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Sustainable Approach of Carbon Nanodots: Agro-Applications for Soil Health

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CARBON is an essential element for all living organisms. This element has unique properties which increased its potential day by day. The nano-form of such element can be found in several patterns such as carbon nanodots (CNDs). Carbon nanodots refer to quasi-spherical nanoparticles of carbon which mainly consist of an amorphous structural core. The current mini-review involves the carbon-based nanomaterials with focus on carbon nanodots, their synthesis (chemical and green pathways) and characterization, agro-applications, CNDs for soil health, nanotoxicity of CNDs. This study may answer many questions on the CNDs including; what is the potential of CNDs in sustainable agriculture? What are the main agricultural applications of CNDs for soil health? Due to their unique properties, CNDs have a distinguished potential in many agricultural applications, such as nanocarriers, sensors, light converters, seed treatments, nanofertilizers, and as a potential agent to control plant-pathogens. Several advantages of CNDs can be noticed including the increased microbial activity, better nutrient availability, and reduced soil pollutants. These nano-enabled methods also can be anticipated to play a pivotal role in the forthcoming agricultural techno-revolution by providing sustainable ways to manage biotic and abiotic stresses in agriculture. The environmental dimension of the expected toxic of CNDs is a crucial global issue that needs more concerns. Further studies are needed for more discover and explanations on CNDs.

Keywords: Soil quality, Soil-plant-microbe nexus, Microbiomes, Rhizosphere, Microbe-microbe nexus, and Nanoparticles.

1. Introduction

In recent years, agricultural practices have faced several issues, due to the growing human population and the increasing demand for large quantities of good quality food, which is crucial for a healthy diet and illness prevention (Patel et al., 2020; Singh et al., 2024a). Further challenges, like mining activities, can result in soil degradation, while soil composition can be altered, which affects soil health over an extended period (Wang et al., 2024; Lal, 2025). Additionally, the usage of synthetic fertilizers and pesticides (Munné-Bosch and Bermejo, 2024), and the problems with soil erosion, loss of biodiversity, contamination of water sources, and depletion of essential minerals (Gamage et al., 2023) should be reduced to support the development of sustainable agriculture system (Gamage et al., 2023; Munné-Bosch and Bermejo, 2024).

Carbon nanodots (CNDs) are a recently commonly researched, absolutely newly explored nanomaterial plant-based product with great potential (Sharma and Soni, 2024). CNDs can be integrated into crop production and soil management with numerous techniques (Chandel et al., 2022; Prokisch et al., 2024). Collectively, Sustainable agriculture systems can be promoted by their biotechnological application of them (Chen et al., 2022a; Li et al., 2024). CNDs have a small size (less than 10 nm in diameter), high surface area, and unique structure (nanocrystalline or amorphous carbon structures), furthermore, it is soluble in water and has high fluorescence, photoluminescence, and minimal toxicity (Hu et al., 2017; Chauhan et al., 2022). CNDS can effectively interact with soil microorganisms, so crop yield and soil health can be improved (Li et al., 2020a; Li

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et al., 2024), which can help to solve the problems with food security (Shafi et al., 2024). The π-π conjugation structure of CNDs can help in electron transfer, which aims a potential in electroanalytical investigations (Montes et al., 2020; Hassanvand et al., 2021). The formation of secondary metabolites, and cholorophyll content can be enhanced by the ability to enhance photosynthesis with light converting (Aggarwal et al., 2024; Tanujaya, 2024). Furthermore, the effectiveness of pesticides and the reduction of disease resistance can be promoted by their nanocarrier propertiesIt results in improvements in crop yield and seed germination (Rehman et al., 2021; Aggarwal et al., 2024).

Plant resilience against abiotic stresses can be also enhanced (Aggarwal et al., 2024; Moustafa et al., 2024). However, several questions are opened about the nanotoxicity of CNDs. Recent research are focusing on the evaluation of its physicochemical properties, but the detailed mechanisms of actions are still unsurveyed. An understanding of CND mechanisms in biological systems is necessary to develop healthy agricultural products without health risks (Makhado et al., 2024; Sharma and Soni, 2024). Our review presents the potential of CNDs in sustainable agriculture. Its unique properties, the ways for the synthesis and characterization, and their potential agricultural applications, like as sensors, light converters, nanocarriers, seed treatments, nano fertilizers, and as a potential agent to control plant-pathogen will be also introduced. The effect of CNDs on soil health, plant-microbe interactions, and nanotoxicity will be also discussed. Furthermore, the attention will be drawn to future perspectives, which should be deeply explored to fight the challenges caused by human population growth and climate change.

2. Carbon-Based Nanomaterials: An Overview

Over the past few decades, advancements in nanoscience and nanotechnology have opened up significant opportunities for creating innovative nanomaterials (Serag et al., 2022; Ghazaryan et al., 2024; Singh et al., 2024b). These nanomaterials, characterized by at least one dimension under 100 nm, exhibit remarkable properties due to their unique optical., magnetic, electrical., and thermal characteristics and high surface area-to-volume ratio (Godeto et al., 2023; Gonfa et al., 2023; Mengstu et al., 2023; Singh et al., 2024c). These properties make them suitable for various innovative technological applications (Mousavi et al., 2017). However, the large-scale production of nanomaterials raises concerns about their potential toxicity to humans and the environment. Therefore, integrating nano-safety research into developing new nanotechnologies is essential (El-Kady et al., 2023). While many studies highlight the significant potential of engineered nanomaterials in advancing life sciences and technology, it is crucial to assess their safety and sustainability before market introduction thoroughly (Ayanda et al., 2024). Nanomaterials can be produced using 'top-down' and 'bottom-up' approaches, which include physical., chemical., and biological (biogenic or green) synthesis methods (Bachheti et al., 2020). They have extensive applications in food processing, agriculture, marine, environmental, biomedicine, pharmaceuticals, textiles, catalysis, sensors, mechanics, and electronics (Husen and Siddiqi, 2023; Singh et al., 2022).

Carbon is one of the most plentiful elements in the Earth's crust, a fact long recognized. The development of carbon materials has significantly progressed from macro-scale to nanoscale due to continuous advancements in nanoscience and technology (Arcudi et al., 2019). Carbon nanomaterials (CNs) depend heavily on their atomic structures and interactions with other materials at the nanoscale (DeCicco et al., 2019). Recent advancements have introduced various nanostructured carbon materials (NCMs) like diamond, graphene (GR), amorphous carbon, carbon 60, carbon nanotubes (CNTs), and carbon dots (CDs) for numerous electrochemical applications (Fig. 1). These materials can be categorized by their dimensions: zero-dimensional (0-D) nanodots, one-dimensional (1-D) nanotubes, two-dimensional (2-D), and three-dimensional (3-D) structures (Benzigar et al., 2018). Carbon-based nanomaterials (CBNs) are a diverse group with at least one dimension under 100 nm (Kong et al., 2024). They exhibit various structures and morphologies and are widely used in nanoelectronics, optics, catalytic chemistry, biomedicine, and sensors due to their excellent electrical conductivity, biocompatibility, stable chemical properties, and large specific surface area (Speranza, 2021; Gonfa et al., 2024). The development of different dimensions of nanomaterials, including CBNs, metal nanomaterials (MNMs), ceramic nanomaterials (CNMs), semiconductor nanomaterials (SNMs), and polymeric and lipid-based nanomaterials, has significantly enhanced human life and the environment (Patil and Chandrasekaran, 2020). Smart devices, particularly carbon-based nanomaterials like graphene quantum dots (GQDs), are increasingly popular due to their quantum properties and absorption capabilities (de Menezes et al., 2020). Safety concerns for CBNs primarily involve occupational exposure during manufacturing and technological applications (Qiao et al., 2024). The main health risks are inhalation and skin exposure during CBN production, especially as dry powders (de la Parra et al., 2024). Additionally, skin exposure is relevant for current CBN applications in cosmetics and skin biosensing using carbon nanotubes or graphene-based materials (Hajishoreh et al., 2023).

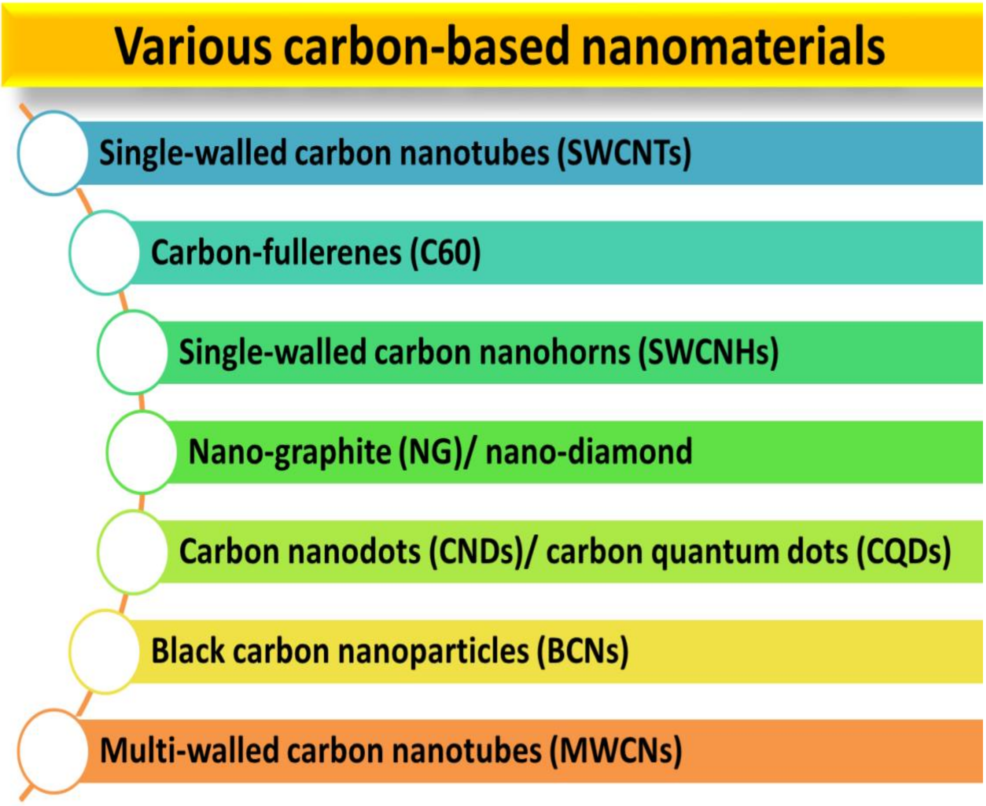

Fig. 1. Different suggested types of carbon-based nanomaterials.

