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Review

Recent Advances in Water Treatment Using Carbon Dots: A Comprehensive Review

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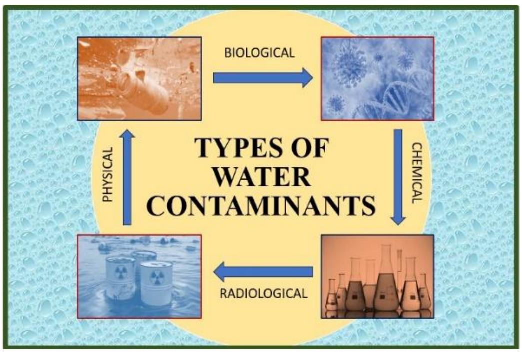
Abstract

Carbon dots (CDs) used in water treatment have attracted widespread interest due to their remarkable properties and versatility in environmental purification. Carbon dots are a family of carbon-based nanomaterials that are known for their excellent fluorescence, superior electrical conductivity, tunable surface chemistry, and biodegradability. These features make them suitable for use in various water treatment processes like the detection and removal of impurities like heavy metals, organic impurities, and microorganisms. Their small size and extremely large surface area make them useful for efficient adsorption as well as for interaction with target contaminants, while optical characteristics make it easy to monitor water quality in real-time. New technologies of CD synthesis, especially green and sustainable synthesis have increased environmental suitability as well as cost-effectiveness. Despite promising development, there remains a challenge in scaling these technologies for large-scale water treatment applications, including CD stability, regeneration, and long-term performance. Current research is endeavouring to move beyond these limitations through novel design of materials and hybrid systems. The synthesis of carbon dots as a water cleaning agent is one such development within sustainable environmental engineering, offering an environmentally friendly as well as highly efficient measure for water purification. This article presents carbon dot synthesis and carbon dot treatment of water during the past five years.

Keywords: Carbon dots, Contaminants, Water treatments, Synthesis, Characterization, Properties



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1. Introduction

Water pollution refers to the pollution of water bodies (e.g., rivers, lakes, oceans, aquifers, and groundwater) with substances that are released directly or indirectly without treatment to remove toxic compounds. The impact of water pollution is widespread and complicated, not just on aquatic organisms but also on human health and the economy. Chemicals, heavy metals, and pathogens are the kind of pollutants that can lead to reduced biodiversity, ecosystem degradation, and toxin accumulation in the food chain. In humans, drinking or coming into contact with polluted water can cause various health issues ranging from acute to chronic [1]. Water pollution impacts ecosystems, the economy, and human health considerably. Toxin build-up in the food chain, lower biodiversity, and environmental pollution can be caused by contaminants such as chemicals, heavy metals, and viruses. Human exposure or ingestion of contaminated water might lead to a range of different health conditions, from acute illness to chronic long-term illnesses. Water contamination is linked with numerous diseases. Poor water quality is linked to more than 80% of infections and 50% of child mortality globally, as a Frontiers in Environmental Science study exposed [2] Expanding demand for clean water and ongoing water pollution underscore the need for new treatment technologies. New pollutants such as medicines and heavy metals are not amenable to conventional treatment. Technologically advanced oxidation technologies and augmented biological treatment processes are efficient, energy-conserving options. Technologies such as photocatalysis and solar/Fenton have the ability to break down contaminants in an environmentally friendly manner. However, there remain challenges to scale up these technologies for larger applications [3,4]. Technologies of advanced treatment need to be employed for water pollution management. Pharmaceuticals and heavy metals are among the emerging contaminants that are resistant to conventional treatments. Advanced oxidation processes (AOPs) and advanced biological processes are two emerging technologies that have efficient energy-saving strategies. Solar/Fenton and photocatalysis processes are able to degrade the pollutants in an eco-friendly way. Scaling them up to commercial production is still not easy, though. Thanks to their enhanced physicochemical and aesthetic properties, carbon dots (CDs), which are a very rare family of nanomaterials, have been gaining more interest for water treatment applications. They are normally <10 nm with outstanding chemical stability, and their fluorescence is tunable with outstanding photoluminescence. They can be applied for pathogen disinfection, organic pollutant degradation, and heavy metal ion adsorption because they have a large surface area and functional surface. There are many carbon-rich precursors used to synthesize CDs, including low-cost and eco-friendly alternatives. Their low toxicity, biocompatibility, and high photocatalytic activity under light irradiation also complement their use in green water treatment systems [5]. Increased interest is concurrent with progress in their synthesis and functionalization so that they are suitable for specific tailoring to specific applications in water treatments, e.g., improved photocatalytic activity and adsorption selectivity of pollutants [6]. Carbon dots (CDs), as a new type of nanomaterial, have caused tremendous interest in water treatment because of their useful physicochemical and optical properties. They are typically smaller than 10 nm, with superior photoluminescence, fluorescence tunability, and chemical stability. Because they have a functionalized surface and high surface area, they prove to be effective for uses like heavy metal ion adsorption, organic pollutant degradation, and pathogen disinfection. CDs are synthesized from a range of carbon-rich precursors, making them low-cost and environmentally friendly sources. Their photocatalytic activity under light irradiation, biocompatibility, and low toxicity render them even more appropriate to use in sustainable water treatment systems [7,8]. Generally, water pollution is a significant challenge to the economy, human health, and the environment. Advances in water treatment technologies, particularly carbon dots synthesis, can address these problems.

This systematic review examines the ubiquity of microplastics in the world's waters, terrestrial and aquatic sources, and their persistence within the environment. The review is cantered on the biological and economic importance of microplastic pollution and the possible harm to human health and economic costs. It also discusses the lack of uniform methodology for microplastic analysis and sampling, which complicates it to compare studies conducted so far. Authors are insistent upon the employment of standard methods for the real estimation of microplastic pollution and its consequences [9,10]. In this review, extra care has been taken in the evaluation of physical impurities, especially heavy metals, in drinking water sources. Authors discuss detection techniques of the metals lead, cadmium, mercury, zinc, arsenic, chromium, nickel, sodium, potassium, and iron through processes like Atomic Absorption Spectrometry (AAS) and flame photometry.

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2. Types of contaminants

Water contaminants can be broadly classified into four types as shown in Figure 1. Water contamination includes a broad range of pollutants that can be categorized into physical, chemical, biological, and radiological types, each uniquely contributing to the decline of water quality and presenting considerable environmental and public health hazards [7]. Physical contamination refers to the presence of suspended solids, sediments, microplastics, and thermal changes that influence water clarity, colour, temperature, and turbidity. These pollutants often stem from soil erosion, urban runoff, industrial cooling processes, and improper waste disposal. While they may not directly induce toxicity, they can disrupt aquatic ecosystems by diminishing light penetration, modifying habitat conditions, and aiding in the transport of chemical and microbial contaminants [8]. Chemical contamination represents the most varied category, including inorganic pollutants such as heavy metals (lead, mercury, cadmium and arsenic), nutrients like nitrates and phosphates, and various salts, alongside organic contaminants such as pesticides, petrochemicals, pharmaceuticals, personal care products, solvents, and persistent organic pollutants (POPs). These chemicals frequently originate from agricultural runoff, industrial discharges, mining operations, landfills, and domestic sewage, and can lead to severe toxicological consequences ranging from carcinogenicity and endocrine disruption to bioaccumulation and long-term ecological imbalance.

2.1 Physical contaminants

Physical properties such as electrical conductivity, temperature, pH, total dissolved solids (TDS), hardness, turbidity, alkalinity, and salinity are sensed with digital electronic kits. The results show that water bodies located close to industrial and municipal waste facilities are more polluted, whereas those that are far away from such facilities are of better quality. The review captures the health implications of water contamination with heavy metals and the significance of continuous monitoring in maintaining safety in water [11]. The review critically examines the extent of the problem of water environments' pollution with microplastics. It emphasizes the complex physical and chemical attributes of microplastics, their origins, and their long-term persistence in the environment. The paper emphasizes the difficulty in monitoring, observing, and measuring microplastics due to the absence of uniform methods. Furthermore, it emphasizes the urgent need for the formulation of an international regulatory framework to prevent the spread of microplastics and ensure environmental as well as human welfare [12,13].

2.2 Chemical contaminants

Water chemical pollutants are derived from a range of sources, and they have profound impacts on aquatic life as well as human health. Industrial effluent is one of the principal sources whereby factories release toxic chemicals like solvents and heavy metals directly into water bodies, leading to serious pollution. Agricultural runoff is another prominent source whereby pesticides, herbicides, and fertilizers enter the water system. Among the riskiest chemical contaminants are heavy metals such as lead, mercury, and cadmium. The metals persist in the environment, accumulate in the food chain, and contain catastrophic health threats. Lead, for instance, chronic exposure can lead to development problems and neurological diseases, especially among children. Mercury pollution, often related to industrial effluence and mining, can induce extreme nervous system damage [14]. Secondly, farm runoff containing pesticides, herbicides, and fertilizers is one of the main sources of chemical pollution. The other main category of pollutants is the Persistent Organic Pollutants (POPs) like DDT, dioxins, and polychlorinated biphenyls (PCBs). They are highly toxic and non-biodegradable. POPs tend to build up in animal tissue and cause biomagnification a process in which their concentration gets increased higher as they move up the food chain. This is a risk to human health, particularly with the ingestion of contaminated aquatic animals [15]. Neonicotinoids and organophosphates pesticides are also among the major challenges because of how they have the ability to interfere with human endocrine function. These chemicals have been associated with reproductive disease, immune system weakening, as well as neurodegenerative disease. In addition to this, they are extremely toxic to pollinators like bees, which form an important pillar of biodiversity and food production across the world [16]. New contaminants like perfluoroalkyl and polyfluoroalkyl substances (PFAS) have come into the limelight because of their persistence and toxicity. PFAS used in firefighting foam, non-stick cookware, and rain gear do not break down easily in the environment. Their exposure over a period has been linked to cancer, liver injury, and immunotoxicity. Overall presence of PFAS in sources of drinking water is raising concerns about the effectiveness levels of the existing systems for water treatment [17]. PCBs and dioxins are other industrial chemicals that are doing the same. PCBs, which were previously used in electrical

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equipment and cooling systems, still remain in sediments despite bans on their application in most countries. The chemicals disrupt hormonal balance and are known to have been associated with aquatic animal reproductive and developmental disorders. Dioxins, which are usually industrial combustion residues, are highly toxic and cause cancer and immune system malfunctions [18]. Emerging research indicates the potential of green technologies to mitigate chemical contamination. Biochar, a carbon-rich substance made from organic waste, has demonstrated effective adsorption characteristics for heavy metals and organic pollutants. Another promising method is phytoremediation, which uses plants to absorb and detoxify pollutants from water [19]. To combat chemical contamination effectively, a holistic approach is essential. This includes strict policy enforcement, innovative treatment technologies, and community-level awareness [20]. By educating the public about safe disposal methods, minimizing pesticide use, and encouraging sustainable agriculture, pollution can substantially be minimized. Through efficient water management activities, long-term environmental sustainability can be achieved by us and human as well as ecosystem health can be protected [21]–[23].

