the reproductive growth period [94]. Other studies reported N-CQDs improving the net photosynthesis rate of maize by as much as 206.8% and 122.9%, and a general increase in photosynthesis rate by 28.6% [89]. N-CDs (5 mg·L – 1) raised corn chlorophyll content by 15.41%, and CDs by 10.00%. Specifically, maximum rate of photosynthetic electron transport (Jmax), increased in rice by 57.3% and corn by 65.5% with CQD treatment [92]. N-CDs dramatically increased ETR by 122.80% in corn, significantly higher than the 35.72% increase observed with CDs [94]. Overall, CQDs increased the electron transport rate in chloroplasts by 25% and the PSI rate by 10.4%. Thus QDs, particularly CQDs, enhance photosynthesis by improving light absorption, facilitating electron transfer, converting UV light into usable energy, and promoting carbon assimilation which collectively improve plant growth, productivity, and health. Table 2 shows different types of interaction mechanisms of QDs in plant, highlighting how they involve in molecular pathway and cell response.

Nanotechnology offers innovative approaches for remediating pesticide residues from contaminated environments, including soil and water bodies [171] These remediation approaches mainly involve adsorption and degradation. Carbon-based nanomaterials such as carbon nanotubes (CNTs), graphene oxide (GO), and electrospun carbon nanofibers (ECNFs) have shown effective adsorption of organophosphate (OP) pesticides through interactions like π-π stacking, hydrophobic forces, hydrogen bonding, and Van der Waals forces. ECNFs, for instance, have achieved up to 90% removal efficiency for ethion, a highly toxic pesticide, and demonstrate good stability and reusability across multiple cycles. Beyond adsorption, CuO nanoparticles with chitosan, achieved over 90% removal of malathion and dichlorvos from soil. Nanophytoremediation, using nanomaterials with plants, has also shown promise, with fullerene nanoparticles and multiwalled carbon nanotubes extracting contaminated pesticides from soil [171]. Nutrients transported within the plant via two primary pathways which the symplastic pathway, where they move through the interconnected cytoplasm via plasmodesmata [117], or the apoplastic pathway that involving movement through cell walls and intercellular spaces [118]. These channels are particularly important for the distribution of materials, such as nutrients or genetic materials delivered via nanoparticles, throughout the plant [110, 119]. The vascular system distributes nutrients, with the xylem carrying water and minerals from roots to aerial parts and the phloem transporting sugars and organic compounds [120].

Wang et al. [121], demonstrated diverse localization and translocation patterns in the xylem and phloem of *Zea mays*. For example, Gupta et al. [18] found that silicon quantum dots (SiQDs) enhanced the water absorption rate of cucumber seedlings' root systems by 74.6%. Additionally, the charge separation mechanism of QDs also enhances photosynthesis by absorbing light and producing excitons that split into electrons and holes, the electrons then transported to the chloroplasts and used in the electron transport chain [122, 123]. In Jia et al. [124], CQDs serve as electron donors, increasing the rate of electron transfer and light processes. CQDs also convert harmful radiation into photosynthetically active radiation (PAR), reducing photoinhibition and improving electron transport efficiency [125]. In plants such as *Vigna radiata*, *Trifolium*, *Oryza sativa*, *and Arabidopsis thaliana*, CiQDs activate key enzymes such as RuBisCo that promoting carbon fixation and assimilation, leading to better growth and productivity [91, 126, 127]. Furthermore, the hydrophilic surface of CQDs aids in water and nutrient uptake, improving growth, especially during seed germination and early growth stages [91]. In studies involving corn, watermelon, and zucchini, silver (Ag) nanoparticles significantly boosted germination rates, produced varying effects [173, 180]. Corn seeds exhibited improved germination rates of up to 6.5 seeds per day at a concentration of 1.5 mg/mL [180]. Watermelon and zucchini seeds showed germination rates of 73.33% and 90% at concentrations of 2 mg/mL and 2.5 mg/mL, respectively [180]. Root length increased in watermelon and zucchini but decreased in corn. Figure 4 shows the QDs application across every agricultural cycles.

