# Advances in Nanotechnology for Environmental Sustainability and Biomedical Innovations

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Edited by

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Hanna J. Maria and Blessy Babukutty

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# CHAPTER 1

# CARBON ARCHITECTONIC FOR WATER TREATMENT

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## Abstract

This chapter examines diverse applications in which carbon-based materials are used to address problems with water treatment. Being a common and valuable element, carbon is found in various shapes, from bulk to nanostructures, each with unique qualities and functions. This chapter thoroughly reviews the various carbon compounds and how they are used in different water treatment procedures. Beginning with a discussion of the qualities and features of bulk carbon materials, such as activated carbon, the chapter emphasizes these materials' outstanding adsorption capacities for removing organic pollutants, heavy metals, and new contaminants from water sources. It thoroughly investigated how nano carbon materials may be used in filtration, adsorption, and catalytic processes, demonstrating their usefulness in water treatment applications. The exciting developments in carbon nanostructures, such as graphene, carbon nanotubes, carbon dots, and graphene quantum dots, are also covered in depth in this chapter. These nanoforms have unique qualities that let them excel in various water treatment procedures, including large surface area, superior electrical conductivity, and configurable band gaps.

**Keywords:** Physisorption, Chemisorption, Catalysis, Membranes, Disinfection

# 1 Introduction

An essential human right and a requirement for sustainable development is having access to clean, safe water. However, causes, including population expansion, industrialization, agricultural practices, and pollution, pose a growing danger to the availability of pure water (Ajith and James, 2016; Azimi et al., 2017). Innovative water treatment technologies are being created in response to these difficulties to guarantee the availability of clean and potable water.

Creating efficient and sustainable water treatment technologies is critically important, and carbon-based materials have emerged as significant players in this arena. Carbon has unique qualities and a wide range of uses for water filtration in its bulk and nanoforms. The wide variety of carbon compounds, such as activated carbon, carbon nanotubes, graphene, carbon dots, as well as graphene quantum dots, have excellent adsorption properties, a large surface area, variable porosity, stability, and chemical reactivity, which makes them the perfect choice for water treatment applications (Long et al., 2021; M. P. et al., 2022).

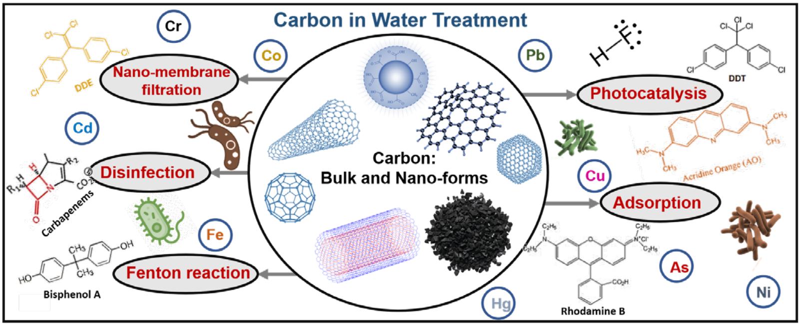

**Fig. 1-1** Schematic representation of carbon material's application in various water purification techniques. Source: Modified from (Ajith et al., 2021).

These carbon materials may efficiently remove a wide range of pollutants from water sources, including organic pollutants, heavy metals, and emerging contaminants (**Figure 1.**). Using bulk and nanoforms of carbon in water purification improves pollutant removal effectiveness and helps create environmentally acceptable and environmentally safe water treatment methods (Ajith and Paulraj, 2022; Raja et al., 2023). In this article, we will explore the possible uses, techniques, and difficulties related to using bulk and nanoforms of carbon in water purification, emphasizing its significant contribution to ensuring populations all over the globe have access to clean and safe water.

## 2 Bulk Carbon Materials for Water Treatment

### 2.1 Activated Carbon

With its vast surface area and highly porous structure, activated carbon is commonly used in water treatment. The terms biochar and activated carbon are used interchangeably. While activated carbon is a biochar that has undergone chemical or physical activation, biochar is produced by biomass pyrolysis. Both solids have a huge surface area and are simple to modify on the surface, making them both popular adsorbents. To create activated carbon, precursor materials like coconut shells, wood, or coal must first be carbonized and activated. The final product has a network of pores that offers plenty of adsorption sites for removing impurities from water (**Figure 2.**). Diverse water treatment applications use activated carbon to remove impurities such as heavy metals, organic pollutants, and new contaminants.

