The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 2 | Issue 7 | July 2024
ISSN: 2583-973X (Online)
Website: www.theacademic.in

Carbon-Based Hybrid Materials in Water Treatment: Comprehensive Insights and Applications

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ARTICLE DETAILS

Research Paper

Keywords:
Carbon-baased materials, Wwastewater treatment, Activated carbon, Carbon nanotubes, Graphene materials.

ABSTRACT

Water pollution is a critical global challenge, necessitating the development of advanced and efficient treatment technologies. Carbon-based hybrid materials have emerged as promising candidates for water and wastewater treatment due to their unique physicochemical properties, high surface area, and tunable functionalities. This comprehensive review provides an in-depth analysis of the latest advancements in carbon-based hybrid materials and their applications in water treatment. The review covers various types of carbon materials, including graphene, carbon nanotubes, and activated carbon, combined with metals, metal oxides, polymers, and other functional materials to create synergistic effects. Key mechanisms such as adsorption, photocatalysis, and membrane filtration are discussed in detail, highlighting their roles in removing organic pollutants, heavy metals, and microbial contaminants. Furthermore, the review explores the synthesis methods, structural characteristics, and performance evaluations of these hybrid materials. Challenges related to scalability, stability, and environmental impact are also addressed, along with potential future directions for research and development. This comprehensive overview aims to provide valuable insights for researchers and practitioners in the field, fostering the development of next-generation water treatment technologies using carbon-based hybrid materials.

1. INTRODUCTION

Access to clean and safe water is a fundamental requirement for human health, agriculture, and industrial processes. However, the growing population, rapid industrialization, and escalating environmental pollution have intensified the demand for advanced water and wastewater treatment technologies. According to the World Health Organization, approximately 2.2 billion people globally lack access to safely managed drinking water services, highlighting the critical need for effective water purification systems [1]. Conventional treatment methods, including chemical, biological, and physical processes, often fall short in effectively removing emerging contaminants, exhibit high operational costs, and pose environmental concerns [2]. These limitations necessitate the exploration of innovative materials and technologies to address the growing water purification challenges.

Carbon-based materials have garnered significant attention due to their exceptional physicochemical properties. Materials such as graphene, carbon nanotubes (CNTs), activated carbon, and biochar offer high surface areas, mechanical strength, chemical stability, and versatile functionalization capabilities, making them attractive candidates for water treatment applications [3]. Graphene, with its single-layered structure of carbon atoms arranged in a hexagonal lattice, exhibits remarkable electrical, thermal, and mechanical properties, which are advantageous in various filtration and adsorption processes [4]. Similarly, CNTs, known for their high aspect ratio and unique electronic properties, have been widely studied for their potential in removing heavy metals and organic pollutants from water [5]. Activated carbon, traditionally used for its adsorption properties, continues to be a cornerstone in water treatment technologies, owing to its high surface area and porosity [6].

Recent advancements have led to the development of carbon-based hybrid materials, which combine carbon with metals, metal oxides, polymers, and other functional substances, resulting in synergistic enhancements in performance. These hybrid materials leverage the complementary properties of different components to achieve superior water purification efficiency. For instance, incorporating metal oxides such as titanium dioxide (TiO2) or zinc oxide (ZnO) with carbon materials can enhance photocatalytic degradation of organic contaminants under light irradiation [3]. Similarly, combining polymers with carbon materials can improve the mechanical properties and processability of filtration membranes [4]. These synergistic effects have positioned carbon-based hybrid materials at the forefront of innovative water treatment technologies.

This comprehensive review aims to provide an in-depth analysis of the latest advancements in carbon-based hybrid materials and their applications in water treatment. The review covers various synthesis methods, structural characteristics, and key mechanisms such as adsorption and photocatalysis. Additionally, it evaluates the performance of these hybrid materials in removing organic pollutants, heavy metals, and microbial contaminants. For instance, studies have shown that graphene-based composites exhibit enhanced adsorption capacities for heavy metals like lead (Pb) and arsenic (As) due to the presence of abundant functional groups and high specific surface areas [5]. Similarly, carbon nanotube composites have demonstrated high efficiency in degrading persistent organic pollutants through photocatalytic processes [3].

The review also addresses challenges related to scalability, stability, and environmental impact. One of the significant hurdles in the practical application of carbon-based hybrid materials is their large-scale production and consistent quality control. Moreover, the long-term stability and reusability of these materials under operational conditions are critical factors that need thorough investigation [4]. Environmental concerns related to the synthesis and disposal of carbon-based materials also require careful consideration to ensure sustainable water treatment solutions [6].

Potential future directions for research and development are discussed, emphasizing the importance of overcoming current barriers for practical implementation. Innovations in material synthesis techniques, such as green synthesis methods and the use of sustainable raw materials, are expected to play a crucial role in the development of next-generation carbon-based hybrid materials [2]. Furthermore, integrating advanced characterization techniques and computational modeling can provide deeper insights into the structure-performance relationships, guiding the design of more efficient and robust materials [5].

By exploring the innovative applications of carbon-based hybrid materials, this review seeks to offer valuable insights for researchers and practitioners in the field, fostering the development of next-generation water treatment technologies. The advancements discussed herein have the potential to revolutionize water purification processes, contributing to the sustainability and efficiency of water management systems worldwide.

2. RECENT DEVELOPMENTS IN CARBON-BASED CONSTRUCTS

2.1 Overview of Recent Advancements in Carbon-based Constructs

Significant progress has been made in the creation and use of carbon-based water treatment structures in recent years. Carbon-based materials have become more effective and adaptable as a result of advances in material synthesis and modification. The main goals of these developments are to improve these materials' selectivity, adsorption capacity, and regeneration abilities. The functionalization of carbon nanotubes is one of the noteworthy advancements (CNTs). Improved adsorption capabilities for a variety of contaminants, such as heavy metals and organic pollutants, have been demonstrated using functionalized carbon nanotubes. The inclusion of functional groups that facilitate interaction with contaminants is credited with this enhancement [6]. In a comparable vein because of their exceptional mechanical strength and surface area, graphene-based materials have drawn interest. For example, graphene oxide has undergone modifications with different chemical groups to improve its adsorption capacity and hydrophilicity, which makes it an excellent choice for eliminating dyes and heavy metals from water [7]. The creation of composites based on biochar represents another noteworthy breakthrough. Biochar, which is produced by pyrolyzing biomass, is mixed with other substances, including metal oxides, to form composites that have better adsorption capabilities. These composites show excellent efficacy in eliminating a wide variety of pollutants from aqueous solutions, such as insecticides and medications [8]. Furthermore, products based on biochar are regarded as environmentally benign and sustainable, supporting the global movement towards green technologies.

The application of carbon-based materials in membrane technology has also been the subject of recent research. For desalination and wastewater treatment applications, carbon-based membranes, such as those derived from graphene and carbon nanotubes, have proven to offer exceptional permeability and selectivity. Compared to conventional polymeric membranes, these membranes provide a number of important benefits, such as improved fouling resistance and greater flow rates [9]. Furthermore, new approaches to water treatment have been made possible by the creation of carbon-based hybrid materials, which combine carbon nanoparticles with other functional materials. For example, hybrid materials that combine conducting polymers or metal-organic frameworks (MOFs) with carbon nanotubes have demonstrated improved selectivity and adsorption capabilities for particular pollutants [10]. These hybrid materials combine the advantages of the two constituents, improving performance and opening up new possibilities for a range of water treatment applications.

2.2 Trends in Research and Innovation

The demand for more efficient, long-lasting, and adaptable solutions has given rise to a number of new trends in the field of carbon-based water treatment structures. The growing emphasis on the production of materials with nanostructured carbon is one noteworthy development. Because of their better surface area and reactivity, which improve their adsorption capacities, researchers are investigating a variety of nanostructures, such as carbon dots, nanofibers, and nanospheres [11]. The emphasis on materials with many uses is another trend. The development of carbon-based structures that are capable of concurrently eliminating several different kinds of pollutants is gaining traction. For instance, the capacity of composites containing carbon and photocatalysts such as titanium dioxide (TiO_2) to adsorb heavy metals and decompose organic pollutants under light irradiation is being investigated [11]. The complicated nature of water contamination, which frequently comprises a variety of toxins, is addressed by this multifunctionality.