2.3 Biological contaminants

Biological contaminants are pathogenic microorganisms like bacteria, viruses, fungi, and parasites that can contaminate food, water, and the environment and result in severe health risks. Biological contaminants can lead to foodborne illness, respiratory disease, and allergic reactions. Bacteria like Salmonella and Escherichia coli can cause food spoilage and make the food unsafe for human consumption. Viruses like norovirus and hepatitis A can infect a host and mutate, making them tougher to survive new environments. Spores that are discharged by molds can lead to serious allergies and breathing ailments, and fungal allergens can trigger Type I allergic reactions, which lead to conditions such as asthma and rhinitis. Additionally, 1, 3-β-D glucans, a component of fungal cell walls, have been known to induce respiratory infections, which also contribute to health problems [24]. Being ubiquitous and potentially having great impact, biological contaminants need to be controlled and understood in order to safeguard public health and ensure food and environmental safety. This comprehensive review addresses the most significant issues that biological contaminants—bacteria, viruses, and fungi—present in biomanufacturing processes. It emphasizes the necessity of strict microbial monitoring to ensure product effectiveness and safety. Traditional techniques like viable cell counting, where the sample is seeded onto agar plates to enumerate colony-forming units, even though are not so speedy or selective. Advanced techniques such as Polymerase Chain Reaction (PCR) are delineated, which are highly specific and sensitive in detecting microbial DNA and hence find application in the rapid identification of the contaminant. The article also addresses some of the frontier technologies, namely flow cytometry and real-time PCR, offering real-time monitoring. The authors advise the employment of combined detection methods in the enhancement of the accuracy and reliability of contamination monitoring of biomanufacturing plants [25].

This paper addresses the prevalence of airborne fungi and bacteria in indoor settings and identifies principal factors influencing their concentrations. Factors such as outdoor air quality, dust, ventilation issues, humidity, and occupancy are discussed as to how they impact indoor air quality. The study identifies the prevailing bacterial genera, including Bacillus spp. (24.1%), Staphylococcus spp. (20.7%), and Micrococcus spp. (20.7%), and fungal genera like Penicillium spp. (25%), Cladosporium spp. (21.9%), and Aspergillus spp. (21.9%). Proper building maintenance and environmental controls are stressed by the authors as needed to prevent the transmission of these biological contaminants and, therefore, to maintain occupant health [26]. This in-depth review discusses the myriad sources of microbial contamination indoors, ranging from human occupants to pets to outdoor air intrusion. It discusses sampling techniques including air, surface, and dust sampling and analytical procedures used to assess microbial diversity and load. The health consequences of indoor exposure to microbial contaminants are investigated, including dangers such as respiratory infections, allergic responses, and other medical conditions. The report also discusses increased significance of indoor air quality with respect to the COVID-19 pandemic and the importance of evidence-based research for creating definitive links between certain pollutants and health implications. Mitigative measures in the form of enhanced ventilation, frequent cleaning, and air conditioning systems are proposed to enhance indoor air quality and reduce health risk [27]. Lastly, the contribution of indoor air quality towards viral transmission, particularly COVID-19, is explored in a recent scoping review. It highlights the role of effective air exchange and filtration to reduce airborne pathogen transmission, calling attention to the fact that ventilation is one of the best tools for managing indoor biological contamination [28].

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2.4 Radiological contaminants

Radiological contaminants are radioactive substances that may enter the environment through natural pathways as well as human activities, such as mining, production of nuclear electricity, and industrial effluent discharge. Contaminants in this context refer to radionuclides like radium (^226Ra), thorium (^232Th), potassium (^40K), and uranium (^238U), which have the potential to accumulate in water, soil, and air. Long-term exposure to them, though low, is highly harmful to health, causing cancer and genetic mutation. Monitoring the levels of radiological pollutants and assessing their potential impacts on the environment and public health is crucial to ensuring safety, especially around industrial and mining activities.

This study addresses soil pollution by radionuclides like ^137Cs and ^90Sr following nuclear activities and accidents. It introduces remediation techniques such as soil removal, stabilization by chemical amendments, and phytoextraction. It refers to the challenges and effectiveness of such techniques, highlighting the significance of cost-effective and effective ways for large-scale pollution [29]. This research discusses the activity concentrations of ^226Ra, ^228Ra, ^234U, ^238U, and ^40K in bottled mineral waters of the Outer Carpathians, Poland. The study pinpoints total dissolved solids to radionuclide content correlations, with some samples registering uranium isotopic ratios indicating disequilibrium. The effective radiation dose rates by ingestion are estimated, providing indications of the potential health effects [30]. The review presents a broad view incorporating contamination by uranium in groundwater and its sources, geochemical behavior, and factors influencing its mobility. It contrasts treatment technologies for the extraction of uranium and documents challenges encountered in sludge disposal. The authors emphasize the need for effective and affordable remediation technology to prevent groundwater contamination by uranium [31]. This study examines the spatial distribution of natural radionuclides (^238U, ^226Ra, ^232Th, and ^40K) in surface soils and river sediments at a uranium mine in South China. It calculates radiological risks in terms of indices like radium equivalent activity and annual gonadal dose equivalent. The findings are indicative of elevated radionuclide levels near mining areas, suggesting potential health risks and remediation [32]. This chapter describes sources and pathways of waterborne radiological contaminants, including natural sources and anthropogenic activities. It discusses monitoring procedures, risk evaluation, and treatment procedures for water to eliminate radionuclides. The article highlights the importance of effective management and disposal procedures for radioactive waste in order to protect the environment and human health [33]. The study evaluates the effectiveness of a greensand filtration system to remove radium from drinking water. It compares variables such as adsorption variables like silica sand and kinetics factors and system performance in decontaminating large volumes of water. Research is provided based on practical applications of the method of radionuclide filtration for removal of radionuclides by water treatment plants [34] Review is being presented on phytoremediation technologies' applications for decontaminating radionuclides in contaminated environments. It explains various phytoremediation techniques employed using plants such as phytoextraction and phytostabilization and criticizes the efficiency based on various regions. The paper makes a determination of the advantages and limitations of phytoremediation, offering recommendations to be followed for future research and application [35].

2.5 Advances in water quality monitoring

Water quality monitoring has improved over time with advances in conventional as well as newer methods. Modern technologies like virtual sensing, cyber-physical systems (CPS), the Internet of Things (IoT), and optical means are discussed in the review article "Advancements in Monitoring Water Quality Based on Various Conventional and Emerging Methods." These help in better real-time monitoring as well as greater accuracy in the data, and thus more effective water quality management. Physical sampling and laboratory analysis are conventional techniques for water quality monitoring, which, though precise, are time-consuming and resource-extensive. The new technologies provide automated and remote monitoring systems, enabling real-time measurement of water quality parameters like turbidity, pH, dissolved oxygen, and contaminants [36].

2.5.1 Virtual Sensing: Predictive models and sensor readings are used to make estimates of water quality parameters, minimizing frequent physical sampling.

2.5.2. Cyber-physical systems (cps): Combine sensors, data analysis, and automation to deliver real-time information about water conditions.

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2.5.3. Internet of things (IOT): Smart water monitoring is made possible through this technology by linking various sensors and devices to cloud platforms for real-time analysis and notification.

2.5.4. Optical methods: Apply advanced imaging and laser technologies to identify variations in water clarity and the presence of contaminants.

Each monitoring method has its own advantages and limitations. Conventional techniques have high reliability but involve labour-intensive processes. IoT and CPS ensure real-time monitoring but are based on stable network infrastructure and heavy initial investment. Optical techniques ensure high precision but can be complicated and expensive to deploy on a large scale. Recent developments in water quality monitoring have transformed the detection, analysis, and management of water pollutants, making water resources safer. The combination of Internet of Things (IoT) and Wireless Sensor Networks (WSNs) has facilitated live data acquisition and transmission, optimizing the efficiency in contamination detection based on networked sensors monitoring pivotal parameters like pH, turbidity, temperature, and dissolved oxygen. Remote sensing and satellite remote sensing have broadened large-area monitoring, gauging turbidity, concentration of chlorophyll, and surface temperature in identifying sources of pollution [37]. Artificial Intelligence (AI) and Machine Learning (ML) have ushered in a significant revolution in water quality monitoring systems. Through the processing of huge amounts of real-time data, the technologies are capable of identifying patterns of contamination as well as predicting potential threats with excellent accuracy. This enables early actions to take place and minimizes reliance on human sampling. AI-based models also assist in sensor network optimization and resource allocation. As more efficient and predictive, AI and ML become essential resources in sustainable water management strategies [38]. Citizen science has been a revolutionary method in water quality monitoring in the last decade, enabling non-experts to play active roles in gathering and analysing environmental information. It improves the spatial and temporal resolution of water quality monitoring, especially in areas where conventional monitoring is constrained. For instance, a study conducted on Ethiopia's Meki River revealed that readings taken by citizen scientists on variables such as pH, turbidity, and nutrients were as good as those taken through conventional laboratory methods, demonstrating the validity of projects undertaken by citizens [39]. Similarly, in the United Kingdom, citizen scientists have played a pivotal role in identifying sources of pollution in rivers like the Avon, and this has led to increased public awareness and policy interventions for improving the quality of water [40]. The instances above illustrate the immense contribution of citizen science towards managing water resources, generating community engagement and providing critical data that inform sustainable practice and policy-making. Such technological advancements, supplemented by increasing community involvement, significantly improve water quality management and lead to environmental sustainability.