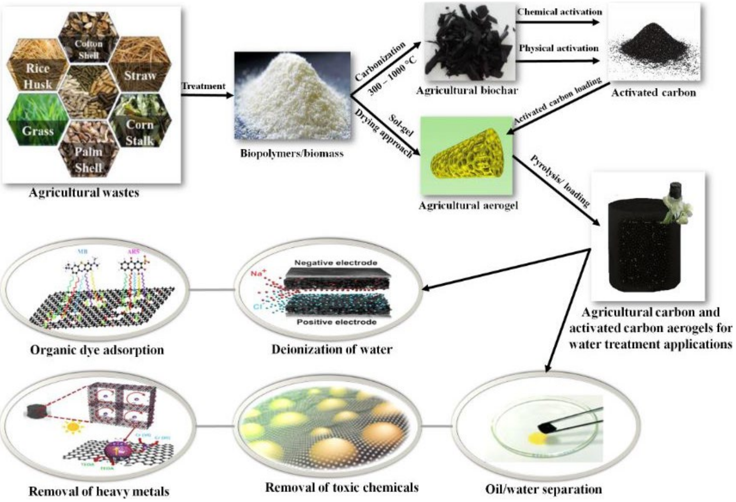

**Fig. 1-2** Schematic representation of the synthesis of activated carbon and its application in water treatment. Source: (Muhammad et al., 2023)

Several case studies have shown the effectiveness of activated carbon in water purification. For instance, activated carbon filters have effectively eliminated organic contaminants from drinking water sources, such as pesticides, medications, and industrial chemicals (Rivera-Utrilla et al., 2011). Activated carbon has removed dyes and other persistent organic pollutants from wastewater. The remarkable performance of activated carbon in water treatment results from the adsorption mechanisms such as pore filling, surface complexation, and electrostatic interactions (Mariana et al., 2021; Rivera-Utrilla et al., 2011).

Nevertheless, the constraints related to its usage must be considered. One of its limitations is the comparatively poor adsorption capacity of activated carbon for some pollutants (Younas et al., 2021). While organic molecules like pesticides and volatile organic compounds are very well adsorbable by activated carbon, some inorganic elements like heavy metals and certain dissolved salts may not be as well removed by activated carbon. Due to this restriction, additional treatment techniques or other adsorbents must be used to purify the water completely.

Another drawback of activated carbon is that it is prone to fouling and loses some of its adsorption ability (Crini et al., 2019; Larasati et al., 2021). Impurities may build up on the surface of activated carbon filters when water flows through them, limiting the number of accessible adsorption sites and lowering the material's overall effectiveness. Routine maintenance, such as backwashing and regeneration, is needed to reduce fouling and preserve optimal performance. Additionally, parameters like pH, temperature, and competing ions can affect the adsorption process of activated carbon and reduce its effectiveness for a given pollutant. The effectiveness of activated carbon in water treatment systems must be carefully considered.

Additionally, there may be environmental effects from manufacturing and disposing of activated carbon (Larasati et al., 2021). An energy-intensive and greenhouse gas-emitting step in manufacturing activated carbon is the high-temperature treatment of carbonaceous materials. Additionally, after the activated carbon has reached the limit of its ability to absorb pollutants, it must be appropriately disposed of to stop the release of those toxins back into the environment. These issues bring home the significance of sustainable practices in the manufacturing, using, and disposing activated carbon for water filtration.

# 3 Nanostructured Carbon Materials for Water Treatment

## 3.1 Carbon Nanotubes

Rolls of graphene sheets make up the cylindrical nanostructures known as carbon nanotubes (CNTs). They have exceptional electrical conductivity, mechanical strength, and aspect ratio. Their length-to-diameter ratio can exceed 1,000,000. Various techniques, including arc discharge, laser ablation, and chemical vapour deposition, can create CNTs. They are excellent for various water treatment applications due to their unique qualities (Sajid et al., 2022).

CNTs are proven to have an extraordinary potential for adsorbing organic pollutants, heavy metals, and other impurities in water treatment. Their enormous surface area and high aspect ratio make it possible to adsorb contaminants effectively (Yin et al., 2020). CNTs have also been used in membranes to improve separation efficiency in procedures like desalination and water purification.

**Figure 3.** summarizes the effects of the CNT functional group on adsorption characteristics. This graph displays the overall pattern of CNT adsorption characteristics following various treatments. The high preference for adsorption of hydrocarbons (such as hexane, benzene, and cyclohexane) over alcohols (such as ethanol and 2-propanol) indicates that the surfaces of raw CNTs are hydrophobic. Functionalization and planar chemicals do so because there is inadequate contact between the CNT and the chemical, which results in increased oxygen content, decreased surface area, and reduced adsorption of nonpolar hydrocarbons. In contrast to increasing the adsorption of nonpolar and planar hydrocarbons, graphitization will remove functional groups and reduce the adsorption of polar compounds.

