CARBON DOTS AS GREEN MATERIALS IN CORROSION PROTECTION: A REVIEW

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ABSTRACT

Carbon dots (CDs) have emerged as a new class of environmentally friendly nanomaterials with significant potential in corrosion protection applications. Owing to their low toxicity, sustainable synthesis routes, rich surface chemistry, and excellent dispersibility, CDs represent a promising alternative to conventional toxic corrosion inhibitors and heavy-metal-based coatings. This mini review summarizes recent advances in the use of carbon dots as green corrosion protection materials, focusing on their synthesis, inhibition mechanisms, incorporation into coatings, and current challenges. The review highlights how CDs contribute to sustainable corrosion mitigation strategies while offering multifunctional performance.

Keywords: Carbon dots; green corrosion inhibitors; sustainable materials; protective coatings; eco-friendly nanomaterials.

INTRODUCTION

Corrosion is an inevitable electrochemical process that leads to the gradual degradation of metals and alloys when exposed to aggressive environments, resulting in enormous economic losses, structural failures, and safety concerns worldwide. It is estimated that corrosion-related damage accounts for a significant percentage of global GDP annually, particularly affecting critical sectors such as oil and gas, transportation, construction, and marine infrastructure. Despite decades of research, corrosion remains a persistent challenge due to the increasing complexity of service environments and the growing demand for durable and cost-effective materials [1-3].

Traditionally, corrosion protection strategies have relied on the use of chromate-based coatings, phosphate treatments, and synthetic organic inhibitors to suppress anodic and cathodic reactions. While these approaches have proven effective, many of the associated chemicals are highly toxic, carcinogenic, and environmentally persistent. Stricter environmental regulations and increasing awareness of occupational health risks have therefore accelerated the search for green, sustainable, and non-toxic corrosion protection technologies that can deliver comparable or superior performance without compromising environmental safety [4-5].

In this context, carbon-based nanomaterials have emerged as attractive candidates for sustainable corrosion protection due to their chemical stability, tunable surface properties, and low environmental footprint. Among them, carbon dots (CDs) represent a unique class of zero-dimensional carbon nanomaterials, typically smaller than 10 nm, characterized by abundant surface functional groups and excellent dispersibility in aqueous and polymeric systems. Carbon dots can be synthesized through simple and scalable routes, often employing renewable biomass precursors, which further enhances their green credentials [6-8].

Initially developed for applications in bioimaging, sensing, and optoelectronics, carbon dots have recently gained attention in corrosion science. Their rich surface chemistry enables strong adsorption onto metal surfaces, facilitating the formation of protective interfacial layers that inhibit corrosion reactions. Moreover, the nanoscale dimensions of CDs allow for uniform surface coverage and effective penetration into coating defects and microvoids. These features, combined with the possibility of heteroatom doping and functionalization, have positioned carbon dots as promising eco-friendly corrosion inhibitors and multifunctional coating additives [9-11].

This mini-review aims to provide a concise overview of recent advances in the application of carbon dots for corrosion protection. Emphasis is placed on green synthesis strategies, corrosion inhibition mechanisms, and the incorporation of CDs into protective coating systems, as well as current challenges and future research directions.

SYNTHESIS AND GREEN CHARACTERISTICS OF CARBON DOTS

The synthesis of carbon dots plays a crucial role in determining their physicochemical properties, surface chemistry, and corrosion inhibition performance. In the context of sustainable corrosion protection, emphasis has increasingly shifted toward green, low-energy, and environmentally benign synthesis routes that minimize the use of toxic reagents and harsh processing conditions [12-14].

Carbon dots can generally be synthesized via top-down or bottom-up approaches. Top-down methods, such as laser ablation, arc discharge, and electrochemical exfoliation, involve the breakdown of bulk carbon materials into nanoscale dots. While these techniques can yield high-purity CDs, they often require expensive equipment, high energy input, and controlled environments, which limit their sustainability and large-scale applicability (Figure 1).

In contrast, bottom-up synthesis routes are more widely adopted for green corrosion protection applications. These methods typically involve the carbonization of small organic molecules or biomass-derived precursors through hydrothermal, solvothermal, microwave-assisted, or pyrolytic processes. Among these, hydrothermal and microwave-assisted methods are particularly attractive due to their simplicity, scalability, low energy consumption, and compatibility with aqueous systems [15-17].

A defining feature of green CD synthesis is the use of renewable and waste-derived precursors, including carbohydrates, amino acids, plant extracts, fruit peels, agricultural residues, and food waste. Such biomass-based sources not only reduce environmental impact but also introduce abundant oxygen- and nitrogen-containing functional groups onto the CD surface. These functional groups enhance water solubility and promote strong adsorption onto metal surfaces, which is essential for effective corrosion inhibition [18-20].