3. Synthesis of carbon dots

Synthesis route is the most significant parameter in controlling structural, surface, and optical properties of carbon dots (CDs), which influence their efficiency in environmental processes, particularly in water treatment. Various synthesis routes (Figure 1) hydrothermal, microwave-assisted, and pyrolysis—dramatically influence critical parameters such as particle size, surface functional groups, and heteroatom doping level. These, in turn, control their efficiency in the elimination of pollutants as well as in environmental remediation. The hydrothermal route is prevalent due to the fact that it can offer a controllable reaction condition that allows for the preparation of highly surface-functionalized CDs. This enhances their adsorption ability towards most pollutants such as heavy metals and organic dyes [41]. CDs prepared through hydrothermal synthesis, for instance, have been found to possess high affinity towards mercury and ferric ions, opening doors for their use in water purification processes. On the contrary, the microwave-assisted synthesis technique is observed to be energy-saving and rapid in terms of reaction rate. The process allows synthesis of CDs with typical morphological and optical properties which can be tuned for targeted purposes like photocatalytic water treatment for decontamination [42]. The rapid heating allows for homogeneous particle sizes and enhances the quantum yield and, as such, these CDs make good candidates in dye degradation processes. The other widely used synthesis process is the pyrolysis method, which involves high-temperature decomposition of carbon-rich precursors. They produce very crystalline CDs and enable the doping of heteroatoms (e.g., sulphur or nitrogen) with great precision, which also improves their electronic and photonic performance [43]. These are of crucial significance in advanced oxidation processes (AOPs), where CDs act as efficient photocatalysts for the degradation of recalcitrant organic contaminants. As a result,

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choosing a synthesis route allows scientists to modify the physicochemical properties of CDs to be highly effective in different environmental applications, particularly water treatment and contaminant degradation.

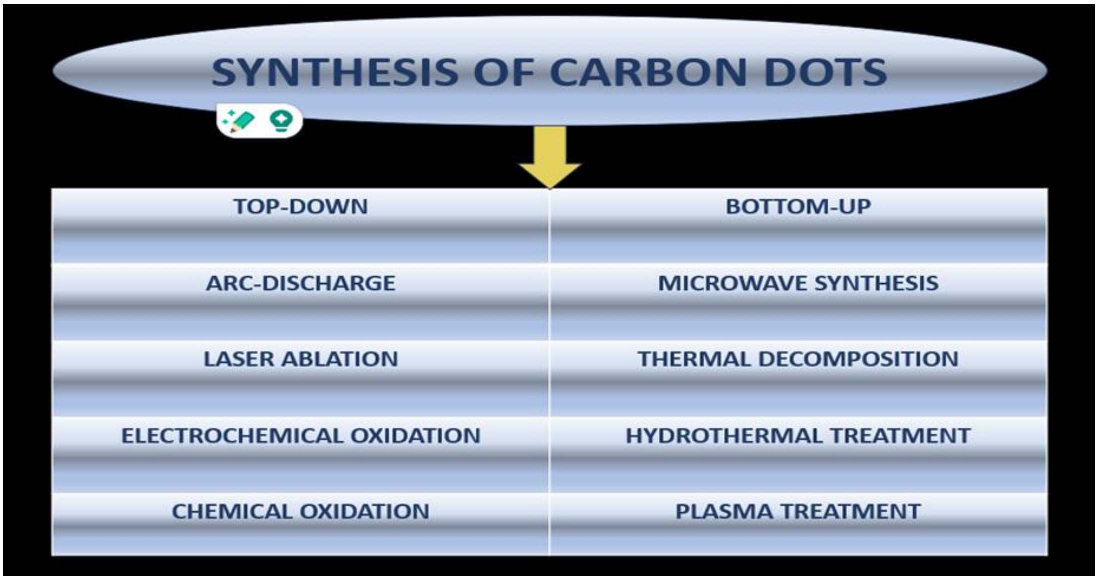

Fig. 1. Various synthetic methods of carbon dots

Synthesis of CDs is possible by many methods, generally categorized into top-down and bottom-up processes. Top-down processes include disintegrating the bigger carbon structures, like graphite or carbon nanotubes, into nanodots. Bottom-up processes emphasize building CDs from molecular precursors using chemical or thermal reactions. Both methods are flexible in terms of adjusting the size, surface functionality, and functional properties of CDs, based on their application. Development in synthesis methods has allowed for the fabrication of CDs with greener, cost-saving, and scalable protocols. Biomass, polymers, and small organic molecules serve as typical precursors, allowing access to environmentally friendly nanomaterial construction. In addition, the conditions of synthesis, such as reaction time, temperature, and pH, significantly influence the optical and structural properties of the final CDs. And pH is an important factor in deciding the optical and structural properties of the final CDs.

3.1 Top-Down method

Laser ablation is a top-down and versatile method for the synthesis of carbon dots (CDs), involving ablation of a carbon source by a laser in liquid conditions (Figure 2A). Laser ablation minimizes chemical impurities and enables control over CD size and properties by factors such as: Laser wavelength, Intensity, Pulse duration. Recent advancements have pointed toward the use of shorter wavelengths for improved control of the surface functionalization, e.g., oxygen-containing groups, for improved photoluminescence (PL) and biocompatibility. Laser ablation remains an attractive and versatile top-down approach towards the synthesis of carbon dots (CDs), in which a solid carbon material is irradiated with a high-energy laser in the presence of a liquid medium. This process is specially valued for providing CDs of low chemical contamination, as no toxic reagents are used, and thereby the process can be applied for biomedical and environmentally friendly applications [44]. Size and surface characteristics of the synthesized CDs can be rigorously controlled by adjusting parameters such as laser wavelength, intensity, pulse length, and also the type of solvent. Shorter laser wavelengths have been found to allow for the synthesis of CDs with high oxygen-functional groups, thereby enhancing their PL, water dispersibility, as well as biocompatibility [45]. Such properties are particularly desirable for use in bioimaging and sensing platforms. Laser-ablated CDs are optically found to exhibit excitation-dependent PL properties with particle sizes ranging from 1–5 nm, along with good structural stability and fluorescence efficiency. Tuning solvents like polyethyleneimine or ethylenediamine during the synthesis process further improves the yield and intensity of fluorescence, rendering them applicable to biosensors and photocatalytic systems in practice [46]. Laser ablation as a whole offers a clean, controllable, and scalable technique for producing high-quality CDs whose property can be tuned for a broad array of applications in environmental remediation and biomedicine.

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This new approach entails sending an electric current through carbon precursors dissolved in solvents to oxidize them and form CDs of a particular size and surface nature. Precursor type, solvent mixture, and current density can be tailored to regulate the photoluminescence and other properties. Electrochemical processes are environmentally friendly and energy-efficient, which explains their increasing popularity for applications in energy storage, chemical sensing, and bio-imaging (Figure 2B). These processes also facilitate doping or functionalization, which improves the optical and biocompatibility characteristics needed in biomedical applications [47]–[49]. In the arc Discharge method, plasma is created in a controlled reactor, fractionating carbon precursors into nanoscale CDs (Figure 2C). CDs produced through arc discharge have been applied for the removal of heavy metal ions and degradation of dyes in wastewater in photocatalysts due to high surface area as well as adsorption characteristics [50,51]. It is a review of carbon dots (CDs) that are synthesized from chemical and green precursors and their application in photocatalytic dye degradation. The article explains how carbon frameworks are oxidized to include oxygen-containing functional groups, which enhance the hydrophilicity of the CDs and the interaction with the pollutants (Figure 1D). The functional groups play a critical role in the degradation of organic dyes and trace metals from water environments efficiently. The review also cites the role of reactive oxygen species (ROS) that are generated under UV light and which contribute to advanced oxidation processes and thus enable the destruction of pollutants [52].

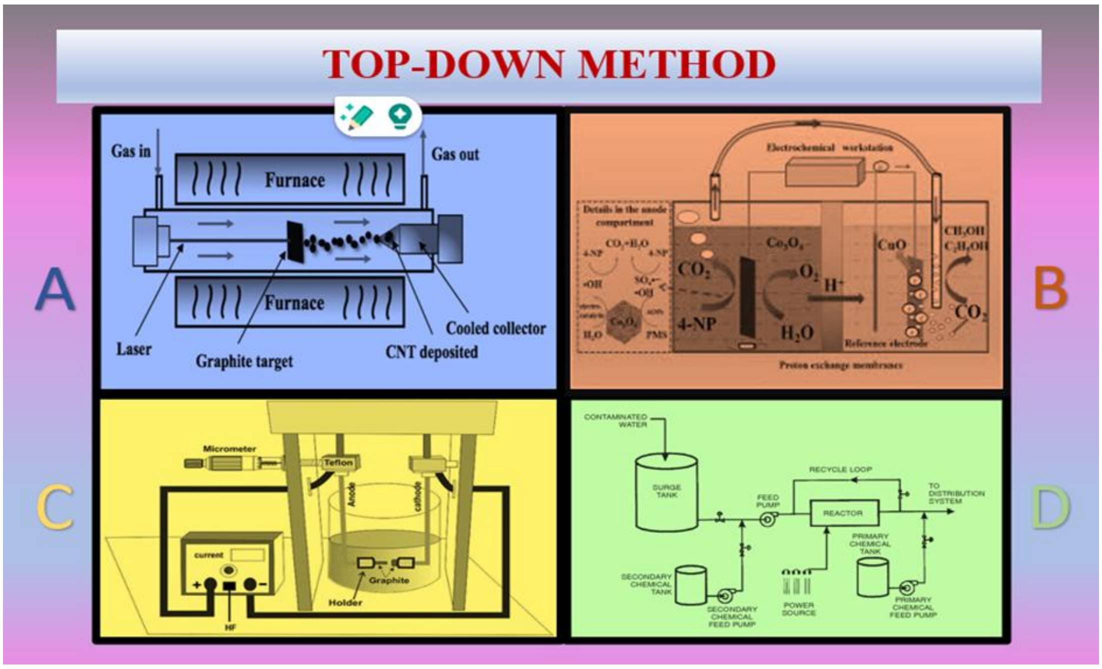

Fig. 2. (A) Laser ablation [53], (B) Electrochemical oxidation [54], (C) Arc discharge [55], (D) Chemical oxidation [56]