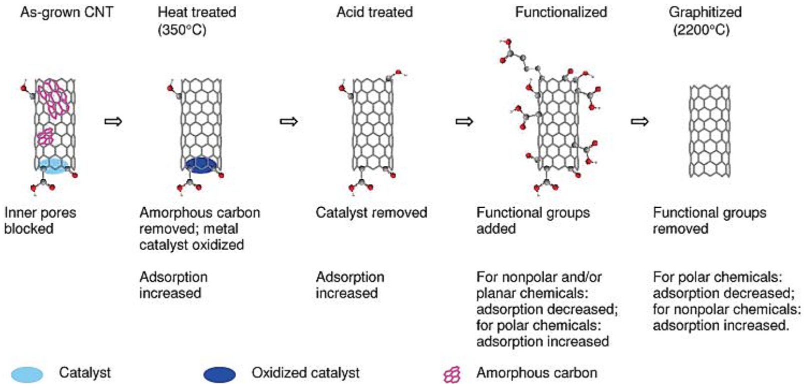

**Figure 3.** CNT functional group effects on adsorption characteristics. Source: (Pan and Xing, 2008).

Despite its prospects, there are hurdles in employing CNTs for water purification, including scalability, cost-effectiveness, and worries about their possible toxicity (Das et al., 2014). Ongoing research strives to solve these issues and realize CNTs' full promise in water treatment applications.

## 3.2 Graphene

The two-dimensional carbon sheet, graphene, made up of carbon atoms organized in a honeycomb lattice, has exceptional mechanical, electrical, and thermal characteristics. It is a promising material for different water treatment applications due to its distinctive structure and outstanding capabilities (Yin et al., 2020). Several techniques can be used to make graphene, including mechanical exfoliation, chemical vapour deposition, and epitaxial growth. It may be used for various water treatment processes, such as adsorption, catalysis, and membrane technology.

The remarkable adsorption capability of graphene is due to both its many π--electron-rich domains and its vast surface area. Due to these characteristics, graphene can absorb various pollutants, including organic pollutants and heavy metals. Graphene-based membranes have excellent water permeability, high selectivity, and fouling resistance, making them the best choice for desalination and water filtration. **Figure 4.** shows the filtration process through graphene.

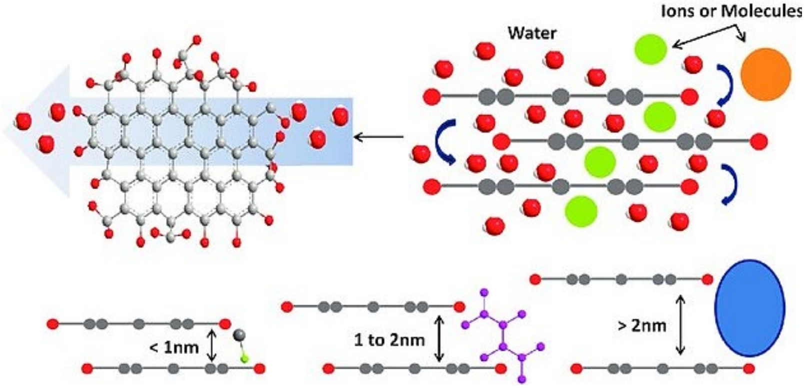

**Fig. 1-4** Schematics of water the filtration process through graphene. Source:(Medina et al., 2015)

Although graphene has demonstrated tremendous potential for use in water treatment applications, there are certain issues that must be resolved before it can be used successfully. The high cost of producing graphene is one of the main obstacles to its usage in water treatment (Bhol et al., 2021; Saleem and Zaidi, 2020). High-quality graphene materials must be produced using complicated and energy-intensive procedures, which raises the cost of manufacturing and restricts the usage of this material in large-scale water treatment systems. The tendency for graphene to amalgamate or stack together to produce bigger particles or aggregates is another disadvantage (Bhol et al., 2021). The effective surface area that is accessible for adsorption may be reduced as a result of this occurrence, which may also impede interactions between graphene and water pollutants.

There are also questions about the long-term stability of graphene in water treatment systems (Bhol et al., 2021). In particular, graphene is vulnerable to oxidation and deterioration when exposed to specific chemicals or extreme environmental conditions. The structure and characteristics of graphene may change due to these degradation processes, which might reduce its efficiency as a catalyst or adsorbent in water treatment applications. Another drawback is the hydrophobic property of graphene, which may alter how it interacts with water and hydrophilic pollutants. The hydrophobicity of graphene may prevent the effective removal of hydrophilic contaminants and may prevent graphene's dispersion in aqueous solutions. To overcome this restriction and increase the adsorption effectiveness for a larger variety of pollutants, surface modification methods or mixing graphene with hydrophilic materials may be required.

## 3.3 Carbon Dots

Fluorescent carbon nanoparticles with diameters typically less than 10 nm are known as carbon dots (C-dots). They have excellent potential for water treatment applications because of their distinctive optical characteristics, good biocompatibility, and adjustable surface functions (M. P. et al., 2022). Different top-down and bottom-up techniques can be used to create C-dots, including hydrothermal synthesis, microwave-aided synthesis, and laser ablation (**Figure 5.**). Their surface might be functionalized to increase their adsorption capability and selectivity towards certain pollutants (Priyadarshini et al., 2023).