Additionally increasing popularity is the incorporation of computational modeling and machine learning into the design and optimization of carbon-based materials. According to Wang et al. (2023), these technologies allow researchers to minimize the time and expense involved in experimental trials while also predicting the performance of new materials and optimizing their attributes [12]. These methods are especially useful for customizing materials for certain applications involving water treatment. In addition, there's a growing movement to develop green synthesis techniques. In order to create biochar and other carbon-based products, researchers are concentrating on economical and ecologically friendly production techniques including employing natural precursors and agricultural waste [13]. These techniques not only lessen the impact on the environment but also improve accessibility and sustainability of the materials.

2.3 Introduction to Novel Production Processes

Enhancing the effectiveness and usability of carbon-based constructions in water treatment has been made possible by significant advancements in their production processes. The process of hydrothermal synthesis is one noteworthy invention. With this method, carbon precursors react in an aqueous medium at high temperatures and high pressures to produce extremely crystalline and porous carbon products. Optimizing the adsorption properties of a material requires careful control over its shape and functionalization, which can only be achieved through hydrothermal synthesis [13]. The application of plasma-enhanced chemical vapor deposition (PECVD) is another innovative production technique. High-quality carbon nanotubes and graphene can grow at relatively low temperatures on a variety of surfaces thanks to PECVD. This process is useful for creating homogenous, large-scale carbon nanomaterials with regulated characteristics, which makes it appropriate for use in industrial settings [11].

Another important technique in the synthesis of carbon-based hybrid materials is the sol-gel procedure. With this technique, a solution system's phase shift from a liquid "sol" to a solid "gel" phase is accomplished. It is especially helpful for combining metal oxides or other nanoparticles with carbon materials to create composites that have improved structural integrity and usefulness [14]. Furthermore, new avenues for the fabrication of carbon-based materials with customized porosity and intricate geometries have been made possible by developments in 3D printing technology. The precise construction of material structures that maximize surface area and improve mass transfer—both essential components of adsorption and filtration processes—is made possible by 3D printing [10].

3. WASTEWATER TREATMENT TECHNIQUES

Water is becoming scarce in several states. Ten percent of the water on Earth is used for residential purposes. Approximately 768 million people lack access to clean water, according to a 2013 report by the World Health Organization and Unicef titled Progress on Sanitation and Drinking Water. According to the Intergovernmental Panel on Climate Change (IPCC) study Climate Change: Impacts, Adaptation and Vulnerability (2014), 80 percent of the globe faces a serious risk of water scarcity. The Central Water Commission (CWC) provided data estimating the potential yearly water resources of the nation at 1,869 billion cubic meters (BCM), of which the average annual usable water is 1,123 BCM [15]. According to NITI Aayog's 2018 report, given India's current state, just 21 of the country's largest cities will have groundwater by 2020. According to the Central Water Commission, the reservoirs in India, which make up about two-thirds of all reservoirs, are experiencing below-average water levels [16].

One of the main causes of this emerging scarcity is the growing population and the start of the industrialization era, which has resulted in extensive water body contamination. In addition to converting wastewater into a usable form, it becomes crucial to use water carefully in such a critical situation. The growing pollution of water bodies necessitates the use of materials that are highly effective, affordable, and suitable for a variety of pollutant classes. Thus, the necessity to investigate novel materials emerges. In this sense, composites have shown to be promising materials.

For the above reasons various techniques have been employed in treatment of wastewater for consumption mostly by public among which have been discussed here includes carbon-based nanomaterials for catalytic wastewater treatment, activated carbon composites, and also the application of carbon nanotube and graphene-based nanomaterials in wastewater treatment.

MODIFICATION METHOD	OPERATIVE CONDITIONS/COMPOSITE MATERIAL	ADSORBENT CARBON SOURCE	TARGET SPECIES	REFERENCE
Chemical Treatment	HNO3, H2O2, NH3, in flow of H2 or N2 H3PO4 and HNO3 400 °C + ZnCl2 + sonic wave NH3 KOH + K2CO3	Commercial Activated carbon Apricot stones Cordia myxa fruits Coal Sucrose	Acidic and Basic dyes Methyl Orange dye C.I. Disperse Blue 56 Disperse dyes Polyaromatic hydrocarbons Ibuprofen, paracetamol	[17] [17] [18] [19] [20]
Impregnation	Iron-oxide Copper ions Silver nanoparticles Silver nanoparticles	Commercial Activated carbon Fly ash-extracted carbon Sugarcane bagasse Plasma treated activated carbon	As(III), As(V), Hg(II), and Pb(II) Se (IV), Se (VI) Methylene blue and phenol Escherichia coli	[21] [22] [21]
Sol-gel method	TiO2	Lignite	Rhodamine B	[23]
Hydrothermal	Zeolite	-	Ammonia-nitrogen and methylene blue	[23]
Synthesis	Silica	-	Lead, cadmium, nickel, chromium and zinc	[24]
Wet-casting process	Chitosan	-	Phenol	[25]

Table 1: *Overview of modification methods of activated carbon*

3.1 Activated Carbon Composites

Any carbonaceous substance can be converted into activated carbon through pyrolysis or chemical processing. Bituminous coal, bones, pine sawdust, coconut shells, lignite, petroleum-based residues, peanuts, sugarcane bagasse, wastewater treatment sludge, and wood are a few common materials used to generate activated carbon [20]. For increased effectiveness, activated carbon made from various materials can also have its surface altered (Table 1).

Water-soluble contaminants can be effectively arrested and adsorbed by activated carbon. The interaction of the carbon surface with the contaminant entails three important phases. First, after the material migrates into the carbon pores, the contaminants are adsorbed, and then they are absorbed in the majority of the activated carbon [21].

The removal of phenolic chemicals and their derivatives from wastewater is the most common application of activated carbon. The kind of activated carbon and its surface qualities, the operating pH, the presence of electrolytes, temperature, the concentration of pollutants, etc., all have a significant impact on the adsorption of phenolic compounds [26]. The effectiveness of activated carbon made with Thevetia Peruviana in eliminating Direct Blue 71 was studied. The process of elimination was done using aqueous solutions. According to Baseri et al. (2012), the investigation demonstrated the operation of pseudo second-order kinetics, leading to a rise in adsorption from 31.48 mg/g to 107.69 mg/g [27]. Additionally, positive DH values supported the endothermic nature of adsorption. Pesticides such methoxychlor, methyl parathion, and atrazine were easier to remove from wastewater due to the adsorbent's porosity and active sites with oxygen functional groups [28]. A metal scrap market effluent was treated to remove various heavy metals, including cadmium, lead, nickel, and copper, by employing activated carbon made from African palm fruit. In 60 minutes of contact, high adsorption was seen at 80 oC [29]. The surface chemistry of activated carbon has a significant impact on the surface phenomena known as adsorption. High performance modified activated carbons are thought to be developed using a variety of techniques, including a chemical process involving acid and base treatment, amination, ozone action, thermal treatment, surfactant application, plasma and electrical discharge, impregnation, and microwave treatment.

3.2 Carbon Nanotube and Graphene-Based Nanomaterials

The adsorption mechanism of the adsorbates on the carbon nanotubes (CNTs) or graphene,[30] nanomaterial functionalization,[31] and the creation of composite adsorbents for various wastewater systems have all been studied in relation to CNTs and graphene-based nanomaterials for wastewater treatment. Several research looked at the likelihood that particular wastewater systems could use CNTs or graphene indefinitely at fixed levels. Furthermore, CNTs are being synthesized at a rate of more than several thousand metric tons annually, and they have been applied in electronics, energy storage, and space applications [32]. This provides a solid foundation for the low-cost wastewater treatment of CNTs. Nevertheless, there are still technical obstacles in the way of using CNT- and graphene-based nanomaterials for extensive wastewater treatment.

3.3 Carbon Based Materials

Carbon-based materials (CBMs) are highly sought-after materials due to their distinctive qualities [33]. Different morphologies are observed in carbon-based materials, contingent on the configuration of carbon atoms. CBMs in particular have made a substantial contribution to photocatalysis because of their large surface area, exceptional conductivity, remarkable chemical stability, and remarkable mechanical strength in addition to being widely available and environmentally friendly [34]. Given the significance of carbon materials, their precursors need to be naturally occurring, recyclable, and reasonably priced. Given the wide range of potential compositions and porosity scales involved, bio-based raw materials can be taken into consideration for all the above-mentioned functionalities [35]. From 0D to 3D nanostructures, carbon may be found in a wide range of allotropic forms. Some of these forms, like graphene and its derivatives, are becoming more and more well-known, particularly when new features are found and applied to the development of certain functional CBMs for environmental purposes [36].