3.2 Bottom-up method

Figure 3A-D represents the bottom-up approaches of carbon dot synthesis techniques. Bottom-up methods for the synthesis of carbon dots (CDs) from molecular precursors are used to control size, surface functionalization, and optical properties of the CDs with high precision. Hydrothermal and solvothermal processes are frequently employed among them due to their simplicity, high yield, and low cost. They involve the high temperature and pressure heat treatment in a sealed reactor of a precursor solution of carbon. This allows the generation of CDs, often doped with nitrogen and allowing for tuneable optical properties. Recent developments point to their utilization towards creating CDs with diverse fluorescence properties, e.g., from citric acid and urea, demonstrating their potential use in bioimaging and photocatalysts. The hydrothermal treatment for the synthesis of nitrogen-doped carbon dots (N-CDs) using citric acid and urea as starting materials is discussed in this paper. The CDs displayed a quantum yield of 35.08% and a size ranging from 1.04–3.42 nm. The N-CDs showed selective fluorescence against the detection of metronidazole and were cytotoxicity low, making them suitable for use in bioimaging [57]. Blue fluorescent blue fluorescent N-doped carbon dots were prepared in this work by diethylenetriamine and citric acid through one-step hydrothermal

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treatment. The CDs had a quantum yield of 58% and were used for selective determination of Co (II) ions in water. The CDs were also applied to imaging in HeLa cells, showing their potential use in bioimaging applications [58]. It is reported in this research the microwave-assisted carbonization of citric acid by the tetraethylammonium ion for the preparation of fluorescent carbon dots (CDs). Microwave-heating provides homogeneity in heating, enabling the rapid preparation of CDs with high yields and controllable features. Excellent fluorescence of the prepared CDs was shown, and they were applied in cellular bioimaging effectively to exhibit their application in bioimaging applications [59]. This study utilizes a one-pot microwave-assisted synthesis for the fabrication of carbon dots (C-DOTS) from citric acid. The fabricated C-DOTS exhibited high quantum yield and high photostability. In vitro and in vivo antimicrobial photodynamic therapy (aPDT) experiments confirmed notable inhibition of Staphylococcus aureus biofilms. The fabricated C-DOTS produced reactive oxygen species (ROS) on activation with light, which killed the microbial cells and biofilm matrices. The technique provides an economical way for the production of carbon-based photosensitizers for aPDT uses [60]. In fact, microwave-induced technique was used to produce negatively charged CDs via citric acid and urea. The produced CDs were found to exhibit good antibacterial activities against resistant bacteria such as Methicillin-resistant Staphylococcus aureus (MRSA) and Vancomycin-resistant Staphylococcus aureus (VRSA). The study highlights the viability of utilizing such CDs as potent antimicrobial agents, showing how it can be used for the treatment of resistant types of bacterial strains [61]. This work describes an efficient and green microwave-assisted route for the synthesis of l-ascorbic acid 6-palmitate reduced (LAP-rGO-CDs) surface-modified carbon dots for potassium ion capacitors application. The LAP-rGO-CDs synthesized showed improved interlayer spacing and higher ion transfer rates, indicating that the synthesized material is particularly appropriate for application in potassium ion capacitors. The electrodes showed an excellent specific capacity of 299 mAh g^{-1} at a current density of 1 A g^{-1} and excellent cycling stability. Besides, an asymmetric full carbon-based K ion capacitor was built and exhibited a maximum energy density of 119 Wh kg^{-1} and power density of 5352 W kg^{-1}. Here, microwave-induced synthesis is shown to be an effective approach for the preparation of N-doped carbon materials with well-controlled properties for energy storage applications [62]. Pyrolysis is a high-temperature thermal breakdown of organic compounds in the absence of oxygen to obtain the formation of CDs. In the current work, carbon quantum dots (CQDs) were prepared by pyrolysis of calcium disodium ethylenediamine tetraacetate (EDTA–2Na–Ca•$4H_2O$) at 400 °C. The resulting CQDs possessed excellent photoluminescence with an ultrahigh quantum yield of 66.03%, one of the highest values recorded. In addition to these CQDs possessed up conversion photoluminescence features at 600–750 nm excitation. The enhanced optical characteristics are due to the well-delineated graphitic core structures achieved in the controlled pyrolysis process, which improve stability and photoluminescent performance [63]. This research investigates thermal decomposition of citric acid for fluorescent carbon dots synthesis. The researchers study the reaction mechanism, which possesses several intermediates accountable for emissive species formation. The carbon dots obtained possess emission maxima at 450 nm. Their dispersibility is enhanced by functionalization with 3-aminopropyltriethoxysilane, rendering them suitable for application in stable fluorescence requirement demanding applications [64]. The present research presents an innovative method of synthesizing carbon dots and graphene-like carbon sheets by thermal decomposition of low molecular weight organic compounds in ionic liquids. The as-synthesized carbon materials are highly dispersible and photoelectrochemically active. The overall performance of the carbon dots and sheets is enhanced in optoelectronic devices, such as photovoltaics [65]. This work presents a green hydrothermal process for high fluorescent plant-based carbon dots (PJ-CDs) preparation from Prosopis juliflora leaves extract. The process involves no toxic chemicals, and it is cheap and sustainable for bulk manufacturing. The prepared PJ-CDs have a quantum yield value of 7.88% and exhibit good properties including low toxicity and excellent biocompatibility and are suitable in biomedical applications [66]. In this research, hydrothermal synthesis of carbon quantum dots (CQDs) has been studied using sucrose as a precursor. The experiment verifies that the control of average size of CQDs is possible by adjusting the filling volume of the sucrose solution within the hydrothermal reactor while other experimental parameters remain constant. For example, the filling volumes of 20%, 50%, and 80% produced mean sizes of CQDs equal to 15 nm, 13 nm, and 4 nm, respectively. This tunability in size is important for the tailoring of optical properties of CQDs to an application [67]. All these synthesis routes are beneficial and chosen depending on the desired carbon dots' properties, i.e., size, surface functionalization, photoluminescence, and solubility.

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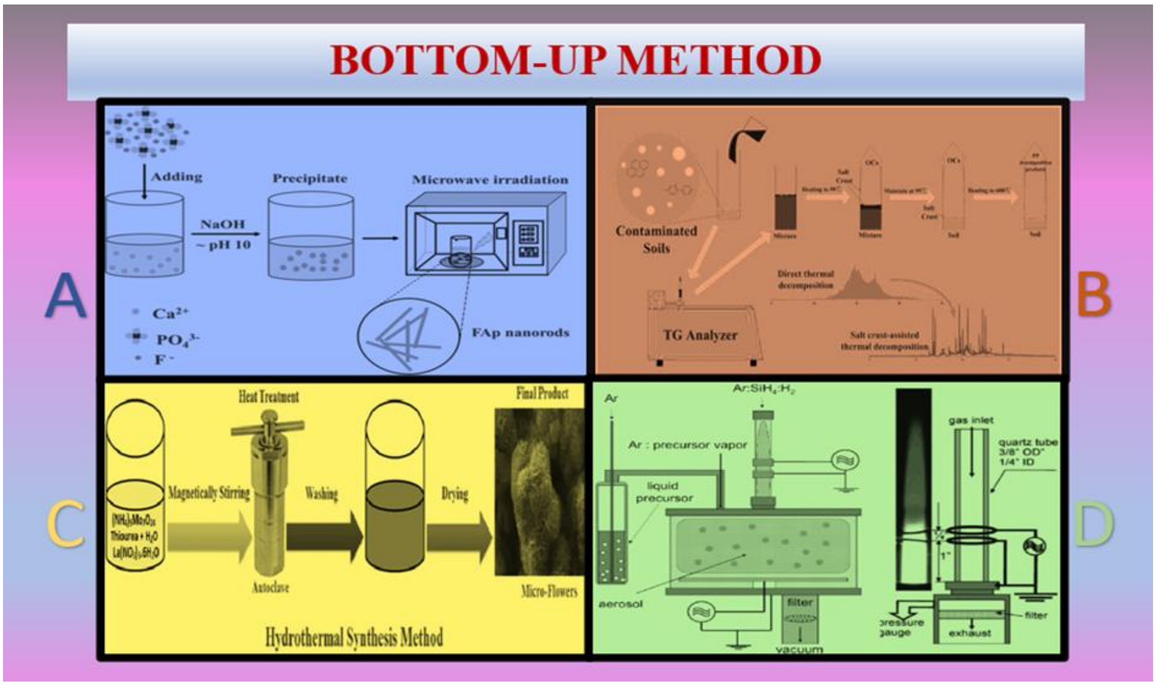

Fig. 3. (A) Microwave synthesis [46], (B) Thermal decomposition [47], (C) Hydrothermal treatment [48], (D) Plasma treatment [49]

3.3 The Chemical Properties of Carbon Dots Applicable to Water Treatment

Carbon dots (CDs) possess a range of novel properties that are extremely beneficial for water purification. Their high fluorescence, which is tunable over a range of wavelengths, is beneficial for the precise detection and identification of a range of pollutants and makes them valuable for sensor-based monitoring systems. The nanoscale dimensions of CDs enable them to possess a humongous surface area, which further facilitates their ability to adsorb and interact with contaminants efficiently. Other than that, their hydrophilicity due to the surface functional groups such as carboxyl (-COOH) and hydroxyl (-OH) enables them to easily disperse in water media and hence render them suitable for use within water purification systems. Apart from the adsorption ability, CDs are also very electrically conductive too, thus making them potential materials for highly sensitive electrochemical sensors for heavy metal and other toxin detection. Their photocatalytic luminance performance also upgrades their efficiency in advanced oxidation processes (AOPs), making photocatalytic degradation of organic pollutants facile. Additionally, CDs are chemically and thermally stable, making them resistant for long periods to different environmental conditions. Their biodegradability and non-toxicity make them environmentally friendly, and their affordability—due to the possibility of their preparation from cheaply accessible carbon-rich precursors like biomass—maximizes their scale-up for practical applications. The other significant benefit of CDs is that they are antimicrobial in nature and can destroy fatal pathogens in water, broadening their application areas to water disinfection as well as the ability to extract chemical contaminants. The combined character enables CDs to be a promising nanomaterial for emerging water treatment applications that possess the potential of providing an efficient and eco-friendly solution towards water pollution problems. Over the past couple of years, an amazing trend towards green and sustainable routes for the synthesis of carbon dots (CDs) has been observed, especially from biomass waste materials. Several research studies have demonstrated the versatility of precursors and synthesis pathways towards CDs with greatly different optical and functional properties. Table 1 report various recent works, including precursor materials, syntheses, and typical properties of the synthesized carbon dots, that imply their potential applications in environmental, biomedical, and sensing areas.