7 Safety, toxicity and environmental impact

Although quantum dots have enormous potential across various fields, their application is limited by toxicity concerns, emphasizing the importance of addressing safety concerns while optimizing their functionality. Numerous factors are believed to contribute to the cytotoxicity of QDs, including their surface properties, size, concentration, exposure route, exposure duration, and coating materials [128, 129] Several QDs synthesized from heavy metal ions such as arsenic, lead, cadmium, and mercury exhibited toxicological effects. Despite their significant potential, the use of cadmium-based QDs is restricted due to their hazardous effects on biological systems and the environment [130]. Researchers have investigated these toxic effects and found that CdSe QDs exhibit toxicity under UV exposure due to their photolysis properties [131, 132]. Another study indicates that the release of cadmium ions from Cd-based QDs can damage cells and organs, as these ions bind to mitochondrial proteins, resulting in cell lysis [133]. Additionally, the frequent use of QDs and their high surface charge facilitate interactions with biomolecules, causing dose-dependent toxicity and limiting their clinical applications. Pristine CdSe QDs have been shown to interact with plant cell walls, particularly cellulose and lignin, through hydroxyl groups, causing structural changes and toxicity [134]. Furthermore, oxidative stress in plants induced by CdSe/ZnS QDs is reflected in the altered ratio of reduced to oxidized glutathione levels [135]. Although the toxicological effects of QDs are frequently associated with the release of cadmium ions, this release is dependent on factors such as QD physicochemical stability, synthesis methods, surface passivation, and environmental conditions [136].

The antibacterial effects of nanomaterials refer to their direct capability to inhibit or kill pathogens, often demonstrated in controlled laboratory environments. For instance, vitamin C-derived CDs show broad-spectrum activity by destroying bacterial walls, perturbing DNA/RNA, and inhibiting gene expression in both Gram-positive and Gram-negative bacteria, as well as fungi like *Rhizoctonia Solani* and *Pyricularia Grisea* [100]. Silver (Ag) and metal oxide nanoparticles (e.g., CuO, ZnO) also exhibit direct antimicrobial properties, often through mechanisms like cell membrane disruption and ROS generation [88]. In contrast, crop protection performance under field conditions encompasses a more comprehensive range of benefits to the plant, extending beyond direct microbial killing to include overall plant health, growth, and resilience within a complex environmental context [173]. Notably, some nanomaterials like polyethyleneimine-coated PEI-MQDs improve plant tolerance to pathogens such as *Verticillium dahliae* by scavenging excessive ROS that accumulate during infection, thereby maintaining the plant's cellular homeostasis rather than directly eliminating the pathogen [96]. Additionally, nanomaterials contribute to crop protection by improving overall plant vigor and stress tolerance, which includes enhancing photosynthetic efficiency, light harvesting, and CO2 assimilation through stomatal conductance [92]. This leads to improved nutrient uptake, water retention, root and shoot development, and increased biomass and yield, making plants more resilient to biotic and abiotic stresses like drought, salinity, and heavy metals [173]. However, the effectiveness of nanomaterials in crop protection is highly dose-dependent and can vary significantly with the nanomaterial type, concentration, plant species, and environmental conditions, with some metal-based nanoparticles exhibiting toxicity at higher doses [173].