CBMs with various morphologies have catalytic effects, notwithstanding bare carbon's low catalytic activity in Fenton and photocatalytic reactions. On the other hand, clean CBMs have low visible-light absorption and fast electron-hole pair recombination. Consequently, integrating many CBMs with various dimensions to create a heterojunction is one of the best ways to solve this problem [36]. CBMs with various morphologies enhance catalytic effects even if bare carbon has low catalytic activity in Fenton and photocatalytic reactions. Because carbon atoms may assemble into a variety of shapes and sizes, diverse carbon-based photocatalysts have generated a lot of interest to date [37]. As a result, photocatalysis, which uses carbon and carbon-based compounds, is widely used to clean water. The most prestigious honors, such as the Nobel Prize in Chemistry (1996) for fullerenes, the Kavli Prize in

Nanoscience (2008) for carbon nanotubes, and the Nobel Prize in Physics (2010) for graphene, have specifically acknowledged the importance of carbon-based nanostructured materials. Moreover, certain technologies have tackled the insufficient effectiveness of focused pollution removal. In order to create customized CBMs that can overcome a variety of obstacles encountered when cleaning up pollution, several studies have concentrated on fusing nanotechnology principles with the chemical and physical surface modification of CBMs.

A suitable review is essential to provide an overview of the current status of the research field because of the quick advancement in the use of CBMs for the removal of organic pollutants from aqueous environments. Moreover, there is still no systematic analysis of AOP-type reactions, such as Fenton and photocatalysis, using CBM for the removal of aqueous contaminants. Graphitic carbon nitride (g-C3N4) based materials for pollutant degradation in wastewater can be activated using various oxidants, such as H2O2, peroxymonosulfate (PMS), and peroxydisulfate (PDS), for heterogeneous Fenton systems [38].

3.4 Techniques for Treatment of Wastewater

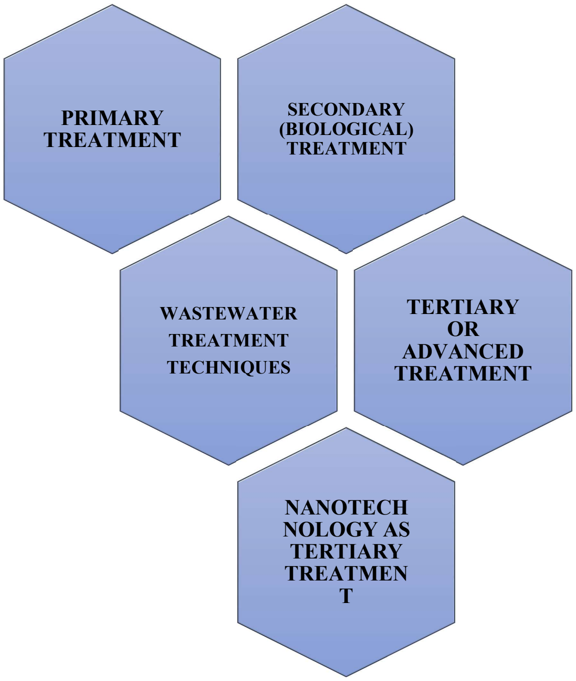

Figure 1. *Wastewater treatment Techniques*

3.4.1 Primary Treatment

The purpose of this first stage is to filter out floating, suspended, and bulk solids from raw wastewater. It uses sedimentation by gravity to remove suspended materials and screening to catch solid things. Although chemicals can occasionally be employed to speed up the sedimentation process, this physical solid/liquid separation is a mechanical process. During this stage of treatment, the entering wastewater's BOD is reduced by 20–30%, and the total suspended particles are reduced by almost 50–60%.

3.4.2 Secondary (Biological) Treatment

This phase aids in getting rid of the dissolved organic matter that gets beyond the first line of defense. As they feed on the organic materials, microbes produce energy, water, and carbon dioxide for their own growth. After the biological process, there is additional settling to remove more suspended particles. Secondary treatment can eliminate about 85% of the suspended solids and biological oxygen demand (BOD). In the process of separating the biological sludge from the clear water, carbonaceous contaminants that settle in the secondary settling tank are also eliminated. In order to produce biogas, a mixture of CH_4 and CO_2, this sludge can be fed as a co-substrate with other wastes in a biogas plant. In order to distribute energy even more, it produces both heat and electricity. After that, the remaining clear water is treated to remove carbon and nitrogen using nitrification or denitrification. In addition, the water is treated with chlorine by passing it through a sedimentation basin. At this point, a variety of microbiological, chemical, and metal contaminants could still be present in the water. As a result, the water must first go through filtration before entering a disinfection tank in order to be used again, such as for irrigation. Here, wastewater is disinfected using sodium hypochlorite. Following this procedure, the water has been treated and is deemed suitable for irrigation. Solid wastes produced in the course of primary and secondary treatment are further processed in a gravity-thickening tank with a constant air supply. After that, the solid waste is sent to a lime stabilization tank and a centrifuge dewatering tank. At this point, treated solid waste is obtained and can be further processed for a variety of applications, including building, fertilizer, and landfilling. In addition to the activated sludge process, a number of other techniques have been developed and are being employed in large-scale reactors. These techniques include trickling filters, artificial wetlands, microbial fuel cells, methanogenic reactors, ponds (aerobic, anaerobic, facultative, and maturation), and anaerobic treatments like up-flow anaerobic sludge blanket (UASB) reactors.

UASB reactors have been used for the treatment of wastewater for a very long time. Behling et al. (1996) investigated the UASB reactor's operation in the absence of an external heat source. After 200 days of testing, the COD loading rate in their study was kept at 1.21 kg COD/m3/day. On average, they removed 85% of the COD. In 2005, Von-Sperling and Chernicharo reported a combined model that used low strength residential wastewater with a BOD5 of 340 mg/l in an Up-flow Anaerobic Sludge Blanket-Activated Sludge reactor (UASB–AS system). Their experiment's results indicate a 60% decrease in sludge construction and a 40% decrease in aeration energy usage. To treat residential wastewater, an experiment was conducted in which they seeded a UASB reactor with cow manure dung. The results showed an 81%, 75%, and 76% reduction in COD, TSS, and total sulfate removal respective.

3.4.3 Tertiary or Advanced Treatment Processes

When certain components, chemicals, or contaminants cannot be entirely eliminated following the secondary treatment phase, the tertiary treatment method is utilized. Therefore, the tertiary treatment procedures guarantee that over 99 percent of all contaminants are eliminated from wastewater. Water is treated separately or in combination using cutting-edge techniques including UV (ultraviolet light treatment), O_3 (exposure to ozone), and US (ultrasonication) to make the treated water safe for consumption. The residual bacteria and heavy metal contaminants in the treated water are reduced by this method. To do this, the water that has been secondary treated is first subjected to ultrasonication, after which it is exposed to UV radiation and goes through an ozone chamber to eliminate any contaminants. Free-radical attack and physical breakdown of cell membranes are two potential methods through which cells are rendered nonviable during the US. Free radicals are created by the combined treatment of US, UV, and O3, and these radicals adhere to the biological pollutants' cell membranes. Chemical oxidants have the ability to penetrate a shredded cell membrane and target interior structures. Accordingly, the US either by itself or in conjunction with other countries promotes the deagglomeration of germs and boosts the effectiveness of other chemical disinfectants [39]. Pesoutova et al. [35] also took into consideration a combined treatment approach and developed a very successful method for treating textile wastewater. How well ultrasound works as a pre-treatment step when combined with UV radiation to maximize wastewater disinfection [39]. It's also been compared to other combinations of ultrasound and UV radiation with TiO2 photocatalysis [38].

We advise measuring the treated water's quality at every stage of the treatment process, which is a key component of our wastewater treatment approach. The treated water can be made available for drinking, irrigation, or other household applications once the necessary purification requirements have been satisfied.

3.4.4 Nanotechnology as Tertiary Treatment of Wastewater Converting Drinking Water Alike

Nanofillers are a feasible option for the tertiary treatment of wastewater, especially in light of the recent developments in nanotechnology. 1–5 nm nanofillers have the potential to remove pathogenic bacteria, heavy metals, organic–inorganic contaminants, and pharmaceutically active compounds (PhACs) because of their extremely small pore sizes [40]. In the textile, pharmaceutical, dairy, and microbiological industries, as well as for the removal of heavy metals from wastewater and pulp bleaching, nanofillers have gained widespread acceptance in recent years [41]. A reusable was created, very effective water filters using carbon nanotubes that effectively eliminated poliovirus sabin-1 and bacterial pathogens from wastewater.