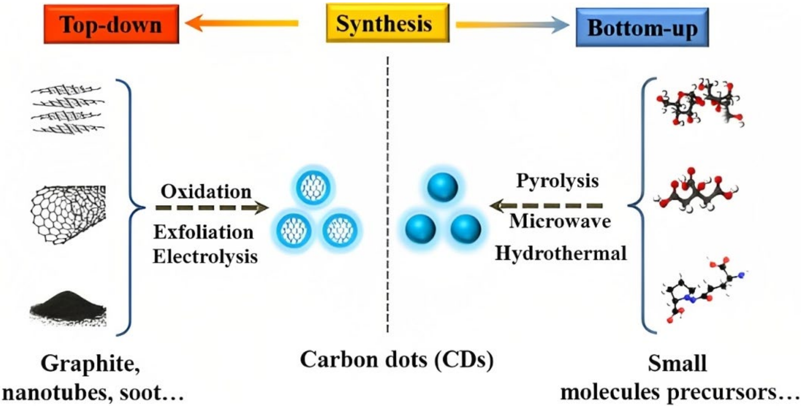

**Fig. 1-5** Top-down and bottom-up C-dots synthesis approaches. Source: (Long et al., 2021)

C-dot's small dimensions and enormous surface area contribute to its high adsorption capacity, which makes it possible to effectively remove various contaminants from water sources, including organic pollutants, heavy metals, and dyes. C-dots have surface functional groups, including hydroxyl, carboxyl, and amine groups, that serve as active sites for stacking interactions, complexation, and electrostatic attraction between metal ions (M. P. et al., 2022; Xu et al., 2020). Carbon dots may also be readily functionalized or changed to increase their affinity for a particular pollutant or to add certain features for specific water treatment applications. This enables effective adsorption and removal of heavy metals and other contaminants from water. Additionally, it has excellent antimicrobial activity, even against multidrug-resistant (MDR) bacteria (Parambil et al., 2023).

Despite their numerous advantages, C-dots also have certain limitations in water purification applications. One limitation is their relatively low stability under harsh operating conditions. C-dots are susceptible to degradation or aggregation, affecting their adsorption efficiency and overall performance. Furthermore, synthesizing C-dots typically involves complex procedures and requires precise control of reaction parameters, which may hinder large-scale production and commercialization (Long et al., 2021; M. P. et al., 2022). The characterization and standardization of C-dots also pose challenges, as their properties and performance can vary depending on the synthesis methods and conditions used. Additionally, the potential toxicity of C-dots and their long-term effects on the environment and human health must be thoroughly investigated to ensure their safe use in water purification (Yang et al., 2009). Overcoming these limitations through further research and development efforts is essential to harness the full potential of C-dots as efficient and sustainable water treatment materials.

## 3.3 Graphene quantum dots

The introduction of graphene quantum dots (GQ-dots) in numerous applications, including water treatment, has gained popularity. These tiny graphene structures have certain qualities that make them very successful at combating problems with water contamination. Small graphene fragments known as GQ-dots generally have diameters between a few to many tens of nanometers (Prabhakar et al., 2022). High surface-to-volume ratio, variable bandgap, and outstanding photoluminescence are unique qualities that make them desirable candidates for water treatment applications (Kumar et al., 2022).

The exceptional adsorption capability of GQ-dots in water purification is one of their main benefits. In addition to chemical molecules, heavy metals, pigments, and even microbes, the enormous surface area of GQ-dots offers a wealth of active sites for adsorption and other water pollutants. GQ-dots can eliminate these contaminants through physical adsorption, chemical reactions, and electrostatic attraction (Nagaraj et al., 2019). GQ-dots' surface chemistry, which includes functional groups like hydroxyl and carboxyl, is essential to improving their adsorption capacity.

GQ-dots have outstanding photocatalytic qualities in addition to their adsorption abilities. Through photoexcitation, GQ-dots can produce reactive oxygen species (ROS) when exposed to light (Nichols and Chen, 2020). These ROS are powerful oxidizers that may efficiently destroy organic contaminants, sanitize water, and eliminate dangerous microbes. GQ-dots' photocatalytic activity may be further increased by altering their surface or doping them with other substances, enabling specialized and effective water treatment applications.

Furthermore, GQ-dots have demonstrated exceptional stability and reusability, making them highly desirable for water treatment processes. They possess high chemical and thermal stability, ensuring their performance even under harsh environmental conditions. Moreover, GQ-dots can be easily separated from the treated water using various filtration techniques, and their properties can be maintained through proper regeneration processes. This reusability aspect contributes to the cost-effectiveness and sustainability of GQ-dots as a water treatment solution.