The benefits of carbon-based nanomaterials (CBNs) may stem from their small size (typically less than 10 nm), their ability to form polar derivatives, and their high biocompatibility (Zadeh Mehrizi and Eshghi, 2021; Castro et al., 2023). These innovative materials are crucial in sensor technology (Tang et al., 2022) and have diverse applications, including improving oil recovery (Shayan et al., 2021), strengthening engineering materials (Sheikh et al., 2021), and serving as strain and external pressure sensors (Her and Liang, 2022; Kang et al., 2021). They are also used in nanocarriers (Jha et al., 2021), drug delivery systems (Navya et al., 2019), wastewater treatment (Villaseñor and Ríos, 2018), phase change materials (Olabi et al., 2021), plant chemical signaling (Zhu et al., 2022), anticorrosion (Ramezanzadeh et al., 2019), innovative construction materials (Guo et al., 2021), mycotoxin detection (Ma et al., 2021), eco-friendly supercapacitors (Landi et al., 2022), and tissue engineering (De Armentia et al., 2020). Compared to other nanoparticles like metal., silica, lipid, and polymer-based nanoparticles, carbon-based nanoparticles are less toxic (Ayanda et al., 2024; Baig et al., 2021) and are used as additives in drilling fluids (Rana et al., 2021). For example, carbon nanotubes (CNTs) and graphene are effective drug-delivery systems for targeting cancer due to their large surface area, high drug-loading capacity, and modifiable surfaces (Navya et al., 2019). Oxidized CNTs are highly efficient at removing heavy metals from the environment because of their rapid adsorption of metal ions (Villaseñor and Ríos, 2018). CNTs, carbon nanofibers (CNFs), and graphene are vital in cement composites for their high surface area, mechanical strength, and electrical conductivity (Guo et al., 2021).

Carbon-based nanomaterials (CBNs) include carbon nanotubes (CNTs), carbon nanofibers (CNFs), graphene, graphene oxide (GO), fullerenes, carbon quantum dots (CQDs), nano-cellulose, and graphite-like carbon nitride (Lu and Zhong, 2022). These nanomaterials exhibit significantly improved mechanical., physical., chemical., and electronic properties compared to their bulk carbon counterparts (Rana et al., 2021). The high thermal conductivity, considerable charge carrier mobility, and density of CBNs are attributed to the sp^2 hybridized carbon atoms in their structures (Deshmukh et al., 2021). Carbon dots (CDs), or carbon nanodots (CNDs), are zero-dimensional carbon-based nanomaterials with sizes under 10 nm. They are water-dispersible, UV-absorbing, highly fluorescent, and biocompatible (Zhang et al., 2024) and are smaller than most viruses and bacteria, primarily composed of sp^2 and sp^3 carbon hybridization (Kurniawan et al., 2024). These properties have made them highly attractive in biomedicine, sensors, optoelectronics, and light-emitting diodes (Yadav et al., 2023). CDs are notable for their intense fluorescence, large surface area, biocompatibility, low cost, simple production, stability, good water solubility, low toxicity, and excellent electrical conductivity (Kang et al., 2020; Nguyen et al., 2024). This versatility has led to their use in agricultural applications, such as nano pesticides, nano fertilizers, and nano antioxidants. Due to their small size, plants can absorb and transport CDs, influencing their physiological, biochemical, and metabolic processes (Kou et al., 2021). Their optical properties also enhance photosynthesis, potentially increasing crop yields (Li et al., 2021). Element-doped CDs can act as nano-fertilizers to support plant growth under stress conditions (Wang et al., 2021; Chen et al., 2025).

Carbon dots (CDs) can form inclusion complexes with various molecules, making them helpful in developing probes and sensors to detect contaminants in food, such as pesticides, herbicides, or heavy metals (Hoang et al., 2023). However, incorporating CDs into food products requires a thorough understanding of their safety (Nguyen et al., 2024). CDs can be synthesized using top-down or bottom-up methods and are generally classified into graphene quantum dots (GQDs), carbon nanodots (CNDs), which include carbon nanoparticles (CNPs) and carbon quantum dots (CQDs), and carbonated polymer dots (CPDs) (Xia et al., 2019). Unlike GQDs, CQDs and CPDs typically have spherical cores linked to surface moieties, with their photoluminescence properties influenced by intrinsic luminescence and quantum confinement effects (Hai et al., 2018). CQDs, known for their quantum confinement effect, exhibit superior optoelectronic properties (Skolariki et al., 2023) and have potential applications as visible light-activated antimicrobial agents (Heidari et al., 2022) and in diagnosing human coronavirus (HCoV-229E) (Saikia et al., 2024). CDs are also used in energy storage applications when mixed with various polymers (Huang et al., 2021) and as biosensing agents (Hussain et al., 2023).

3. Carbon Nanodots: Synthesis and Characterisation

3.1. Synthesis Method of CNDs

3.1.1. Chemical Synthesis of CNDs

Carbon nanodots (CNDs) are fluorescent nanoparticles with dimensions smaller than 10 nm, known for their unique propertiesThey can be synthesized primarily through top-down and bottom-up approaches (Singh et al., 2018), as illustrated in Fig. . The top-down techniques involve using larger precursor molecules through physical methods such as arc-discharge, laser ablation, and plasma treatmentConversely, the bottom-up approach synthesizes CNDs from smaller precursor molecules, employing methods like hydrothermal/solvothermal synthesis, microwave-assisted synthesis, and thermal decomposition (Sharma & Das, 2019). The microwave and hydrothermal methods are two of the most common synthesis methods due to their effectiveness (Nguyen et al., 2024). CDs are widely applied in sensing, catalysis, bioimaging, and biomedicine due to their excellent photoluminescence, water solubility, and low toxicity (Sharma & Das, 2019). Recent research has focused on developing large-scale production methods for CDs, including hydrothermal/solvothermal., microwave-assisted, and microfluidic techniques (Chen et al., 2023). These advancements in synthesis methods and functionalisation have expanded the potential applications of CDs in areas such as mechanical property enhancement, flame retardancy, and energy storage (Chen et al., 2023).

3.1.2. Green Synthesis of CNDs

Green synthesis of nanoparticles using plant extracts has emerged as an environmentally friendly alternative to traditional methods. This approach utilizes natural phytochemicals such as alkaloids, flavonoids, and terpenoids as reducing and stabilizing agents (Md Ishak et al., 2019; Singh et al., 2018). The process is simple, cost-effective, and can be conducted at room temperature without hazardous chemicals (Khatami et al., 2018; Mittal et al., 2013). Various metal and metal oxide nanoparticles, including silver, gold, zinc oxide, and iron oxide, have been successfully synthesized using this method (Md Ishak et al., 2019; Singh et al., 2018). The resulting nanoparticles exhibit high stability, low toxicity, and enhanced solubility (Khatami et al., 2018). These green-synthesized nanoparticles have potential applications in environmental remediation, such as antimicrobial activity, catalysis, pollutant removal., and heavy metal sensing (Singh et al., 2018). Additionally, they show promise in medical applications (Mittal et al., 2013). This eco-friendly approach represents a significant advancement in sustainable nanotechnology (Khatami et al., 2018).

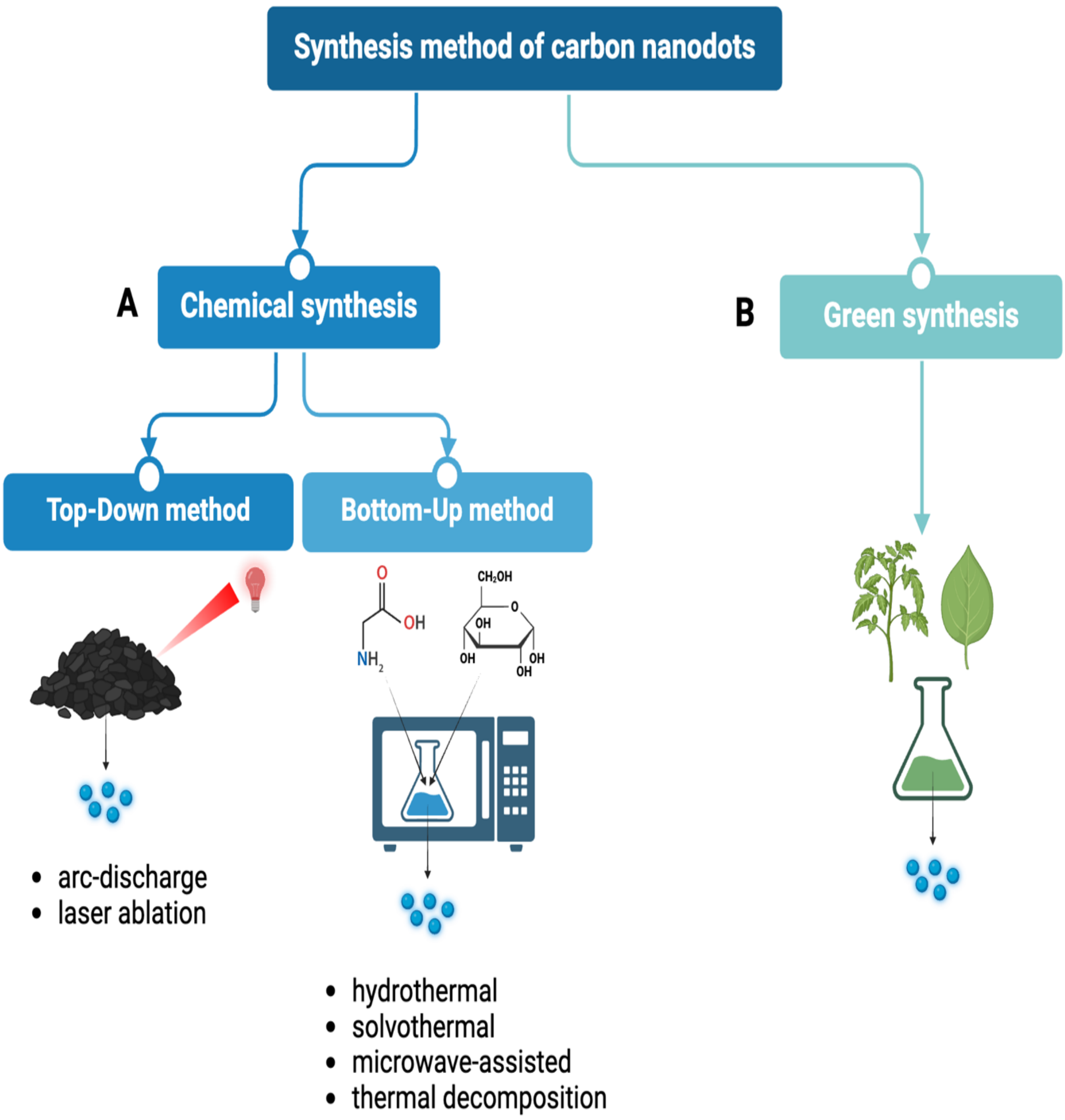

Fig. 2. Schematic diagram of common synthesis method of carbon nanodots (CNDs) including A, chemical synthesis of CNDs and B, Green synthesis of CNDs.