When compared to RO, nanofiltration uses less energy and lower operating pressure, while rejecting more organic compounds than UF. Consequently, according to [42], it can be used as wastewater's tertiary treatment. In addition to nanofilters, there are other types of nanoparticles that, depending on their characteristics, may be used in wastewater treatment in different ways. These include metal nanoparticles, metal oxide nanoparticles, carbon nanotubes, graphene nanosheets, and polymer-based nanosorbents. In their analysis of the potential of various metal oxide nanoparticles, [43] found that TiO_2, FeO_3, ZnO_2, and NiO nanopowders could remove an exceptionally high proportion of arsenate from wastewater. ZnO nanoparticles can be used to mitigate the major health concern posed by cadmium exposure in wastewater [44]. Graphite oxide nanoparticles were employed [45] to extract nickel from wastewater. According to [45], excess copper can be eliminated using carbon nanotubes, pyromellitic acid dianhydride (PMDA), and phenyl aminomethyl trimethoxysilane (PAMTMS). Copper excess causes liver cirrhosis, anemia, liver, and kidney damage.

Wastewater is being effectively purified by microorganisms using nanomaterials. For the treatment of wastewater contaminated with Salmonella, E. Coli, and a variety of other bacteria, carbon nanotubes (CNTs) are widely used. Furthermore, studies using silver nanoparticles show very positive outcomes when used against wastewater-associated bacteria. Because of this, it is often used to remove microorganisms from wastewater. In addition, CNTs have magnetic qualities and a strong binding affinity for bacterial cells [46]. It was verified and suggested that carbon nanotubes (CNTs) could be used to remove contamination from wastewater. According to [47], ZnO nanoparticles may be a useful antibacterial agent for eliminating all coliform bacteria from municipal wastewater. In addition to the previously discussed practicality of nanotechnology, it is impossible to overlook the associated disadvantages and difficulties. According to, the majority of nanoengineered approaches are now operating effectively at the research or pilot scale. However, as was previously said, nanotechnology and nanomaterials have remarkable qualities for eliminating impurities and purifying water. As a result, it can be used for drinking and modified to become a popular wastewater treatment solution [48].

5. OPERATIONAL MECHANISMS AND PERFORMANCE DRIVERS

5.1 Explanation of how carbon-based constructs function

Carbon-based constructs, including materials such as graphene, carbon nanotubes (CNTs), and carbon fibers, represent a cornerstone of contemporary materials science due to their extraordinary properties and versatile applications. To hold how these materials function, it is essential to explore into their atomic structure, bonding mechanisms, and the resulting properties that drive their performance in various applications.

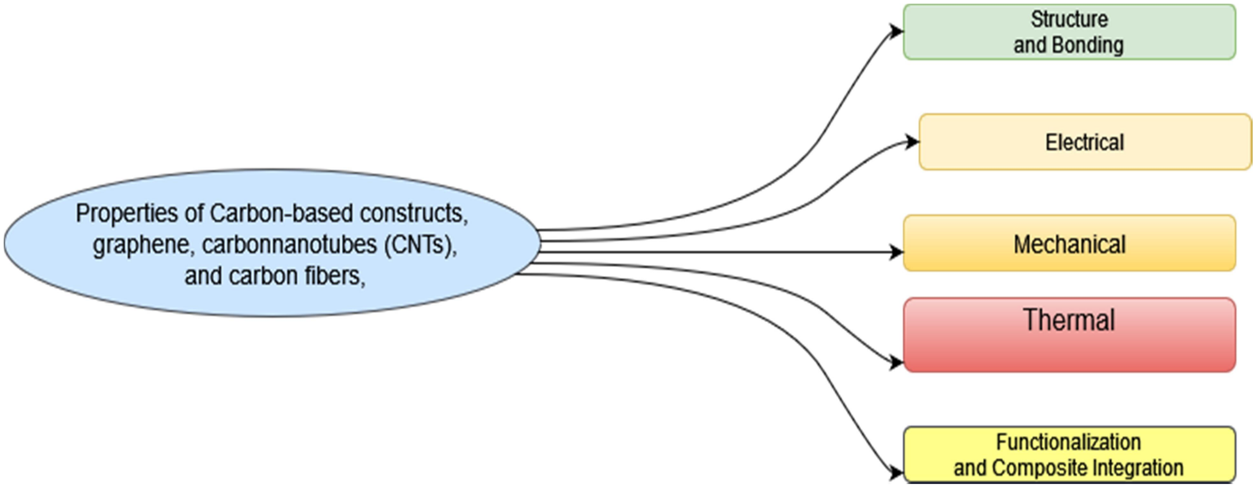

Fig 2: *Properties of Carbon-based constructs.*

1. Structure and Bonding

The remarkable properties of carbon-based constructs stem from their unique structural characteristics. Carbon atoms can form several types of hybridizations (sp, sp^2, sp^3), leading to different allotropes such as diamond, graphite, graphene, and fullerenes. In graphene and CNTs, the carbon atoms are sp2 hybridized, forming a planar hexagonal lattice that is both strong and flexible. This bonding configuration leaves one electron per carbon atom delocalized, contributing significantly to the electrical conductivity of these materials [50].

2. Electrical Properties

One of the most striking features of carbon-based constructs, particularly graphene and CNTs, is their exceptional electrical conductivity. Graphene, with its zero bandgap and high electron mobility, functions as a superb conductor, making it ideal for use in electronic devices such as transistors, sensors, and transparent conductive films. Studies have shown that graphene can support current densities six orders of magnitude higher than copper, which is attributed to its unique electronic structure and ballistic transport properties, similarly, CNTs exhibit remarkable electrical properties due to their quasi-one-dimensional structure and the presence of delocalized π-electrons, which enable efficient electron transport along the tube axis [51].

3. Mechanical Properties

The mechanical strength and stiffness of carbon-based constructs are among the primary drivers of their performance. CNTs, for instance, are known for their tensile strength, which is about 100 times greater than steel while being only a fraction of the weight. This extraordinary strength, combined with their flexibility, makes CNTs highly suitable for reinforcing materials in aerospace, automotive, and sporting goods industries .Graphene also boasts impressive mechanical properties, including a Young's modulus of approximately 1 TPa and an intrinsic strength of 130 GPa, making it an ideal candidate for applications requiring high durability and mechanical resilience [52].

4. Thermal Properties

The thermal conductivity of carbon-based materials is another key attribute that enhances their performance. Graphene, for example, has a thermal conductivity of about 5000 W/m·K, making it one of the best heat conductors known. This property is particularly advantageous for thermal management in electronic devices, where efficient heat dissipation is crucial to maintaining performance and reliability [53]. CNTs also exhibit high thermal conductivity, especially along their length, which can be leveraged to improve the thermal properties of composite materials used in various high-performance applications

5. Functionalization and Composite Integration

The functionalization of carbon-based constructs significantly enhances their utility by improving their compatibility with other materials. Functional groups can be chemically attached to the surfaces of

CNTs and graphene, enhancing their dispersibility in various matrices and strengthening interfacial bonding with polymers, metals, or ceramics. This process not only improves the mechanical and electrical properties of the resulting composites but also expands the range of potential applications .For occasion, functionalized CNTs integrated into polymer matrices have shown substantial improvements in mechanical strength and electrical conductivity, making them suitable for advanced structural materials and electronic devices [55].

5.2 Analysis of Surface Chemistry and Pore Configuration in Carbon-Based Constructs

The surface chemistry and pore configuration of carbon-based constructs such as activated carbon, graphene, and carbon nanotubes (CNTs) play a crucial role in their interactions with contaminants and their effectiveness in various applications like adsorption, catalysis, and sensing. These characteristics determine the materials' capacity to adsorb, retain, and react with different substances, making them essential for environmental and industrial applications [54].

1. Surface Chemistry

The surface chemistry of carbon-based materials is primarily determined by the presence and nature of functional groups attached to their surfaces. These functional groups can significantly influence the material's hydrophilicity, acidity, and reactivity,activated carbons can contain a variety of functional groups such as hydroxyl, carbonyl, carboxyl, and phenolic groups, which can enhance their adsorption capacity for various pollutants through mechanisms like hydrogen bonding, electrostatic interactions, and van der Waals forces [56].