Reaction conditions, such as temperature, time, and precursor composition, can be readily tuned to control CD size, surface charge, and functional group density. Moreover, heteroatom doping (e.g., nitrogen, sulfur, phosphorus, or boron) can be achieved either by selecting appropriate precursors or by introducing benign dopant sources during synthesis. Doped CDs often exhibit enhanced electron-donating ability and stronger interaction with metal substrates, leading to improved inhibition efficiency [21-23].

Importantly, green synthesis routes eliminate or significantly reduce the need for post-synthesis purification steps involving organic solvents or hazardous chemicals. The resulting carbon dots are typically dispersible in water and compatible with environmentally friendly coating formulations. This makes them particularly suitable for incorporation into waterborne coatings, sol–gel matrices, and bio-based polymer systems used in corrosion protection [24-26].

Overall, the green synthesis of carbon dots aligns well with the principles of sustainable chemistry and circular economy. By combining low-cost renewable precursors, mild processing conditions, and tunable surface functionality, green-synthesized CDs provide a versatile and environmentally responsible platform for next-generation corrosion protection materials.

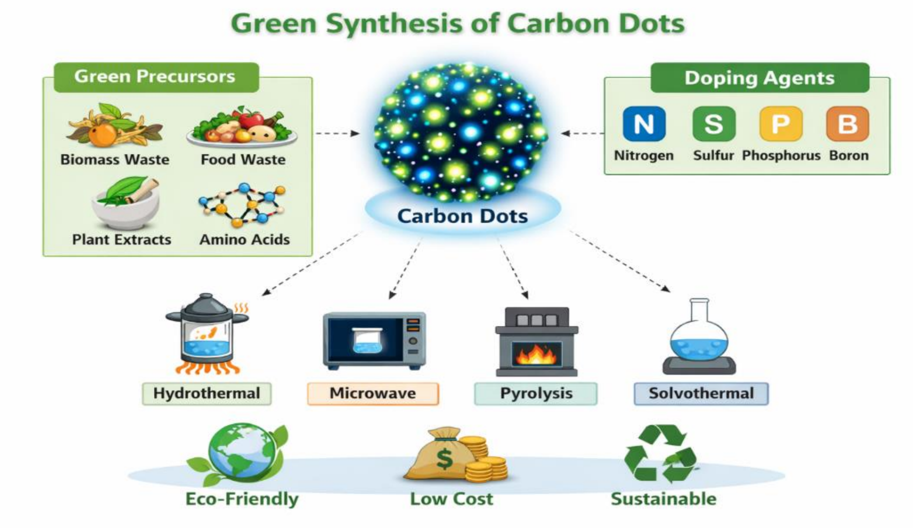

Figure 1. Synthesis and Green Characteristics of Carbon Dots.

CORROSION INHIBITION MECHANISMS OF CARBON DOTS

The corrosion protection performance of carbon dots (CDs) is primarily governed by their adsorption-driven inhibition mechanisms, which arise from their unique nanoscale dimensions and rich surface chemistry. When introduced into a corrosive medium, CDs readily adsorb onto metal surfaces through a combination of electrostatic attraction, coordination bonding, and π–electron interactions [27-29]. This adsorption leads to the formation of a compact and adherent protective film that acts as a physical and chemical barrier, restricting the ingress of aggressive species such as chloride ions, dissolved oxygen, and water molecules (Figure 2).

Electrostatic interactions play a dominant role, particularly in acidic or saline environments, where protonated functional groups (e.g., $–NH_3^+$) on CD surfaces interact with negatively charged metal surfaces or adsorbed anions. Simultaneously, lone-pair electrons from heteroatoms such as oxygen, nitrogen, sulfur, or phosphorus can coordinate with vacant d-orbitals of metal atoms, resulting in chemisorption and enhanced interfacial stability. Additionally, π–electron clouds associated with sp^2-hybridized carbon domains contribute to surface adsorption through donor–acceptor interactions, further strengthening the protective layer [30-32].

Electrochemical studies consistently indicate that CDs behave as mixed-type corrosion inhibitors, suppressing both anodic metal dissolution and cathodic reduction reactions. By blocking active anodic sites, CDs reduce the rate of metal ion release, while their coverage of cathodic regions limits oxygen reduction or hydrogen evolution reactions. This dual inhibition behavior contributes to a significant decrease in corrosion current density without causing substantial shifts in corrosion potential, a characteristic feature of mixed-type inhibitors.

