Carbon Quantum Dot for Seed Treatment and as Photosynthetic Enhancer

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Abstract - The application of nanomaterials in agriculture has gained significant attention in recent years as a potential solution to address challenges in crop productivity and sustainability. Carbon quantum dots (CQDs), a class of nanomaterials with unique properties, have shown promise in various applications across multiple domains. In the realm of agriculture, CQDs have emerged as potential photosynthetic enhancers when used in seed treatment. This review paper aims to comprehensively explore the utilization of carbon quantum dots for enhancing photosynthesis and seed germination. To enhance agricultural productivity while ensuring environmental sustainability. Carbon quantum dots are introduced as nanoscale materials with distinct characteristics and versatile synthesis methods. Their potential role as agents to enhance photosynthesis and seed germination is situated within the broader context of sustainable agricultural practices.

Index Terms - Carbon quantum dot, photosynthesis, seed treatment, agriculture, productivity.

I. INTRODUCTION

Quantum dots, sometimes referred to as "artificial atoms," are nanostructured materials that have drawn a lot of attention because of their distinctive characteristics, which include both optical and electrical capabilities. The quantum dots, a new family of fluorophores that is optically stable and has many potential uses in fields like agriculture and health, might significantly alter the current industrial landscape.

These "artificial atoms" are zero-dimensional dot-sized (less than 10 nm) nanomaterials that are comparable to exciton Bohr radius. There is evidence that QDs have a major impact on physiological processes in plants. QDs can trigger photosynthesis even at low concentrations, which promotes plant development and ultimately increases production. The manufacture of QDs involves the use of substances including cadmium (Cd), zinc (Zn), telluride (Te), selenide (Se), mercury (Hg), lead (Pb), graphene (Ge), silicon (Si), carbon (C), and sulfur (S)[1].

According to reports, CDs are advantageous for plant development, resilience, and photosynthesis. A new generation of CNPs with particle sizes smaller than 10 nm is known as carbon dots (CDs). Due to their desirable qualities, including ultrasmall and uniform size, adjustable photoluminescence, tunable functionalization, high hydrophilicity, simple cell penetration, and benign biocompatibility, they also have a significant potential for use in agriculture applications [2].

Due to its qualities including low toxicity, biocompatibility, high water solubility, affordability, chemical inertness, and eco-friendliness, CQDs have garnered a lot of attention and investigation. With comparable fluorescence qualities, CQDs have a significant potential benefit over semiconductor based QDs in a variety of sectors. First, because of their biocompatibility, superior water solubility, and environmentally favorable design, CQDs are a better choice to be applied to biomedicine, drug delivery, biosensing, bioimaging, and environmental applications. Second, the environment is abundant with the element carbon. It reduces the cost of CQD production. Third is the chemical property. CQDs benefit from inertness' stability and improved storage [3].

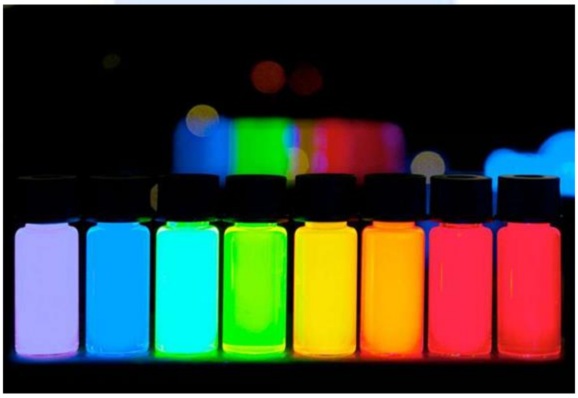


Figure 1: Quantum dot [Wikipedia]

Through chloroplast photosynthesis, plants transform solar energy into chemical energy. But less than 10% of sunlight is used by chloroplasts, and they can only use it in the visible spectral range (400–700 nm), primarily in the blue and red. Plant photosynthesis does not use UV or nIR light sources. However, the fact that CQDs are engaged in the process of turning dangerous UV radiation into harmless photo synthetically active radiation without any appreciable energy transfer suggests that UV light may be used safely in photosynthesis when combined with QDs [4].