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Table 1. Summary of recent studies on carbon dot synthesis using biomass precursors, highlighting their synthesis methods and key properties

S. No	Title of the Paper	Year	Precursor	Synthesis Method	Properties and Application of Synthesized Carbon Dots	Ref. no
1	Green synthesis of biocompatible carbon dots using aqueous extract of Trapa bispinosa peel	2013	Trapa bispinosa peel	Green synthesis	Biocompatible, fluorescent	[68]
2	Green Synthesis of Biomass-Based Fluorescent Carbon Dots for the detection and adsorption of Fe (III)	2023	Biomass	Green synthesis	Fluorescent, Fe(III) detection and adsorption	[69]
3	Preparation of Biomass-Based Carbon Dots with Aggregation Luminescence Enhancement from Hydrogenated Rosin for Biological Imaging and Detection of Fe^{3+}	2020	Hydrogenate d rosin	Hydrothermal	Aggregation-induced emission, Fe^{3+} detection, suitable for biological imaging	[70]
4	Sustainable synthesis of biomass-derived carbon quantum dots and their catalytic application for the assessment of α,β-unsaturated compounds	2022	Biomass	Hydrothermal	Catalytic properties, assessment of α,β-unsaturated compounds	[71]
5	Assessment of biomass-derived carbon dots as highly sensitive and selective templates for the sensing of hazardous ions	2023	Biomass	Hydrothermal	Sensitive and selective sensing of hazardous ions	[72]
6	Biomass-Derived Carbon Dots and Their Applications	2019	Biomass	Various	Diverse applications including bioimaging and sensing	[73]
7	Green approach synthesis of carbon quantum dots from agave bagasse and their use to boost seed germination and plant growth	2023	Agave bagasse	Green synthesis	Promotes seed germination and plant growth	[74]
8	Green synthesis of carbon quantum dots from wasted enzymatic hydrolysis lignin catalyzed by organic acids for UV shielding and antioxidant fluorescent flexible film	2022	Wasted lignin	Green synthesis	UV shielding, antioxidant properties	[75]
9	Preparation of Multicolour Biomass Carbon Dots Based on Solvent Control and Their Application in Cr(VI) Detection and Advanced Anti-Counterfeiting	2022	Biomass	Solvent control	Multicolor emission, Cr(VI) detection, anti-counterfeiting applications	[76]
10	Biomass-Derived Carbon Dots and Their Sensing Applications	2022	Biomass	Green synthesis	Sensing applications	[77]
11	Green Carbon Dots: Synthesis, Characterization, Properties and Biomedical Applications	2023	Biomass	Green synthesis	Biomedical applications	[78]
12	Recent Trends and Advancements in Green Synthesis of Biomass-Derived Carbon Dots	2023	Biomass	Green synthesis	Various applications	[79]
13	Recent trends in the use of green sources for carbon dot synthesis–A short review	2021	Green sources	Various	Overview of green synthesis methods and applications	[80]
14	Advances in the Methods for the Synthesis of Carbon Dots and Their Emerging Applications	2021	Various	Various	Overview of synthesis methods and emerging applications	[81]
15	A Review of Carbon Dots Produced from Biomass Wastes	2020	Biomass wastes	Various	Properties and applications of carbon dots from biomass wastes	[82]

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16	Carbon Dots: Synthesis, Properties and Applications	2021	Various	Various	Comprehensive review on synthesis, properties, and applications	[83]
17	Carbon Dots: Classification,Properties, Synthesis, Characterization, and Applications in Health Care—An Updated Review (2018–2021)	2021	Various	Various	Health care applications	[84]
18	Biomass-Based Carbon Dots: Current Development and Future Perspectives	2021	Biomass	Various	Current developments and future perspectives	[85]
19	Recent Progress of Carbon Dot Precursors and Photocatalysis Applications	2019	Various	Various	Photocatalysis applications	[86]
20	Biogreen Synthesis of Carbon Dots for Biotechnology and Nanomedicine Applications	2018	Green sources	Green synthesis	Biotechnology and nanomedicine applications	[87]
21	Green synthesis of carbon quantum dots and applications: An insight	2023	Green sources	Green synthesis	Insights into applications	[88]
22	Biomass-derived carbon dots: synthesis, modification and application in batteries	2025	Biomass	Various	Battery applications	[89]
23	Carbon quantum dots functionalized gold nanorod mediated delivery of doxorubicin: Tri-functional nano-worms for drug delivery	2021	Carbon quantum dots	Functionalization	Drug delivery applications	[90]
24	Green synthesis of silica and silicon from agricultural residue sugarcane bagasse ash – a mini review	2023	Sugarcane bagasse ash	Green synthesis	Overview of synthesis methods and applications	[91]
25	Green synthesis of graphene oxide-based nanocomposite by Polycladia myrica: antibacterial, anti-algae, and acute zooplanktonic responses	2023	Polycladia myrica	Green synthesis	Antibacterial, anti-algae properties	[92]
26	Green synthesis of carbon dots from Allium sativum peel for solar conversion and cell imaging	2019	Allium sativum peel	Green synthesis	Solar conversion, cell imaging applications	[93]
27	Green synthesis of carbon dots from Ocimum sanctum for effective fluorescent sensing of heavy metal ions	2020	Ocimum sanctum	Green synthesis	Fluorescent sensing of heavy metal ions	[94]
28	Bio-based carbon dots production via hydrothermal conversion of microalgae Chlorella pyrenoidosa	2022	Chlorella pyrenoidosa	Hydrothermal	High photoluminescence, biocompatibility, potential for bioimaging applications.	[95]
29	Green synthesis of biomass-derived carbon quantum dots for photocatalytic degradation	2023	Watermelon peels, grape pomace	Hydrothermal	Good solubility, photostability, effective in photocatalytic degradation of methylene blue dye.	[96]
30	Formation of Carbon Quantum Dots via Hydrothermal Carbonization	2021	Hydroxyme-thylfurfural, furfural, microcrystal-line cellulose	Hydrothermal	Green luminescence under UV light, broad light absorption, potential for optoelectronic applications.	[97]
31	Green synthesis of fluorescent N-doped carbon quantum dots from castor seeds	2024	Castor seeds	Hydrothermal	High stability in water, antimicrobial activity, potential for pH sensing applications.	[98]
32	Hydrothermal synthesis of carbon dots derived from Blumea lacera for sensing applications	2024	Blumea lacera	Hydrothermal	Strong fluorescence, effective for sensing applications, eco-friendly synthesis.	[99]
33	Green hydrothermal synthesis of N-doped carbon dots from Highland barley	2019	Highland barley	Hydrothermal	Water-soluble, high quantum yield, potential for	[100]

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					bioimaging and sensing applications.	
34	Efficient continuous hydrothermal flow synthesis of carbon quantum dots from biomass	2020	Biomass precursor	Hydrothermal	Environmentally benign, scalable production, potential for nanosensing applications.	[101]
35	Green synthesis of carbon quantum dots and their environmental applications: An insight	2025	Biomass	Hydrothermal	High quantum yield, photostability, applications in environmental sensing and photocatalysis.	[102]
36	Research on green synthesis and performance analysis of biomass-based carbon quantum dots	2025	Biomass	Hydrothermal	Cost-effective, sustainable development, potential applications in bioimaging and sensing.	[103]
37	Preparation and application of biomass-derived carbon quantum dots	2023	Biomass	Hydrothermal	Unique optical and electronic properties, applications in ion detection and bioimaging.	[104]
38	Green synthesis of carbon quantum dots from bagasse for scale inhibition	2023	Bagasse	Hydrothermal	Effective scale inhibition, good dispersibility, potential for industrial applications.	[105]
39	Development of biomass waste-based carbon quantum dots and their application in bioimaging	2023	Biomass waste	Hydrothermal	High fluorescence, biocompatibility, effective for bioimaging applications.	[106]
40	Green synthesis of carbon quantum dots from Prosopis juliflora leaves extract	2023	Prosopis juliflora leaves	Hydrothermal	High fluorescence, eco-friendly synthesis, potential for biomedical applications.	[107]
41	Hydrothermal synthesis of modified lignin-based carbon dots derived from biomass waste for fluorescence determination of valsartan	2024	Lignin extracted from date seeds	Hydrothermal	High fluorescence, water solubility, stability, effective for drug detection applications.	[108]
42	Green synthesis of carbon quantum dots from Phragmites communis and its protective effect on Artemia salina under copper stress	2024	Phragmites communis	Green synthesis	Protective effect against copper-induced stress in aquatic organisms, potential for environmental remediation.	[109]
43	Green synthesis of tunable fluorescent carbon quantum dots from lignin and their application in anti-counterfeit printing	2021	Lignin	Green synthesis	Tunable fluorescence, application in anti-counterfeit printing.	[110]
44	Impact of green carbon dot nanoparticles on seedling emergence, crop growth and seed yield in blackgram (Vigna mungo L. Hepper)	2024	Peanut shell (Agro waste)	Green synthesis	Seed priming & foliar spray to enhance germination, growth and yield.	[111]

4. Characterization

4.1 Size and quantum yield

The quantum yield (QY) of carbon dots (CDs) is an essential parameter governing their quantum yield, which, in turn, affects their photocatalytic efficiency. Smaller CDs usually exhibit greater QY due to the quantum confinement effect, where smaller particle size leads to discrete energy levels, which allows improved electron-hole separation and improves electrical characteristics. This effect substantially increases their light-absorbing ability and their light to chemical energy conversion, making them highly efficient in photocatalytic reactions. CD properties need to be tailored by optimizing the synthesis conditions. The alteration of reaction temperature, time, and precursor ratios can regulate the size and surface functionalization of CDs, thereby optimizing their QY [112]. For instance, it was demonstrated via a study that CDs synthesized for 12 hours at below 180 °C and at the optimum precursor ratio yielded a QY of 62.98% by virtue of synergies of surface state and carbon core state [113]. Surface passivation and heteroatom doping (nitrogen, sulphur, phosphorus, etc.) continue to enhance the optical and electronic properties of CDs. These modifications introduce the new levels of energy and surface conditions, which promote QY and facilitate the generation of reactive oxygen species (ROS) necessary for effective photocatalytic degradation of pollutants.