Recently, many researchers have chosen green synthesis as a new approach to synthesizing CNDs, as illustrated in Fig. 2. Various plant sources, including *Trapa bispinosa* peel (Mewada et al., 2013), guava leaves (Ramanarayanan & Swaminathan, 2020), and *Lawsonia inermis* leaves (Mary Alex et al., 2020), have been used to produce CNDs through methods such as hydrothermal synthesis and carbonization. These green synthesis approaches yield CNDs typically smaller than 10 nm, exhibiting fluorescent properties and good biocompatibility. Plant extract-derived CNDs demonstrate potential applications in cosmetics, offering antioxidant, anti-inflammatory, and UV protective properties (Ngoc et al., 2023). Additionally, they show promise in photocatalytic degradation of dyes for water purification (Ramanarayanan & Swaminathan, 2020). The synthesis methods for plant-based CNDs include pyrolysis carbonization, chemical oxidation, hydrothermal, microwave-assisted, and ultrasonic techniques (Ngoc et al., 2023). These eco-friendly CNDs present opportunities for sustainable nanotechnology in various fields, including cosmetics and environmental applications.

3.2. Characterization of CNDs

3.2.1. Optical Properties

Carbon nanodots (CNDs) are luminescent carbon nanomaterials with unique optical properties, including UV-Vis absorption, fluorescence, and phosphorescence (Lin et al., 2012; Zhao et al., 2020), illustrated in Fig. 3A. CNDs exhibit excitation-dependent and excitation-independent photoluminescence, with absorption peaks typically in the UV-Vis range (Zhao et al., 2015). Their fluorescence can be enhanced or quenched by various substances, suggesting potential applications in sensing and analysis (Lin et al., 2012). The optical properties of CNDs are attributed to surface defects, band bending, quantum confinement effects, and multiple emissive centers (Zhao et al., 2015; Liu, 2020). These properties can be tuned through synthesis methods and post-treatment, such as UV irradiation (Zhao et al., 2015). CNDs show promise in various fields, including bioimaging, biosensing, catalysis, and energy harvesting (Zhao et al., 2015). Understanding the optical mechanisms of CNDs is crucial for developing tailored materials with specific functional purposes (Liu, 2020).

3.2.2. Morphology and Structure

The structure and morphology of CNDs can be characterized using various techniques, listed in Fig. 3B. Transmission Electron Microscopy (TEM) allows for probing single nanoscale objects, while X-ray Diffraction (XRD) provides structural information representative of the whole material volume (Jurkiewicz et al., 2018). These methods, along with Scanning Electron Microscopy (SEM), are crucial for analyzing the size, shape, and structural properties of CNDs (Mintz et al., 2021; Abinaya et al., 2022). Studies have shown that different types of CDs, such as black CNDs, carbon nitride dots, and yellow CNDs, exhibit varying degrees of functionalization and disorder (Mintz et al., 2021). The combination of TEM and XRD can reveal detailed information about complex microstructures in non-monodisperse quantum dots, including size, shape, and planar defects, which is essential for understanding their optoelectronic properties and potential applications (Neumann et al., 2020).

3.2.3. Surface Chemistry

The properties of CNDs can be tuned through surface modification (Ren et al., 2019; Zhou et al., 2019). Various characterization techniques are used to measure the surface chemistry of CNDs, including UV-vis absorption, photoluminescence spectroscopy, X-ray spectroscopy, and Fourier Transform Infrared (FTIR) spectroscopy (Ren et al., 2019; Fawaz et al., 2023) (Fig. 3C). These methods reveal the presence of functional groups such as carboxyl, amino, and hydroxyl on the CNDs surface, which influence their photoluminescence properties and interactions with water (Ren et al., 2019). X-ray photoelectron spectroscopy can determine the O/C atomic ratio, indicating the degree of oxidation (Tan et al., 2013). Surface passivation with ligands like TTDDA, PLL, cysteine, and chitosan can enhance fluorescence quantum yield (Tan et al., 2013). The surface chemistry of CNDs plays a critical role in their applications, particularly in biotechnology and bioimaging (Zhou et al., 2019; Fawaz et al., 2023).

3.2.4. Surface Charge and Colloidal Stability

Dynamic Light Scattering (DLS) and zeta potential measurements are essential techniques for characterizing CNDs, in terms of their size, surface charge, and colloidal stability (Carvalho et al., 2018) (Fig. 3D). DLS is used to determine particle size and evaluate stability over time, pH, and temperature conditions, while zeta potential provides information about surface charge and interactions (Carvalho et al., 2018). These techniques are crucial for assessing nanoparticle behavior in various solutions, including water and cell culture media, with or without serum (Murdock et al., 2008). Factors such as agglomeration, sonication, and solution composition can significantly impact nanoparticle characteristics and their subsequent biological interactions (Murdock et al., 2008). Understanding these properties is vital for developing effective nano-formulations for therapeutic applications and accurately interpreting toxicity studies (Carvalho et al., 2018). Proper characterization using DLS and zeta potential measurements helps researchers optimize nanoparticle formulations for specific biomedical applications and target tissues.

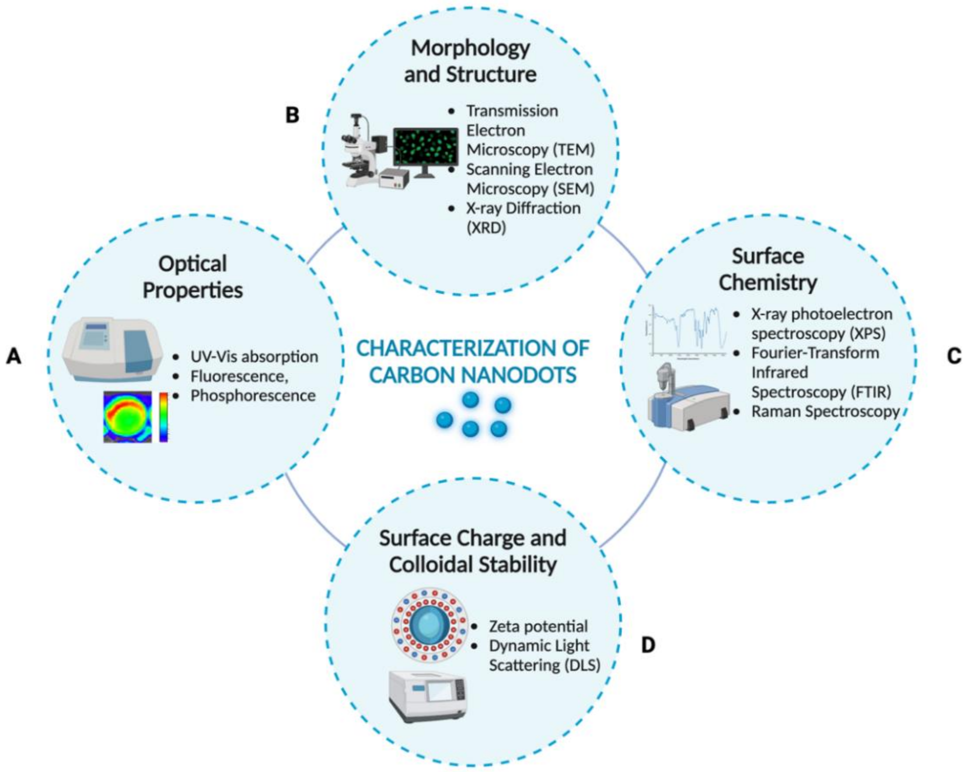

Fig. 3. Characterization of carbon dots includes four primary groups: A, optical properties; B, morphology and structure; C, surface chemistry; D, surface charge and colloidal stability.

4. Agro-Applications of Carbon Nanodots (CNDs)

Carbon nanodots (CNDs) exhibit biocompatibility, a high quantum yield, low toxicity, sustainability, excellent water solubility, and stability under light exposure (Xu et al., 2004). CNDs provide significant opportunities for various agricultural uses by utilizing their distinct characteristics. CNDs enhance photosynthesis and nutrient uptake (Wang et al., 2023a), promoting seed development (Chen et al., 2020a) and strengthening plant resilience (Wang et al., 2022); they also open new avenues for sustainable growth. Their multifunctional roles are essential for (1) monitoring soil and environmental health as CNDs-based sensors, (2) boosting plant growth and nutrient delivery, (3) protecting crops through disease management, and (4) optimizing photosynthesis for increased yield and resource efficiency, as illustrated in Fig. 4.

Carbon nanodots exhibit unique photophysical characteristics, such as tunable fluorescence and high quenching efficiency, which makes them ideal for optical and electrochemical sensing applications (Buiculescu et al., 2016; Ding et al. 2015). Their broad fluorescence spectrum and controlled emission behavior enable the development of various optical biosensors (Buiculescu et al., 2016). CNDs can be used as fluorescent nanomaterials for sensing environmental pollutants (Rasheed, 2023a), especially detecting heavy metal pollution in water systems. Annamalai et al. (2022) developed CNDs-based sensors for simultaneously detecting Cr^{6+} and Hg^{2+}, as the overuse of pesticides poses significant threats to human health and ecosystems, these CNDs-based sensors offer promising solutions for monitoring and controlling pesticide residues in food and the environment (Mishra et al., 2022). CNDs have been used to create highly sensitive fluorescent sensors capable of detecting pesticides like diazinon, glyphosate, and amicarbazone at nanogram-per-milliliter levels in real samples (Ashrafi Tafreshi et al., 2020). Wu et al(2022) developed a glyphosate nanosensor with an impressive detection limit of 0.8 ng/ml, utilizing an "off-on" fluorescence mechanismRed-emitting CNDs have been synthesized to detect organophosphorus pesticides at pg/L levels (Li et al., 2020b). These CND-based sensors can be integrated with various recognition elements such as antibodies, aptamers, enzymes, and molecularly imprinted polymers to enhance selectivity and sensitivity (Rasheed, 2023b). The fluorescent properties of CNDs can be greatly enhanced by doping and surface functionalization, adding to their versatility and efficacy (Nguyen et al., 2024). For example, one study involved the synthesis of S, N-doped CNDs to create paper-based chemiluminescence sensors for detecting bendiocarb pesticides in fruit juice and water (Al Yahyai et al., 2021). The results revealed that adding potassium permanganate ($KMnO_4$) elevated the fluorescence intensity significantly, indicating improved detection sensitivity.