The unique properties of GQ-dots also enable the development of advanced sensing technologies for water quality monitoring. GQ-dots can be functionalized with specific molecules or nanomaterials to selectively detect and quantify various contaminants in water. Their high sensitivity, rapid response, and low detection limits make them valuable tools for real-time water quality assessment, ensuring the safety and purity of drinking water sources.

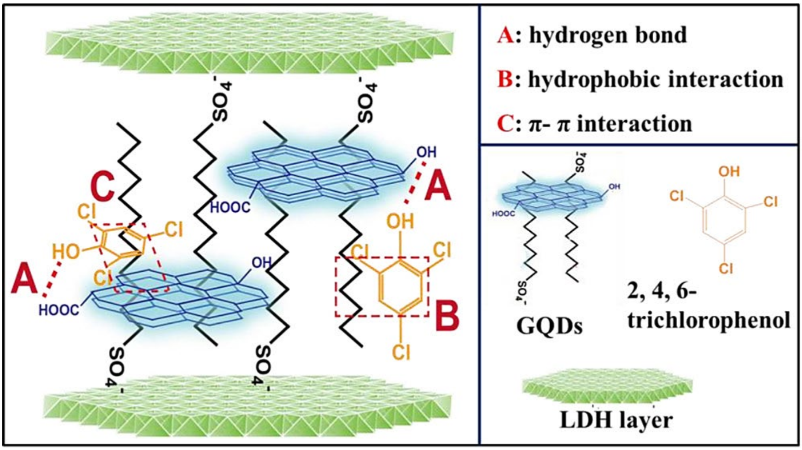

**Fig. 1-6** Schematics of immobilizing and dispersing GQ-dots in the 2D hydrophobic interlayer of layered double hydroxides and adsorption of 2,4,6-trichlorophenol. Source: (Yao et al., 2017)

However, further research is still needed to fully explore GQ-dots' potential in water treatment and address challenges such as scalability, long-term stability, and potential environmental impacts. By immobilizing and dispersing GQ-dots in the 2D hydrophobic interlayer of layered double hydroxides (LDHs), Yao and colleagues were able to address the problems of high-water solubility and aggregation of GQ-Dots and achieve highly effective adsorption for nonionic organic species, 2,4,6-trichlorophenol (**Figure 6.)** (Yao et al., 2017). Regulatory considerations and understanding the fate and behavior of GQ-dots in aquatic ecosystems are also crucial for their safe and responsible application.

## 4 Carbon-Based Nanocomposites and Hybrid Materials

Researchers have combined carbon-based materials with other nanoparticles to create hybrid materials and nanocomposites to improve the performance of carbon-based materials in water treatment (Parambil et al., 2024). Synergistic effects can be produced by combining carbon materials' unique qualities with other nanoparticles' functionality.

The flexibility of hybrid materials and carbon-based nanocomposites is an additional benefit. To improve their particular water treatment characteristics, they may be customized and changed by adding various functional groups, nanoscale structures, or other elements (Noamani et al., 2019; Xin et al., 2021). This adaptability enables the creation of materials with better resistance to fouling or the formation of biofilms, excellent chemical stability, and specific adsorption capabilities. Additionally, hybrid materials and carbon-based nanocomposites frequently have great mechanical qualities, including high strength and durability, making them appropriate for various water treatment applications (Noamani et al., 2019; Oladunni et al., 2018). They can be applied as coatings on different surfaces, adsorbent columns, or filtering membranes to remove impurities from water sources effectively. Additionally, these materials are readily regenerative and reusable, which lessens the need for frequent replacement and lowers waste production.

Hybrid materials and carbon-based nanocomposites also have the potential to be used in more sophisticated treatment methods than adsorption. Carbon-based binary or ternary nanocomposites comprising metal nanoparticles, graphene, CNT, and C-dots have demonstrated improved catalytic activity for the breakdown of organic contaminants in water (Ajith et al., 2020; M. P. et al., 2022; Salehi et al., 2020). Similarly, adding carbon components to polymer matrices has produced advanced membranes with enhanced antifouling and separation efficiency (Salehi et al., 2020). These hybrid materials and carbon-based nanocomposites show significant promise for tackling water treatment issues, such as eliminating new contaminants, heavy metals, and persistent organic pollutants.

# 5 Advanced Water Treatment Processes using Carbon Materials

## 5.1 Membrane Filtration

A popular technique for purifying water and removing contaminants is membrane filtration. The performance and separation effectiveness of membranes can be improved by adding carbon elements. Unique attributes of carbon-based membranes include variable pore size, hydrophilicity, and antifouling capabilities. These membranes can remove heavy metals, chemical substances, and suspended particles altogether. Additionally, carbon-based membranes have exceptional mechanical and chemical durability, enabling their use in challenging water treatment scenarios.