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Through optimization of these parameters, researchers can develop extremely efficient CDs for specific photocatalytic and environmental uses, creating possibilities for sustainable technologies in water treatment and solar energy conversion [114].

4.2 Surface functional groups

Surface functional groups such as hydroxyl (-OH), carboxyl (-COOH), and amine ($-NH_2$) play an important role in the chemical and environmental functionality of carbon dots (CDs) and greatly influence their solubility, stability, and pollutant interaction when dispersed in aqueous mediums. The functional groups induce hydrophilic nature of CDs to maintain them well dispersed in water, an aspect that is of high significance in water purification applications. Functionalization with –OH and –COOH groups also endow negative surface charges to enable strong electrostatic attraction of positively charged heavy metal ions such as Pb^{2+}, Hg^{2+}, and Cr (VI). For instance, Ghosal et al. demonstrated that acid-treated CDs that were enriched with –COOH groups displayed efficient dye removal such as methylene blue through combined adsorption and photocatalysis process [115,116]. Conversely, the availability of $–NH_2$ groups provides metal-binding coordination sites and enhances organic contaminant affinity by hydrogen bonding or π–π interactions. In a related observation, Papanikolaou et al. showed $–NH_2$-abundant CDs to exhibit elevated fluorescence sensitivity towards transition metals, affirming their involvement in charge transfer interactions essential for metal sensing and remediation [117]. Contemporary synthesis methods such as hydrothermal, microwave, or solvothermal processes allow for having precise control of surface chemistry, and it is possible to vary functional group density and enhance environmental stability of CDs under actual wastewater conditions. Experiments showed that the presence of such functional groups not only increases adsorptive capability but also boosts photocatalytic activity by serving as active sites for electron transfer and ROS generation under visible illumination. Incorporation of CDs into O-CN nanosheets by electrostatic self-assembly not only enhances visible light adsorption but also boosts segregation of photogenerated electron-hole pairs by trapping electrons [118]. Additionally, doping with nitrogen, sulphur, and phosphorus, used alongside these groups, optimizes bandgap fine-tuning and increases efficiency in charge carrier separation, reducing recombination while increasing rates of degradation of dyes and drugs [119]. In conclusion, strategic engineering of surface functional groups on CDs is a powerful means to develop low-cost, sustainable, and high-performance materials for water purification, heavy metal detoxification, and dye degradation. Such references collectively indicate that surface functional groups of CDs have significant functions in controlling their interaction with environmental contaminants, solubility, stability, and photocatalytic activity. Through the modulation of these groups by means of a variety of synthesis and modification procedures, CDs may be optimized to meet specific applications in environmental remediation and other areas.

4.3 Doping with heteroatoms

Doping carbon dots (CDs) with heteroatoms like nitrogen (N), sulphur (S), and phosphorus (P) has proved to be a highly effective means of improving their electrical, optical, and catalytic properties, especially for photocatalytic applications. The introduction of such heteroatoms in the carbon lattice alters the electronic band structure of CDs, leading to enhanced charge separation, diminished electron-hole recombination, and enhanced visible light absorption. These features greatly enhance their photocatalytic activity, making them more effective in environmental remediation processes, particularly in organic pollutant degradation in water. This review article provides an extensive overview of the doping methods for improving the photocatalytic activity of carbon dots (CDs). It incorporates multiple heteroatoms such as nitrogen (N), sulphur (S), and phosphorus (P) and reports on how their introduction into the carbon matrix governs the electronic structure of CDs. Nitrogen doping is specifically famous to boost the charge carrier dynamics and photoluminescence of CDs. Sulphur doping increases the redox potential, whereas phosphorus doping enhances the electron-donating ability of CDs. These modifications render heteroatom-doped CDs highly active towards photocatalytic uses like water purification, where they facilitate the degradation of organic pollutants and promote visible-light-driven water purification [120]. In this work, the photoelectrochemical activity of WO_3 nanoflakes in water oxidation reactions is evaluated with the incorporation of nitrogen-doped carbon dots (N-CDs). Nitrogen doping increases electron density and efficiency in the transfer of charges by a massive degree, thereby enhancing photocatalytic performance. N-CDs facilitate quick charge separation and lower recombination rates by modifying the surface properties of the WO_3 nanoflakes, thereby enhancing overall photocatalytic efficiency. The results point out that nitrogen doping of CDs assists in improving photocatalytic activity and stability in water splitting and environmental

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remediation [121]. In this article, the authors compare photocatalytic activities of heteroatom-doped carbonaceous materials (such as CDs) with those of their undoped versions. Heteroatom doping with elements such as nitrogen, sulphur, and phosphorus into carbon materials changes their electronic structure to enhance their photocatalytic activity through elevated electron transfer and harvesting of light. The paper brings to perspective the importance of doping in enhancing charge carrier mobility and separation, a notion important for environmental remediation, particularly the elimination of pollutants in water [122]. This review examines the contribution of heteroatom doping to the improvement of carbon-based photocatalyst characteristics such as carbon dots for solar fuel production and environmental remediation. The authors explain how phosphorus, sulphur, and nitrogen doping enhance charge carrier mobility, photocatalysis, and photostability after illumination with visible light. Heteroatom-doped CDs have been identified as efficient materials for processes like water splitting and pollutant degradation with improved efficiency to photodegrade organic pollutants and detoxify water under visible light [123]. Syntheses of heteroatom-doped carbon quantum dots based on Cucurbita pepo (pumpkin) and their use in visible-light-driven photocatalytic deceleration of dye have been discussed in this research work. The nitrogen and sulphur heteroatom doping were observed to greatly improve the photocatalytic performance of the CDs. The doping not only favors charge separation but also facilitates the capability of the CDs to generate reactive oxygen species (ROS), such as hydroxyl radicals and superoxide anions, which are required to disrupt the organic pollutants. The research shows the potential of heteroatom-doped CDs to be used in environmental remediation and wastewater treatment with natural sunlight [124]. Not only do heteroatom doping improve the optical and electrical characteristics of CDs but also make them more capable for actual applications in green water treatment. By making use of the improved electronic structure of doped CDs and enhanced ROS generation, scientists continue to develop novel means of pollution control, delivering cleaner water supplies and a cleaner planet.

4.4 Post-synthesis modification

Surface functionalization and passivation are important post-synthesis procedures that enhance the stability and photoluminescent (PL) properties of carbon dots (CDs). The treatments adjust the surface chemistry of CDs to enhance their performance in environmental applications such as pollutant detection and degradation. Surface passivation involves coating CDs with insulating films to protect them from environmental contaminants, thereby improving their stability and PL emission. This article elaborates on the role of surface passivation and functionalization in enhancing the photoluminescent (PL) characteristics and stability of carbon dots. Surface passivation protects the CDs from degradation by the environment and increases their PL intensity, which is vital in sensing and pollutant degradation applications. Functionalization with specific groups increases the selectivity of CDs for pollutants, thus increasing their efficiency in environmental applications. The article discusses various surface modifications, including ligand attachment, to tailor the chemical properties of CDs to desorb pollutants [125]. The overview discusses heteroatom doping (nitrogen, sulfur, phosphorus) effects on the photoluminescent property and photocatalytic activity of carbon dots (CDs). The doping greatly alters the electronic properties to facilitate interaction between CDs and targeted pollutants. The study highlights the need for post-synthesis processes such as surface passivation and functionalization to optimize the efficiency of CDs in environmental applications, particularly in water purification and pollutant degradation [126]. The article summarizes post-synthesis surface passivation and functionalization to optimize the photocatalytic activity of carbon dots. It highlights how the treatments optimize the stability, selectivity, and efficiency of CDs in photocatalytic reactions. The study also covers doping of CDs with heteroatoms such as nitrogen and sulphur to improve their photocatalytic performance as well as their interaction with environmental pollutants. The study emphasizes that the engineering of the surface chemistry of CDs for specific environmental applications such as water purification is of crucial significance [127]. Through the optimization of their surface chemistry, such adjustments improve the adsorption by CDs towards targeted pollutants, thus enhancing their performance in environmental applications like water treatment, energy transformation, and chemical degradation reactions.

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5. Applications of carbon dots in water treatment

Table 2 shows the various applications of carbon dots in water treatment for targeted pollutants. Carbon dots (CDs), or carbon quantum dots (CQDs), have been found to be potential nanomaterials in water treatment on account of the interesting features like superior water solubility, minimal toxicity, and tunable fluorescence. These attributes make them very attractive for applications in environmental monitoring and removal of pollutants in aqueous media. Metal ion sensing is one of the most prominent uses of CDs. Their fluorescent characteristics are useful to sense harmful metal ions in aqueous environments, i.e., lead, mercury, and cadmium, which are toxic to human beings and aquatic organisms as well [128]. In addition, green syntheses of CDs through microwave approaches with plant-based precursors further increase their environmental friendliness, potentially useful for practical applications in water treatment at large scales. This environmentally friendly method of synthesis also lessens the use of harmful chemicals and encourages the utilization of renewable resources, further increasing the sustainability of water treatment procedures. Recent research also demonstrates the efficacy of CDs in the adsorption of organic pollutants, the removal of dyes, and the degradation of pharmaceutical contaminants in water. The versatility and environmentally friendly nature of carbon dots have provided opportunities for their use in environmental as well as biomedical applications. CDs are applied in water treatment due to their large adsorption capacity, high photocatalytic activity under UV or visible light, and capability of producing reactive oxygen species (ROS) that contribute to the degradation of organic pollutants. In addition, the use of CDs in water treatment systems may offer affordable solutions to mitigate worldwide water pollution problems, particularly in areas where access to clean water sources is limited [129].