The pre-harvest process (seed germination, nano-fertilizer, plant growth regulator, targeted delivery of fertilizers, pesticides, and biomolecules, photosynthesis, and stress tolerance) and post-harvest process (antibacterial preservation of harvested fruits, intelligent anti-counterfeit packaging) are the two main aspects of the role of CDs in the entire crop life cycle [5].

Ⅱ. Mechanism of CQD- induced enhancement:

The synthesis of carbon quantum dots (CQDs) through environmentally conscious methods has emerged as a pioneering avenue in nanotechnology. In this study, we present a green approach to produce carbon quantum dots utilizing agave bagasse, an agricultural waste product. These CQDs, characterized by their nanoscale dimensions and unique optical properties, offer a sustainable alternative in the realm of nanomaterials.

The primary objective of this research is to investigate the application of agave bagasse-derived carbon quantum dots in enhancing seed germination and fostering plant growth. Through a series of comprehensive experiments and analyses, we explore the impact of CQD-treated seeds on germination rates, early-stage seedling development, and subsequent plant growth.

The findings reveal the remarkable potential of agave bagasse-derived carbon quantum dots as a stimulant for seed germination and plant growth. Enhanced germination rates and expedited seedling emergence are observed, accompanied by improved physiological attributes. This includes heightened chlorophyll content, increased photosynthesis rates, and greater biomass accumulation.

Furthermore, this study delves into the underlying mechanisms of CQD-mediated effects on seed germination and plant growth. Insights into nutrient availability, biochemical signaling, and cellular processes provide a comprehensive understanding of the enhanced growth observed in CQD-treated plants.

The utilization of agave bagasse, an agricultural byproduct, as a precursor for carbon quantum dot synthesis aligns with sustainable practices, offering dual benefits of waste utilization and nanomaterial production. The implications of this research extend beyond agriculture, promising to contribute to the development of eco-friendly nanotechnologies with applications spanning various industries.

In conclusion, this study showcases a green synthesis method for carbon quantum dots derived from agave bagasse and demonstrates their proficiency in promoting seed germination and augmenting plant growth. The convergence of sustainable nanomaterial synthesis and agricultural advancement highlights the potential for eco-conscious innovation in both fields[6].

This study focuses on investigating the impacts of carbon dots on rice plants, encompassing their role in enhancing growth and bolstering disease resistance mechanisms.

The research begins by detailing the synthesis and characterization of carbon dots employed in the study. These nanoscale entities, possessing unique optical and surface properties, are then applied to rice plants through various experimental setups.

The growth-promoting effects of carbon dots on rice plants are thoroughly examined. Parameters such as seed germination rates, root and shoot development, chlorophyll content, and overall biomass are meticulously assessed. The results reveal a substantial positive influence, with carbon dot-treated rice plants showcasing accelerated growth rates and augmented physiological attributes.

In addition to growth enhancement, this study delves into the role of carbon dots in improving disease resistance in rice plants. The interactions between carbon dots and plant defense mechanisms are explored, shedding light on the potential activation of innate immune responses. Through careful analysis of disease incidence, pathogen proliferation, and gene expression patterns, the study demonstrates the ability of carbon dots to fortify the plant's defense arsenal.

Furthermore, mechanistic insights into the crosstalk between carbon dot-induced growth promotion and disease resistance are elucidated. The potential involvement of signaling pathways and biochemical cascades is discussed, providing a comprehensive perspective on the intricate interplay between these dual benefits.

Ultimately, the findings underscore the transformative potential of carbon dots in agriculture. The study not only establishes carbon dots as agents for promoting rice plant growth and disease resistance but also offers a deeper understanding of the underlying processes. The implications of this research extend to sustainable crop management practices, where carbon dot applications hold promise in bolstering crop yield and resilience in the face of pathogenic challenges.