Cytotoxicity in QDs might result from core degradation or reactive oxygen species (ROS) production [129]. Studies on plants highlight the genotoxic effects of QDs, such as DNA damage, which occurs when QDs and DNA are exposed to UV light or darkness, leading to the formation of free radicals [137]. For instance, undifferentiated cells of *Medicago sativa* exposed to mercaptopropanoic acid-functionalized CdSe/ZnS QDs exhibited increased DNA strand breaks [138]. Remarkably, some research found that smaller QDs were less harmful even at higher concentrations, highlighting the crucial part that size plays in QD-induced toxicity [139]. According to a study by Gao et al. [140] that examined the harmful effects of CQDs and CdSe quantum dots on *Chromochloris zofingiensis*, CQDs are considered less toxic compared to CdSe quantum dots due to differences in their chemical composition. To overcome the toxicity challenges associated with QDs, several strategies can be implemented to reduce their toxicological effects. First, the approach involves using non-toxic quantum dot materials, such as carbon, silicon, and group I – III – VI_2 materials, which exhibit lower toxicity and are more suitable for biological application [141]. Another strategy is coating QDs with a shell to reduce toxicity, enhance water solubility, and provide a surface for ligand binding. For instance, CdSe QDs coated with polyethylene glycol (PEG) demonstrate improved aqueous solubility [142]. Additionally, encapsulating QDs in biocompatible materials like phospholipid micelles has been shown to enhance their biocompatibility and minimize potential adverse effects. Hu et al. [143] demonstrated that encapsulating lead sulfide (PbS) QDs within PEGylated phospholipid micelles helped reduce their toxicity and MTS assays on Panc-1 cells, the in vitro showed over 80% viability at high QD concentrations (250 µg/ml) while in vivo, Balb/C mice demonstrated no significant pathological changes or histological abnormalities compared to control mice after injected four weeks of micelle-encapsulated QDs formulation. The study revealed that micelle-encapsulated PbS QDs exhibit significantly lower cytotoxicity compared to polyanhydride-coated PbSe QDs [143, 144], indicating phospholipid micelle encapsulation as an effective strategy for developing low-toxicity heavy-metal-based QDs appropriate for particular in vitro and in vivo applications. These findings highlight that employing non-toxic materials, protective coatings, and biocompatible encapsulation strategies effectively reduces the toxicity of QDs, making them safer for particular biological applications. The various types of QDs, along with their safety profiles and toxicity considerations, are summarized in Table 3.

The usage of nanomaterials in open-field agriculture faces significant regulatory challenges due to a lack of comprehensive scientific understanding and the absence of standardized testing protocols and frameworks [146]. There is inadequate data, especially on long-term effects on aquatic species and the transformation and degradation kinetics of nanomaterials in soil [146]. Regulatory bodies like the European Commission and the US Environmental Protection Agency (EPA) are already investigating these risks [103]. A major challenge is the lack of consensus on the dose necessary to cause toxicity or the specific biological effects generated by nanomaterials, which complicates the development of clear guidelines [88]. Environmental concerns include the potential for long-term accumulation in soil ecosystems, affecting beneficial soil microbiota, and the potential for nanomaterials to accumulate in plants and the food chain, necessitating further toxicity studies [146, 174]. Moreover, the potential implications of QDs for food safety, particularly concerning their translocation to edible plant parts, reveal a

Table 3 Summary of quantum Dots (QDs) Types, safety Profiles, and toxicity considerations

Type of QDs	Example of Compositions	Key Safety/Toxicity Considerations	Mitigation Strategies	Citation
Cadmium-based QDs	• CdSe • CdS • CdTe • CdSe/ZnS • CdTe/CdS	- High toxicity due to the release of cadmium ions (Cd^{2+}), which can induce oxidative stress. - Induces reactive oxygen species (ROS) production, leading to cell damage. - May lead to cell death through apoptosis and pyroptosis. - Can accumulate in organs like the liver and spleen.	- Surface coating or functionalization with materials like PEG to prevent ion release. - Use of core-shell structures (e.g., CdSe/ZnS) to reduce exposure of core materials. - Encapsulation in micelles to minimize toxicity.	[141], [129]
Carbon QDs (CQDs)	• GQDs • CQDs	- Generally less toxic than heavy-metal-based QDs - Produce lower levels of ROS. - Can be easily synthesized and are often water-soluble. - May still cause oxidative stress and affect cell metabolism at high concentrations. - Genotoxicity can be induced under certain conditions. - Some studies report no cytotoxicity from modified forms of carbon quantum dots (CQDs).	- Surface modification with biocompatible materials. - Conjugation with biomolecules like folic acid. - Use of non-toxic materials for synthesis.	[129], [140], [141]
Silicon QDs (SiQDs)	• Silicon-based	- Generally considered non-toxic. - Produce non-toxic silicic acid. - Toxicity depends on size, shape, and surface modification.	- Control of size and surface properties during synthesis. - Surface functionalization with biocompatible materials.	[129]
Indium QDs	• InP • InAs • InP/ZnS • InZnP • InZnPS	- Generally less toxic than cadmium-based QDs. - Can accumulate in organs like the liver and spleen. - Toxicity can vary depending on the surface coating and aging of QDs.	- Use of biocompatible coatings. - Control of aging conditions	
Other Metal QDs	• ZnO • $CuInS_2$/ZnS • Ag_2Se	- ZnO quantum dots (QDs) can induce reactive oxygen species (ROS) production. - Toxicity of QDs is dependent on composition and surface chemistry. - Ag_2Se QDs may exhibit toxicity based on their size.	- Control of surface chemistry. - Use of appropriate coatings. - Selection of less toxic elements for core materials.	[130], [140], [141]