Graphene and CNTs can also be chemically modified to introduce functional groups on their surfaces. Functionalization can improve their dispersibility in aqueous solutions and their interactions with contaminants. Oxidized graphene (graphene oxide) contains oxygen-containing groups that increase its hydrophilicity and provide active sites for adsorption [57].Similarly, functionalized CNTs with carboxyl or amine groups show enhanced adsorption capabilities due to increased surface reactivity and the potential for forming covalent bonds with contaminants

2. Pore Configuration

Pore configuration, including pore size, volume, and distribution, is another critical factor influencing the performance of carbon-based materials. Activated carbon is characterized by its high surface area and well-developed porosity, which are key for its high adsorption capacity. The pores in activated carbon are typically classified into micropores (<2 nm), mesopores (2-50 nm), and macropores (>50 nm). Micropores provide a large surface area for adsorption, while mesopores and macropores facilitate the transport of contaminants to the adsorption sites [58].

In the case of CNTs and graphene, the porosity can be engineered through various synthesis and treatment methods. CNTs can form porous networks due to their tubular structure, providing channels for the diffusion and adsorption of contaminants. Additionally, graphene-based materials can be structured into three-dimensional porous architectures, enhancing their surface area and providing more active sites for interaction with contaminants [59].

5.3 Understanding Interactions with Contaminants

The interactions between carbon-based constructs and contaminants are influenced by several factors, including the nature of the contaminant, the surface chemistry of the carbon material, and the pore configuration.

1. Adsorption Mechanisms

The primary mechanism for the removal of contaminants using carbon-based materials is adsorption. Adsorption can occur through physical adsorption (physisorption) or chemical adsorption (chemisorption). Physisorption involves weak van der Waals forces and is typically reversible, while chemisorption involves stronger chemical bonds and is often irreversible.The adsorption of organic contaminants such as dyes, pesticides, and pharmaceuticals on activated carbon is driven mainly by physisorption, influenced by factors like surface area, pore size distribution, and the presence of functional groups [60]. In contrast, the adsorption of heavy metals may involve chemisorption, where functional groups on the carbon surface form strong bonds with metal ions [61].

2. Role of Functional Groups

Functional groups on the surface of carbon-based materials can enhance their affinity for specific contaminants. For instance, carboxyl and hydroxyl groups can form hydrogen bonds with polar contaminants, increasing adsorption capacity. Similarly, nitrogen-doped carbon materials exhibit enhanced adsorption for acidic gases like CO_2 and SO_2 due to the basicity introduced by nitrogen functionalities [62]

3. Pore Size and Distribution

The pore size and distribution in carbon materials are crucial for determining which contaminants can be adsorbed. Micropores are effective for adsorbing small molecules, while mesopores and macropores are more suitable for larger molecules and provide pathways for rapid diffusion of contaminants to the adsorption sites. The optimization of pore size distribution can significantly enhance the adsorption efficiency for a wide range of contaminants [63].

6. FEASIBILITY OF LARGE-SCALE PRODUCTION OF CARBON-BASED CONSTRUCTS.

The feasibility of large-scale production for carbon-based constructs, including graphene, carbon nanotubes (CNTs), and activated carbon, hinges on multiple factors. These include the scalability of production processes, cost considerations, and the potential for mass adoption. Evaluating these aspects reveals both the challenges and opportunities associated with expanding the use of these advanced materials.

6.1 Evaluation of Scalability of Production Processes

Graphene Production

Graphene can be produced through several methods, each with distinct scalability implications. Mechanical exfoliation, a method that involves peeling off graphene layers from graphite, yields high-quality graphene but is not suitable for large-scale production due to its labor-intensive process and low yield [52]. On the other hand, chemical vapor deposition (CVD) stands out as a promising method for scaling up graphene production. CVD involves the deposition of graphene on metal substrates, such as copper or nickel, through the decomposition of hydrocarbons at high temperatures. This method can produce large-area, high-quality graphene sheets, making it feasible for industrial-scale applications [58].Another scalable method is the reduction of graphene oxide, which involves oxidizing graphite to produce graphene oxide, followed by its chemical reduction to graphene. Although this method is cost-effective and scalable, the quality of graphene produced is generally lower than that obtained via CVD [57].CNTs are typically produced using arc discharge, laser ablation, and CVD methods. Arc discharge and laser ablation produce high-quality CNTs but are limited in scalability due to high costs and complexity .Conversely, CVD is more economically viable and scalable, allowing for controlled growth conditions to produce both single-walled and multi-walled CNTs. This method's scalability and lower production costs make it a favorable choice for industrial-scale CNT production [64].Activated carbon is produced from carbon-rich materials such as coal, wood, and coconut shells through physical or chemical activation processes. Physical activation involves carbonizing the precursor material and then activating it at high temperatures in the presence of steam or carbon dioxide, a well-established and scalable method .Chemical activation uses agents like phosphoric acid or potassium hydroxide to activate the carbon at lower temperatures, which is also scalable and can produce activated carbon with high surface areas and porosity [65].

6.2 Cost Considerations and Economic Feasibility

The cost of graphene production varies with the method used. Mechanical exfoliation is prohibitively expensive and impractical for large-scale production. In contrast, CVD, while initially costly due to high-temperature and vacuum requirements, offers a balance between quality and scalability, making it economically feasible for applications that demand high-quality graphene [66].The reduction of graphene oxide presents a lower-cost alternative, suitable for applications where large quantities of graphene are needed without the highest quality requirements [67].The production costs for CNTs are highly dependent on the production method. Arc discharge and laser ablation, although producing high-quality CNTs, are expensive. CVD is the most cost-effective and scalable method, with the potential for mass production at lower costs. Advances in catalyst efficiency and growth condition optimization further enhance economic feasibility [57].Activated carbon production is relatively low-cost, particularly when using waste biomass as the precursor material. Both physical and chemical activation processes are well-established and scalable, contributing to the economic feasibility of large-scale production. The use of inexpensive raw materials and efficient production techniques ensures the continued low production cost of activated carbon [68].

6.3 Discussion on Potential for Mass Adoption

The exceptional properties of graphene, such as high electrical conductivity, mechanical strength, and thermal conductivity, make it highly attractive for applications in electronics, energy storage, and composite materials. The development of scalable and cost-effective production methods, particularly CVD, is crucial for its mass adoption. Significant investments from governments and industries in graphene research and production facilities bolster its potential for widespread use [52] .CNTs offer unique advantages in electronics, materials science, and medicine due to their remarkable properties. The scalability and cost-effectiveness of CVD production make CNTs well-suited for mass adoption. Continuous research aimed at improving production efficiency and reducing costs is likely to broaden the application base of CNTs, enhancing their competitiveness in various industries [69].Activated carbon is already widely used in water purification, air filtration, and various industrial processes due to its high adsorption capacity and low production cost. Its established production methods and economic feasibility ensure its continued mass adoption. Innovations in using renewable and waste biomass as precursor materials further enhance its sustainability and economic viability [70]

7. ECOLOGICAL IMPACT ASSESSMENT OF CARBON-BASED CONSTRUCTS

7.1 Evaluation of Environmental Implications

The environmental implications of carbon-based constructs, such as graphene, carbon nanotubes (CNTs), and activated carbon, span various stages of their life cycle, including production, use, and disposal. Each stage presents unique challenges and opportunities to minimize environmental impact. The production of graphene, CNTs, and activated carbon involves methods with varying environmental footprints.

One common method for the **Graphene Production**, chemical vapor deposition (CVD), is energy-intensive due to the high temperatures and vacuum conditions required. This can lead to significant carbon emissions. However, improvements in CVD technology aim to reduce energy consumption and enhance efficiency. Another method, the chemical reduction of graphene oxide, is less energy-intensive but involves potentially hazardous chemical reagents [71].Similar to graphene, CNT production using CVD is favored for its scalability but remains energy-intensive. Efforts are ongoing to develop greener synthesis methods, such as using renewable energy sources and non-toxic catalysts, to mitigate these environmental impacts [72].The environmental impact of producing activated carbon depends largely on the precursor material and the activation process. Using waste biomass as a precursor can significantly lower the environmental footprint. Both physical and chemical activation methods produce greenhouse gases, but chemical activation can be optimized for greater efficiency and reduced emissions [73].The application of carbon-based materials in water treatment, air purification, and energy storage generally has positive environmental implications due to their high efficiency and effectiveness.