In conclusion, this research highlights the multifaceted impacts of carbon dots on rice plants, showcasing their capacity to enhance growth and elevate disease resistance. The convergence of nanotechnology and agriculture presented in this study offers a glimpse into the innovative solutions that could shape the future of sustainable crop production [7].

Ⅲ. Synthesis method of CQD:

Hydrothermal method:

Hydrothermal synthesis, a prominent solution-based technique, plays a pivotal role in fabricating nanomaterials across an extensive temperature spectrum. This review spotlights the foundational principles, versatile applications, and advantages associated with hydrothermal synthesis in the realm of nanotechnology.

The abstract commences by unveiling the essence of hydrothermal synthesis—a process orchestrating controlled reactions of precursor solutions under elevated pressure and temperature conditions. The intricate balance between kinetics and thermodynamics within hydrothermal environments underpins the creation of nanomaterials bearing tailored compositions and morphologies.

Surveying a gamut of nanomaterial classes synthesized through hydrothermal pathways—including nanoparticles, nanotubes, and nanowires—the review navigates the landscape of nucleation, growth, and assembly processes. The convergence of factors such as precursor choice, reaction parameters, and surfactant additives intricately shapes the resultant nanomaterial characteristics.

Moreover, the adaptive potential of hydrothermal synthesis unfolds across multifarious domains. From catalysis and energy storage to biomedical applications and environmental rectification, the versatility of hydrothermal synthesis resonates profoundly. This technique empowers the fine-tuning of nanomaterial attributes, fostering their integration into state-of-the-art technologies.

The abstract culminates by addressing future prospects and challenges within hydrothermal synthesis. Scalability, environmental considerations, and unconventional reaction conditions emerge as pathways of progression. Hydrothermal synthesis, emblematic of nanotechnological progress, continues to be an indomitable force shaping the realm of nanomaterials.

In synopsis, this review unveils hydrothermal synthesis as a transformative force, enabling the production of nanomaterials that propel advancements across various sectors. The confluence of synthesis mechanisms, diverse nanomaterial manifestations, and potential applications underscores the pivotal role of hydrothermal methods in propelling nanotechnology forward [8].

Microwave assisted:

Microwave (MW) heating has emerged as a transformative technique, akin to the Bunsen burner of the 21st century, revolutionizing the synthesis of diverse materials including organic compounds, polymers, inorganic substances, and nanomaterials. This innovation has enabled precise, high-yield synthesis of catalytic and nanomaterial systems, surpassing conventional methods. By skillfully modulating MW parameters and solvents, researchers venture into the forefront of advanced nanomaterial design. Despite debates surrounding the thermal versus nonthermal nature of MW effects, recent strides in hardware development, particularly using silicon carbide (SiC) reactors and fiber optic temperature probes, have illuminated this discourse.

This Account furnishes an overview of MW-assisted synthesis, spotlighting novel equipment prototypes, varied classes of organic reactions harnessed with nanomaterials, and the creation of multifunctional nanomaterials. These nanomaterials span a spectrum of dimensionalities, encompassing spheres, hexagons, nanoprisms, stars, and nanorods. Synthesizing well-defined nanomaterials and nanocatalysts holds significance in nanotechnology and catalysis, enabling tailored size, shape, and compositional engineering for enhanced applications. MW-assisted techniques are harnessed for creating noble and transition core-shell metallic nanoparticles, with adjustable shell thicknesses. Magnetic nanocatalysts, shaped by MW-selective heating, gain prominence for organic synthesis under mild conditions.

The synergy of sustainable nanomaterials and benign media aligns seamlessly with greener methodologies in organic synthesis. MW heating contributes significantly to sustainable process development, notably in flow systems, advancing process intensification. In sum, the magic of MW heating opens avenues for precise and efficient synthesis of diverse nanomaterials and catalysts, offering transformative potential in sustainable chemical processes and nanotechnology[9].

