

Review

Aquatic Biomass-Based Carbon Dots: A Green Nanostructure for Marine Biosensing Applications

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Abstract

Aquatic biomass—ranging from fish scales and crustacean shells to various algae species—offers an abundant, renewable source for carbon dot (CD) synthesis, aligning with circular economy principles. This review highlights recent studies for valorizing aquatic biomass into high-performance carbon-based nanomaterials—specifically aquatic biomass-based carbon dots (AB-CDs)—briefly summarizing green synthesis approaches (e.g., hydrothermal carbonization, pyrolysis, and microwave-assisted treatments) that minimize environmental impact. Subsequent sections highlight the varied applications of AB-CDs, particularly in biosensing (including the detection of marine biotoxins), environmental monitoring of water pollutants, and drug delivery systems. Physically AB-CDs show unique optical and physicochemical properties—tunable fluorescence, high quantum yields, enhanced sensitivity, selectivity, and surface bio-functionalization—that make them ideal for a wide array of applications. Overall, the discussion underlines the significance of this approach; indeed, transforming aquatic biomass into carbon dots can contribute to sustainable nanotechnology, offering eco-friendly solutions in sensing, environmental monitoring, and therapeutics. Finally, current challenges and future research directions are discussed to give a perspective of the potential of AB-CDs; the final aim is their integration into multifunctional, real-time monitoring and therapeutic systems—for sustainable nanotechnology innovations.

Keywords: aquatic biomass; carbon dots; valorization; green synthesis; biosensor; marine biotoxins



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1. Introduction

Carbon-based nanostructures are materials made of graphitic carbon with at least one dimension in the nano-scale; they can be divided into different groups according to their composition and/or sources. More specifically, carbon dots (CDs) can be divided into carbon quantum dots (CQDs), graphene quantum dots (GQDs), and carbonized polymer dots (CPDs) [1]. CDs show very good performance for different aquatic biotechnological and pharmaceutical applications; however, they are often prepared with complex processes

with a severe impact on the environment, with the use of toxic solvents, and/or high-energy consumption [2].

To improve (namely, to decrease) the impact on the environment associated with CD preparation, different routes are being explored; there is indeed growing interest in developing more sustainable carbon-based nanostructures from natural sources. Within this frame, the use of aquatic biomass for their synthesis is a very promising strategy.

Aquatic biomass carbon dots (indicated hereafter in the entire manuscript as AB-CDs) are CDs prepared from aquatic sources, such as animals or plants; they may include algae, fish scales, crab shells, etc.

Figure 1 [2] shows the comparison between semiconductor quantum dots (QDs) and AB-CDs. Semiconductor QDs are often composed of heavy metals like cadmium (Cd) or lead (Pb); this makes them potentially toxic to the environment. Moreover, the environmental impact associated with their synthesis is also quite high.

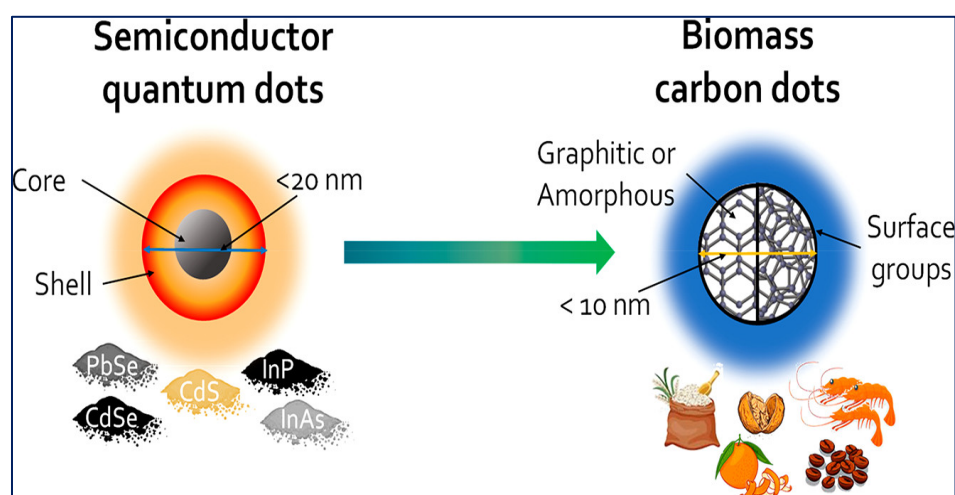


Figure 1. Biomass-derived quantum dots. Reprinted with permission from Wareing et al. [2]. Copyright 2021 American Chemical Society.

AB-CDs, on the other hand, are graphitic or amorphous carbon-based nanostructures synthesized from renewable and non-toxic sources.

Because of this, the use of AB-CDs as an alternative to semiconductor quantum dots has been a significant research focus, driven by their environmental benefits. Moreover, the literature also shows that AB-CDs can have excellent functional properties, such as high fluorescence, high sensitivity, biocompatibility, and reduced cytotoxicity, and that they are suitable for a variety of applications, including biosensing, bioimaging, environmental remediation, and drug delivery. AB-CDs are reported to have a very small size ($< 10\text{ nm}$); also, in some cases, they retain peculiar structural features of the biomass of origin, which give them distinct advantages in sustainable applications [3,4].

These nanostructures, derived from bio-products such as chitin, chitosan, peptides, oils, and collagen, are rich in carbon, nitrogen, and oxygen—essential elements for developing carbon-based nanostructures. This makes them ideal for synthesizing green nanostructures with various applications in biosensing, pollutant detection, bioimaging, and renewable energy [5–7].

On the other hand, monitoring seafood for toxicity is essential to manage the risks of marine biotoxins. However, there are several limitations in sensing for marine biotoxins by using traditional analytical methods along with animal bioassays. Indeed, alternative evaluation systems for sensing marine biotoxins are highly desirable, especially bio/immunosensor-based technologies [8,9]. In the literature, there are a limited number

of reviews that focus on aquatic biomass-specific CD synthesis challenges and marine biotoxin sensing applications. Therefore, this review bridges aquatic biomass valorization, green aquatic biomass CD synthesis, and marine toxin biosensing, thus addressing a gap in the sustainable nanomaterial literature. The different aspects of the process are analyzed and discussed in detail, i.e., the different preparation methods, their specific application as biosensors, and the sustainability of the preparation processes.

2. Valorization of Aquatic Biomass

This section examines the valorization of aquatic biomass for sustainable CDs synthesis. We focus on converting bio-waste (e.g., fish scales, crustacean shells, algal biomass) into functional nanomaterials, emphasizing green synthesis methods, structural properties, and applications in biosensing and environmental monitoring within a circular economy framework.

The utilization of aquatic food bio-waste/by-products as raw biomaterials for the production of different valuable molecules for biofuels, high-value chemicals, and carbon-based nanomaterial, a concept known as “VALORIZATION” of aquatic biomass, is gaining interest, as part of the vision of a circular economy and zero waste policies [10]. The fish by-products are usually composed of heads (accounting for 9–12 percent of total fish weight), viscera (12–18 percent), skin (1–3 percent), bones (9–15 percent), and scales (about 5 percent) [5,11].

Aquatic biomass, including biomaterials like fish scales and crustacean shells (e.g., crab, shrimp, and prawn), can be used to develop CDs (Figure 2) [12]. This figure clarifies two approaches for synthesizing CDs from different carbon sources: the top-down and bottom-up methods. The top-down starts with bulk carbon precursors (graphene/carbon nanotubes) and breaks them down using treatments (e.g., electrochemistry) to form CDs. On the other hand, the bottom-up approach constructs CDs from atomic or molecular precursors (e.g., glucose and amino acids) via green chemical treatments like the hydrothermal method to form these carbon-based nanostructures. These biomaterials sources, rich in chitin/chitosan and other natural polymers, offer a green route to synthesizing carbon-based nanostructures with excellent chemical, physical, and biological properties, contributing to sustainable aquatic biotechnology applications.