The nanoscale size of carbon dots enables uniform surface coverage and effective penetration into surface defects, grain boundaries, and microcrevices that are typically inaccessible to larger inhibitor molecules. This feature is particularly advantageous for enhancing corrosion resistance under localized corrosion conditions such as pitting and crevice corrosion [33-35].

Furthermore, heteroatom doping has been shown to significantly enhance the inhibition efficiency of CDs. Nitrogen-, sulfur-, or phosphorus-doped CDs exhibit increased electron density and improved donor capability, strengthening metal–inhibitor interactions and promoting the formation of more stable adsorption layers. Doping can also modify the electronic structure of CDs, facilitating stronger charge transfer processes at the metal–solution interface.

Overall, the corrosion inhibition mechanism of carbon dots involves a synergistic combination of physical barrier formation, chemical adsorption, and electrochemical suppression of corrosion reactions. These mechanisms, coupled with their environmentally benign nature, make CDs highly attractive as next-generation green corrosion inhibitors.

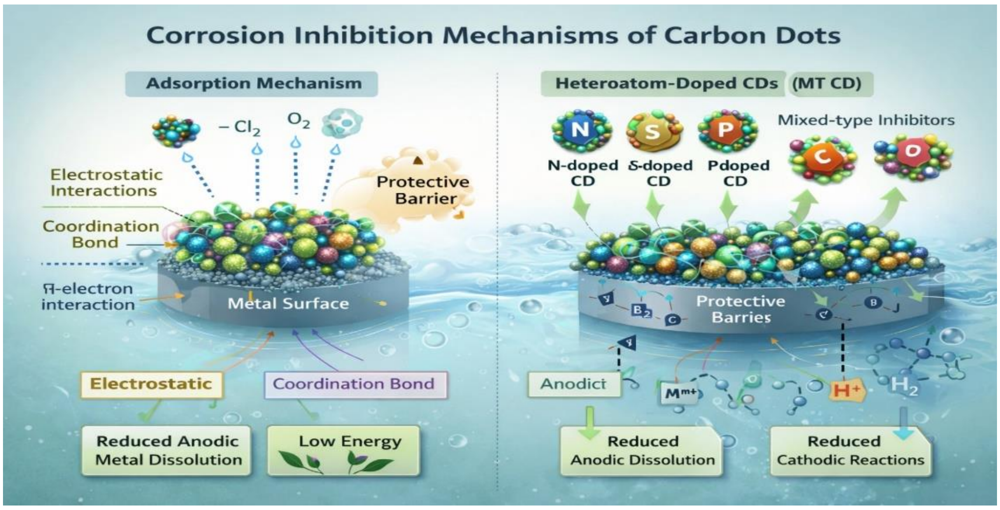

Figure 2. Corrosion Inhibition Mechanisms of Carbon Dots.

CARBON DOTS IN COATINGS AND COMPOSITE SYSTEMS

Beyond their application as standalone corrosion inhibitors, carbon dots (CDs) have been increasingly incorporated into protective coating and composite systems to enhance long-term corrosion resistance. Owing to their nanoscale dimensions and rich surface functionality, CDs can be uniformly dispersed within polymeric matrices, sol–gel coatings, and epoxy-based systems without significantly altering processing conditions [35-37]. Their incorporation leads to improved coating integrity by filling microvoids, pores, and interfacial defects, thereby increasing coating compactness and reducing the permeability of corrosive species (Figure 3).

In polymeric coatings, CDs function as multifunctional nanofillers that enhance both barrier and interfacial properties. Strong interfacial interactions between functional groups on CD surfaces and polymer chains promote better adhesion to metal substrates and improve coating cohesion. As a result, coatings containing CDs exhibit reduced water uptake, lower ion diffusion rates, and enhanced resistance to coating delamination under corrosive environments [38-40].

Carbon dots have also shown promising performance in sol–gel and hybrid coatings, where they contribute to the formation of dense and crack-free networks. The presence of CDs can mitigate shrinkage-induced cracking during sol–gel curing and improve mechanical stability. In epoxy systems, CDs not only enhance corrosion resistance but also improve mechanical properties such as hardness, flexibility, and scratch resistance, which are critical for durable protective coatings.

In addition to barrier enhancement, CDs impart multifunctionality to coating systems. Their intrinsic fluorescence enables the development of smart coatings capable of real-time corrosion monitoring, where fluorescence changes signal coating degradation or localized corrosion initiation. Moreover, CDs can participate in self-healing mechanisms by acting as reservoirs for corrosion inhibitors or by facilitating the reformation of protective films at damaged sites. These multifunctional characteristics distinguish CDs from conventional fillers and inhibitors.