Others:

Electrochemical synthesis:

Electrochemical synthesis is reliant on a three-electrode system, comprising the working electrode composed of a carbon precursor, along with counter and reference electrodes. Variations in outcomes stem from the chosen carbon precursor and experimental configuration[10]. Commonly, carbon fiber, graphene, and graphite serve as widely adopted precursors, rendering this approach cost-effective and amenable to large-scale carbon quantum dot (CQD) production. This method is further advantageous due to its reliance on readily available materials, sidestepping the use of environmentally aggressive chemicals. Nonetheless, a significant drawback lies in the laborious and time-intensive purification processes necessary for the resulting CQDs [11].

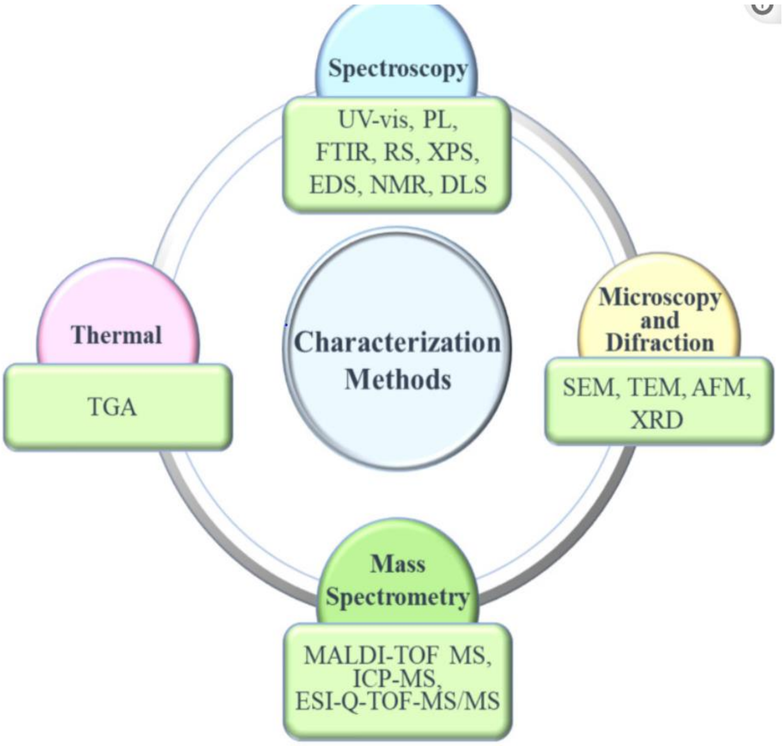
Niu et al. [12] detailed the creation of green-fluorescent N-doped carbon quantum dots (N-CQDs) via an electrochemical (EC) bottom-up route, utilizing pyrocatechol and ethylenediamine as both precursors and electrolytes. The N-CQDs exhibited a quantum yield (QY) of 30.6%. These N-CQDs were subsequently employed in a fluorescence assay, enabling the monitoring of alkaline phosphatase activity through a turn ON–OFF–ON–OFF mechanism. This assay hinged on the specific competitive interaction of N-CQDs with Fe3+ and pyrophosphate anions, coupled with the hydrolysis of pyrophosphate anions in the presence of alkaline phosphatase. Huang et al. [43] developed ionic liquid-functionalized carbon dots (IL-CDs) using the ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate, employing the electrochemical method. Incorporating these IL-CDs into a ratiometric fluorescent assay, which included 2,3-diaminophenazine (DAP), facilitated the assessment of alkaline phosphatase activity through FRET. IL-CDs emitted a blue fluorescence signal at 470 nm, while 2,3-diaminophenazine (DAP) exhibited a yellow fluorescence signal at 570 nm.

Sonochemical synthesis/ ultrasonication:

The sonochemical method presents itself as another environmentally friendly synthesis approach, capable of generating significant quantities of carbon quantum dots (CQDs) without resorting to harmful or toxic substances. This technique involves subjecting the reaction mixture to intense ultrasonic waves, inducing cavitation and the creation of high-pressure vapor bubbles within the solvent [13]. The conversion of ultrasonic energy into mechanical energy facilitates CQD formation through nucleation, polymerization, and aromatization processes [14]. Precise control over ultrasonic wave frequency, power, sonication time, and carbon precursors employed plays a pivotal role in defining the physical and chemical attributes of the resulting CQDs. Notably, this method uniquely allows the doping of CQDs with bulk metals, including Ga, In, Bi, Sn, Pb, Cd, Sb, and Zn [15].