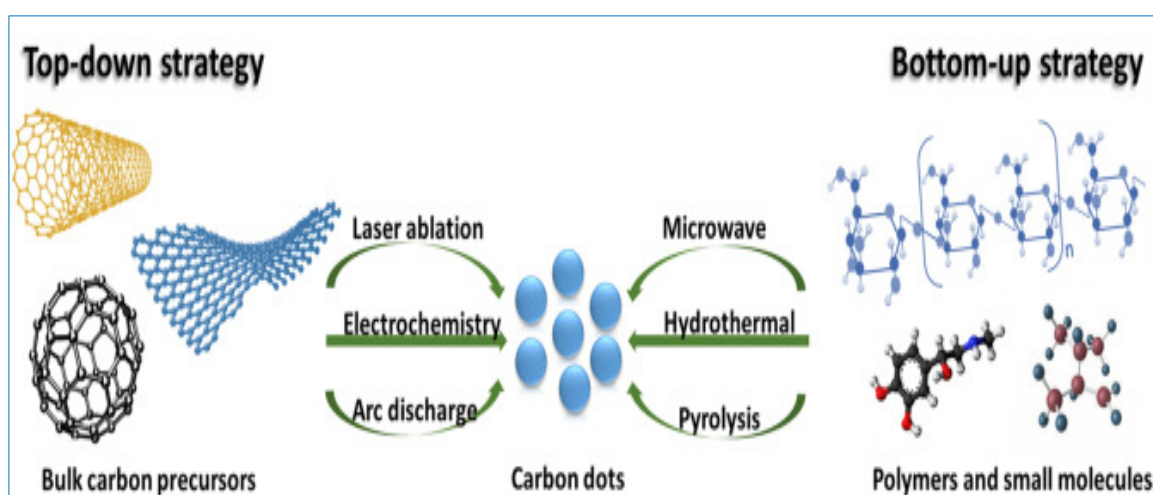


Figure 2. Various methods for CD synthesis [12].

Quantum dots, particularly carbon quantum dots (CQDs) as well as graphene quantum dots (GQDs), can be produced using pyrolysis or hydrothermal treatments; they have excellent photo-physical and electrochemical performance and optical properties. This

allows their use in aquatic biotechnology, bioimaging, biosensing, drug delivery, optoelectronics, environmental applications, and energy storage [13]. In the field of aquatic biotechnology, more specifically in biosensing, the choice of nanostructures becomes vital for their fundamental properties as well as for their adaptability to interface with different biomolecules. Indeed, carbon-based nanostructures, including CQDs and GQDs, are highly promising for aquatic biotechnological applications. Their unique properties, simplicity, high sensitivity, and cost-effectiveness contribute to their potential in this field [14–18].

2.1. Aquatic Animal Biomass-Based Carbon Dots and Their Application

The valorization of aquatic biomass is a very wide field, as these sources have been used to extract different high-added-value compounds for different applications [19,20]. In this work, however, attention will be placed only on investigations aimed at the preparation of AB-CDs.

Several works report the use of fish scales as an AB-CD source. Liu et al. [21], in fact, reported the use of fish scales (fresh carp) to supply new green carbon-based nanostructures through novel solvothermal synthesis (200 °C for 8 h, heating in N, N-dimethylformamide (DMF) solvents). In addition, they confirmed the efficacy of these CDs as a probe in bioimaging applications. Correspondingly, Yang et al. [22] recently prepared graphitized carbon derived from scales of tilapia fish via enzymatic hydrolysis treatment and applied it for the sensing of dopamine in human sweat samples. Fish scales were also used by Zhang et al. [23]; they developed an environmentally friendly one-step method to prepare AB-CDs from grass fish scales via high-temperature pyrolysis (400 °C for 4 h). Moreover, Xu et al. [24] used silver carp scales to prepare green CDs using both hydrothermal and microwave methods; the results showed that CDs obtained using the hydrothermal one showed higher emission quantum yields. The same research group also reported on fish-scale-derived AB-CDs for the sensing of quercetin [25].

Another study on fish scales was performed by Zhang et al. [26], who developed a simple and low-cost method by applying hydrothermal treatment to carp scales. These CDs showed high fluorescence activity and low cyto-toxicity. Furthermore, these CDs performed as a carbon-based nanostructure for clinical and environmental applications (Fe³⁺ sensing in both human serum and real water samples).

Fewer studies are available on fish bones. Mu et al. [27] developed a N-doped carbon nanostructure from fish bone by-products through one-step carbonization, without the addition of any chemical activator as a catalyst. The carbonization temperature was optimized to achieve a layered structure in 3D flake nitrogen-doped hierarchical porous carbon (NPC). These results indicate that NPC carbonized at 850 °C is effective for electrochemical applications. These promising results indicate that bones could be further explored in this field.

Tuna skin has also been employed to produce AB-CDs; more specifically, Gopika et al. [28] reported on CDs prepared from *Thunnus albacares* skin via a hydrothermal method (180 °C/1 h); the developed materials were tested for anticorrosive coating applications.

Studies on shells from different aquatic sources are also present in the literature. Wu et al., for instance, derived the aquatic biomass of shrimp shells to obtain CDs through hydrothermal treatment (200 °C/6 h) and employed a colorimetric system for the sensing of H₂O₂ and glucose [29]. Kechagias et al. [30] valorized the biomass of crayfish shells (*Nephrops norvegicus*) by employing the hydrothermal method (220 °C for 8 h) to obtain CDs in addition to applying these CDs for strawberry packaging applications due to their antioxidant and antibacterial properties.

In some studies, aquatic sources were also employed in combination with other residues to produce CDs. Kumar et al. [31], for instance, combined an oyster mixture with

the shell of palm kernel to make CDs; they employed a hydrothermal reaction (160 °C for 4 h) in a citric acid environment. These CDs were applied in several applications such as bioimaging, inflammatory markers, and theragnostic agents.

Based on prior research, various methods have been employed for developing green CDs from aquatic biomass (Table 1). This table summarizes and compares various methods, highlighting their sources, differences, and efficiencies across different applications.

Table 1. Overview of various methods and sources for developing green CDs from aquatic animals biomass.

Source	Method	Conditions	Advantages	Disadvantages	Quantum Yield (%)	Applications	References
Fish scales (carp)	Hydrothermal	200 °C/8 h, DMF solvent	High fluorescence yield and bioimaging	Toxic solvent (DMF)	31.71	Bioimaging	[21]
Tilapia fish scales	Enzymatic hydrolysis	Room temp., enzymatic pre-treatment	Eco-friendly and selective detection	Time-intensive enzymatic process	N/A	Dopamine sensing in sweat	[22]
Grass fish scales	Pyrolysis	400 °C/4 h	Environmentally friendly and simple setup	Energy-intensive process	23.8	Environmental sensing	[23]
Tuna skin	Hydrothermal	180 °C/1 h	High yield and rapid synthesis	Limited scalability	N/A	Anticorrosive coatings	[28]
Shrimp shells	Hydrothermal	200 °C/6 h	Simple setup and high yield	Limited scalability	N/A	H ₂ O ₂ and glucose sensing	[29]
Crayfish shells	Hydrothermal	220 °C/8 h	Antioxidant and antibacterial properties	High energy consumption	8	Food packaging	[30]
Palm kernel and oyster shells	Hydrothermal	160 °C/4 h	Biocompatibility and theragnostic applications	High process temperature	22	Bioimaging and inflammatory markers	[31]

As it can be seen, hydrothermal treatment is the most common method for synthesizing and developing green CDs due to its simplicity, rapidity, cost-effectiveness, and ability to derive CDs from aquatic biomass-based sources. These aquatic biomass-based CDs demonstrate significant potential in biosensing, medical diagnostics, and environmental monitoring. Nevertheless, each treatment for synthesizing CDs presents its challenges. For sustainability and low environmental impact, however, it is important to use green solvents such as water, ethanol, ionic liquids, and glycerol; toxic solvents, like, for instance, dimethylformamide, should be avoided.