significant knowledge gap regarding direct human consumption. CDs, especially plant-derived Carbon Dots (PD-CDs), are broadly promoted for their unparalleled potential in the development of advanced biomaterials [175, 176]. They are frequently described as exhibiting negligible cytotoxicity, excellent photostability, exceptional biocompatibility, ease of surface modification, and outstanding chemical inertness. Specific examples like mung bean-derived CDs are noted for advantages such as low toxicity, good biocompatibility and high stability [91]. Furthermore, *Salvia miltiorrhiza*-derived CDs were assessed as safe and exhibit excellent biocompatibility, making them suitable for application in plants for delaying the aging of post-harvest cabbage [175].

Additionally, QDs emerge as significant tools for smart farming and sensor networks, and their application methods are compatible with modern precision agriculture and potentially drone-assisted delivery. In the context of sensor networks, GQDs have been specifically developed as highly sensitive and affordable soil moisture sensors [102]. These resistive micro-sensors, featuring interdigitated electrodes and GQDs as the channel material, can measure soil moisture content in various soil environments with a rapid response time of 2–3 min, and exhibit stability for several months. This allows for continuous, accurate monitoring of soil moisture, which is essential for optimizing crop yield and water management. The small size and quantum properties of GQDs make them suitable for miniaturized devices, paving the way for advanced sensor formulations in future agricultural technology [102]. Furthermore, smart farming relies on monitoring vegetation indicators, detecting disease, and evaluating fruit maturity [89]. This encompasses tracking both internal crop factors, such as biochemical information within tissues or cells, plant health characteristics, and growth rates, as well as external environmental elements like soil moisture and nutrient status [176]. By collecting multimodal crop and soil data, smart farming enables farmers to continuously monitor, analyze, and even predict crop growth and yield in real-time. This capability facilitates the targeted and precise application of resources, including water, fertilizers, and pesticides, leading to refined crop management, intelligent operations, and scientific decision-making that enhance cultivation efficiency and agricultural sustainability [102, 176]. Key technologies driving smart farming include micro-nano sensing, flexible electronics, micro-electromechanical systems (MEMS), biotechnology, artificial intelligence (AI), machine learning, and hyperspectral sensing, which together enable miniaturized, intelligent, and multi-modal sensors [102, 176]. QDs are also being explored for their application in smart delivery systems, particularly for plant disease management [177]. A prominent example involves the use of surface-modified ZnO QDs [97, 177, 178]. The natural antibiotic Kasugamycin (KAS) was successfully attached to the surface of ZnO QDs, forming KAS-ZnO QDs that exhibited exceptional pH-responsive properties and increased photostability [177, 178]. In greenhouse experiments, these KAS-ZnO QDs were utilized for the controllable delivery of KAS and Zn(II) species, leading to a significant reduction in bacterial fruit blotch incidence, showcasing the potential of QDs as carriers for targeted agrochemical delivery [177, 179]. QDs, with their tunable optical characteristics and excellent photoluminescence, can serve as bright and stable fluorescence-based bioimaging probes for visualizing biological structures and processes [146]. This capability, combined with technologies like hyperspectral imaging and remote sensing, can provide farmers with real-time data on crop physiology, condition, yield, disease, and nutrient status, enhancing precision agriculture [89, 146].