In 2019, He et al. [16] achieved a groundbreaking feat by producing CQDs-based lubricants through sonochemical synthesis utilizing citric acid, urea, and poly(ethylene glycol) (PEG). Under ultrasonic treatment at room temperature for 60 minutes, CQDs with an average size of 2.38 nm were synthesized, demonstrating highly efficient lubricating properties.

IV Characterization method:



Common characterization methods for CQD [17]

V. Antimicrobial activity in CQD:

Travlou et al. [18] undertook a comprehensive study exploring the connection between the introduction of various heteroatoms into carbon quantum dots (CQDs) and their exhibited bactericidal activity. Sulfur and nitrogen-doped CQDs (S-CQDs and N-CQDs) were synthesized using poly(sodium-4-styrene sulfonate) and polyvinylpyrrolidone, respectively. Investigation of CQDs' bactericidal efficacy encompassed Gram-negative (Escherichia coli, CECT 831) and Gram-positive (Bacillus subtilis subsp. subtilis 168) bacterial strains. Notably, N-CQDs demonstrated higher bactericidal activity compared to S-CQDs, with CQDs' surface chemistry and sizes directly impacting their effectiveness. The mechanism behind N-CQDs' bactericidal effect involves electrostatic interactions between their protonated forms and bacterial cell membrane lipids, potentially augmented by the generation of reactive oxygen species on CQDs' surfaces. Notably, amides and amines were found to enhance the bactericidal effect. S-CQDs exhibited size-dependent action and negatively charged surfaces due to sulfonic/carboxylic group dissociation and sulfates. The minimum inhibition concentrations of synthesized CQDs were on par with or lower than those of antibiotics or silver nanoparticles.

Song et al. [19] devised an intriguing method by passing cigarette smoke through water, generating a solution of brownish yellow CQDs. These CQDs exhibited antibacterial activity against Escherichia coli, Staphylococcus aureus, ampicillin-resistant E. coli (AREC), and kanamycin-resistant E. coli (KREC) within a maximum concentration of 1000 μg mL−1. The bactericidal mechanism involved the disruption of DNA double helix structure without inducing morphological changes in bacteria. Remarkably, these CQDs remained highly effective even after breaking down into smaller particles and organic fragments when exposed to horseradish peroxidase (HRP) and H2O2, indicating sustained antibacterial activity over several days.

Material source and chemical composition were found to significantly impact the practical applicability of CQDs. Various types of CQDs were synthesized from leaves of camphor trees, mulberry, lalang grass rhizome, and schizonepeta tenuifolia, yet failed to inhibit bacterial growth, underscoring the influence of starting materials.

Muktha et al.[20] employed pomegranate and watermelon peels to synthesize CQDs using microwave-assisted methods. Antimicrobial activity against Fusarium oxysporum fungus and bacteria, including Staphylococcus aureus, Pseudomonas aeruginosa, Bacillus subtilis, and Escherichia coli, was assessed. CQDs derived from pomegranate peel (P-C dots) displayed more significant antimicrobial effects compared to those from watermelon peel (W-C dots). P-C dots exhibited potent antifungal activity, whereas W-C dots showed no antifungal effects. Furthermore, both P-C dots and W-C dots displayed anticancer effects against MCF-7 and HepG2 cell lines.

Li et al. [21] introduced degradable and low-toxicity CQDs synthesized from vitamin C as the carbon precursor via an electrochemical method. These CQDs could be completely degraded into CO2, CO, and H2O under mild visible light irradiation at around 37°C within 20 days. Antibacterial activity against Staphylococcus aureus, Bacillus subtilis, and Escherichia coli (non-resistant and ampicillin-resistant), as well as antifungal activity against Rhizoctonia solani and Pyricularia grisea, was assessed. The most effective bacteriostatic and fungistatic concentrations were reported at 100 and 300 μg mL−1, respectively. The proposed mechanism involved CQDs entering bacteria or fungi via diffusion, leading to microbial wall disruption, binding to DNA and RNA, and inhibition of gene expression, ultimately resulting in microbial death at low CQDs concentrations.