Enzymatic processes are also employed; they are sustainable, as they are generally performed in water and are more eco-friendly; however, they can be slow and need accurate optimization. On the other hand, pyrolysis is a straightforward technique but has a tendency to be energy-intensive, limiting its use in large-scale production.

2.2. Aquatic Plant Biomass-Based Carbon Dots and Their Application

Aquatic plant biomass is an abundant and renewable natural resource for producing bio-energy and high-value bio-products along with carbon-based nanostructures; Figure 3 shows a summary of some possible extractable high-added-value compounds [32].

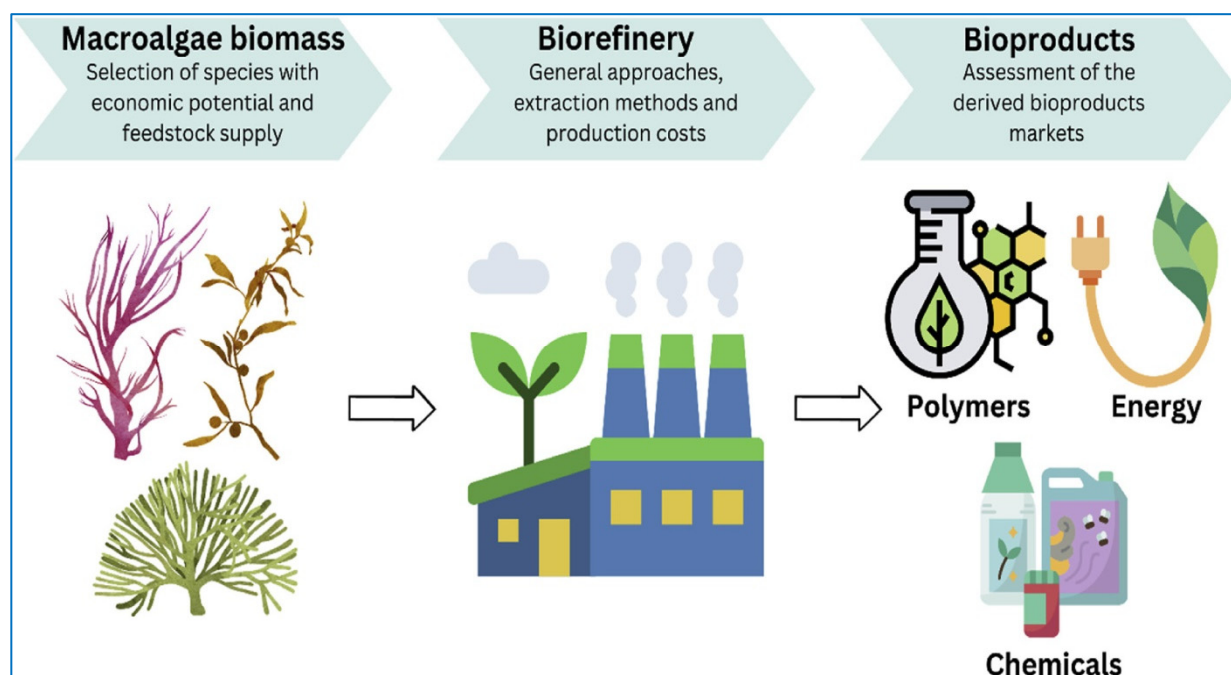


Figure 3. Schematic summary of some aquatic plants' valorization and products [32].

Algae are one of the most common aquatic sources employed in valorization processes; indeed, algal extracts contain biotechnological compounds with anti-(microbial, oxidative, inflammatory, and cancer) effects, which make them suitable for functional, pharmaceutical, therapeutic, and restorative applications (see Figure 4 [33]).

Regarding CD production from algae, the literature reports several studies.

Algal blooms are used as the main carbon source to synthesize highly luminescent CDs (~8 nm), with luminescence/photo-stability in various environments, low cyto-toxicity, and excellent cell permeability [34]. In another study, green CDs co-doped with nitrogen and sulfur (N/S-CDs) were synthesized from *Dunaliella salina* (harmful green alga); the hydrothermal method was employed (200 °C/5 h), without any chemical treatments. The obtained N/S-CDs (3.2 ± 0.5 nm, with low toxicity, antioxidant effects, photo-stability, fluorescence, and water solubility) were applied as multi-functional probes for algal-based imaging, Fe(III) sensing, antioxidant effects, and photo-degradation [35]. A similar approach was used by Singh et al. [36], who prepared green algal nitrogen–phosphorous CDs (A-NPCDs) from the biomass of *Dunaliella salina* (halophilic microalgae) using hydrothermal treatment (200 °C/3 h). The obtained A-NPCDs were applied as fluorescent probes for Hg (II)/Cr (VI) sensing.

Other algal sources employed to produce CDs include laver and wakame [37] and *Chlorella Sorokiniana* [38]; the materials obtained in the first work were employed in nanomedicine (imaging on zebrafish) while those from the second were employed as a chrome (VI/III) sensor.

Macrophyte aquatic plants have also been studied as a CD source; water hyacinth, for instance, has been employed to produce AB-CDs. In this study, a different preparation approach was followed; in fact, the dried biomass was first washed in ethanol and then activated with phosphoric acid. Subsequently, it was carbonized at 160 °C. The resulting material was employed as a pretilachlor sensor [39].