Investigations have shown that carbon-based membranes are helpful in various water treatment processes, including desalination, wastewater treatment, and drinking water purification. Incorporating carbon materials into membrane technology offers significant potential for creating environmentally friendly and effective water treatment techniques. CNT membranes are gaining popularity in the field of water treatment. CNT membranes are often divided into four categories: electrochemical CNT membrane, mixed matrix CNT membrane, and vertically aligned CNT membrane (**Figure 7.**).

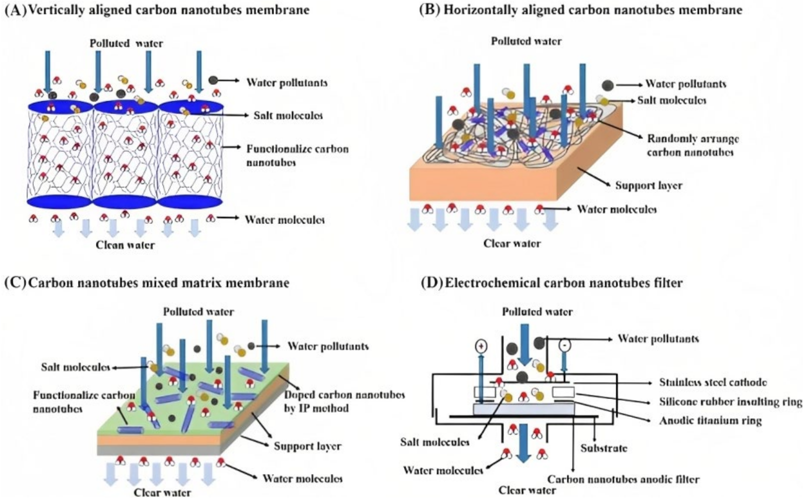

**Fig. 1-8** Water passes through four types of CNT membranes. Source: (Li et al., 2021) (a) vertically aligned CNT membrane, (b) horizontally aligned CNT mem-

brane that is randomly arranged horizontally on a porous support layer, (c) mixed matrix CNT membrane that is directly doped into the polymer membranes via interfacial polymerization or phase inversion, and (d) electrochemical CNT membrane.

## 5.2 Catalytic Processes

Additionally, carbon-based materials have extraordinary catalytic abilities that may be used in water treatment procedures. These substances can function as catalysts to oxidize pollutants using sophisticated techniques like photocatalysis and electrocatalysis.

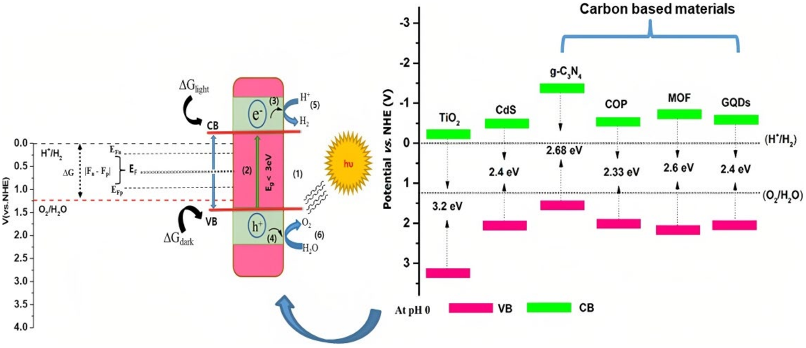

**Fig. 1-9** Bad gap of different carbon materials and catalytic activity. Source: (Sahani et al., 2022)

Graphene, CNT, and activated carbon are examples of carbon-based catalysts that have been shown to have high catalytic activity, primarily due to their unique band gap properties, when it comes to the breakdown of organic contaminants. Their distinct surface chemistry and ability to transport electrons aid in the effective filtration of impurities from water. These catalysts may also be readily functionalized or changed to improve their catalytic activity and selectivity. A material's band gap impacts its capacity to absorb light energy and form electron-hole pairs, which are required for photocatalytic processes to begin. **Figure 9.** Shows the bad-gap of different carbon materials.  Graphene has excellent electrical conductivity but low absorption in the visible light spectrum because of its zero band gap. However, by adding defects or heteroatom doping, graphene's band gap may be adjusted to improve its light absorption capabilities and photocatalytic efficiency.

Similarly, CNTs have a small band gap, making them efficient at using solar energy for photocatalysis. Because of their CNTs' one-dimensional structure, which has a wide surface area, pollutants may be adsorbate more effectively, which improves the electron transfer process. Additionally, depending on their size and surface functionalization, C-dots have variable band gaps. Due to their strong photocatalytic efficiency and ability to absorb a wide spectrum of visible light, they have this feature.GQ-dots, a further potential carbon-based material, have distinctive band gap characteristics due to quantum confinement phenomena. GQ-dots have a size-dependent band gap that allows them to absorb light from various wavelengths. Additionally, they have unique quantum confinement properties that improve electron-hole separation and facilitate effective charge transfer, improving photocatalytic degradation's effectiveness.