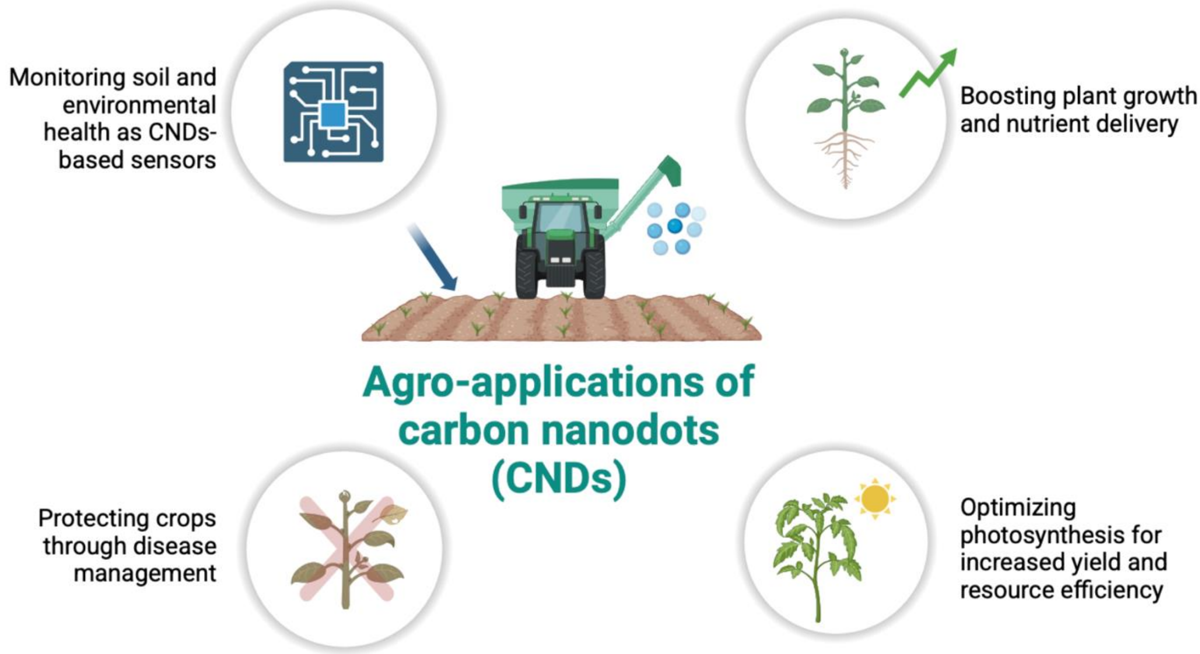

Fig. 4. Four primary applications of carbon nanodots (CNDs) in agriculture.

Due to their small size, hydrophilic surface groups, and electron donor-acceptor properties, CNDs can enhance seed germination rates (Chen et al., 2020b; Guo et al., 2022; Liang et al., 2023), promote root development (Chen et al., 2020b), and increase biomass accumulation (Chen et al., 2020b; Han et al., 2022) in various plant speciesStudies have shown that CNDs can significantly improve crop yields and quality through various mechanismsWhen applied to hydroponic lettuce cultivation, pollen-derived CNDs demonstrated remarkable growth-promoting effects and potential as a bioimaging probe (Zheng et al., 2017). CNDs also can nutrient absorption and photosynthesis (Guo et al., 2022). In soybeans, soil application of CNDs improved nitrogen bioavailability and drought tolerance by enhancing nitrogen fixation, regulating rhizosphere processes, and upregulating key genes involved in nutrient transport (Wang et al., 2022). The versatility of CNDs extends to targeted delivery of agrochemicals, stress resistance improvement, and post-harvest applications, making them a valuable tool for sustainable agriculture (Guo et al., 2022).

Carbon nanodots have shown promising applications in plant-pathogen control and crop stress managementStudies demonstrate that CNDs can inhibit the growth of various plant pathogens, including *Phytophthora infestans* and fungal species (Kostov et al., 2022). When complexed with dsRNA, functionalized CNDs enhance spray-induced gene silencing efficacy against *Phytophthora* pathogens, reducing the need for chemical fungicides (Wang et al., 2023b). CNDs can penetrate plant cells, reach the nucleus, and boost growth by increasing enzyme activity and carbohydrate generation (Li et al., 2018). They also improve plant tolerance to various stresses, including heat, drought, and pathogens (Zia et al., 2024). Notably, CNDs can enhance rice plant disease resistance by increasing thionin gene expression and can be degraded to form plant hormone analogs, promoting growth and increasing yield (Li et al., 2018).

Carbon nanodots (CNDs) can penetrate plant cells and integrate with chloroplasts because of their nano-size, enhancing electron transfer and increasing light absorption (Wang et al., 2023b). They act as both photosensitizers and light converters, transforming ultraviolet light into usable blue light for photosynthesis (Hu et al., 2024; Lv et al., 2023). Applying CNDs has increased photosynthetic parameters, pigment content, and biomass in various plants, including maize (Milenković et al., 2021), Arabidopsis thaliana (Hu et al., 2024), wheat seedlings (Lv et al., 2023), and lettuce (Hu et al., 2022). Additionally, CNDs can mitigate UV light stress and enhance CO2 fixation rates(Hu et al., 2024; Lv et al., 2023). Cheng et al (2023) reported that CNDs can promote chlorophyll synthesis, increase enzyme activity, and upregulate gene expression associated with photosynthesis, leading to higher net photosynthetic rates and increased biomass production.

5. Carbon Nanodots for Soil Health

Maintaining soil health is essential for sustainable agriculture and environmental protection. However, intensive farming, pollution, and climate change compromise soil quality, posing serious threats to global food security and ecosystem stability (Tahat et al., 2020). Recently, nanotechnology, particularly carbon nanodots (CNDs), has emerged as a promising solution for improving soil health. These nano-enabled methods are anticipated to play a pivotal role in the forthcoming agritech revolution by providing sustainable ways to manage biotic and abiotic stresses in agriculture (Bartolucci et al., 2022). Moreover, CNDs offer several advantages, including better nutrient availability, increased microbial activity, and reduced soil contaminants (Ahmed et al., 2023). Recently, the application of engineered nanomaterials (ENMs) as nano-agrochemicals has shown great promise in improving pest and pathogen management. ENMs can enhance crop yields and functionality by precisely and selectively enriching beneficial microbiomes, reducing agriculture's environmental impact (An et al., 2022). ENMs are typically categorized into four types: inorganic or metal-based, carbon-based, polymer-based, and composite-based (Mitchell et al., 2021). Carbon-based ENMs, such as carbon nanotubes, carbon dots, and graphene nanoparticles, have been studied for their role in engineering plant-associated microbiomes in agriculture (Karadurmus et al., 2022). For example, Chen et al(2022b) found that adding multi-walled carbon nanotubes (MWCNTs) at a concentration of 1000 mg kg^{-1} improved the beneficial microbial community in the soil of black nightshade (*Solanum nigrum* L.). Nano-enabled agrochemicals can enhance crop resilience and efficiency by improving microbiomes (Zhang et al., 2020). These nano-agrochemicals have boosted nutrient-use efficiency and soil function by altering the rhizospheric microbiome, enhancing nitrifying and denitrifying bacterial communities (Kalwani et al., 2022). Additionally, recent studies have shown that engineered nanomaterials (ENMs) have significant plant growth-promoting potential due to their ability to modify plant-beneficial microbes, which undergo physical, chemical., and biological transformations once in the environment (Kumar et al., 2021).

These transformations, such as accumulation, dissolution, sedimentation, corona formation, and oxidation-reduction, result in modified ENMs with properties different from the original material. These changes affect the behavior, fate, and biological impact of ENMs in the environment (Fincheira et al., 2021). Engineered nanomaterials (ENMs) have been demonstrated to boost agricultural productivity by enhancing nutrient utilization efficiency, improving soil conditioning, modulating soil microbes, and promoting sustainable agriculture. Recent research has shown that applying carbon dots at a concentration of 5 mg kg^{-1} significantly improved soybean (Gmax) growth by increasing nitrogenase activity by 8.6% and stimulating the secretion of root exudates, including polyketides (69.0%), fatty acids (163.5%), and organic acids (102.0%). This application also enhanced beneficial microbiota such as Actinobacteria, Proteobacteria, Gemmatimonadetes, and Acidobacteria (Wang et al., 2022). Additionally, nano-enabled strategies have been employed as sustainable methods to enhance plant resilience to abiotic stresses like drought, salt, heavy metals, and heat (Kah et al., 2019).

Numerous studies have highlighted nano-agrochemicals' potential to alleviate environmental stresses (Kalwani et al., 2022). For instance, applying carbon dots (CDs) at a concentration of 5 mg l^{-1} to soybean foliage reduced drought stress by enhancing crop yield (21.5%), photosynthesis (32.6%), carbohydrate transport (35.4%), nitrogen content (13.2%), and scavenging of reactive oxygen species (ROS). Additionally, this amendment significantly increased the secretion of root exudates (auxins, organic acids, and amino acids), leading to a 37% rise in beneficial microbiomes such as Glomeromycota, Actinobacteria, Acidobacteria, and Ascomycota in the rhizospheric soil (Ji et al., 2023). Conversely, specific carbon nanotubes can mitigate the harmful effects of toxic substances and enhance microbial functions. For example, multi-walled carbon nanotubes (MWCNTs) can provide additional surface area for the sorption of poly-aromatic hydrocarbons (PAHs), thereby boosting the population of microorganisms like gram-positive bacteria that are sensitive to PAHs (Shrestha et al., 2015). Applying single-walled carbon nanotubes (0.5–5.0 g kg^{-1} directly to soil) increased the relative abundance of Proteobacteria and Bacteroidetes while decreasing Actinobacteria and Chloroflexi, thereby reducing organic matter degradation due to changes in microbial functions (Wu et al., 2019). Additionally, using carbon black (0.1–1000 mg kg^{-1}) for soybean plants (Gmax) boosted the abundance of bacteria that decompose organic matter but decreased methanogenic, chitinolytic, and nitrate-reducing bacteria. This application also enhanced microbial functions, improving xylanolytic and cellulolytic activity and aerobic ammonia oxidation (Ge et al., 2018). Carbon nanodots (CNDs) aim to develop a more efficient and sustainable agricultural system that enhances plant growth and health by reducing dependence on synthetic fertilizers and pesticides, thus lessening agriculture's negative environmental and human health impacts.

6. Nanotoxicity of Carbon Nanodots

Nanotoxicology investigates the potential toxicity of nanoscale materials to live organisms and biological systems, establishing it as a specialized domain within nano-science. Although carbon is not viewed as an innately hazardous element, the precise material and structural configurations of CNDs may constitute potential dangers to human health, hence generating public concern (Zhu et al., 2007; Seabra et al., 2014). Oh et al., (2016) reported that quantum dots toxicity may be associated with physicochemical characteristics, including core/shell materials, sizes, surface charge, the nature of surface ligands (which confer colloidal stability), the existence of additional surface modifications, and interactions with diverse molecules (such as proteins) found in biological environments (Oh et al., 2016). There is a significant impact of surface functionalization of carbon nanodots on cell survival., reactive oxygen species production, and cell cycle. Havrdova et al., (2016) found that the negatively charged CNDs halted the G2/M phase of the cell cycle, promoted proliferation, and resulted in increased oxidative stress; however, they did not penetrate the cell nucleus. The outcomes of radio-labeling CNDs indicated their excretion via the kidneys and stool. This indicates that CNDs do not accumulate and are not significantly detrimental to live organisms (Malhan et al., 2024). Conversely, positively charged CNDs exhibit the highest cytotoxicity, penetrating the cell nucleus and causing significant alterations in the G0/G1 phase of the cell cycle, even at concentrations of 100 µg mL^{-1} (Havrdova et al., 2016). However, Wang et al (2013) produced photoluminescent CNDs with good stability, water solubility, and great dispersibility. The results showed that the fluorescent CNDs at varied doses did not impose any substantial harmful effect on rats and mice under the different doses. There were no physical abnormality or injury as well as no gene toxicity was found. Often CNDs toxicity is related to its production or fabrication methods, precursors used and its dosage (Fig. 5).