Table 2. Various applications of carbon dots in water treatment

Application Area	Mechanism	Target Pollutants	Remarks
Adsorption	Surface functional groups bind contaminants	Heavy metals (Pb^{2+}, Hg^{2+}, Cr^{6+}), dyes	High surface area and abundant oxygen/nitrogen groups
Photocatalysis	Light-induced ROS generation	Organic dyes (methylene blue, rhodamine B)	Often doped with metals/non-metals for enhanced activity
Fluorescent Sensing	Quenching/enhancement of fluorescence	Metal ions (Fe^{3+}, Cu^{2+}), pesticides	High sensitivity and selectivity, can be used in situ
Antibacterial Treatment	ROS production under light	Bacteria in wastewater	Useful in disinfection of contaminated water
Membrane Modification	Blending with filtration materials	Particulate and microbial pollutants	Improves membrane antifouling and hydrophilicity

5.1 Contaminant adsorption

In the past half-decade, scientists have been actively working to purify water from toxins with the application of carbon dots (CDs), tackling the most pressing environmental issue of water pollution. Carbon dots have proven to be very promising in adsorbing a wide range of contaminants such as heavy metals, organic pollutants, and emerging contaminants due to their exceptional properties such as high surface area, tunability, and functionalization capabilities. Here, I give a summary of recent developments in the application of CDs to the adsorption of different contaminants from water, by type of pollutant, along with ten reference documents from the past five years pointing out key findings and advancements in the field.

5.2 Heavy metals removal

Carbon dots (CDs) are proven materials to remove heavy metal ions from water because they have a high surface area, functional groups, and tunable fluorescence properties. Past studies have demonstrated their efficiency in adsorption and sensing of harmful ions such as lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}), and chromium (Cr^{3+}) from aqueous solutions. As an example, a study by Mahar et al. [130] reported that CDs synthesized from tapioca exhibited an 80.6% efficiency in removal of lead ions from aqueous solutions. Adsorption was via Langmuir and Freundlich isotherms, which indicate the favorable adsorption behavior. The study also found that the zeta potential of CDs at pH 7 was −31.7 mV, which means that there were surface negative charges that permit adsorption of positively charged lead ions [130]. Another study by Jlassi et al. [131] developed a clay-carbon dot nanocomposite that achieved a 95% efficiency for the removal of lead ions using a UV light source. The composite exhibited a maximum adsorption capacity of 400 mg/g at room temperature and pH 8. The adsorption kinetics were pseudo-second-order type, and the treatment

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process was more efficient under light, leaving room for potential photocatalytic applications for water treatment. Moreover, a review by Khaled et al. [132] discussed the coupling of CDs with such materials as metal-organic frameworks, zeolites, and biopolymers with a view to enhancing their heavy metal adsorption capacity and stability. The review cited how such composites were able to achieve up to 2000 mg/g adsorption capacities, placing them among the significant potential candidates for water treatment processes on the industrial scale. These studies emphasize the effectiveness and multi-functionality of carbon dots in the decontamination of water from heavy metals and present eco-friendly and efficient alternatives for environmental purification.

5.3 Adsorption of organic pollutants

The higher adsorption potential of green carbon dots (CDs) for the majority of toxic chemicals, ranging from organic pollutants like dyes and drugs to heavy metals, has been recently supported by evidence. The CDs are usually smaller than 10 nanometres in diameter and could be made more eco-friendly by employing renewable and non-toxic precursors [133]. The π-π interactions, hydrogen bonding, and electrostatic interactions are the bases for the adsorption mechanisms of CDs and hence render them highly effective at adsorbing organic molecules. Surface functionalization and doping of the CDs also boost their adsorption capacity and selectivity towards target pollutants. For example, in a study conducted by Alves et al. [133], new carbon dots/titanate nanotubular hybrid materials with improved optical and photocatalytic performance were produced. The hybrids had excellent photocatalytic activity for the degradation of organic pollutants under UV irradiation, suggesting their use in the treatment of the environment. Additionally, Burkhardt et al. [134] discusses the use of the Polanyi potential theory in the simulation of the adsorption of organic compounds on carbon nanomaterials, insights into adsorption mechanisms, and assisting in the building of effective adsorbents to be used in environmental applications. They highlight the possible utility of CDs as an affordable and scalable adsorbent for the elimination of organic contaminants from water, an ecofriendly strategy for the management of environmental pollution.

5.4 Photocatalytic degradation

Carbon dots (CDs) have been of specific interest as effective photocatalysts for the degradation of organic pollutants in water under visible light. Their distinctive physicochemical properties—i.e., strong visible-light absorption, tunable photoluminescence, high surface area, water dispersibility, and high surface functional group density—allow them to generate reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide anions (O_2^{-}•), which can oxidize a wide range of pollutants such as synthetic dyes, phenolic compounds, pesticides, and pharmaceutical residues. Green synthesis processes using natural materials like plant extracts, fruit peels, and biomass wastes are gaining prominence due to their environmental friendliness, economical cost, and low toxicity [135,136]. The ROS degrade pollutants and mineralize them into harmless end products like CO_2 and H_2O and are hence a clean and renewable process of water purification. The photocatalytic performance of CDs can be significantly enhanced with post-synthetic treatment processes such as heteroatom doping (e.g., nitrogen, sulphur, phosphorus), which induce surface defects and alter bandgap energy to facilitate increased light absorption and electron transfer [137]. CDs are often coupled with metal oxides (e.g., TiO_2, ZnO) or other semiconductor materials to form nanocomposites that improve the efficiency of charge separation, inhibit electron-hole recombination, and broaden the absorption spectrum to the visible spectrum [138]. However, the downsides still exist in terms of photostability under prolonged irradiation being poor, difficulty of large-scale production, and scarce mechanistic understanding of the ROS generation processes in complex water matrices. Recent research has highlighted not just the efficiency of degradation but also advanced material characterization techniques like FTIR, XPS, TEM, and PL spectroscopy to understand surface chemistry and interaction mechanisms at a molecular level. These advances are bringing into view opportunities for the production of highly efficient, stable, and scalable carbon dot-based materials for applications in environmental remediation [139].

5.5 Electrochemical treatment

Carbon dots (CDs) have generated immense attention in the field of electrochemical treatment processes for the detection and degradation of environmental pollutants. CDs are nanomaterials characterized by their tolerable fluorescence, good conductivity, and easy functionalization, hence making them good candidates for electrochemical sensors [140]. Present studies have shown that CDs are able to effectively identify pollutants like heavy metals, organic compounds, and bacteria by experiencing

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electrochemical interactions that convert into measurable current or potential changes. This electrochemical response characteristic is due to interacting with the target pollutants and can be made more sensitive through doping with heteroatoms or surface modification [141]. Aside from their sensor properties, CDs are also credited with degrading organic pollutants through electrochemical processes. Carbon dots, when incorporated into electrochemical reactors, are capable of forming reactive oxygen species (ROS) like hydroxyl radicals (•OH), which oxidize and break down pollutants such as dyes, pesticides, and pharmaceuticals. This catalytic process is even more enhanced by the very good electrochemical reactivity of CDs that facilitates electron transfer reactions involved in contaminant degradation [142]. Further, recent studies show that encapsulation of CDs in composite materials with metal oxides or conducting polymers enhances their electrochemical activity and catalytic activity in degrading pollutants in water treatment applications [143]. Moreover, the biocompatibility and diversity of carbon dots also make their way into the modification of electrochemical sensors and reactors. The surface chemistry of CDs, including the ability to exchange functional groups, promises to develop effective sensors that are capable of selectively sensing and breaking down a wide range of environmental pollutants. It has been indicated that the combination of CDs with other nanomaterials, e.g., graphene or metal-organic frameworks, yields improved pollutant removal efficiency and sensor stability [144]. Additionally, the integration of these nanomaterials in electrochemical platforms offers a sustainable way of water treatment technology [145].

5.6 Membrane Technology

Carbon dots (CDs) have been of significant interest in membrane science due to their different functional properties like increased hydrophilicity, antifouling characteristics, antibacterial activity, and photocatalytic properties. Integration of CDs into the membrane architecture has shown excellent boosts in water permeability and fouling removal by organic matter and microorganisms. For example, sulfonic acid-functionalized CD-modified membranes demonstrated a remarkable permeate flux of 42.1 L/m^2•h and rejection rate of 93.6% for Na_2SO_4 because of enhanced surface hydrophilicity and surface negative charge [146]. Apart from fouling prevention, CDs have inherent antibacterial property that aids in antimicrobial resistance of membranes. These are, for the most part, ascribed to the disruption of bacterial membranes during interaction with CDs, as supported by studies showing strong antibacterial activity against pathogens like E. coli [147]. CDs also significantly enhance photocatalytic activity when incorporated into membranes exposed to UV or visible light. They facilitate the production of reactive oxygen species (ROS), namely hydroxyl radicals (•OH), which are effective at degrading organic pollutants and cleaning water. Notably, CD/TiO_2 nanocomposite-immobilized membranes exhibited high water permeability and dye removal efficiency, besides self-cleaning properties enabled by photocatalysis. Moreover, immobilization of various nanomaterials, including nanoparticles, nanofibers, and nanocomposites, into membranes promotes their mechanical stability, filtration selectivity, as well as self-cleaning ability, which are all vital for ensuring long-term membrane efficacy in water treatment operations [148]. Surface engineering technologies, like plasma-assisted graft polymerization, also improve membrane performance. For instance, grafting hydrophilic polymers like poly (methacrylic acid) enhances surface wettability and reduces protein fouling, enhancing membrane lifetime and performance [149]. In conclusion, the integration of CDs with other nanomaterials offers a systematic method for enhancing membrane technologies for water treatment. Mass application is however constrained by several factors including the long-term stability of CDs, economic feasibility, and potential environmental risks. Current research is aimed at circumventing the limitations and developing the next generation of CDs for even more effective and more sustainable membrane systems.