The synergistic interaction between carbon dots and coating matrices leads to a significant improvement in long-term corrosion protection, particularly under aggressive conditions such as high salinity, humidity, and acidic environments. While promising results have been demonstrated at the laboratory scale, further research is required to optimize CD loading, dispersion stability, and long-term durability to enable industrial-scale implementation.

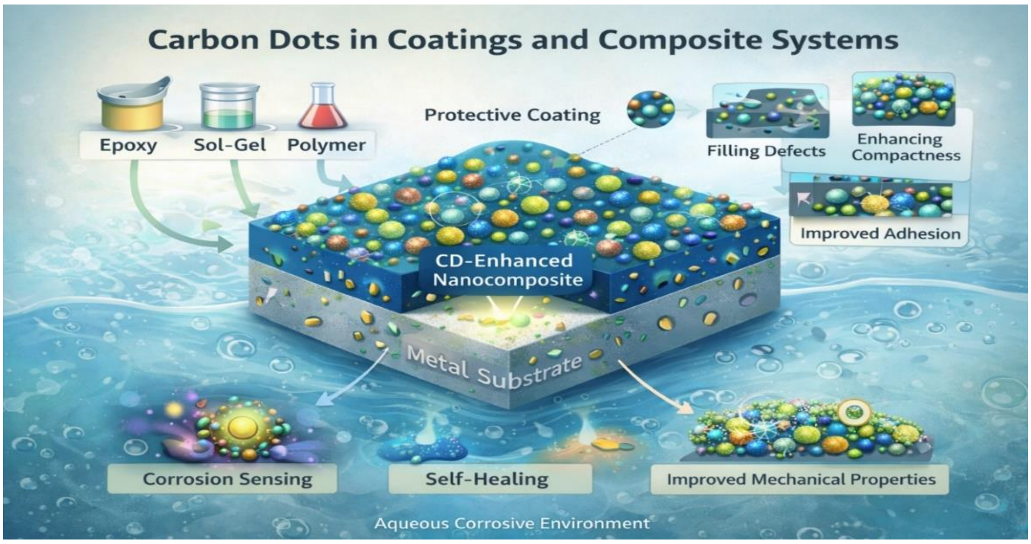

Figure 3. Carbon Dots in Coatings and Composite Systems.

ADVANTAGES AND CHALLENGES

Carbon dots (CDs) offer several compelling advantages that make them highly attractive as green corrosion protection materials. One of the most significant benefits is their low toxicity and excellent environmental compatibility, particularly when synthesized from renewable biomass precursors using green chemistry routes. This feature addresses growing regulatory and environmental concerns associated with conventional corrosion inhibitors.

Another key advantage lies in the sustainable and cost-effective synthesis of CDs. The use of abundant natural resources and waste-derived precursors, combined with mild processing conditions, enables scalable production with a reduced environmental footprint. Additionally, carbon dots often exhibit high corrosion inhibition efficiency at relatively low concentrations, which minimizes material usage while maintaining effective protection [15-17].

Carbon dots also demonstrate strong compatibility with a wide range of coating systems, including polymeric, sol–gel, epoxy, and waterborne formulations. Their nanoscale size and surface functionality facilitate uniform dispersion and strong interfacial interactions, allowing them to be seamlessly integrated into existing corrosion protection technologies without significant modifications.

Despite these advantages, several challenges must be addressed before widespread industrial adoption can be achieved. Controlling large-scale reproducibility remains a critical issue, as variations in precursor composition and synthesis conditions can lead to inconsistencies in CD size, surface chemistry, and performance. Furthermore, the long-term stability of carbon dots under harsh service environments, such as high salinity, extreme pH, temperature fluctuations, and UV exposure, is not yet fully understood [16, 21].

Another limitation is the lack of standardized evaluation protocols for assessing the corrosion inhibition performance of CDs, particularly in coating systems. Differences in testing conditions and performance metrics make it difficult to directly compare results across studies. Future research should therefore focus on optimizing CD surface chemistry, improving long-term durability, and establishing standardized testing methodologies to enable reliable performance benchmarking. Overall, addressing these challenges will be essential to unlocking the full potential of carbon dots as next-generation, sustainable corrosion protection materials.

CONCLUSIONS

Carbon dots represent a promising class of green corrosion protection materials that align with the growing demand for sustainable industrial practices. Their unique physicochemical properties, combined with eco-friendly synthesis routes, make them strong candidates for next-generation corrosion inhibitors and smart coatings. Future efforts should focus on large-scale production, mechanistic understanding, and field-level validation to accelerate their transition from laboratory research to industrial implementation.

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