Cong et al. (2019) found low toxicity from the CNDs from the duck roast even after the prolonged exposure of 36 h with 91.2% viability in PC12 cells. Janus et al. (2019) found the N-doped chitosan-based CNDs had 94% viability for 48 h in human skin fibroblasts. Pulmonary delivery of nucleic acid by carbon dot-based nanocarriers was done by Pierrat et al. (2015) where higher level of transgene expression was observed in the cytoplasmic membrane with lesser toxicity under in vivo and invitro conditions. Fan et al. (2019) highlighted the importance of other more specific CNDs factors, such as nitrogen concentration, nature of the passivation agent and carbonization technique, in CNDs toxicity Altogether, not a single CNDs component appears as a most crucial characteristic, pointing to the complexity of forecasting the safety of CNDs, most probably due of interplays between their varied physicochemical qualities. Liu et al. (2021) found that laboratory-synthesized and commercial CNDs exposed to white, fluorescent light can decompose into hazardous compounds, toxic to both normal HEK-293 cells and malignant HeLa and HepG2 cells. They identified 1431 compounds, 499 of which are associated with cytotoxicity. In contrast to earlier assertions of biocompatibility, their findings demonstrate that CNDs photodegrade and produce chemicals capable of inducing cytotoxicity in human cells. This photo inducing toxicity depends on the concentration of CNDs used and irradiation period (Liu et al., 2021). At the microscopic level, CNDs can induce oxidative stress, inflammation, and cytotoxicity, leading to various adverse effects, including cellular death. The consequences are generally attributed to the generation of reactive oxygen species (ROS), impairment of cellular membranes, and disruption of essential cellular functions such as mitochondrial function and DNA repair. By investigating the essential mechanisms underlying these interactions, scientists can endeavour to develop nanomaterials that are not as harmful and possess less adverse effects. Moreover, it is essential to comprehend the aspects influencing the behaviour of carbon-based nanomaterials in biological systems, including their size, surface characteristics, and aggregation state (Seabra et al., 2014; Havrdova et al., 2016; Malhan et al., 2024).

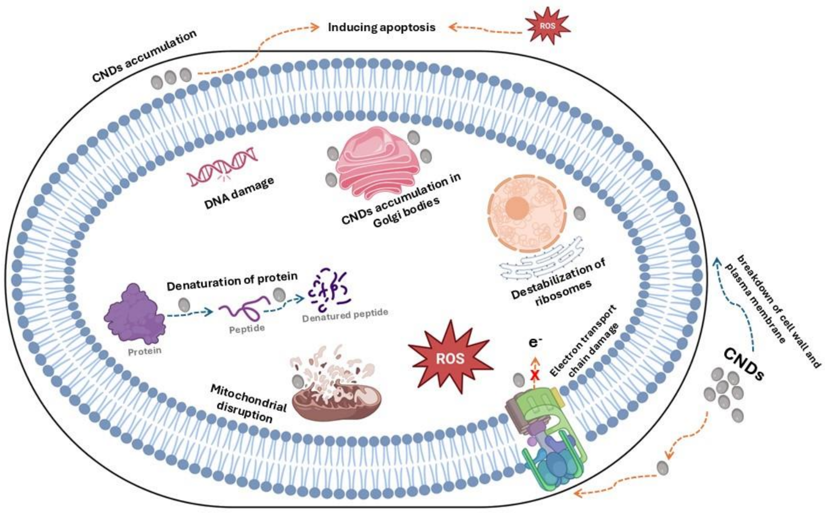

Fig. 5. Suggested nanotoxicity of carbon nanodots in plants.

7. Conclusions and Future Perspectives

This review offers valuable insights into the current knowledge of carbon nanodots (CNDs) but also highlights limitations in their synthesis, understanding of photo-physics, structural variability, and the need for further research to exploit the potential of CNDs fully. Future research should aim to develop more effective synthesis methods to better control the size, structure, and surface functionalization of CNDs, allowing for tailored properties for specific applications. There is a need for deeper investigation into the fundamental photo-physical properties of CNDs, focusing on the mechanisms behind their fluorescence and the influence of structural features on their optical behavior. This understanding is crucial for optimizing CNDs for applications such as bioimaging and nanosensing. The paper stresses the importance of conducting field trials to validate the effectiveness of CNDs in sustainable agriculture and improved crop health, as well as understanding their long-term impacts. Without these trials, the practical application of CNDs in agriculture remains uncertain. Future research should explore the relationship between the structural characteristics of CNDs and their optical responses, studying different sub-types to understand how variations in core and surface structures affect their photoluminescence and other properties.

Additionally, future work should investigate the application of CNDs in various fields, including nano-medicine, environmental sensing, and energy harvesting, to optimize them for specific uses. Given the potential toxicity of some nanomaterials, comprehensive studies on the biocompatibility and ecological impact of CNDs in agroecosystems are necessary. Standardized assessment methods are needed to evaluate their safety and effectiveness in the plant-soil system and understand their interactions with microorganisms, especially at field scales. Understanding these interactions is essential for safe applications in bioimaging and therapeutics. The paper emphasizes the need for interdisciplinary collaborations among nanotechnologists, microbiologists, chemists, agriculturists, and engineers to advance the field of CNDs. In summary, it suggests that future research should focus on improving synthesis methods, deepening the understanding of photo-physics, exploring structure-property relationships, investigating application-specific uses, and addressing environmental and toxicity concerns to harness CNDs' potential fully.

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8. References

Abinaya S, Baby A, Gurunathan K, Sreeja PB, Jose SP (2022). Structural and morphological characterization of hydrothermally synthesized N-Carbon Dot@ Fe_3O_4 composites for heavy metal ion detection. Materials Today: Proceedings, 64, 1854–1858.

Aggarwal K, Dixit V, Pal AK, Chaubey KK, Barman S, Pandey S, Rajawat S, Khandelwal T, Gangwar M (2024). Recent research on the use of carbon nanomaterials in plant growth and development. Carbon-Based Nanomaterials: Synthesis, Agricultural, Biomedical, and Environmental Interventions, 123–144.

Ahmed T, Noman M, Gardea-Torresdey JL, White JC, Li B (2023). Dynamic interplay between nano-enabled agrochemicals and the plant-associated microbiome. Trends Plant Sci., 28(11), 1310–1325.

Al Yahyai I, Al-Lawati HAJ, Hassanzadeh J (2021). A paper-based chemiluminescence detection device based on S, N-doped carbon quantum dots for the selective and highly sensitive recognition of bendiocarb. Anal. Methods, 13(31), 3461–3470.

An C, Sun C, Li N, Huang B, Jiang J, Shen Y, Wang C, Zhao X, Cui B, Wang C, Li X, Zhan S, Gao F, Zeng Z, Cui H, Wang Y (2022). Nanomaterials and nanotechnology for the delivery of agrochemicals: strategies towards sustainable agriculture. J. Nanobiotechnol., 20(1), 11.

Arcudi F, Đorđević L, Prato M (2019). Design, synthesis, and functionalization strategies of tailored carbon nanodots. Accounts Chem. Res., 52(8), 2070–2079.

Ashrafi Tafreshi F, Fatahi Z, Ghasemi SF, Taherian A, Esfandiari N (2020). Ultrasensitive fluorescent detection of pesticides in real sample by using green carbon dots. PLoS One, 15(3), e0230646.

Ayanda OS, Mmuoegbulam AO, Okezie O, Durumin Iya NI, Mohammed SE, James PH, Muhammad AB, Unimke AA, Alim SA, Yahaya SM (2024). Recent progress in carbon-based nanomaterials: critical review. J. Nanopart. Res., 26(5), 1–42.

Bachheti RK, Fikadu A, Bachheti A, Husen A (2020). Biogenic fabrication of nanomaterials from flower-based chemical compounds, characterization and their various applications: a review. Saudi J. Biol. Sci., 27(10):2551–2562.

Baig N, Kammakakam I, Falath W (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Mater. Adv., 2(6), 1821–1871.

Bartolucci C, Scognamiglio V, Antonacci A, Fraceto LF (2022). What makes nanotechnologies applied to agriculture green? Nano Today, 43, 101389.

Benzigar MR, Talapaneni SN, Joseph S, Ramadass K, Singh G, Scaranto J, Ravon U, Al-Bahily K, Vinu A (2018). Recent advances in functionalized micro and mesoporous carbon materials: synthesis and applications. Chem. Soc. Rev., 47(8), 2680–2721.

Buiculescu R, Stefanakis D, Androulidaki M, Ghanotakis D, Chaniotakis NA (2016). Controlling carbon nanodot fluorescence for optical biosensing. Analyst, 141(13), 4170–4180.

Carvalho PM, Felício MR, Santos NC, Gonçalves S, Domingues MM (2018). Application of light scattering techniques to nanoparticle characterization and development. Front. Chem., 6, 237.

Castro KPR, Colombo RNP, Iost RM, da Silva BGR, Crespilho FN (2023). Low-dimensionality carbon-based biosensors: the new era of emerging technologies in bioanalytical chemistry. Anal. Bioanal. Chem., 415:3879–3895.

Chandel M, Kaur K, Sahu BK, Sharma S, Panneerselvam R, Shanmugam V (2022). Promise of nano-carbon to the next generation sustainable agriculture. Carbon, 188, 461–481.

Chauhan DS, Quraishi MA, Verma C (2022). Carbon nanodots: recent advances in synthesis and applications. Carbon Lett., 32(7), 1603–1629.

Chen F, Shen Z, Shi R, Zhang X, Zhang H, Li W, Lei B (2025). Carbon dots-mediated plant adaptive responses to abiotic stress. Mater. Res. Bull., 182, 113137.

Chen L, Wang C, Liu C, Chen S (2023). Facile access to fabricate carbon dots and perspective of large-scale applications. Small, 19 (31), 2206671.

Chen Q, Cao X, Li Y, Sun Q, Dai L, Li J, Guo Z, Zhang L, Ci L (2022a). Functional carbon nanodots improve soil quality and tomato tolerance in saline-alkali soils. Sci. Total Environ., 830, 154817.

Chen Q, Chen L, Nie X, Man H, Guo Z, Wang X, Jin G, Ci L (2020a). Impacts of surface chemistry of functional carbon nanodots on the plant growth. Ecotox. Environ. Safe., 206, 111220.

Chen Q, Ren X, Li Y, Liu B, Wang X, Tu J, Guo Z, Jin G, Min G, Ci L (2020b). Promotion effect of nitrogen-doped functional carbon nanodots on the early growth stage of plants. Oxf. Open Mater. Sci., 1(1), itab002.