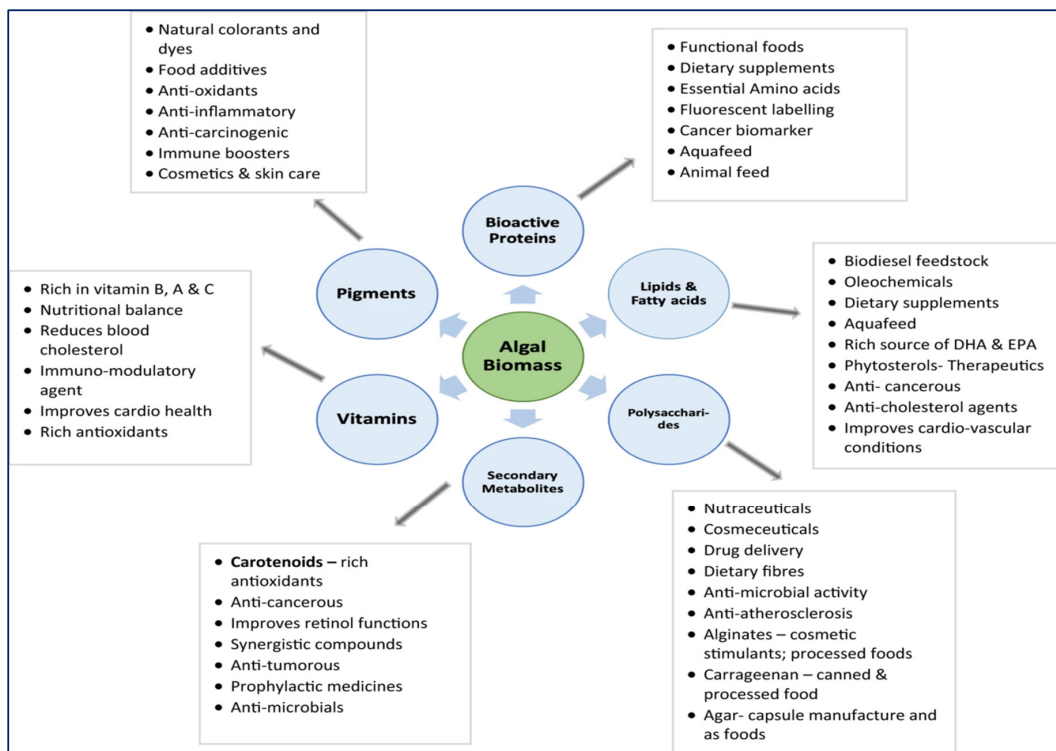


Figure 4. Summary of algal biomass valorization and its biotechnological applications—(DHA: Docosahexaenoic acid; EPA: Eicosapentaenoic acid) [33].

Table 2 summarizes the key aspects of each study; indeed, they show the potential of this source for AB-CD production.

Table 2. Outline of various methods and sources for developing green CDs from aquatic plant biomass.

Source	Synthesis Method	Key Features	Quantum Yield (%)	Applications	Reference
<i>Dunaliella salina</i>	Hydrothermal (200 °C/5 h)	N/S-co-doped, low toxicity, and fluorescent	5.93	Algal imaging, Fe(III) sensing, and as an antioxidant	[35]
<i>Dunaliella salina</i>	Hydrothermal (200 °C/3 h)	Nitrogen-phosphorus doped and fluorescent	8	Hg(II)/Cr(VI) sensing	[36]
Laver, Wakame (algae)	Hydrothermal (200 °C/8 h)	High fluorescence and stable	N/A	Zebrafish imaging and nano-medicine	[37]
<i>Chlorella sorokiniana</i>	Green synthesis	Stable and low cytotoxicity	N/A	Chrome (VI/III) sensing	[38]

3. Carbon Dots for Biosensing and Marine Biotoxins

This section reviews carbon dot (CD)-based biosensing technologies for marine biotoxin detection, addressing critical seafood safety challenges. We analyze electrochemical, optical, and immunoassay systems enhanced by CD nanostructures, focusing on sensitivity improvements for biotoxins like saxitoxins (STXs) and tetrodotoxins (TTXs), and

highlight the role of green-synthesized CDs in enhancing sensitivity and biocompatibility. Key themes include interdisciplinary integration (aquatic biotechnology, nanotechnology, and marine toxicology), real-world applicability in monitoring programs, and sustainability advantages over conventional methods.

Recently, studies on marine biotoxins along with carbon dot (CD) applications have become an important scientific direction, developing in the frameworks of aquatic biotechnology, bionanophysics, analytical chemistry, marine biochemistry, marine biology, marine toxicology, and several other scientific fields. Therefore, biosensing technologies based on CDs are an alternative for the effective sensing of sea foodborne pathogens as well as marine biotoxins. Therefore, for several signal transducers developed to sense marine biotoxins, their sensitivity varies significantly based on the transducers in addition to the bionanomaterials used as analytes. On the other hand, the development of highly sensitive electrochemical/bio/immunosensors based on CDs for simple, sensitive, rapid, effective sensing and identification of marine biotoxins for confirming seafood safety is still an interesting task [40]. The basic sensing systems of chemical sensors are presented in Figure 5. The main purpose of chemical sensors is to sense targets, biomolecules (e.g., marine biotoxins), for monitoring and diagnosis.

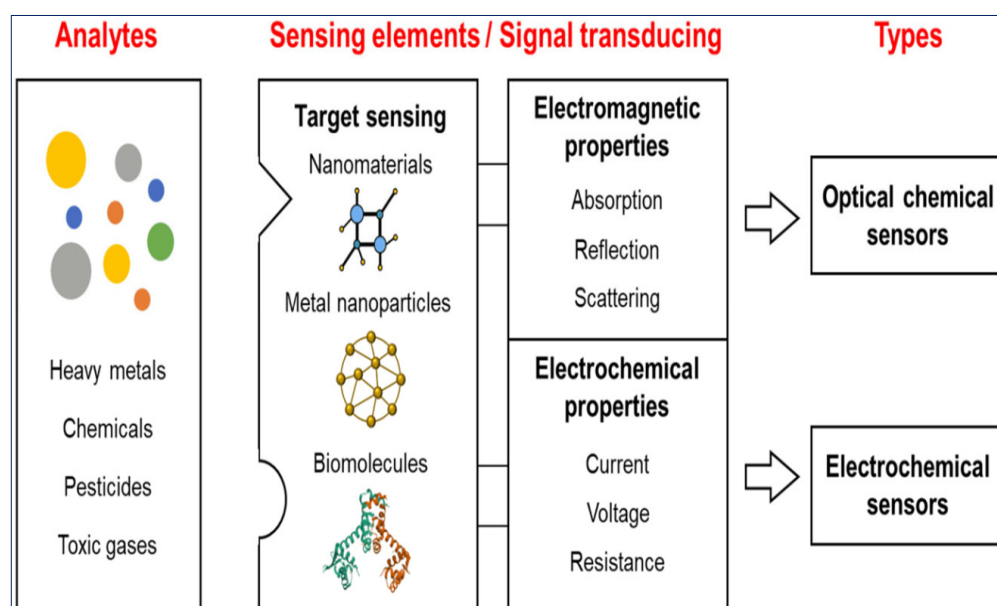


Figure 5. Chemical sensor types [41].

3.1. Background and Biosensing System Technologies of Marine Biotoxins

In recent years, the field of aquatic biotechnology has expanded substantially. Therefore, aquatic biotechnology has deep linkages with bionanophysics, analytical chemistry, marine biochemistry, molecular biology, and pharmacology. Marine biotoxins are responsible for avian poisonings; moreover, they can also cause significant problems to fish and other aquatic animals (i.e., the development of diseases as well as mortality). In addition to this, marine biotoxins can also lead to poisoning of humans and other aquatic animals, due to the consumption of contaminated seafood, mainly shellfish, due to their filter feeding on toxic algae, which are the target of the most extensive monitoring efforts [42].

Marine biotoxins have emerged as major threats in aquatic food and medicine fields. For this reason, designing better systems for sensing and monitoring biotoxins is of great significance. Lately, bio/immunosensors have been progressively used due to their simplicity, high sensitivity, low cost, lower sample volume, and fast detection. As a result, Tang et al. [43] aimed to generalize the application of various sensors in biotoxin sensing in

recent years, with specific focus on their optical, immuno/electrochemical, piezoelectric, and photo/thermal biotechnological applications and challenges for improving biotechnology in seafood safety. Marine biotoxins cause severe toxic symptoms (even death) (see Figure 6). They are natural compounds produced by certain microalgae; they can contaminate different marine species, i.e., fish, aquatic animals and mollusks. Biotoxins, which can be hazardous for both sea life and human health, include molecules such as domoic acid (DA) and its isomers, okadaic acid (OA) and dinophysistoxins (DTXs), saxitoxins (STXs), tetrodotoxins (TTXs), pectenotoxins (PTXs), yessotoxins (YTXs), azaspiracids (AZAs), ciguatoxins (CTXs), palytoxins (PLTXs) and ovatoxins (OVTXs), and brevetoxins (PbTx); moreover, some cyclic imines also belong to this class (spirolides (SPXs), gymnodimines (GYMs), pinnatoxins (PnTXs), pteriatoxins, procenterolides, and portimine). These biotoxins are responsible for various biological activities and can exert deleterious effects on human health [44].