Carbon dots (CDs) can elicit bacteriostatic or bactericidal effects through several distinct pathways, each bearing significance. These routes encompass mechanical disruption of bacterial membranes, causing physical harm, and the subsequent degradation of the bacterial cell wall, resulting in the leakage of cytoplasmic contents (as depicted in Figure 2B) . Moreover, CDs can induce inactivation through photothermal therapy (PTT), leveraging localized temperature elevation upon illumination [15]. Another pivotal avenue involves the direct generation of reactive oxygen species (ROS), either independently or under light stimulation, fostering oxidative stress. Furthermore, CDs can inflict damage and fragmentation upon DNA and proteins (as illustrated in Figure 2C) [50]. CD integration into bacterial membranes is recognized to promote membrane damage, further contributing to bacterial inactivation.

Particularly noteworthy are nitrogen-doped CDs that exhibit photosensitizing properties. These CDs serve as catalysts for ROS generation when exposed to UV or visible light, inducing bacterial oxidative stress by producing species such as hydrogen peroxide (H2O2), hydroxyl radicals (·OH), superoxide anions (·O2−), and singlet oxygen (1O2) through interactions with water and dissolved oxygen. Additionally, near-infrared (NIR) laser absorption-induced photothermal effects are frequently exploited to raise localized temperatures, leading to bacterial demise [22].

Ⅵ. As a photosynthetic enhancer:

In response to the expanding global population and heightened food requirements, efforts have been directed toward optimizing soil conditions and fertilizers to amplify crop yield. Nonetheless, the growth of plants remains constrained by the inefficiencies inherent in the photosynthesis process. Photosynthesis, the vital mechanism through which green plants harness light energy to transform water and carbon dioxide into oxygen and sugars for their growth, is marked by its inefficiency. Merely a meager 2-4% of the accessible light energy gets converted into new plant growth. Leveraging the availability of non-toxic carbon quantum dots (CQDs), an innovative solution has emerged aimed at augmenting the photosynthesis process.

Upon incubation of carbon quantum dots (CQDs) with chloroplasts, an intriguing phenomenon occurs as the dots effectively envelop the entire chloroplast surface. This interaction manifests as the absorption of the CQDs' blue light emission by the chloroplasts, inducing a concomitant reduction in the photoluminescence of the dots in a manner contingent on their quantum yield (Li et al., 2021). Notably, augmenting the surface passivation of CQDs can potentiate their charge transfer capacity. A study by Chandra et al. (2014) demonstrated that amine functionalized CQDs exhibit robust conjugation to the chloroplast surface, thereby heightening electron transfer and expediting the pathways integral to light reactions. Additionally, Li et al. (2021) highlighted that CQDs play a role in the conversion of harmful ultraviolet (UV) radiation into harmless photosynthetically active radiation, devoid of significant energy transfer. This insightful finding underscores the secure utilization of UV light in the photosynthesis process facilitated by quantum dots.

Ⅶ. Future scope and conclusion:

In conclusion, the utilization of carbon quantum dots (CQDs) in the realm of agriculture and plant science has opened up innovative avenues for enhancing various aspects of plant growth, development, and sustainability. CQDs offer unique properties such as fluorescence, biocompatibility, and surface functionalization, which have been harnessed to improve seed germination, boost photosynthetic efficiency, and augment disease resistance in plants. The versatility of CQDs as photosynthetic enhancers and their potential to modulate physiological processes hold promise for addressing challenges posed by increasing food demands and environmental stressors.

The diverse synthesis methods of CQDs, including hydrothermal, electrochemical, and sonochemical routes, have been explored for their potential to yield effective nanomaterials. These methods allow the production of CQDs from various precursor materials, contributing to sustainable practices through waste utilization and greener methodologies. Moreover, investigations into the antibacterial and antifungal properties of CQDs further extend their applications, indicating their potential in mitigating plant diseases and promoting crop health.