Chen X, Wang J, You Y, Wang R, Chu S, Chi Y, Hayat K, Hui N, Liu X, Zhang D, Zhou P (2022b). When nanoparticle and microbes meet: The effect of multi-walled carbon nanotubes on microbial community and nutrient cycling in hyperaccumulator system. J. Hazard. Mater., 423, 126947.

Cheng B, Yang Z, Chen F, Yue L, Cao X, Li J, Qian H-L, Yan X-P, Wang C, Wang Z (2023). Biomass-derived carbon dots with light conversion and nutrient provisioning capabilities facilitate plant photosynthesis. Sci. Total Environ., 901, 165973.

Cong S, Liu K, Qiao F, Song Y, Tan M (2019). Biocompatible fluorescent carbon dots derived from roast duck for in vitro cellular and in vivo C. elegans bio-imaging. Methods, 168, 76–83.

De Armentia SL, Del Real JC, Paz E, Dunne N (2020). Advances in biodegradable 3D printed scaffolds with carbon-based nanomaterials for bone regeneration. Materials, 13:1–49.

de la Parra S, Fernández-Pampín N, Garroni S, Poddighe M, de la Fuente-Vivas D, Barros R, Martel-Martín S, Aparicio S, Rumbo C, Tamayo-Ramos JA (2024). Comparative toxicological analysis of two pristine carbon nanomaterials (graphene oxide and aminated graphene oxide) and their corresponding degraded forms using human in vitro models. Toxicology, 504, 153783.

de Menezes FD, Alencar LMR, dos Santos CC, da Silva MIB, Santos-Oliveira R (2020). Using graphene quantum dots for treating radioactive liquid waste. Environ. Sci. Pollut. Res., 27:3508–3512.

DeCicco RC, Luo L, Goroff NS (2019). Exploiting unsaturated carbon–iodine compounds for the preparation of carbon-rich materials. Accounts Chem. Res., 52(8), 2080–2089.

Deshmukh MA, Park SJ, Hedau BS, Ha TJ (2021). Recent progress in solar cells based on carbon nanomaterials. Sol. Energy, 220:953–990.

Ding S, Cargill A, Das S, Medintz I, Claussen J (2015). Biosensing with förster resonance energy transfer coupling between fluorophores and nanocarbon allotropes. Sensors, 15(6), 14766–14787.

El-Kady MM, Ansari I, Arora C, Rai N, Soni S, Verma DK, Singh P, Mahmoud AED (2023). Nanomaterials: A comprehensive review of applications, toxicity, impact, and fate to environment. J. Mol. Liq., 370, 121046.

Fan J, Claudel M, Ronzani C, Arezki Y, Lebeau L, Pons F (2019). Physicochemical characteristics that affect carbon dot safety: lessons from a comprehensive study on a nanoparticle library. Int. J. Pharm., 569, 118521.

Fawaz W, Hasian J, Alghoraibi I (2023). Synthesis and physicochemical characterization of carbon quantum dots produced from folic acid. Sci Rep, 13(1), 18641.

Fincheira P, Tortella G, Seabra AB, Quiroz A, Diez MC, Rubilar O (2021). Nanotechnology advances for sustainable agriculture: current knowledge and prospects in plant growth modulation and nutrition. Planta, 254, 1–25.

Gamage A, Gangahagedara R, Gamage J, Jayasinghe N, Kodikara N, Suraweera P, Merah O (2023). Role of organic farming for achieving sustainability in agriculture. Farming System, 1(1), 100005.

Ge Y, Shen C, Wang Y, Sun Y-Q, Schimel JP, Gardea-Torresdey JL, Holden PA (2018). Carbonaceous nanomaterials have higher effects on soybean rhizosphere prokaryotic communities during the reproductive growth phase than during vegetative growth. Environ. Sci. Technol., 52(11), 6636–6646.

Ghazaryan K, Pandey D, Singh S, Varagyan V, Alexiou A, Petropoulos D, Kriemadis A, Rajput VD, Minkina D, Singh RK, Sousa JR, Kumar S, El-Ramady H, Singh O, Singh A (2024). Enhancing crop production: unveiling the role of nanofertilizers in sustainable agriculture and precision nutrient management. Egypt. J. Soil Sci., 64(3), 981–1007.

Godeto YG, Ayele A, Ahmed IN, Husen A, Bachheti RK (2023). Medicinal plant-based metabolites in nanoparticles synthesis and their cutting-edge applications: an overviewIn: Bachheti RK, Bachheti A (eds) Secondary metabolites from medicinal plants CRC Press, Boca Raton, USA, pp 1–34.

Gonfa YH, Bachheti A, Husen A, Bachheti RK (2024). Carbon-Based smart nanomaterials: an overview. Carbon-Based Nanomaterials: Synthesis, Agricultural., Biomedical., and Environmental Interventions, 1–17.

Gonfa YH, Tessema FB, Tadesse MG, Bachheti A, Bachheti RK (2023). Medicinally important plant roots and their role in nanoparticles synthesis and applications In: Bachheti RK, Bachheti A (eds) Secondary metabolites from medicinal plants CRC Press, Boca Raton, USA, pp 227–242.

Guo B, Liu G, Li W, Hu C, Lei B, Zhuang J, Zheng M, Liu Y (2022). The role of carbon dots in the life cycle of crops. Ind. Crop. Prod., 187, 115427.

Guo R, Suo Y, Xia H, Yang Y, Ma Q, Yan F (2021). Study of piezoresistive behavior of smart cement filled with graphene oxide. Nanomaterials, 11:1–12.

Hai X, Feng J, Chen X, Wang J (2018). Tuning the optical properties of graphene quantum dots for biosensing and bioimaging. J. Mater. Chem. B, 6, 3219–3234.

Hajishoreh NK, Jamalpoor Z, Rasouli R, Asl AN, Sheervalilou R, Akbarzadeh A (2023). The recent development of carbon-based nanoparticles as a novel approach to skin tissue care and management-A review. Exp. Cell Res., 113821.

Han S, Wang J, Ren Y, Yang B, Liu X, Yang J, Liu L, Meng K, Shan W, Qin S (2022). Fabrication of sodium dinitrophenol derived carbon dots and its effect on seed germination of cotton. Micro Nano Lett., 17(7), 149–154.

Hassanvand Z, Jalali F, Nazari M, Parnianchi F, Santoro C (2021). Carbon nanodots in electrochemical sensors and biosensors: A review. Chem Electro Chem, *8*(1), 15–35.

Havrdova M, Hola K, Skopalik J, Tomankova K, Petr M, Cepe K, Polakova K, Tucek J, Bourlinos AB, Zboril R (2016). Toxicity of carbon dots – effect of surface functionalization on the cell viability, reactive oxygen species generation and cell cycle. Carbon, 99, 238–248.

Heidari G, Hassanpour M, Nejaddehbashi F, Sarfjoo MR, Yousefiasl S, Sharifi E, Bigham A, Agarwal T, Borzacchiello A, Lagreca E, Natale CD, Nikfarjam N, Vasseghian Y (2022). Biosynthesized nanomaterials with antioxidant and antimicrobial properties. Mater. Chem. Horizons, 35–48.

Her SC, Liang YM (2022). Carbon-based nanomaterials thin film deposited on a flexible substrate for strain sensing application. Sensors, 22:1–12

Hoang NM, Ngoc NTB, Huong PTL, Huyen PTT, Duy DQ, Dao V-D,Tu LT (2023). Dual emission carbon dots for simultaneous detections of Pb^{2+} and Fe^{3+} ions in water via distinct sensing mechanisms. J. Fluoresc., 33(4):1359–1366.

Hu H, Cheng W, Wang X, Yang Y, Yu X, Ding J, Lin Y, Zhao W, Zhao Q, Ledesma-Amaro R, Chen X, Liu J, Yang C, Gao X (2024). Enhancing plant photosynthesis using carbon dots as light converter and photosensitizer. bioRxiv.

Hu J, Jia W, Wu X, Zhang H, Wang Y, Liu J, Yang Y, Tao S, Wang X (2022). Carbon dots can strongly promote photosynthesis in lettuce (*Lactuca sativa* L.). Environ. Sci.: Nano, 9(4), 1530–1540.

Hu Q, Gong X, Liu L, Choi MM (2017). Characterization and analytical separation of fluorescent carbon nanodots. J. Nanomater., (1), 1804178.

Huang D, Chen Y, Cheng M, Lei L, Chen S, Wang W, Liu X (2021). Carbon dots-decorated carbon-based metal-free catalysts for electrochemical energy storage. Small, 17(4), 2002998.

Husen A, Siddiqi KS (2023). Advances in smart nanomaterials and their applications. Elsevier Inc., 50 Hampshire St., 5th Floor, Cambridge, MA 02139, USA.

Hussain MM, Khan WU, Ahmed F, Wei Y, Xiong H (2023). Recent developments of Red/NIR carbon dots in biosensing, bioimaging, and tumor theranostics. Chem. Eng. J., 465, 143010.

Janus Ł, Piątkowski M, Radwan-Pragłowska J, Bogdał D, Matysek D (2019). Chitosan-based carbon quantum dots for biomedical applications: synthesis and characterization. Nanomaterials, 9, 274.

Jha R, Singh A, Sharma PK, Porwal O, Fuloria NK (2021). Graphene-based nanomaterial system: a boon in the era of smart nanocarriers. J. Pharm. Invest., 51:245–280.

Ji Y, Yue L, Cao X, Chen F, Li J, Zhang J, Wang C, Wang Z, Xing B (2023). Carbon dots promoted soybean photosynthesis and amino acid biosynthesis under drought stress: Reactive oxygen species scavenging and nitrogen metabolism. Sci. Total Environ., 856, 159125.

Jurkiewicz K, Pawlyta M, Burian A (2018). Structure of carbon materials explored by local transmission electron microscopy and global powder diffraction probes. C, 4(4), 68.

Kah M, Tufenkji N, White JC (2019). Nano-enabled strategies to enhance crop nutrition and protection. Nat. Nanotechnol., 14(6), 532–540.

Kalwani M, Chakdar H, Srivastava A, Pabbi S, Shukla P (2022). Effects of nanofertilizers on soil and plant-associated microbial communities: Emerging trends and perspectives. Chemosphere, 287, 132107.

Kang C, Huang Y, Yang H, Yan XF, Chen ZP (2020). A review of carbon dots produced from biomass wastes. Nanomaterials, 10(11):2316.

Kang K, Park J, Kim K, Yu KJ (2021). Recent developments of emerging inorganic, metal and carbon-based nanomaterials for pressure sensors and their healthcare monitoring applications. Nano. Res., 14:3096–3111

Karadurmus L, Cetinkaya A, Kaya SI, Ozkan SA (2022). Recent trends on electrochemical carbon-based nanosensors for sensitive assay of pesticides. Trends Environ. Anal. Chem., 34, e00158.

Khatami M, Alijani H, Nejad M, Varma R (2018). Core@ shell Nanoparticles: Greener Synthesis Using Natural Plant Products. Appl. Sci., 8(3), 411.