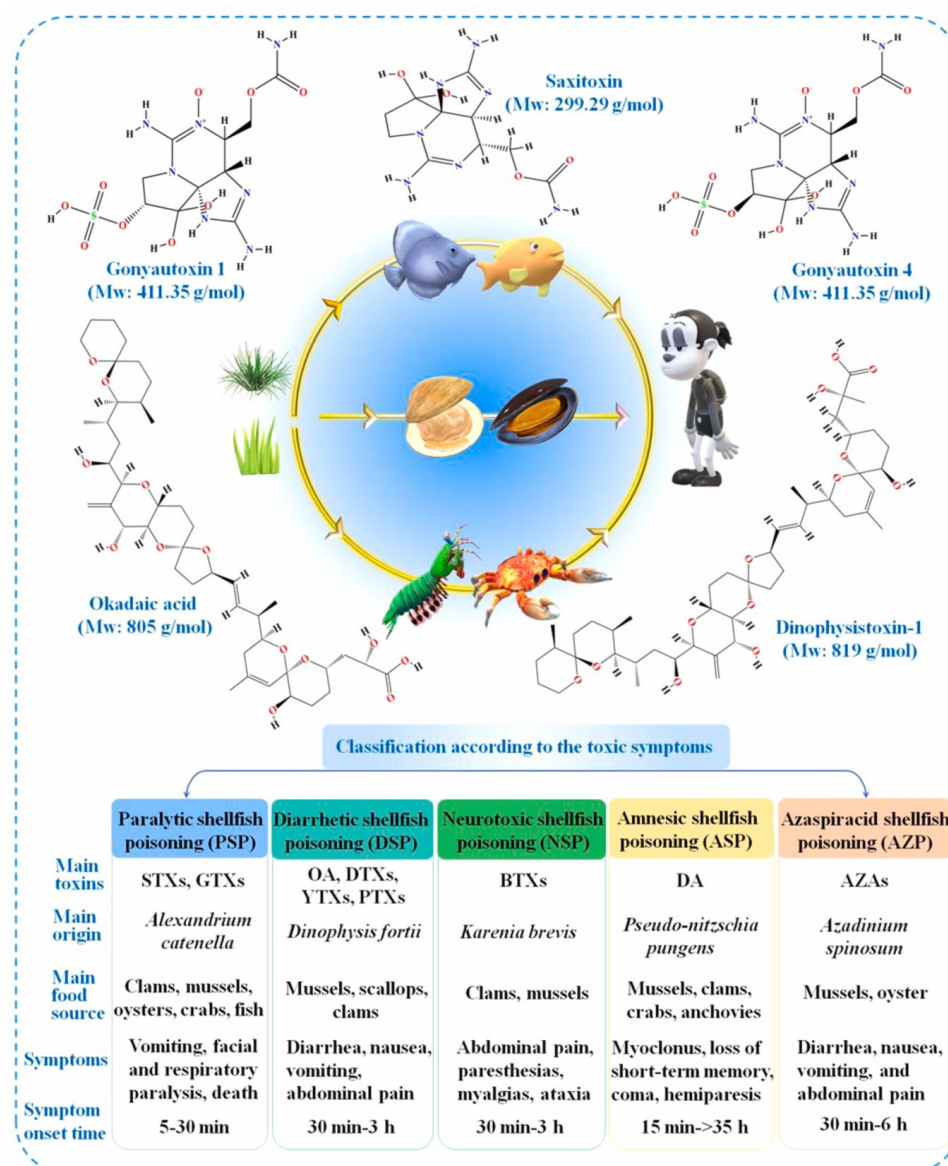


Figure 6. Marine biotoxins' toxic symptom classifications. Reprinted with permission from Zhao et al. [45]. Copyright 2022 Elsevier.

More recently, the monitoring of shellfish has been officially conducted in parts in Europe (UK) and parts of the European Union, Asia (Japan), the US, Canada, and New

Zealand. In addition, many developing countries have also gained capacity to screen and detect shellfish for biotoxins, and the number of human poisoning reports has continuously increased. To conclude, it is vital to combine biotoxin/HAB monitoring with clinical–epidemiological surveillance, as well as medical and hygienic regulations [46]. The emergence of marine biotoxins in several geographical areas is a concern, with considerable impact on seafood contamination and, therefore, public health. Various groups of marine biotoxins, in particular (STX), (TTX), CTXs, and PLTXs, along with DA (Amnesic Toxins) and OA (Diarrheic Toxins), are biotoxins that have just now emerged in some coastal areas. Furthermore, climate change and nutrient availability are considered as the vital factors in the expansion of all of these biotoxins into new regions; however, this could also be due to more intense biological invasions, more sensitive analytical methods, or perhaps even an increased scientific interest in these natural contaminations [47].

Some aquatic phytoplankton can harm humans through biotoxin production, which threatens aquatic food security and human health. These biotoxins are responsible for natural fisheries or aquaculture fish mortality and may cause economic losses. Hence, Hallegraeff et al. [48] differentiated between trends in the occurrence of causative microalgal organisms, the sensing of biotoxins in aquatic food, human poisonings, and aquatic animal and marine mortalities. Moreover, Roggatz et al. [49] stated that the paralytic neurotoxins SXT and TTX significantly impact two ecological keystone molecules in the ocean and that increasing temperatures and declining pH increase the abundance of toxic forms in the sea.

On the other hand, among various aquatic animals' species, the puffer fish (Fugu) is the species that accumulates the most tetrodotoxins (TTXs). In several studies of TTX, it has been found that the cultivated nontoxic Fugu, when fed with TTX-containing feed, becomes toxic [50]. TTX and TTXs are heat-resistant with neurotoxic activity and highly potent natural biotoxins found to be increasingly prevalent in the aquatic environment. Therefore, further research evaluating the toxicity and sensing of TTXs is required to detect and develop vastly sensitive sensing systems [51].

Essentially, safety and quality are important issues for seafood manufacturing. For this reason, highly sensitive, simple, reliable, rapid, and cost-effective sensing systems should be developed, such as electrochemical bio/immunosensors. Therefore, improving sensors can significantly support the screening of aquatic food chains and aquatic products [52].

Traditional detection methods range from traditional animal-based bioassays to advanced analytical techniques like liquid chromatography and biosensors [53], as reported in Figure 7.

3.2. Applications of Carbon-Based Nanomaterials in Biosensing

In the last 5 years, because of their high sensitivity, simplicity, selectivity, and efficiency, and low cost, electrochemical immunosensors—which use an antibody as a particular bioreceptor to identify the target analyte—are rapidly becoming more and more popular; in particular, screen-printed electrodes (SPEs), in which the antibody is either adsorbed directly on the electrode in its original form or altered using carbon nanomaterials, have shown significant potential for this kind of application.