6. Challenges and opportunities

Carbon dots are still difficult to mass-produce due to the lack of affordability in the synthesis process and necessity of specific precursors. The majority of the existing synthesis methods used today involve high-cost raw materials and complex processes, and therefore the process is not achievable to mass produce for widespread application. Cost-effective and efficient synthesis methods for CDs are needed to make them readily available for practical water treatment. Improvements in green and sustainable synthesis pathways can reduce the costs without compromising the quality and functional properties of CDs, opening up their possibility for more extensive use in water purification technologies [150]. Long-term stability is one of the primary issues in using carbon dots for water treatment. Although CDs exhibit excellent photocatalytic and adsorption properties in the short term, their activity may decrease over time, especially under extreme environmental conditions such as extreme pH, temperature fluctuation, and high ionic strength of the water.

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These degradations can affect significantly their ability to remove contaminants and pollutants, and therefore their reusability. The long-term stability of CDs in water treatment systems is thus critical to enable continuous and effective operation. Modification of CD surface through functionalization or encapsulation may enhance their photochemical and chemical stability to prolong their lifetime within water treatment systems and possibly reduce the replacement or regeneration frequency [151]. Furthermore, the environment and human health consequences of carbon dots, particularly at high concentrations, are still poorly understood. Although CDs are shown to be nontoxic when present in quantities, their accumulation in ecosystems—in aquatic ecosystems, for instance—could have unexpected consequences. The biocompatibility and biodegradability of CDs must be studied to determine whether they are safe for aquatic organisms, humans, or ecosystems if accumulated over a period. Investigating the long-term effects of carbon dot exposure, including bioaccumulation and toxicity, is important in order to provide assurance of their safe and sustainable use in water treatment technologies. While some studies have focused on the synthesis of biodegradable CDs that biodegrade to non-toxic by-products, additional research will be necessary to fully understand the environmental effects of CDs under actual conditions [152]. In membrane filtration technologies, carbon dot use may lead to membrane fouling, which lowers the efficiency of the filtration process. CDs on the surface of the membrane may promote adsorption of organic and inorganic molecules, leading to pore blocking of the membrane and a decline in the filtration efficiency with time. Furthermore, prolonged interaction between CDs and materials of the membrane results in membrane structure degradation, thereby reducing its lifespan. Proper integration of CDs into membranes thus becomes essential to facilitate for their presence to enhance the function of the membrane without compromising its integrity. Methods like encapsulating CDs in the membrane structure or with hybrid materials might be employed to minimize fouling without affecting the mechanical properties of the membrane. Further, surface treatment or coating of CDs can also minimize the negative impact on membrane performance by reducing fouling or degradation-causing interactions [153].

6.1 Carbon dot stability and recyclability

The stability and recyclability of carbon dots (CDs) are challenging when it comes to water treatment since their chemical structure and optoelectronic properties can be damaged by harsh conditions like varying pH, temperature, and ionic strength, thus reducing their effectiveness. Extended UV exposure or harsh conditions also reduce CDs further, resulting in inefficient removal of contaminants. Recyclability is another issue of concern since it is difficult to recycle CDs from filtration or membrane units and desorb adsorbed contaminants for reuse. However, surface functionalization of CDs with specific molecules or films could enhance the stability, degradation resistance, and recyclability of CDs. More efficient recycling techniques, e.g., encapsulation of CDs into polymer or metal-organic frameworks (MOFs) composite materials, would make the technology sustainable and cost-effective by enabling multiple reuses of CD in water treatment applications [154,155].

6.2 Scale-up and practical implementation

Large-scale mass production of carbon dots (CDs) from laboratory to industrial levels is a big challenge because current methods are time-consuming, expensive, and hard to up-scale with a compromise on material quality. Precursor cost, synthesis cost, and process method cost is a major stumbling block for large-scale mass production for water treatment applications. In addition, incorporating CDs into conventional water treatment systems, e.g., filtration membranes or photocatalytic reactors, has to be done with care in order not to allow them to negatively affect system performance. There are possible solutions to the above issues, however. Green synthesis processes may provide cost-effective and sustainable solutions, improving scalability. Also, engineering hybrid systems to match CDs with other materials, such as graphene or functionalized polymers, can introduce enhanced scalability and integration into water treatment systems as well as the possibility of enhanced functionality and reduced costs [156,157].

6.3 Environmental and health implications

The potential for health and environmental impacts of carbon dots (CDs) is of major concern, specifically toxicity, ecotoxicity, and bioaccumulation. Carbon dots will emit harmful by-products, permeate into the water cycle, and accumulate within aquatic life, posing risks along the whole food chain and possibly impacting ecosystem health. This highlights that there needs to be more ecotoxicity studies in order to better understand the long-term ramifications of CDs and degradation products on environments. Despite that,

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promising directions involve designing biodegradable CDs or surface-functionalized analogues that degrade to non-toxic byproducts. Systematic studies of toxicity, bioaccumulation, and degradability in aquatic environments are necessary before one can determine the safety and sustainability of CDs for global use [158,159].

6.4 Regulatory considerations

Lack of normalized procedures for testing and regulating carbon dots (CDs) in water treatment is a significant challenge in that it may slow the application of CDs on a large scale without normalized standards. Adherence to water quality standards, such as heavy metal and microbial impurities limits, needs to be followed, and rigorous monitoring is needed to prevent CD or degradation product release into treated water. However, the establishment of regulatory standards for nanomaterials in water treatment presents an opportunity to promote innovative and safe utilization [160]. By establishing acceptable levels of CD concentration in treated water, these standards could potentially satisfy safety and effectiveness. Scientific research collaboration with the industry and regulatory authorities will be instrumental in the formulation of guidelines, which should be transparent so that CDs can be utilized effectively and as per health and environmental requirements [161,162].

6.5 Future Directions and Conclusion

Carbon dots (CDs) have received immense limelight for their possible application in water treatment technologies as a consequence of their desirable characteristics like high surface area, fluorescence tunability, biocompatibility, and nontoxicity. Carbon dots (CDs) are found to be emerging nanomaterials for future water treatments based on the fact that they possess interesting properties such as superior photoluminescence, high surface area, chemical inertness, low cytotoxicity, and amenability to functionalization. Their application in processes like photocatalysis, membrane doping, pollutant sensors, and adsorption has been extensively reported. Nevertheless, some limitations at the moment prevent their commercial-scale use. One of the main problems is scalability in synthesis procedures; the majority of laboratory-scale procedures involve energy-and-expensive steps or need complex equipment and toxic reagents. Future research directions must include the green synthesis of CDs from renewable feedstocks like agricultural waste and biopolymers, which are environmentally friendly, low-cost, and scalable alternatives [163,164]. The long-term durability and recyclability of CDs under real environmental conditions like pH variations, ionic strength, and UV exposure are critical parameters that must be optimized carefully. Modifications such as heteroatom-doping (e.g., N, S, P) and surface passivation have been reported to be promising in enhancing stability and photocatalytic activity, and more research needs to be carried out in standardizing such techniques [165,166]. CDs included in nanocomposites or hybrid materials such as metal-organic frameworks (MOFs), graphene oxide, or functionalized membranes could exhibit superior performance in filtration, antifouling, and pollutant degradation without compromising membrane integrity [167,168]. Most importantly, the ecotoxicological and environmental impacts of CDs remain inadequately explored. While CDs are assumed to be less toxic than other nanomaterials, comprehensive ecotoxicological studies that determine their fate, bioaccumulation, and exposure effects after prolonged periods in aquatic environments and organisms are urgently required [169,170]. Lifecycle assessments and safe-by-design principles must be incorporated from the onset in the development process to forecast and avoid any adverse effects. Besides, control through regulations and enforcement of standard methods for testing, application, and disposal of CDs are currently lacking but must be put in place to ensure public safety and environmental stability [171]. Alliances between academicians, industry, and policymakers are required to translate laboratory-scale success into technology suitable for commercialization. In the future, multispectral CDs based on solar-powered water purification, online contaminant sensing, and integrating with intelligent treatment systems have great potential in addressing the global requirement for clean and safe water, particularly in low-resource and decentralized settings [172,173].

7. Conclusion

Carbon dots (CDs) are one of the most recent breakthroughs in water treatment, offering tunable properties with potential to address the world water pollution challenges. From pollutant sensing and removal to use in photocatalysis and filtration, CDs present a number of possibilities to transform purification processes. The fate of CDs in water treatment will hinge on research that enhances their efficiency, scalability, and environmental friendliness. In the future, blending CDs with other nanomaterials and emerging

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technologies, such as membrane systems and photocatalytic reactors, may create more efficient, lower-cost options. Their use in real-time monitoring and pollution sensing is also promising for the early identification of waterborne pollutants, which is essential to public health. Realizing the maximum potential of CDs as a resource in water treatment will hinge on multidisciplinary approaches using materials science, environmental engineering, and nanotechnology. All these advancements place CDs as a viable solution for sustainable and efficient answers to the global water crisis. This paper has emphasized the position of carbon dots as a new generation of nanomaterials for water treatment. Multiple pollutants including heavy metals, dyes, pesticides, and microbial strains have been targeted with success using CDs due to their tunable surface chemistry, excellent aqueous dispersibility, and intense photoluminescence. Various synthesis approaches, from conventional chemical processes to green and biomass-based ones, have made it possible to synthesize CDs with various functional groups in adsorption, photocatalysis, and detection of pollutants. High degradation rates, enhancement of selectivity, and sensitive detection of pollutants are among the significant potential shown by CDs in previous research. Although major advances have been made, a few limitations persist. Large-scale reproducibility, long-term stability in actual wastewater systems, regeneration capacity, and environmental safety of CDs are uninvestigated areas. Mitigation of these hurdles calls for the design of eco-friendly, scalable synthesis pathways, functionalization surface engineering for target contaminants, and combining CDs with membranes, polymers, or hybrid nanomaterials. Overall, CDs present a renewable and flexible material platform connecting laboratory breakthroughs and practical water treatment technologies. Through ongoing developments, carbon dots promise to bring effective, economical, and eco-friendly solutions to global water purification challenges.

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