Kong J, Wei Y, Zhou F, Shi L, Zhao S, Wan M, Zhang X (2024). Carbon quantum dots: properties, preparation, and applications. Molecules, 29(9), 2002.

Kostov K, Andonova-Lilova B, Smagghe G (2022). Inhibitory activity of carbon quantum dots against Phytophthora infestans and fungal plant pathogens and their effect on dsRNA-induced gene silencing. Biotechnol. Biotechnol. Equip., 36(1), 949–959.

Kou E, Yao Y, Yang X, Song S, Li W, Kang Y, Qu S, Dong R, Pan X, Li D, Zhang H, Lei B (2021). Regulation mechanisms of carbon dots in the development of lettuce and tomato. ACS Sustain. Chem. Eng., 9(2), 944–953.

Kumar A, Rastogi S, Haider Y, Kumar S, Chauhan S, Passey J (2021). Morphometric variations of the lateral surface of calcaneus: Can standard plate sizes fit all? J. Clinical Orthopaedics and Trauma, 13, 156–162.

Kurniawan D, Xia Z, Dai L, Ostrikov KK, Chiang WH (2024). Zero-dimensional nano-carbons: Synthesis, properties, and applications. Appl. Phys. Rev., 11(2).

Lal, R. (2025). Managing Soil Health in Africa (MASHA) by Re-carbonization of Its Agroecosystems. Egypt. J. Soil Sci., 65(3), 301–320.

Landi G, La Notte L, Palma AL., Sorrentino A, Maglione MG, Puglisi G (2022). A comparative evaluation of sustainable binders for environmentally friendly carbon-based supercapacitors. Nanomaterials, 12:1–16.

Li H, Huang J, Lu F, Liu Y, Song Y, Sun Y, Zhong J, Huang H, Wang Y, Li S, Lifshitz Y, Lee S-T, Kang Z (2018). Impacts of carbon dots on rice plants: boosting the growth and improving the disease resistance. ACS Appl. Bio Mater., 1(3), 663–672.

Li H, Su D, Gao H, Yan X, Kong D, Jin R, Liu X, Wang C, Lu G (2020a). Design of red emissive carbon dots: robust performance for analytical applications in pesticide monitoring. Anal. Chem., 92(4), 3198–3205.

Li J, Li X, Kah M, Yue L, Cheng B, Wang C, Wang Z Xing B (2024). Unlocking the potential of carbon dots in agriculture using data-driven approaches. Sci. Total Environ., 944, 173605.

Li Y, Pan X, Xu X, Wu Y, Zhuang J, Zhang X, Zhang H, Lei B, Hu C, Liu Y (2021). Carbon dots as light converter for plant photosynthesis: Augmenting light coverage and quantum yield effect. J. Hazard. Mater., 410, 124534.

Li Y, Xu X, Wu Y, Zhuang J, Zhang X, Zhang H, Lei B, Hu C, Liu Y (2020b). A review on the effects of carbon dots in plant systems. Mat. Chem. Front., 4(2), 437-448.

Liang L, Wong SC, Lisak G (2023). Effects of plastic-derived carbon dots on germination and growth of pea (*Pisum sativum*) via seed nano-priming. Chemosphere, 316, 137868.

Lin L, Wang X-X, Lin S-Q, Zhang L-H, Lin C-Q, Li Z-M, Liu J-M (2012). Research on the spectral properties of luminescent carbon dots. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 95, 555–561.

Liu M (2020). Optical Properties of Carbon Dots: A Review. Nanoarchitectonics, 1(1), 1–12

Liu Y-Y, Yu N-Y, Fang W-D, Tan Q-G, Ji R, Yang L-Y, Wei S, Zhang X-W, Miao A-J (2021). Photodegradation of Carbon Dots Cause Cytotoxicity. Nat. Commun., 12, 812.

Lu D, Zhong J (2022). Carbon-based nanomaterials engineered cement composites: a review. J Infrastructure Preservation and Resilience, 3:1–20.

Lv J, Yang W, Miao Y (2023). Preparation of N-doped carbon dots and application to enhanced photosynthesis. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 297, 122763.

Ma X, Li X, Zhang W, Meng F, Wang X, Qin Y, Zhang M (2021). Carbon-based nanocomposite smart sensors for the rapid detection of mycotoxins. Nanomaterials, 11:1–24.

Makhado BP, Oladipo AO, Gumbi NN, De Kock LA, Andraos C, Gulumian M, Nxumalo EN (2024). Unravelling the toxicity of carbon nanomaterials–From cellular interactions to mechanistic understanding. Toxicol. Vitro, 105898.

Malhan A, Guleria M, Das U, Singh S, Prajapati BG, Mohite P, Bhattacharya S, Chidrawar, VR, Puri A, Datta D (2024). Navigating the future of cancer management through carbon nanodots: A review. Nano-Structures & Nano-Objects, 39, 101217.

Mary Alex A, Kiran MD, Hari G, Krishnan A, Jayan JS, Saritha A (2020). Carbon dots: A green synthesis from Lawsonia inermis leaves. Materials Today: Proceedings, 26, 716–719.

Md Ishak NAI, Kamarudin SK, Timmiati SN (2019). Green synthesis of metal and metal oxide nanoparticles via plant extracts: An overview. Mater. Res. Express, 6(11), 112004.

Mengstu A, Esubalew S, Abate L, Husen RKBA, Bachheti A (2023). Medicinal plant-based flavonoid-mediated nanoparticles synthesis, characterization, and applications In: Bachheti RK, Bachheti A (eds) Secondary metabolites from medicinal plants CRC Press, Boca Raton, USA, pp 35–52.

Mewada A, Pandey S, Shinde S, Mishra N, Oza G, Thakur M, Sharon M, Sharon M (2013). Green synthesis of biocompatible carbon dots using aqueous extract of Trapa bispinosa peel. Materials Science and Engineering: C, 33(5), 2914–2917.

Milenković I, Borišev M, Zhou Y, Spasić SZ, Leblanc RM, Radotić K (2021). Photosynthesis Enhancement in Maize via Nontoxic Orange Carbon Dots. J. Agric. Food Chem., 69(19), 5446–5451.

Mintz KJ, Bartoli M, Rovere M, Zhou Y, Hettiarachchi SD, Paudyal S, Chen J, Domena JB, Liyanage PY, Sampson R, Khadka D, Pandey RR, Huang S, Chusuei CC, Tagliaferro A, Leblanc RM (2021). A deep investigation into the structure of carbon dots. Carbon, 173, 433–447.

Mishra S, Mishra S, Patel SS, Singh SP, Kumar P, Khan MA, Awasthi H, Singh S (2022). Carbon nanomaterials for the detection of pesticide residues in food: A review. Environ. Pollut., 310, 119804.

Mitchell MJ, Billingsley MM, Haley RM, Wechsler ME, Peppas NA, Langer R (2021). Engineering precision nanoparticles for drug delivery. Nat. Rev. Drug Discov., 20(2), 101–124.

Mittal AK, Chisti Y, Banerjee UC (2013). Synthesis of metallic nanoparticles using plant extracts. Biotechnol. Adv., 31(2), 346–356.

Montes C, Soriano ML, Villaseñor MJ, Ríos Á (2020). Carbon-based nanodots as effective electrochemical sensing tools toward the simultaneous detection of bioactive compounds in complex matrices. J. Electroanal. Chem., 878, 114573.

Mousavi SZ, Nafisi S, Maibach HI (2017). Fullerene nanoparticle in dermatological and cosmetic applications. Nanomedicine: Nanotechnology, Biology and Medicine, 13(3), 1071–1087.

Moustafa MM, Abd El-wahed AH, Hamad SA, Sheta MH (2024). Improved water use efficiency and yield of drip-irrigated pepper under full and deficit irrigation conditions. Egypt. J. Soil Sci., 64(2), 423–442.

Munné-Bosch S, Bermejo NF (2024). Fruit quality in organic and conventional farming: advantages and limitations. Trends Plant Sci. 29(8), 1071–1087.

Murdock RC, Braydich-Stolle L, Schrand AM, Schlager JJ, Hussain SM (2008). Characterization of nanomaterial dispersion in solution prior to in vitro exposure using dynamic light scattering technique. Toxicological Sciences, 101(2), 878–894.

Navya PN, Kaphle A, Srinivas SP, Bhargava SK, Rotello VM, Daima HK (2019). Current trends and challenges in cancer management and therapy using designer nanomaterials. Nano Converg., 6:1–30.

Neumann S, Menter C, Mahmoud AS, Segets D, Rafaja D (2020). Microstructure characteristics of non-monodisperse quantum dots: On the potential of transmission electron microscopy combined with X-ray diffraction. CrystEngComm, 22(21), 3644–3655.

Ngoc LTN, Moon J-Y, Lee, Y-C (2023). Plant extract-derived carbon dots as cosmetic ingredients. Nanomaterials, 13(19), 2654.

Nguyen DH, El-Ramady H, Prokisch, J (2024). Food safety aspects of carbon dots: a review. Environ. Chem. Lett., 1–24.

Oh E, Liu R, Nel A, Gemill KB, Bilal M, Cohen Y, Medintz IL (2016). Meta-Analysis of cellular toxicity for cadmium-containing quantum dots. Nat. Nanotechnol., 11, 479–486.

Olabi AG, Wilberforce T, Elsaid K, Sayed ET, Ramadan M, Atiqure Rahman SM, Abdelkareem MA (2021). Recent progress on carbon-based nanomaterial for phase change materials: prospects and challenges. Thermal. Sci. Eng. Progr., 23:1–16.

Patel SK, Sharma A, Singh GS (2020). Traditional agricultural practices in India: an approach for environmental sustainability and food security. Energy, Ecology and Environment, 5(4), 253-271.

Patil S, Chandrasekaran R (2020). Biogenic nanoparticles: a comprehensive perspective in synthesis, characterization, application and its challenges. J. Genetic Eng. Biotechnol., 18:1–23.

Pierrat P, Wang R, Kereselidze D, Lux M, Didier P, Kichler A, Pons F, Lebeau L (2015). Efficient in vitro and in vivo pulmonary delivery of nucleic acid by carbon dot-based nanocarriers. Biomaterials, 51, 290–302.

Prokisch J, Nguyen DH, Muthu A, Ferroudj A, Singh A, Agrawal S, Rajput VD, Ghazaryan K, El-Ramady H, Rai M (2024). Carbon nanodot–microbe–plant nexus in agroecosystem and antimicrobial applications. Nanomaterials, 14(15), 1249.

Qiao J, Chen Z, Zhao J, Ren J, Wang H, Zhi C, Li J, Xing B, Nie H (2024). Graphene promotes the growth of Vigna angularis by regulating the nitrogen metabolism and photosynthesis. PLoS One, 19(3), e0297892.

Ramanarayanan R, Swaminathan S (2020). Synthesis and characterisation of green luminescent carbon dots from guava leaf extract. Materials Today: Proceedings, 33, 2223–2227.