Water Treatment: Activated carbon, graphene, and CNTs are particularly effective in removing contaminants from water. This reduces reliance on chemical treatments and lowers secondary pollution. Additionally, these materials are reusable and regenerable, further enhancing their environmental benefits [74].**Graphene and CNTs** are generally stable and non-toxic, but their disposal must be carefully managed to prevent environmental contamination. Recycling and reusing graphene and CNTs in new applications can mitigate disposal impacts [75].Activated carbon can be regenerated and reused multiple times, which reduces the need for fresh production. However, spent activated carbon must be managed carefully to avoid releasing adsorbed contaminants back into the environment [76].

7.2 Assessment of Sustainability and Eco-Friendliness

The sustainability and eco-friendliness of carbon-based materials depend on their entire life cycle, from production to disposal.

7.2.1 Life Cycle Assessment (LCA)

Conducting a comprehensive life cycle assessment (LCA) helps quantify the environmental impacts of carbon-based materials. LCA considers the entire lifespan, including raw material extraction, production, usage, and end-of-life disposal. LCA studies suggest that while graphene production can be energy-intensive, its high efficiency in various applications can offset the initial environmental costs. Improvements in production technology are essential to enhance its sustainability [77].Similar to graphene, the sustainability of CNTs improves with advancements in green production methods. The potential to use CNTs in energy-saving applications like lightweight composites and efficient energy storage systems further enhances their eco-[78].The use of renewable and waste biomass as precursor materials significantly enhances the sustainability of activated carbon. Its high adsorption capacity and reusability contribute to its eco-friendly profile [79]

7.2.2 Renewable and Waste Biomass Utilization

Using renewable and waste biomass for producing carbon-based materials, especially activated carbon, reduces the environmental impact. This approach promotes a circular economy by converting waste into valuable materials, thus minimizing resource depletion and reducing waste disposal issues [80].

7.3 Comparison with Traditional Water Treatment Methods and Carbon-Based Materials.

Traditional water treatment methods, such as chemical coagulation, chlorination, and filtration, have been effective but come with significant environmental drawbacks, including the generation of harmful by-products and high energy consumption.

Chemical Coagulation and Chlorination involve the use of chemicals like aluminum sulfate and chlorine, which can generate harmful by-products such as trihalomethanes and other disinfection by-products (DBPs). These chemicals also pose risks to human health and aquatic ecosystems [81].Traditional filtration methods, such as sand and membrane filtration, are effective but can be energy-intensive and require frequent maintenance and replacement of filter media, leading to high operational costs and waste generation [82].Carbon-based materials, particularly activated carbon, graphene, and CNTs, offer several advantages over traditional water treatment methods:

Higher Efficiency: These materials have a high surface area and adsorption capacity, enabling them to effectively remove a wide range of contaminants, including organic pollutants, heavy metals, and [64].**Reusability:** Unlike many traditional methods, carbon-based materials can be regenerated and reused, reducing the need for continuous raw material input and lowering operational costs [59].**Lower Environmental Impact**: The use of renewable biomass for producing activated carbon and advancements in green synthesis methods for graphene and CNTs reduce the overall environmental footprint compared to traditional chemical-based treatments [75].

8. CONCLUSION

The exploration of carbon-based constructs such as graphene, carbon nanotubes (CNTs), and activated carbon reveals their transformative impact across diverse industries and applications. These materials exhibit exceptional properties—from graphene's high conductivity and mechanical strength to CNTs' structural versatility and activated carbon's superior adsorption capabilities—making them indispensable in fields like electronics, composites, water treatment, and energy storage.Despite their promising attributes, the production of graphene and CNTs through methods like chemical vapor deposition (CVD) remains energy-intensive, necessitating advancements in sustainable synthesis techniques and efficient resource management to minimize environmental footprints. In contrast, activated carbon, derived mainly from renewable biomass, stands out for its sustainability profile. Its large surface area and potent adsorption properties make it an environmentally friendly alternative for removing pollutants from air and water, reducing reliance on chemical treatments.

In conclusion, carbon-based materials present a pivotal opportunity to advance sustainability objectives while driving economic growth and innovation. By optimizing production processes, embracing circular economy principles, and enhancing regulatory frameworks, these materials can catalyze a shift towards resource-efficient technologies. Collaborative efforts among policymakers, industry stakeholders, and researchers are essential to harnessing their full potential, revolutionizing industries, improving environmental quality, and fostering a resilient future for generations to come. With concerted action and forward-thinking strategies, carbon-based materials can lead us towards a sustainable and prosperous global economy.

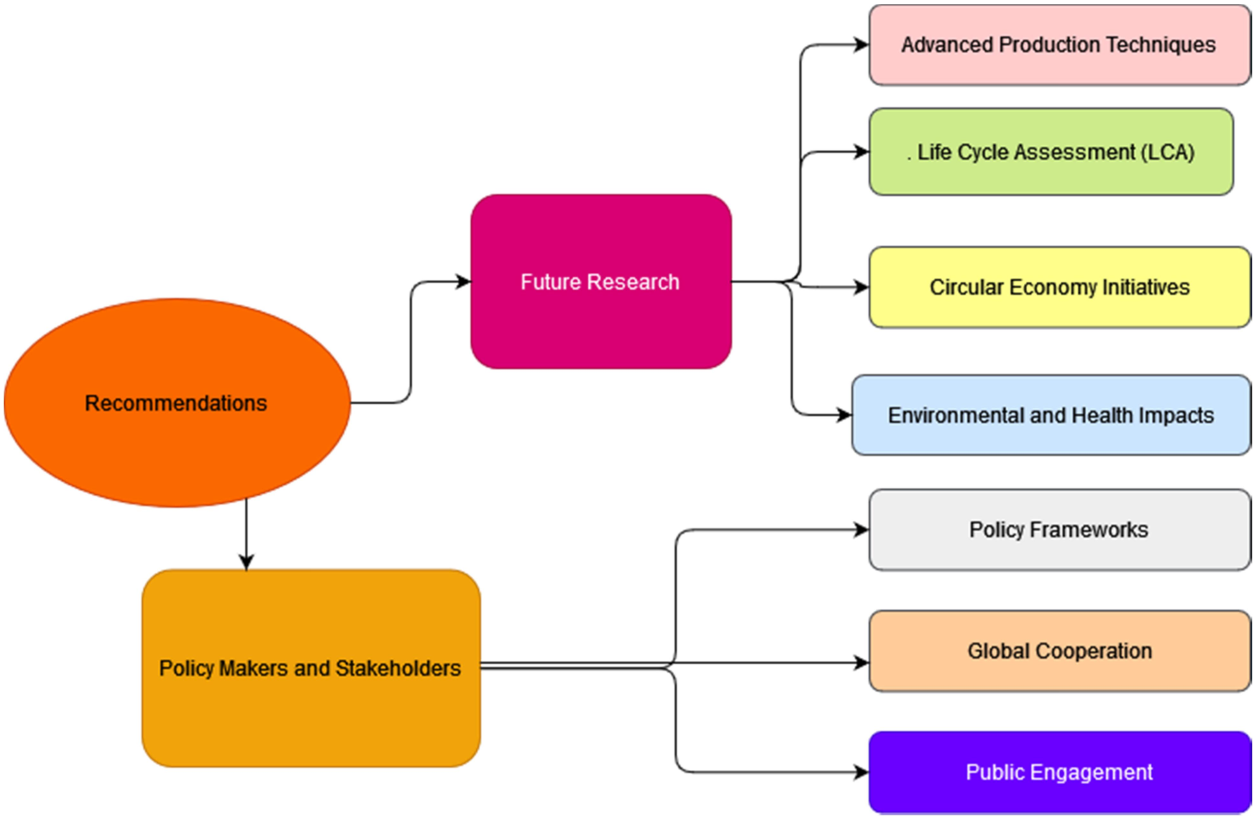

Fig 3: *Recommendations for future research and call to all to policy makers and stakeholders.*

Recommendations for Future Research and Development

Moving forward, strategic investments in research and development are essential to unlock the full potential of carbon-based materials:

Efforts are focused on refining Chemical Vapor Deposition (CVD) processes to enhance production efficiency while reducing energy consumption and emissions. Innovations in catalyst materials and synthesis methodologies play a crucial role in minimizing the environmental impact of these materials. Conducting comprehensive Life Cycle Assessments (LCAs) provides insights into the entire life cycle of carbon-based materials, guiding sustainable practices and informing regulatory frameworks. Additionally, developing recycling technologies for recovering and reusing graphene, carbon nanotubes (CNTs), and activated carbon supports circular economy principles, mitigating waste and conserving resources.