Carbon-based catalysts' stability, scalability, and cost-effectiveness are challenged, notwithstanding their potential. These problems are being addressed through ongoing research to create effective and long-lasting catalytic technologies for water treatment applications.

## 6 Challenges and Perspectives

The following are the challenges in the potential applications of carbon-based materials in water purification.

**1. Cost-effectiveness:** In large-scale water treatment applications, the price of carbon-based materials might be a limiting issue. To create efficient synthesis techniques and recycling plans, further study is required.

**2. Sustainability:** Concerns regarding the effects of carbon-based nanoparticles on ecosystems and human health are raised by the possibility of their release into the environment. It is vital to investigate their long-term impacts thoroughly.

**3. Scalability:** For broad adoption in water treatment procedures, it is crucial to scale the manufacture of carbon-based materials without sacrificing their distinctive features.

**4. Licensing and standardization:** Creating rules and guidelines for using carbon-based substances in water treatment would guarantee their secure and efficient application.

Potential applications of carbon-based materials in the purification of water include:

**1.** Incorporating carbon materials with other cutting-edge technologies, such as nanotechnology, biotechnology, and artificial intelligence, improves their performance and broadens their uses.

**2.** Investigating innovative structures and materials based on carbon that has qualities suitable for particular uses in water treatment.

**3.** The creation of efficient and sustainable synthesis techniques for carbon-based materials.

**4.** Working with engineers and legislators to make it easier to apply research findings to real-world problems with water treatment.

## 7 Conclusion

The potential for using carbon-based materials to address water shortages and pollution issues is enormous, as they come in bulk forms and nanostructures. They are appealing for various water treatment applications because of their distinctive qualities, which include large surface area, variable porosity, and excellent adsorption capacity. Every carbon-based substance, from graphene and carbon dots to activated carbon and carbon nanotubes, has unique benefits and uses in water treatment techniques. However, several obstacles must be solved to fully realize the prospect of carbon-based materials for water treatment, including cost-effectiveness, scalability, environmental impact, and legislation. To advance the sector and guarantee that everyone has access to clean, safe water, it is essential to continue research and development activities and to collaborate across disciplines.

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# CHAPTER 2

# MAKING THE NANOTECHNOLOGY INNOVATION SUSTAINABLE, FAIR AND SAFE: CONCEPTUALIZATION OF A STRUCTURED VALUE SENSITIVE DESIGN BASED ETHICS ASSESSMENT MODEL FOR NANOTECHNOLOGY INNOVATION FOR MYCOTOXIN REMEDIATION

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## 1 Introduction

Recent innovations and advancements in nanotechnology, despite their transformative potential, have attracted critical attention due to associated concerns such as health risks, environmental hazards, high costs and limited accessibility, challenges related to patient data privacy, inadequate assessment of community needs, and complex issues involving intellectual property rights and patent regulations [1–6].These challenges necessitate a comprehensive review and evaluation of technological research innovations through the lens of established ethical principles [7,8].Recent academic sources support that the ethics assessment of research and innovation stems from the foundational recognition that such endeavors are inherently value-laden rather than value-neutral [9–11].Ethics assessments provide the scope for research and innovation to maximize its benefit and reduce the risk of its application [12]. Ethics assessment serves as a critical framework for guiding research and innovation toward maximizing societal benefit while minimizing potential risks associated with their application. By systematically evaluating ethical dimensions, such assessments ensure that emerging innovations are developed and implemented in ways that are inclusive, equitable, and socially responsive. The use of structured ethics assessment methodologies facilitates the identification, analysis, and resolution of potential ethical concerns inherent in innovative processes. Prominent approaches in this domain—such as Anticipatory Technology Ethics (ATE), Value-Sensitive Design (VSD), and the Ethical Matrix (EM)—provide conceptual and procedural tools to embed ethical reflection within the design and deployment of novel technologies. Within this framework, nanotechnology-based interventions for mycotoxin remediation in wheat grain represent an emerging frontier in food safety innovation, necessitating careful ethical scrutiny to ensure their responsible development and equitable application [17, 19].

Fungi produce highly toxic secondary metabolites known as mycotoxins, which can significantly affect crops. Mycotoxins often pose a direct threat to human and animal health through contamination of food and feed commodities. Conventional mycotoxin detection and remediation methods have significant limitations, as a strenuous effort is needed for mycotoxin detection and remediation. In this context, emerging nanotechnology-based innovations for mycotoxin remediation could be a sustainable solution because they may deliver improved outcomes with less resource consumption. Given the observed risks associated with nanotechnology innovations, such as health risks, environmental hazards, high cost and limitations in access to use, and participant data privacy, it is important to perform systematic ethics assessments of nanotechnology innovations for mycotoxin remediation.