Ramezanzadeh B, Karimi B, Ramezanzadeh M, Rostami M (2019). Synthesis and characterization of polyaniline tailored graphene oxide quantum dot as an advance and highly crystalline carbon-based luminescent nanomaterial for fabrication of an effective anti-corrosion epoxy system on mild steel. J. Taiwan Inst. Chem. Eng., 95:369–382.

Rana A, Khan I, Saleh TA (2021). Advances in carbon nanostructures and nanocellulose as additives for efficient drilling fluids: trends and future perspective-a review. Energy Fuels, 35:7319–7339.

Rasheed T(2023a). Carbon dots as potential greener and sustainable fluorescent nanomaterials in service of pollutants sensing. TrAC Trends in Analytical Chemistry, 158, 116841.

Rasheed T(2023b). Carbon dots as robust class of sustainable and environment friendlier nano/optical sensors for pesticide recognition from wastewater. TrAC Trends in Analytical Chemistry, 160, 116957.

Rehman A, Feng J, Qunyi T, Korma SA, Assadpour E, Usman M, Han W, Jafari SM (2021). Pesticide-loaded colloidal nanodelivery systems; preparation, characterization, and applications. Adv. Colloid Interface Sci., 298, 102552.

Ren J, Weber F, Weigert F, Wang Y, Choudhury S, Xiao J, Lauermann I, Resch-Genger U, Bande A, Petit T (2019). Influence of surface chemistry on optical., chemical and electronic properties of blue luminescent carbon dots. Nanoscale, 11(4), 2056–2064.

Saikia BK, Roy K, Konwar R (2024). Preliminary report on therapeutic potential of coal-derived carbon quantum dots against SARS-CoV-2 virus. Virology, 593, 110036.

Seabra AB, Paula AJ, De Lima R, Alves OL, Durán N (2014). Nanotoxicity of graphene and graphene oxide. Chem. Res. Toxicol., 27, 159–168.

Serag E, El-Maghraby A, El Nemr A (2022). Recent developments in the application of carbon-based nanomaterials in implantable and wearable enzyme-biofuel cells. Carbon Lett., 32:395–412.

Shafi Z, Pandey VK, Singh R, Rustagi S (2024). Carbon dots-nanosensors: advancement in food traceability for a sustainable environmental development. Food Control, 110693.

Sharma A, Das J (2019). Small molecules derived carbon dots: Synthesis and applications in sensing, catalysis, imaging, and biomedicine. J. Nanobiotechnol., 17(1), 92.

Sharma V, Soni V (2024). Advancement in carbon nanoparticle synthesis and their application: a comprehensive review. American J. Nano Res. Appl., 12(5), 1–14.

Shayan Nasr M, Esmaeilnezhad E, Choi HJ (2021). Effect of carbon-based and metal-based nanoparticles on enhanced oil recovery: a review. J. Mol. Liq., 338:1–17.

Sheikh TM, Anwar MP, Muthoosamy K, Jaganathan J, Chan A, Mohamed AA (2021). The mechanics of carbon-based nanomaterials as cement reinforcement-a critical review. Constr. Build. Mater., 303:1–21.

Shrestha B, Anderson TA, Acosta-Martinez V, Payton P, Cañas-Carrell JE (2015). The influence of multi-walled carbon nanotubes on polycyclic aromatic hydrocarbon (PAH). bioavailability and toxicity to soil microbial communities in alfalfa rhizosphere. Ecotox. Environ. Safe., 116, 143–149.

Singh A, Rajput VD, Varshney A, Sharma R, Ghazaryan K, Minkina T, Alexiou A, El-Ramady H (2024c). Revolutionizing crop production: Nanoscale wonders-current applications, advances, and future frontiers. Egypt. J. Soil Sci., 64(1), 221–258.

Singh A, Rawat S, Rajput VD, Minkina T, Mandzhieva S, Eloyan A, Singh RK, Singh O, El-Ramady H,Ghazaryan K (2024b). Nanotechnology products in agriculture and environmental protection: advances and challenges. Egypt. J. Soil Sci., 64(4), 1355–1378.

Singh J, Dutta T, Kim K-H, Rawat M, Samddar P, Kumar P (2018). 'Green' synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. J. Nanobiotechnol., 16(1), 84.

Singh R, Sharma A, Saji J, Umapathi A, Kumar S, Daima HK (2022). Smart nanomaterials for cancer diagnosis and treatment. Nano Converg., 9:1–39.

Singh SK, Krishna H, Sharma S, Singh RK, Tripathi AN, Behera TK (2024a). Organic farming in vegetable crops: Challenges and opportunities. Vegetable Sci., 51, 1–10.

Skolariki T, Stalikas CD, Chatzimitakos T (2023). Optical properties and applications of zero-dimensional carbon nanomaterials. Zero-Dimensional Carbon Nanomaterials: Material Design Methods, Properties and Applications, 153.

Speranza G (2021). Carbon nanomaterials: synthesis, functionalization and sensing applications. Nanomaterials, 11(4), 967.

Tahat MM, Alananbeh KM, Othman YA, Leskovar DI (2020). Soil health and sustainable agriculture. Sustainability, 12(12), 4859.

Tan M, Zhang L, Tang R, Song X, Li Y, Wu H, Wang Y, Lv G, Liu W, Ma X (2013). Enhanced photoluminescence and characterization of multicolor carbon dots using plant soot as a carbon source. Talanta, 115, 950–956.

Tang J, Wu Y, Ma S, Yan T, Pan Z (2022). Sensing mechanism of a flexible strain sensor developed directly using electrospun composite nanofiber yarn with ternary carbon nanomaterials. IScience, 25:1–20.

Tanujaya J (2024). Effects of waste organic samples and extraction methods towards the absorption range of carbon nanodots and how it affects plants' growth. Int. J. Regional Innovation, 4(1).

Villaseñor MJ, Ríos Á (2018). Nanomaterials for water cleaning and desalination, energy production, disinfection, agriculture and green chemistry. Environ. Chem. Lett., 16:11–34.

Wang C, Ji Y, Cao X, Yue L, Chen F, Li J, Yang H, Wang Z, Xing B (2022). Carbon dots improve nitrogen bioavailability to promote the growth and nutritional quality of soybeans under drought stress. ACS Nano, 16(8), 12415–12424.

Wang C, Yang H, Chen F, Yue L, Wang Z, Xing B (2021). Nitrogen-doped carbon dots increased light conversion and electron supply to improve the corn photosystem and yield. Environ. Sci. Technol., 55(18), 12317–12325.

Wang K, Gao Z, Gao G, Wo Y, Wang Y, Shen G, Cui D (2013). Systematic safety evaluation on photoluminescent carbon dots. Nanoscale Res. Lett., 8, 1–9.

Wang L, Lu P, Feng S, Hamel C, Sun D, Siddique KH, Gan GY (2024). Strategies to improve soil health by optimizing the plant–soil–microbe–anthropogenic activity nexus. Agriculture, Ecosystems & Environment, 359, 108750.

Wang Z, Li Y, Zhang B, Gao X, Shi M, Zhang S, Zhong S, Zheng Y, Liu X (2023a). Functionalized carbon dot-delivered RNA nano fungicides as superior tools to control phytophthora pathogens through plant RDRP1 mediated spray-induced gene silencing. Adv. Funct. Mater., 33(22), 2213143.

Wang Z, Zhang Y, Zhang S, Ge M, Zhang H, Wang S, Chen Z, Li S, Yang C (2023b). Natural xylose-derived carbon dots towards efficient semi-artificial photosynthesis. J. Colloid Interface Sci., 629, 12–21.

Wu F, You Y, Zhang X, Zhang H, Chen W, Yang Y, Werner D, Tao S, Wang X (2019). Effects of various carbon nanotubes on soil bacterial community composition and structure. Environ. Sci. Technol., 53(10), 5707–5716.

Wu J, Chen X, Zhang Z, Zhang J (2022). “Off-on” fluorescence probe based on green emissive carbon dots for the determination of Cu2+ ions and glyphosate and development of a smart sensing film for vegetable packaging. Microchim. Acta, 189(3), 131.

Xia C, Zhu S, Feng T, Yang M, Yang B (2019). Evolution and synthesis of carbon dots: From carbon dots to carbonized polymer dots. Adv. Sci., 6, 1901316.

Xu X, Ray R, Gu Y, Ploehn HJ, Gearheart L, Raker K, Scrivens WA (2004). Electrophoretic analysis and purification of fluorescent single-walled carbon nanotube fragments. J. Am. Chem. Soc., 126(40), 12736–12737.

Yadav PK, Chandra S, Kumar V, Kumar D, Hasan SH (2023). Carbon quantum dots: synthesis, structure, properties, and catalytic applications for organic synthesis. Catalysts, 13, 422.

Zadeh Mehrizi T, Eshghi P (2021). Investigation of the effect of nanoparticles on platelet storage duration 2010–2020. Int. Nano Lett., 1–31.

Zhang H, Liu Y, Qu S (2024). Recent advances in photo-responsive carbon dots for tumor therapy. Responsive Materials, 2(2), e20240012.

Zhang W, Jia X, Chen S, Wang J, Ji R, Zhao L (2020). Response of soil microbial communities to engineered nanomaterials in presence of maize (*Zea mays* L.) plants. Environ. Pollut., 267, 115608.

Zhao Q, Song W, Zhao B, Yang B (2020). Spectroscopic studies of the optical properties of carbon dots: Recent advances and future prospects. Mat. Chem. Front., 4(2), 472–488.

Zhao Y, Liu X, Yang Y, Kang L, Yang Z, Liu W, Chen L (2015). Carbon dots: from intense absorption in visible range to excitation-independent and excitation-dependent photoluminescence. Fullerenes, Nanotubes and Carbon Nanostructures, 23(11), 922–929.

Zheng Y, Xie G, Zhang X, Chen Z, Cai Y, Yu W, Liu H, Shan J, Li R, Liu Y, Lei B (2017). Bioimaging application and growth-promoting behavior of carbon dots from pollen on hydroponically cultivated rome lettuce. ACS Omega, 2(7), 3958–3965.

Zhou Y, Mintz KJ, Sharma SK, Leblanc RM (2019). Carbon dots: diverse preparation, application, and perspective in surface chemistry. Langmuir, 35(28), 9115–9132.

Zhu L, Chang DW, Dai L, Hong Y (2007). DNA damage induced by multiwalled carbon nanotubes in mouse embryonic stem cells. Nano Lett., 7, 3592–3597.

Zhu L, Chen L, Gu J, Ma H, Wu H (2022). Carbon-based nanomaterials for sustainable agriculture: their application as light converters, nanosensors, and delivery tools. Plants, 11:1–12

Zia MU, Sambasivam PT, Chen D, Bhuiyan SA, Ford R, Li Q (2024). A carbon dot toolbox for managing biotic and abiotic stresses in crop production systems. EcoMat, 6(5), e12451.