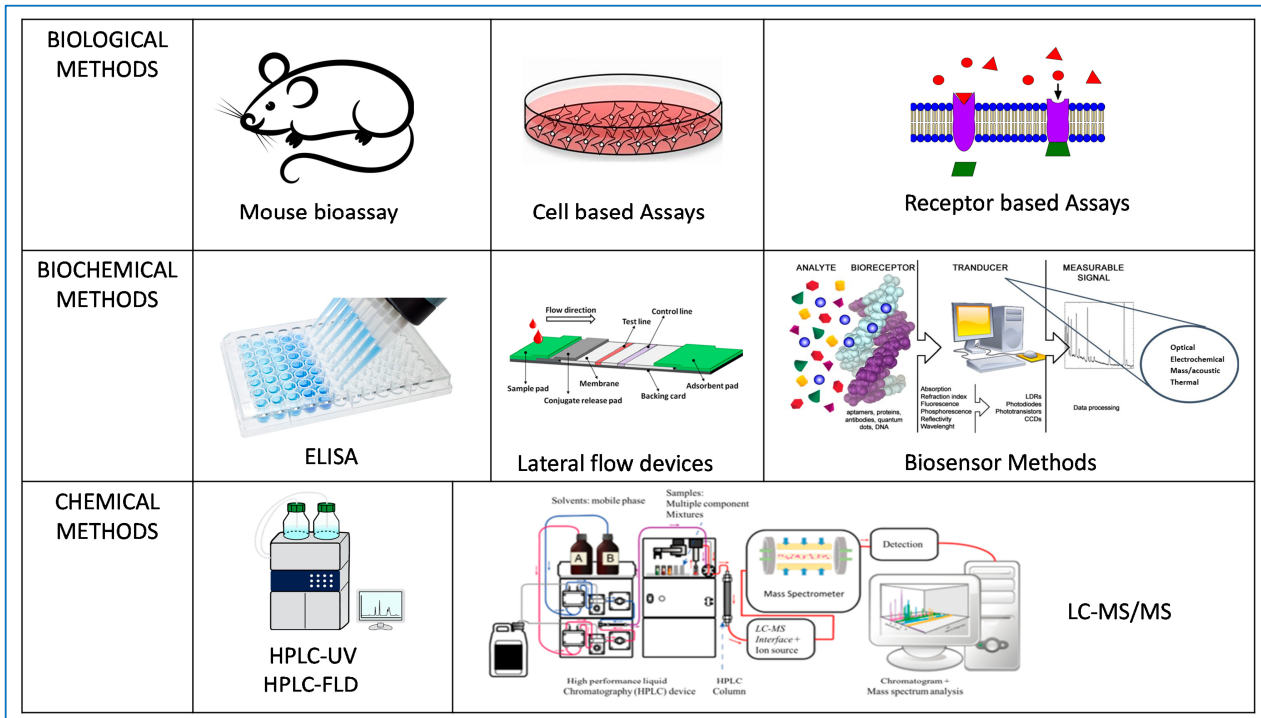


Figure 7. Summary of several methods for the sensing of marine biotoxins [53].

SPE technology, modified with selective antibodies for these toxins, has been widely applied for developing novel immunosensing systems and analytical performance. Yuxiang et al. [54], in their review, report on the advantages and disadvantages of each immunoassay; a comparison between the different tests is performed to indicate which one is the most suitable method according to the biotoxins that need to be detected.

Among the various biosensing systems, electrochemical biosensors (Figure 8) are principally suitable for marine biotoxins because they are easily fabricated, simple, portable, and low-cost, and electrochemical signals (electrical current and potential) can be collected by peripheral devices with low energy consumption.

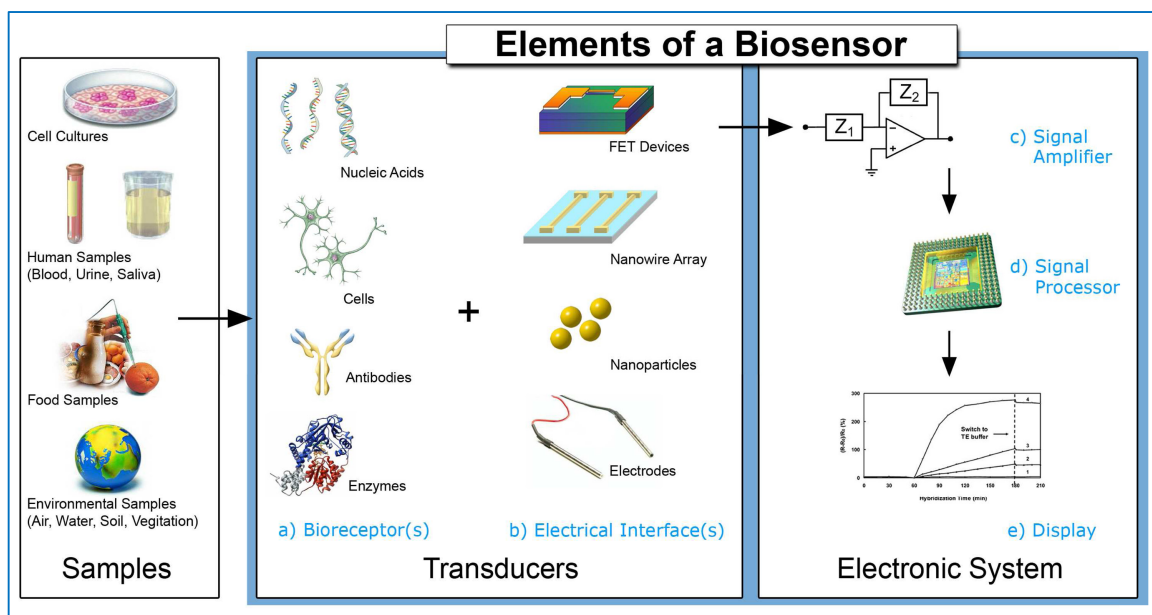


Figure 8. Electrochemical biosensor schematic [55].

Accordingly, Shen et al. [56] established novel electrochemical immunosensors. On this immunosensor, chitosan and nafion are used (range from 2 to 1250 ng/mL—LOQ of 4 µg/kg). Similarly, Li et al. [57] designed a unique non-toxic and highly efficient electrochemical and colorimetric sensing platform for the detection of TTX based on a monoclonal antibody (mAb) and mimotope. Recently, Daniso et al. [58] applied an Organic Light-Emitting Diode (OLED) immunosensor to detect TTX. This work based on the ELISA test and the OLED system, respectively.

Moreover, saxitoxin (STX) (C₁₀H₇N₇O₄—low molecular weight 299 g/mol) is naturally the best-known neurotoxin; the paralytic shellfish poisoning (PSP) biotoxin has a significant ecological and economic impact, due to its presence in aquatic food (bivalve shellfish). Therefore, a specific and suitable system for STX sensing and monitoring is essential to prevent adverse effects on aquatic animal and human health. As a result, Kim, et al. [59] recently developed a sensor (fluorometric) using graphene oxide (GO) for STX (LOD 1.5 ppb), showing very good sensitivity. However, Serrano et al. [60] developed an electrochemical biosensor for sensing STX. This method is label-free and simple and presented sensitivity for sensing concentrations above 0.3 µg/L. Therefore, Bratakou et al. [61] showed the preparation of a biosensor (fast response 5–20 min, depending on biotoxin concentration), based on a lipid film and combined saxitoxin antibody on graphene nanosheets. Likewise, an STX fluorescence nanobiosensor was fabricated by Sun et al. [62] based on quantum dots (molecularly imprinted silica layers). In the same way, Zhu et al. [63] recently developed a magnetic fluorescent biosensor modified with green quantum dots (cDNA@g-QDs) through the bridge of an STX aptamer and complementary DNA (cDNA) for STX.

Major innovations in electrochemical/bio/immunosensors are immobilization in addition to the interface capabilities of the bionanomaterial with SPE techniques. The use of green nanostructures (namely, CDs and GQDs) and sandwich-type systems has recently increased the signal response [41,64].