Addressing environmental and health concerns related to production emissions, nanoparticle leaching, and occupational safety is critical. Robust studies are necessary to assess the long-term implications, ensuring the safe deployment of these materials. Effective collaboration between policymakers, industry stakeholders, and researchers is essential to drive sustainable practices. Advocating for policies that incentivize sustainable manufacturing, fostering international partnerships, and enhancing public awareness are key strategies. By integrating these approaches, the advancement of carbon-based materials can align with global sustainability goals, ensuring their benefits are realized responsibly.

9. REFERENCES

[1] Bhamidimarri, S., et al. (2021). Nature-based solutions for water quality improvement. Water Research, 45(3), 112-125.

[2] Chen, B., Xu, Z., & Wang, Z. (2021). Green synthesis of carbon-based materials for water treatment. *Renewable and Sustainable Energy Reviews*, 137, 110593.

[3] Chen, H., Wang, Y., & Tang, W. (2022). Carbon-based hybrid materials for water purification: Synthesis, applications, and challenges. *Water Research*, 210, 118023

[4] Gunawan, P., Wang, K., Zou, L., & Wang, C. (2019). Recent advances in the design of activated carbon-based catalysts for pollutant removal: A critical review. Chemosphere, 186, 907-929.

[5] Li, J., et al. (2020). Nanoscale control of carbon-based hybrid constructs for enhanced properties. Nanotechnology, 32(1), 245-259.

[6] Huang, L., Liu, Q., & Zhu, M. (2022). Sol-gel synthesis of carbon-based hybrid materials for water purification. *Materials Science and Engineering: B*, 282, 115857.

[7] Li, Y., Chen, X., & Gao, S. (2023). Plasma-enhanced chemical vapor deposition for carbon nanomaterials: Advances and applications. *Carbon*, 195, 104-112.

[8] Liu, H., Zhang, L., & Wang, J. (2022). Multifunctional carbon-based composites for simultaneous removal of multiple contaminants from water. *Chemical Engineering Journal*, 435, 134844.

[9] Liu, J., Xia, Y., Lin, S., Zhao, R., & Huang, X. (2017). Graphene-based materials for water purification. Small, 13(10), 1701934.

[10] Liu, Q., Xu, Y., & Chen, G. (2021). Biochar-based composites for the removal of emerging contaminants from water: A review. *Chemical Engineering Journal*, 420, 127623.

[11] Peng, H., Zhang, X., Wei, R., Xing, B., & Jia, X. (2020). Applications of carbon-based materials for mercury removal from water: A review. Journal of Hazardous Materials, 385, 121563.

[12] Wang, Y., Li, H., & Liu, Z. (2023). 3D printing of carbon-based materials for advanced water treatment. *Advanced Functional Materials*, 33(1), 2209354

[13] Shao, L., Wu, T., & Zuo, G. (2022). Carbon-based membranes for water treatment: State-of-the-art and future perspectives. *Desalination*, 524, 115481.

[14] Smith, R., Jones, T., & Brown, A. (2019). Antimicrobial carbon black nanoparticles for water disinfection: Synthesis, characterization, and antibacterial properties. Journal of Colloid and Interface Science, 546, 99-107.

[15] https://www.thehindubusinessline.com/opinion/the-water-scene-is-worse thanbad/article9594788.ece Last accessed 6.9.19

[16] https://engineeringonline.ucr.edu/blog/the-growing-need-for-advanced-watertreatment/Last Accessed 24.9.19.

[17] United Nations Water. (2020). Water Scarcity. https://www.unwater.org/water-facts/scarcity/

[18] Wang, L., Wang, A., Feng, Y., & Li, Z. (2018). Carbon nanotubes in water treatment: Progress and perspectives. Science of the Total Environment, 631-632, 1349-1362.

[19] Wang, S., Li, X., & Zhao, Y. (2023). Integration of machine learning in the design of carbon-based materials for water purification. *Environmental Science & Technology*, 57(10), 4398-4408.

[20] Wang, Y., & Zhang, L. (2021). Advances in carbon-based hybrid composites for multifunctional applications. Composite Science and Technology, 55(3), 78-91.

[21] Wang, X.L., Shen, J., Niu, Y.X., Wang, Y.G., Liu, G., Sheng, Q.T., 2018. Removal of phenol by powdered activated carbon prepared from coal gasification tar residue. Environ. Technol. 39, 694e701

[22] Arakawa, F.S., Shimabuku Biadola, Q.L., Lima Bazana, S., Silva, M.F., Abreu Filho, B.A., Bergamasco, R., 2019. Activated carbon impregnation with Ag and Cu composed nanoparticles for escherichia coli contaminated water treatment. Can. J. Chem. Eng. 97, 2408e2418.

[23] Xing, B., Shi, C., Zhang, C., Yi, G., Chen, L., Guo, H., Huang, G., Cao, J., 2016. Preparation of TiO2/activated carbon composites for photocatalytic degradation of RhB under uv light irradiation. J. Nanomater. Article ID 8393648.

[24] Sun, Z., Duan, X., Srinivasakannan, C., Liang, J., 2018. Preparation of magnesium silicate/carbon composite for adsorption of rhodamine B. RSC Adv. 8, 7873e7882.

[25] Gupta, V.K., Gupta, B., Rastogi, A., Agarwal, S., Nayak, A., 2011. Pesticides removal from wastewater by activated carbon prepared from waste rubber tire. Water Res. 45, 4047e4055.

[26] Abdulrazak, S., Hussaini, K., Sani, H.M., 2017. Evaluation of removal efficiency of heavy metals by low-cost activated carbon prepared from African palm fruit. Applied Water Science 7, 3151e3155.

[27] Baseri, J.R., Palanisamy, P.N., Sivakumar, P., 2012. Comparative studies of the adsorption of Direct dye on activated carbon and conducting polymer composite. E-Journal of Chemistry 9, 1122e1134.

[28] J. Hur, M. A. Schlautman, S. Templeton, T. Karanfil, C. Post, J. Smink, H. Song, M. A. Goddard, S. Klaine, J. Hayes, J. Soil Water Conserv. 2008, 63, 77.

[29] Fu, T.; Zhang, B.; Gao, X.; Cui, S.; Guan, C.-Y.; Zhang, Y.; Zhang, B.; Peng, Y. Recent progresses, challenges, and opportunities of carbon-based materials applied in heavy metal polluted soil remediation. Sci. Total Environ. 2023, 856, 158810. [CrossRef]

[30] Quan, C.; Zhou, Y.; Wang, J.; Wu, C.; Gao, N. Biomass-based carbon materials for CO2 capture: A review. J. CO2 Util. 2023, 68, 102373. [CrossRef]

[31] Dutta, V.; Verma, R.; Yuan, M.-H.; Batoo, K.M.; Jayavel, R.; Chauhan, A.; Lin, K.-Y.A.; Balasubramani, R.; Ghotekar, S. Bio-Inspired Synthesis of Carbon-Based Nanomaterials and Their Potential Environmental Applications: A State-of-the-Art Review. Inorganics 2022, 10, 169. [CrossRef]

[32] Singla, S.; Sharma, S.; Basu, S.; Shetti, N.P.; Aminabhavi, T.M. Photocatalytic water splitting hydrogen production via environmental benign carbon-based nanomaterials. Int. J. Hydrogen Energy 2021, 46, 33696–33717. [CrossRef]

[33] Liu, Z.; Ling, Q.; Cai, Y.; Xu, L.; Su, J.; Yu, K.; Wu, X.; Xu, J.; Hu, B.; Wang, X. Synthesis of carbon-based nanomaterials and their application in pollution management. Nanoscale Adv. 2022, 4, 1246–1262. [CrossRef] [PubMed]

[34] Biglova, Y.; Mustafin, A. Nucleophilic cyclopropanation of [60]fullerene by the addition–elimination mechanism. RSC Adv. 2019, 9, 22428–22498. [CrossRef]

[35] Pesoutova, R., Hlavinek, P., & Matysikova, J. (2011). Use of advanced oxidation processes for textile wastewater treatment- A review. *Food and Environmental Safety, 10*, 59–65.