7.1 Future perspectives

Quantum dots (QDs) hold immense potential for revolutionizing agricultural practices, yet several critical areas require further exploration to fully unlock their capabilities. One of the key challenges lies in optimizing the physicochemical properties of QDs, such as composition, size, surface charge, and quantum yield. Each of these factors significantly influences the biological activity and interactions of QDs with plants, which in turn affects their efficacy in agricultural applications. Future research should therefore focus on understanding how these properties can be fine-tuned to maximize their beneficial outcomes while minimizing potential risks. Specifically, a mechanism approach will be necessary to evaluate how different QD properties impact plant growth, disease resistance, and the overall health of crops under diverse environmental conditions. As research progresses, the focus will likely shift toward developing more environmentally friendly and biocompatible QDs, addressing the concerns associated with heavy metal toxicity. This will involve exploring alternative materials like carbon, silicon, and group $I-III-VI_2$ materials for QD synthesis. It is necessary to consider environmental safety as QDs gain prominence in plant applications; long-term field studies and ecotoxicological assessments are essential to evaluate their environmental impact and potential risks to natural ecosystems such as flora and fauna. The transition from heavy metal-based QDs to safer alternatives such as carbon and graphene quantum dots represents a viable solution to mitigate toxicity concerns. Furthermore, advancements in surface modification techniques, such as advanced coatings and biocompatible encapsulation strategies, will play a crucial role in mitigating toxicity and enhancing the stability and targeting capabilities of QDs. Emerging technologies like green synthesis of nanomaterials, nanobiofertilizers, and precision agriculture are expected to significantly enhance the effectiveness of QD-based coatings. Future seed coatings could integrate functionalized nanoparticles capable of releasing nutrients and growth stimulants in response to specific environmental triggers, revolutionizing seed germination and crop growth to make agriculture more resilient to climate change. For instance, encapsulating QDs in phospholipid micelles has been shown to reduce toxicity and improve biocompatibility. Another emerging research is developing multifunctional QDs that could involve integrating sensing, imaging, and delivery capabilities into a single QD platform. These multifunctional QDs could be used to monitor plant health, detect pathogens or nutrient deficiencies, and deliver targeted treatments, all in a single application.

more in-depth discussion about the future perspectives. and give limitations and knowledge gaps in current QD applications in agriculture.

7.2 Limitations and gaps

Despite the promising advancements, several critical limitations and knowledge gaps persist in the application of QDs in agriculture. There is a significant controversy regarding the extent of QDs' toxicological impact, with no consensus on the dose necessary to cause toxicity or the specific biological effects generated. There is a general lack of standardized toxicological evaluation and common assays to test CQD toxicity. Additionally, information on the long-term effects of CQDs on aquatic species is essentially non-existent. Thorough investigation of the potential environmental risks of introducing carbon nanomaterials into the environment is required, especially if they are to be used in the food sector. Moreover, the stability of QDs in soils is questionable over both short and long terms, with transformations leading to the release of potentially toxic metal species that can have enhanced mobility. Aggregation can also reduce mobility but doesn't prevent transformation over time. There is also a lack of knowledge concerning the electron transfer mechanisms of CQD/chloroplast interactions across different crop types, and the electron transfer rate may vary depending on the plant species. Furthermore, no research has determined how long CQDs remain active in leaves after application. By addressing these challenges through interdisciplinary research, standardized testing, and scalable production methods will be crucial to fully realize the potential of QDs in sustainable agriculture.

8 Conclusions

In conclusion, QDs represent a groundbreaking nanotechnology with the potential to transform agricultural practices and address global food security challenges. Their unique optical and electronic properties, particularly size-tunable fluorescence, photostability, and tunable emission, offer unprecedented opportunities for advancing agricultural applications. QDs can be employed to enhance plant growth and yield by optimizing photosynthesis, improving nutrient uptake, and mitigating the impact of plant diseases. Their ability to act as sensitive and selective sensors also holds promise for monitoring soil health, detecting contaminants, and optimizing resource management. Although the potential benefits of QDs in agriculture are vast, addressing concerns related to their potential toxicity remains paramount. Therefore, future research should prioritize the development of environmentally friendly and biocompatible QDs, ensuring their safe and sustainable integration into agricultural practices. The continued exploration of QD applications in agriculture holds the key to unlocking a more efficient, resilient, and sustainable future for global food production.

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Author contributions
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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval
Not applicable. This article does not contain any studies involving human participants or animals performed by any of the authors.

Consent to publication
Not applicable.

Consent to participate
I Wan Nur Zarifah Wan Azamuddin voluntarily agree to participate in this research study.

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