Looking ahead, the future scope of CQDs in agriculture appears promising. Further research could focus on optimizing CQD formulations, concentrations, and application methods to maximize their impact on crop yield, disease resistance, and overall plant health. Exploring the interactions between CQDs and different plant species, as well as the intricate mechanisms underlying their effects on photosynthesis and physiological processes, would provide deeper insights. Moreover, evaluating the long-term environmental effects and biodegradability of CQDs in the context of sustainable agriculture would be crucial.

Efforts to translate laboratory findings into practical field applications will be pivotal. Large-scale field trials and demonstrations are essential to validate the efficacy, safety, and economic feasibility of CQD-based interventions in real-world agricultural scenarios. Collaborative interdisciplinary research involving plant scientists, nanotechnologists, and environmental experts will be instrumental in advancing our understanding of CQDs' potential benefits and challenges in agriculture.

In essence, the integration of carbon quantum dots into agricultural practices represents a promising frontier, with the potential to revolutionize crop production, improve food security, and contribute to environmentally conscious farming practices. Continued exploration, innovation, and collaboration are key to unlocking the full potential of CQDs in shaping the future of sustainable agriculture.

REFERENCES

1]A. Gupta, S. K. Mehta, K. Kunal, K. Mukhopadhyay, and S. Singh, “Quantum dots as promising nanomaterials in agriculture,” in Agricultural Nanobiotechnology, Elsevier, 2022, pp. 243–296. doi: 10.1016/B978-0-323-91908-1.00016-X.

[2] S. Y. Lim, W. Shen, and Z. Gao, “Carbon quantum dots and their applications,” Chem. Soc. Rev., vol. 44, no. 1, pp. 362–381, 2015, doi: 10.1039/C4CS00269E.

[3] S.-T. Yang et al., “Carbon Dots for Optical Imaging in Vivo,” J. Am. Chem. Soc., vol. 131, no. 32, pp. 11308–11309, Aug. 2009, doi: 10.1021/ja904843x.

[4] Y. Li et al., “Carbon dots as light converter for plant photosynthesis: Augmenting light coverage and quantum yield effect,” J. Hazard. Mater., vol. 410, p. 124534, May 2021, doi: 10.1016/j.jhazmat.2020.124534.

[5] B. Guo et al., “The role of carbon dots in the life cycle of crops,” Ind. Crops Prod., vol. 187, p. 115427, Nov. 2022, doi: 10.1016/j.indcrop.2022.115427.

[6] R. Guerrero-Gonzalez, F. Vázquez-Dávila, E. Saucedo-Flores, R. Ruelas, O. Ceballos-Sánchez, and J. E. Pelayo, “Green approach synthesis of carbon quantum dots from agave bagasse and their use to boost seed germination and plant growth,” SN Appl. Sci., vol. 5, no. 8, p. 204, Jul. 2023, doi: 10.1007/s42452-023-05428-2.

[7] H. Li et al., “Impacts of Carbon Dots on Rice Plants: Boosting the Growth and Improving the Disease Resistance,” ACS Appl. Bio Mater., vol. 1, no. 3, pp. 663–672, Sep. 2018, doi: 10.1021/acsabm.8b00345.

[8] Y. X. Gan, A. H. Jayatissa, Z. Yu, X. Chen, and M. Li, “Hydrothermal Synthesis of Nanomaterials,” J. Nanomater., vol. 2020, p. e8917013, Jan. 2020, doi: 10.1155/2020/8917013.

[9] M. B. Gawande, S. N. Shelke, R. Zboril, and R. S. Varma, “Microwave-assisted chemistry: synthetic applications for rapid assembly of nanomaterials and organics,” Acc. Chem. Res., vol. 47, no. 4, pp. 1338–1348, Apr. 2014, doi: 10.1021/ar400309b.