At present, various research studies on the preparation, development, synthesis, modification, or application of carbon-based nanostructures have been performed. CDs are a novel class of carbon nanostructures developed recently and have attracted considerable interest compared to conventional semiconductor and biosensor applications. Moreover, CDs have unique properties such as optical properties, physicochemical properties, low toxicity, biocompatibility, environmental friendliness, low cost, and simple synthetic routes; these brilliant characteristics have led to many biotechnological applications of CDs in the areas of aquatic biotechnology and chemo- and bio/immunosensing, bioimaging, drug delivery, photocatalysis and electrocatalysis. Accordingly, Pan et al. [65] summarized and showed different characteristics of carbon-based nanostructures and their biotechnological applications in aquatic food safety as well as biosensing (chemo-bio/immunosensor). They reported the important role of carbon-based nanostructures (including graphene and CDs) for applying and testing different chemo-bio/immunosensors along with their applications in food safety, especially for the sensing of all sorts of toxic substances.

Furthermore, Wang et al. [66] developed a unique sensor based on CDs for a domoic acid (DA) sensing system with an LOD down to 10 nM. In addition, Nelis et al. [67] applied a new system based on screen-printed electrode technology along with carbon black modified as an electrochemical immunosensor for the sensing of the marine biotoxins DA and OA. This sensor presented good LODs (for DA: 1.7 ng mL⁻¹ in buffer; 1.9 ng mL⁻¹ in mussel extract; for OA: 0.15 ng mL⁻¹ in buffer; 0.18 ng mL⁻¹ in mussel extract).

Some types of nanosensors summarized in Table 2 show various nanosystems for marine biotoxin sensing, from electrochemical immunosensors to fluorometric biosensor systems. However, electrochemical systems like screen-printed electrodes (SPEs) are

simple, cost-effective, and can be easily fabricated. On the other hand, optical and fluorescent systems, including OLEDs and carbon quantum dot-based sensors, offer great specificity and sensitivity. Despite these developments, the scalability of such sensors and their integration into portable nanosystems remain challenges. The integration of green nanostructures, such as AB-CDs, into these nanosystems is a key opportunity to enhance performance, increase environmental sustainability, and decrease costs. This advancement reflects the prospective of biosensors in certifying seafood safety and advancing aquatic biotechnology applications.

3.3. Applications of AB-CDs in Biosensing System Technologies

In 2023, an interesting review on the recycling of aquatic biomass for electrochemical applications was published by Onfray et al. [68]. Aquatic biomass is, in particular, a promising resource for synthesizing CDs as well as biochar via pyrolysis and hydrothermal technologies. These carbon-based nanostructures show excellent sensitivity, conductivity, electrochemical performance, high surface area, and functional groups, making them ideal for electrochemical biosensor applications. Ab-CDs offer higher fluorescence, quantum yield and biocompatibility, enabling the detection of biotoxins and heavy metals in addition to organic pollutants in aquatic and seafood systems. In comparison, Ab-CDs are more suited for high-sensitivity applications demanding fluorescence-based sensing, such as marine biotoxin sensing, due to their brilliant optical properties and specificity. Conversely, biochar can be applied in sensors for environmental applications, such as sensing heavy metals and organic pollutants, due to its simpler production method, availability, high porosity, conductivity, and cost-effectiveness. Prospect research objects to enhance synthesis efficiency, and advance multifunctional systems for sustainable, real-time monitoring in aquatic environments and seafood safety [69,70].

Consequently, it will be essential to design novel, highly accurate systems for aquatic biotechnological applications to specifically sense marine biotoxins based on green nanostructures immediately. In conclusion, for sensing marine biotoxins, analytical systems such as enzyme-linked immunosorbent assay (ELISA), high-performance liquid chromatography (HPLC), and liquid chromatography–mass spectrometry (LC–MS) are applied with limitations. For that reason, performance and designing a unique system of bionanosensors for biotoxin detection offers a novel trend as applying bionanoreceptors such as nanostructures especially carbon dots, could be applied to create different nanosensors, without the limitations of traditional detection technologies.

4. Critical Discussion and Future Outlook

This section critically evaluates the sustainability advantages, synthesis challenges, and emerging applications of AB-CDs. We assess energy efficiency metrics versus conventional nanomaterials, address scalability and biocompatibility limitations, and propose future research directions—including AI-integrated monitoring systems and hybrid nanostructures—for advancing marine biotoxin sensing within a circular blue economy framework.

The synthesis of CDs from aquatic biomass is a rapidly developing field, focused on the sustainability and abundance of these natural resources. Aquatic biomass offers a renewable and green alternative to conventional CD precursors. These biomaterials are often by-products from aquatic and seafood manufacturing, aligning with the principles of a blue circular economy and aquatic biomass valorization. Studies confirm that doping (e.g., nitrogen and sulfur) can enhance the properties of AB-CDs, such as photoluminescence and catalytic performance. Regardless of the relatively current focus on AB-CDs, their potential

for applications in biosensing, bioimaging, catalysis, and renewable energy nanosystems has attracted significant interest [71,72].

AB-CDs show exceptional promise in marine biosensing, achieving detection limits as low as 0.15 ng/mL for biotoxins like okadaic acid (OA) (Table 3) through sustainable synthesis. Their biocompatibility and tunable fluorescence enable selective biotoxin recognition in seafood matrices; despite this, however, there are still some critical issues which need to be addressed, as listed below.

- **Biomass Variability:** Quantum yield inconsistency (5–25%) due to heterogeneous waste composition (e.g., fish scales vs. algae) (see Table 4), reducing detection reproducibility.
 - *Animal-derived CDs:* Higher heterogeneity (5–15% QY) from diverse protein/calcium profiles.
 - *Plant/Algal CDs:* More consistent QY (15–25%) via uniform polysaccharides and natural N/S doping.
- **Scalability:** Batch-processing limits versus industrial-scale demands.

Table 3. Overview of some types of bionanosensors for marine biotoxins.

Type of Sensor	Marine Biotoxin	LOD/Range	Nanostructures	Reference
Electrochemical immunosensor	TTX	2–1250 ng/mL (LOQ 4 µg/kg)	Chitosan and Nafion	[56]
Electrochemical and colorimetric	TTX	Electrochemical: 1 × 10 ⁻⁵ µg/mL Colorimetric: 1.83 × 10 ⁻⁴ µg/mL	Biomimetic mineralized material (HRP/anti-TTX mAb@ZIF-8)	[57]
OLED-based immunosensor	TTX	44 ng/g	Not specified	[58]
Fluorometric sensor	STX	1.5 ppb	Graphene oxide (GO)	[59]
Electrochemical biosensor	STX	Above 0.3 µg/L	Aptamers	[60]
Lipid film biosensor	STX	Fast response (5–20 min)	Graphene nanosheets	[61]
Fluorescent nanobiosensor	STX	20.0–100.0 µg/L; LOD: 0.3 µg/kg in shellfish	Quantum dots and molecularly imprinted silica layers	[62]
Magnetic fluorescent biosensor	STX	0.6 nM	Green quantum dots (g-QDs), Fe ₃ O ₄ @Au-Pt nanozymes, and STX aptamer	[63]
Sensor based on carbon dots (CDs)	DA	10 nM	Carbon dots (CDs)	[64]
Screen-printed electrochemical	DA, OA	DA: 1.7 ng/mL; OA: 0.15 ng/mL (buffer)	Carbon black	[65]

Addressing these factors requires standardized biomass preprocessing and continuous-flow reactors to enable commercial deployment.

Considering the sustainability of the process, on the other hand, AB-CDs present significant advantages.