In the context of nanotechnology incubation for mycotoxin remediation, ethics assessment is important, as innovation has a significant influence on food, agriculture and ecological systems. The applicability of technology ethics assessment methods is broadly based on assessing innovations at different levels, i.e., anticipatory technology ethics (ATE), which was developed for assessing the ethical aspects of emerging technologies in the future [13]. Value-sensitive design is based on assessing and incorporating values during the design phase of research and innovation [14]. An ethical matrix is a tool that enables innovators to perform ethical augmentation with existing innovations [15, 16]. Considering the phase of nanotechnology innovation in mycotoxin remediation and the need for diverse stakeholders, it is important to apply a value-sensitive design approach. Mycotoxins are a class of highly toxic compounds produced by specific types of fungi found in food, crops and organic materials. Mycotoxins are produced under very specific conditions of humidity, temperature and growth factors that favor the growth of fungi. Mycotoxins pose serious health hazards to humans and animals when ingested, inhaled, or absorbed through the skin. The major mycotoxins include aflatoxins, ochratoxin A, zearalenone, patulin, fumonisins and trichothecenes. Owing to the toxicity of mycotoxins and the threat caused by these compounds to livestock and humans, various international agencies have recommended stringent regulatory levels, norms and monitoring of mycotoxins. Therefore, farmers, consumers and policymakers are highly concerned with mycotoxin remediation [17].

Value-sensitive design is a systematic assessment approach that considers the incubation of suitable ethical values with respect to emerging innovation and technology. Batya Friedman and her team from Washington University developed a value-sensitive design model. The core of VSD is articulated in a form of triangulation with empirical, conceptual, and technical assessments.

Nanotechnology provides various strategies for environmental remediation, including smart nanostructured carbon composite-based packaging, the storage of agricultural products and value-added food products produced from these raw materials [17]. Recently, innovative methods, such as essential oil-impregnated nanostructures and smart antifungal nanocoatings on storage surfaces, have also been recommended to limit the damage caused by mycotoxins in the fields of agriculture and food processing [18]. The incorporation of these advanced technologies in field-level activities raises ethical concerns due to the lack of such frames in the current scenario. In this context, to address this newly rising issue of cutting edge-level technology implementation in the field, we present a conceptual framework for the ethical assessment of innovations in nanotechnology for mycotoxin remediation based on VSD approach.

## 2

The VSD approach uses 3 major methods for the ethical assessment of innovations. The 3 methods have their own objectives in the ethical assessment of innovations.

- Conceptual method: Identifying the stakeholders related to innovations
- Empirical method: Identifying the user's perceived values related to innovations
- Technical methods: Analyzing the model of innovation, which evolved from conceptual methods to technical methods.

# 3 Conceptual framework of VSD assessment for novel nanotechnology innovations in mycotoxin remediation

## 3.1 Conceptual Method

In the conceptual phase of the assessment of mycotoxin remediation innovation, the specific stakeholders and applicability of values need to be understood through stakeholder analysis and the stakeholder token approach.

## 3.2 Stakeholder Analysis

Stakeholder analysis will be carried out to identify major direct and indirect stakeholders. The stakeholders will be identified through help from previous literature on mycotoxin remediation with nanotechnology and with information from identified stakeholders. In this context, the major stakeholders can be farmers, food technologists, nanoscientists, environmental scientists, food supply chain managers and representatives from the general population since food consumers are important in the context of mycotoxin remediation in foods.

## 3.3 Stakeholder Tokens

The stakeholder token approach is used to assess interactions between different stakeholders. Value is also dependent on interactions between stakeholders. In the assessment of mycotoxin remediation innovation, specifically curated role play activity can be conducted to analyze the emergence and perception of values between different stakeholders.

# 4 Empirical Method

In this phase of assessment, comprehensive assessments of the perception and applicability of ethical values with respect to mycotoxin remediation innovation can be achieved through value source analysis and coevolution of technology and social structure approaches.

## 4.1 Value Source Analysis

In the context of mycotoxin remediation, innovation value sources can be identified by conducting specific objective-centered questionnaire-based surveys.

## 4.2 Coevolution of Technology and Social Structure

Technology incubation can be coevolved through proper conscience over existing law, regulation, and usefulness. This can be achieved through the engagement of experts from these relevant domains. In the context of mycotoxin remediation innovation, Delphi method-based expert panel interviews can be conducted with food safety regulatory experts, food product licensing authorities, legal experts, and social workers working in the domain of food safety and food access. It is important to review the process of consensus achieved through Delphi panel discussion. Focused group discussions need to be held to assess the collective perceptions of stakeholders regarding the applicability of values for innovation in mycotoxin remediation.

# 5 Technical Method

In the final phase, the prototype model of innovation developed after the conceptual and empirical phases is analyzed. The Technical phase uses the Value Scenario and Value-oriented Mockup, Prototype or Field Deployment approach for assessment.

## 5.1 Value Scenario

The values that are suitable for mycotoxin remediation innovation are identified after the conceptual and empirical phases. These values are analyzed with stakeholders through semi-structured interviews.