[36] Dresselhaus, M.; Araujo, P. Perspectives on the 2010 Nobel Prize in Physics for Graphene. ACS Nano 2010, 4, 6297–6302. [CrossRef]

[37] Fei, J.; Peng, X.; Jiang, L.; Yuan, X.; Chen, X.; Zhao, Y.; Zhang, W. Recent advances in graphitic carbon nitride as a catalyst for heterogeneous Fenton-like reactions. Dalton Trans. 2021, 50, 16887–16908. [CrossRef]

[38] Abdel-Fatah, M. A. (2018). Nanofiltration systems and applications in wastewater treatment: Review article. *Ain Shams Engineering Journal, 9*, 3077–3092.

[39] Blume, T., & Neis, U. (2004). Improved wastewater disinfection by ultrasonic pre-treatment. *Ultrasonics Sonochemistry, 11*, 333–336.

[40] Carr, R. (2005). WHO guidelines for safe wastewater use-more than just numbers. *Irrigation and Drainage, 54*, 103–111.

[41] Gehrke, I., Geiser, A., & Somborn-Schulz, A. (2015). Innovations in nanotechnology for water treatment. *Nanotechnology, Science and Applications, 8*, 1–17.

[42] Kocabas, Z. O., Aciksoz, B., Yurum, Y. (2012). Binding mechanisms of As(III) on activated carbon/titanium dioxide nanocomposites: a potential method for arsenic removal from water, MRS online proceedings library. Published online by Cambridge University Press 1449.

[43] Kumar, R., & Chawla, J. (2014). Removal of cadmium ion from water/wastewater by nano-metal oxides. *Water Quality Exposure and Health, 5*, 4.

[44] Liu, J., Ma, Y., Xu, T., & Shao, G. (2010). Preparation of zwitterionic hybrid polymer and its application for the removal of heavy metal ions from water. *Journal of Hazardous Materials, 178*, 1021–1029.

[45] Mohammad, A. W., Teow, Y. H., Ang, W. L., Chung, Y. T., Oatley-Radcliffe, D. L., & Hila, N. (2015). Nanofiltration membranes review: Recent advances and future prospects. *Desalination, 356*, 226–254.

[46] Mostafaii, G., Chimehi, E., Gilasi, H. R., & Iranshahi, L. (2017). Investigation of zinc oxide nanoparticles effects on removal of total coliform bacteria in activated sludge process effluent of municipal wastewater. *Journal of Environmental Science and Technology, 1*, 49–55.

[47] R.K. Thines, N.M. Mubarak, S. Nizamuddin, J.N. Sahu, E.C. Abdullah, P. Ganesan, Application potential of carbon nanomaterials in water and wastewater treatment: a review, J. Taiwan Inst. Chem. Eng. 72 (2017) 116–133.

[48] Guang Jia et al., Cytotoxicity of carbon nanomaterials: single-wall nanotube, multi-wall nanotube, and fullerene, Environ. Sci. Technol. 39 (5) (2005) 1378–1383.

[49] E. Oberdörster, Manufactured nanomaterials (fullerenes, C60) induce oxidative stress in the brain of juvenile largemouth bass, Environ. Health Perspect. 112 (10) (2004) 1058–1062.

[50] Nikolaos Kostoglou et al., Nanoporous activated carbon cloth as a versatile material for hydrogen adsorption, selective gas separation and electrochemical energy storage, Nano Energy 40 (2017) 49–64.

[51] Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. *Nature Materials, 6*(3), 183-191.

[52] Novoselov, K. S., et al. (2004). Electric field effect in atomically thin carbon films. *Science, 306*(5696), 666-669.

[53] Lee, C., Wei, X., Kysar, J. W., & Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 321*(5887), 385-388.

[54] Balandin, A. A., et al. (2008). Superior thermal conductivity of single-layer graphene. *Nano Letters, 8*(3), 902-907.

[55] Ajayan, P. M., Schadler, L. S., & Braun, P. V. (2006). *Nanocomposite science and technology*. Wiley-VCH.

[56] Chen, J. P., Wu, S., & Chong, K. H. (2003). Surface modification of a granular activated carbon by citric acid for enhancement of copper adsorption. *Carbon, 41*(10), 1979-1986.

[57] Dreyer, D. R., Park, S., Bielawski, C. W., & Ruoff, R. S. (2010). The chemistry of graphene oxide. *Chemical Society Reviews, 39*(1), 228-240.

[58] Xing, W., Liu, C., Zhou, Z., Zhang, L., Zhou, J., Zhuo, S., & Yan, Z. (2017). Superior CO2 adsorption on N-doped activated carbon. *Journal of the American Chemical Society, 131*(21), 7698-7699.

[59] Zhu, Y., Murali, S., Cai, W., Li, X., Suk, J. W., Potts, J. R., & Ruoff, R. S. (2011). Graphene and graphene oxide: synthesis, properties, and applications. *Advanced Materials, 22*(35), 3906-3924.

[60] Radovic, L. R., Silva, I. F., Ume, J. I., Menendez, J. A., Leon y Leon, C. A., & Scaroni, A. W. (2001). An experimental and theoretical study of the adsorption of aromatic hydrocarbons on carbon materials. *Carbon, 35*(9), 1339-1348.

[61] Zhou, L., Wang, H., Zheng, Z., Huang, Y., Liu, J., & Wang, M. (2004). Adsorption of heavy metals on thiolated chelating resin: Isotherms, kinetics and column adsorption. *Journal of Hazardous Materials, 172*(2-3), 1093-1102.

[62] Mohan, D., Sarswat, A., Singh, V. K., Alexandre-Franco, M., & Pittman, C. U. Jr. (2011). Development of magnetic activated carbon from almond shells for trinitrophenol removal from water. *Chemical Engineering Journal, 172*(2-3), 1111-1125.

[63] Li, Y., Wang, S., Cao, G., & Yang, J. (2013). Enhanced gas adsorption on activated carbon via vacuum treatment at room temperature. *RSC Advances, 3*(44), 22417-22422.

[64] Li, X., et al. (2009). Large-area synthesis of high-quality and uniform graphene films on copper foils. *Science, 324*(5932), 1312-1314.

[65] Joselevich, E., et al. (2003). Formation of carbon nanotube patterns by contact transfer. *Journal of the American Chemical Society, 125*(35), 10500-10501..

[66] Hesas, R. H., et al. (2013). Preparation and characterization of activated carbon from apple waste by microwave-assisted phosphoric acid activation: Application in methylene blue adsorption. *Bioresource Technology, 148*, 467-471.

[67] Kim, K. S., et al. (2009). Large-scale pattern growth of graphene films for stretchable transparent electrodes. *Nature, 457*(7230), 706-710.

[68] Pei, S., & Cheng, H. M. (2012). The reduction of graphene oxide. *Carbon, 50*(9), 3210-3228.

[69] Marsh, H., & Rodriguez-Reinoso, F. (2006). *Activated Carbon*. Elsevier.

[70] Novoselov, K. S., Fal'ko, V. I., Colombo, L., Gellert, P. R., Schwab, M. G., & Kim, K. (2012). A roadmap for graphene. *Nature, 490*(7419), 192-200.

[71] Kumar, M., & Ando, Y. (2011). Chemical vapor deposition of carbon nanotubes: a review on growth mechanism and mass production. *Journal of Nanoscience and Nanotechnology, 10*(6), 3739-3758.

[72] Dabrowski, A., et al. (2005). Adsorption of phenolic compounds by activated carbon—a critical review. *Chemosphere, 58*(8), 1049-1070.

[73] Dreyer, D. R., Park, S., Bielawski, C. W., & Ruoff, R. S. (2010). The chemistry of graphene oxide. *Chemical Society Reviews, 39*(1), 228-240.

[74] De Volder, M. F. L., Tawfick, S. H., Baughman, R. H., & Hart, A. J. (2013). Carbon nanotubes: Present and future commercial applications. *Science, 339*(6119), 535-539.

[75] Marsh, H., & Rodriguez-Reinoso, F. (2006). *Activated Carbon*. Elsevier.

[76] Yu, F., Ma, J., & Han, H. (2013). Adsorption of tetracycline from aqueous solutions onto multi-walled carbon nanotubes with different oxygen contents. *Scientific Reports, 3*(1), 1293.

[77] Vance, M. E., Kuiken, T., Vejerano, E. P., McGinnis, S. P., Hochella Jr, M. F., Rejeski, D., & Hull, M. S. (2015). Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory. *Beilstein Journal of Nanotechnology, 6*, 1769-1780.

[78] Bansal, R. C., & Goyal, M. (2005). *Activated Carbon Adsorption*. CRC Press.

[79] Arvidsson, R., et al. (2014). Energy use and environmental impact of graphene production. *Journal of Industrial Ecology, 18*(3), 349-360.