Table 4. Quantum yield consistency in AB-CDs.

Parameter	Aquatic Animal Biomass-Based CDs	Aquatic Plant Biomass-Based CDs	References
Quantum Yield Range	5–15%	15–25%	[28,31]
Primary Sources	Fish scales and crustacean shells	Micro/macroalgae	[21,28,29,35,36]
Variability Drivers	<ul style="list-style-type: none"> Protein diversity Ca²⁺ Seasonal changes 	<ul style="list-style-type: none"> Uniform polysaccharides Stable N/S doping Consistent cultivation 	[28,31]
Key Advantage	Enhanced conductivity	Natural heteroatom doping	[27,35]

AB-CDs synthesis consumes 40–60% less energy than semiconductor QDs (e.g., CdSe or PbS QDs) [73–76] (Table 5), primarily due to the following:

- Simple reaction conditions: Hydrothermal methods for AB-CDs operate at 160–220 °C, avoiding high-temperature pyrolysis (>500 °C) or vacuum processes required for semiconductor QDs.
- Shorter processing times: Microwave-assisted AB-CD synthesis achieves full carbonization in 1–4 h vs. 8–24 h for semiconductor QDs.
- Renewable energy compatibility: Solar- or biomass-powered reactors further reduce energy footprints by 30%.

Table 5. Energy consumption comparison for CD synthesis methods.

Synthesis Method	Avg. Energy (kWh/kg)	Temp. Range (°C)	Time (h)
AB-CDs (Hydrothermal)	50–80	160–220	1–8
Semiconductor QDs	120–200	300–500	8–24
Chemical Precursor CDs	90–150	200–400	6–12

While studies on AB-CDs are less abundant compared to other forms of biomass, recent aquatic biotechnology is expanding rapidly. Aquatic animal biomass-based carbon dots (fish scales and crustacean shells) are valued for their protein and calcium-rich composition, supporting high-quality AB-CD production, while aquatic plants biomass-based carbon dots (algae and seaweed) are often explored due to high growth rates and simplicity of cultivation. Recent challenges, such as variability in aquatic biomass composition as well as scalability issues, persist; however, developments in synthesis technology, including hydrothermal/pyrolysis treatments and microwave-assisted and ultrafast technologies, are presently addressing these limitations. The increasing importance of sustainable biomaterials and the growing demand for multifunctional green nanostructures suggest that research into aquatic biotechnology applications will continue, offering exciting prospects for innovation [74,75].

On the other hand, the improvement of sensors using nanotechnology, natural and sustainable sources for marine biotoxin applications, is vital for better environmental monitoring and seafood safety. Thus, bionanosensors are of significant interest in the aquatic biotechnology field, namely, carbon-based nanostructure sensors, because they are simple, rapid, low-cost, sustainable, eco-friendly, reliable, have low toxicity, and are portable, in addition to their unique properties, namely, their simplicity and high sensitivity. More and more biosensing systems (Figure 9) are becoming available day by day, developed and designed for the detection of marine biotoxins based on novel green nanostructures for seafood safety and various aquatic biotechnology applications. The use of such aquatic

biomass-based carbon dots will contribute to developments in line with the principles of the circular blue economy. The development of modified SPEs with green nanostructures, namely, CDs, will lead to the sensing of marine biotoxins through new types of sensor systems with enhanced performance, allowing for the quicker detection of toxins, possibly reaching lower detection limits.

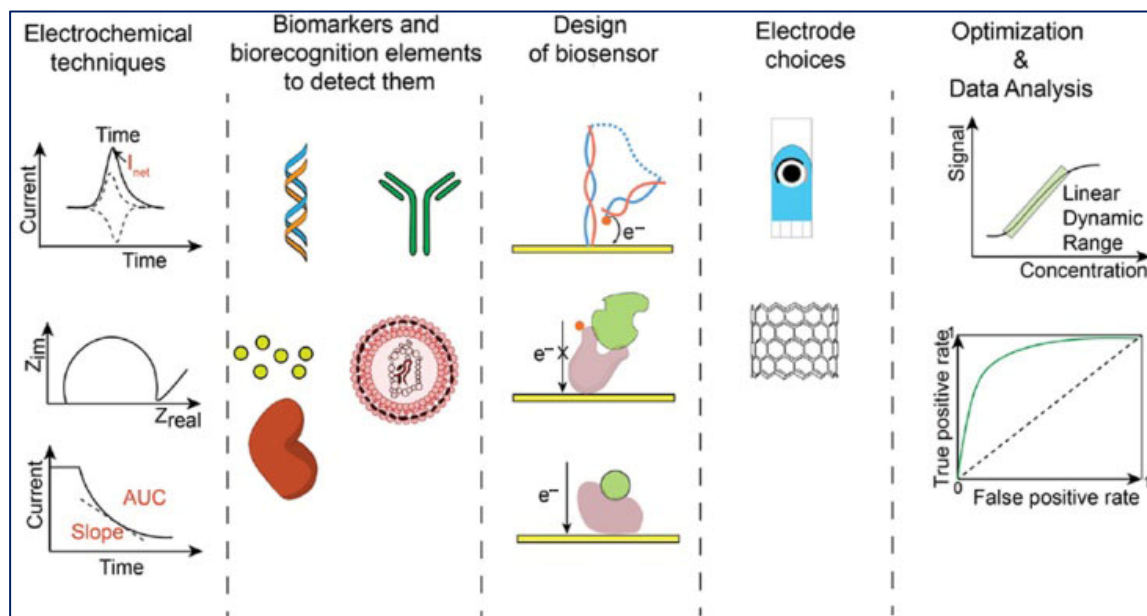


Figure 9. Biosensing system technologies. Reprinted with permission from Sankar et al. [77]. Copyrights 2024 American Chemical Society.

This review briefly highlights the recent applications of and studies on aquatic biomass-based carbon dots as easy-to-fabricate, highly sensitive, and versatile systems in aquatic biotechnology applications, especially for marine biotoxins sensing. The integration of green nanostructures, including CDs, has significantly improved the sensitivity and specificity of SPE-based/immuno/electrochemical biosensors for sensing marine biotoxins.

Future integration of AB-CDs into multifunctional systems faces challenges, such as ensuring long-term biocompatibility for therapeutic applications, optimizing stability under diverse environmental conditions (e.g., pH and salinity), and harmonizing these nanomaterials with existing diagnostic or monitoring infrastructure. Moreover, energy-efficient synthesis methods and real-time data interoperability between sensors and analytical systems require refinement. Hybrid systems integrating AB-CDs with plasmonic nanoparticles or polymers could amplify multifunctionality, while AI-driven sensor networks might enhance predictive analytics for marine biotoxin outbreaks.

To sum up briefly, various green carbon-based nanostructures, including CDs and GQDs, are brilliant bionanostructures for the construction and design of biosensor nanosystems due to their excellent performance. The improvement of advanced preparation biotechnology, nanotechnology, and biosensing technologies will lead to more progress in the use of green synthesized CDs/GQDs in studies on aquatic biotechnology applications and analysis, specifically marine biotoxin sensing. In summary, the significant number of current studies on the nanofabrication, properties, and biotechnological applications of aquatic biomass-based carbon dots should increase, and progressively more aquatic biomass-based CDs should be developed with exceptional sensitivity, simplicity, efficiency, and applicability. In conclusion, AB-CDs hold great promise for sustainable, multifunctional, real-time monitoring and therapeutic systems. Therefore, this review uniquely

bridges aquatic biomass valorization, green CD synthesis, and marine biotoxin biosensing, offering an integrated perspective on sustainable nanomaterials.

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