[10] “Biogreen Synthesis of Carbon Dots for Biotechnology and Nanomedicine Applications | Nano-Micro Letters.” https://link.springer.com/article/10.1007/s40820-018-0223-3 (accessed Aug. 26, 2023).

[11] M. Farshbaf, S. Davaran, F. Rahimi, N. Annabi, R. Salehi, and A. Akbarzadeh, “Carbon quantum dots: recent progresses on synthesis, surface modification and applications,” Artif. Cells Nanomedicine Biotechnol., vol. 46, no. 7, pp. 1331–1348, Oct. 2018, doi: 10.1080/21691401.2017.1377725.

[12] F. Niu, Y.-L. Ying, X. Hua, Y. Niu, Y. Xu, and Y.-T. Long, “Electrochemically generated green-fluorescent N-doped carbon quantum dots for facile monitoring alkaline phosphatase activity based on the Fe3+-mediating ON-OFF-ON-OFF fluorescence principle,” Carbon, vol. 127, pp. 340–348, Feb. 2018, doi: 10.1016/j.carbon.2017.10.097.

[13] A. Das and P. T. Snee, “Synthetic Developments of Nontoxic Quantum Dots,” ChemPhysChem, vol. 17, no. 5, pp. 598–617, Mar. 2016, doi: 10.1002/cphc.201500837.

[14] L. Li and T. Dong, “Photoluminescence tuning in carbon dots: surface passivation or/and functionalization, heteroatom doping,” J. Mater. Chem. C, vol. 6, no. 30, pp. 7944–7970, 2018, doi: 10.1039/C7TC05878K.

[15] R. Kumar, V. B. Kumar, and A. Gedanken, “Sonochemical synthesis of carbon dots, mechanism, effect of parameters, and catalytic, energy, biomedical and tissue engineering applications,” Ultrason. Sonochem., vol. 64, p. 105009, Jun. 2020, doi: 10.1016/j.ultsonch.2020.105009.

[16] C. He, H. Yan, X. Li, and X. Wang, “In situ fabrication of carbon dots-based lubricants using a facile ultrasonic approach,” Green Chem., vol. 21, no. 9, pp. 2279–2285, 2019, doi: 10.1039/C8GC04021D.

[17] H. B. A. Sousa, C. S. M. Martins, and J. A. V. Prior, “You Don’t Learn That in School: An Updated Practical Guide to Carbon Quantum Dots,” Nanomaterials, vol. 11, no. 3, p. 611, Mar. 2021, doi: 10.3390/nano11030611.

[18] N. A. Travlou, D. A. Giannakoudakis, M. Algarra, A. M. Labella, E. Rodríguez-Castellón, and T. J. Bandosz, “S- and N-doped carbon quantum dots: Surface chemistry dependent antibacterial activity,” Carbon, vol. 135, pp. 104–111, Aug. 2018, doi: 10.1016/j.carbon.2018.04.018.

[19] Y. Song et al., “Degradable Carbon Dots from Cigarette Smoking with Broad-Spectrum Antimicrobial Activities against Drug-Resistant Bacteria,” ACS Appl. Bio Mater., vol. 1, no. 6, pp. 1871–1879, Dec. 2018, doi: 10.1021/acsabm.8b00421.

[20] H. Muktha, R. Sharath, N. Kottam, S. P. Smrithi, K. Samrat, and P. Ankitha, “Green Synthesis of Carbon Dots and Evaluation of Its Pharmacological Activities,” BioNanoScience, vol. 10, no. 3, pp. 731–744, Sep. 2020, doi: 10.1007/s12668-020-00741-1.

[21] H. Li et al., “Degradable Carbon Dots with Broad-Spectrum Antibacterial Activity,” ACS Appl. Mater. Interfaces, vol. 10, no. 32, pp. 26936–26946, Aug. 2018, doi: 10.1021/acsami.8b08832.

[22] M. Ghirardello, J. Ramos-Soriano, and M. C. Galan, “Carbon Dots as an Emergent Class of Antimicrobial Agents,” Nanomaterials, vol. 11, no. 8, p. 1877, Jul. 2021, doi: 10.3390/nano11081877.