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Green Nanotech: A Review of Carbon-Based Nanomaterials for Tackling Environmental Pollution Challenges

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ABSTRACT

In recent times, nanotechnology has experienced widespread acclaim across diverse sectors, including but not limited to tissue engineering, drug delivery systems, biosensors, and the mitigation and monitoring of environmental pollutants. The unique arrangement of carbon atoms in sp3 configurations within carbon nanomaterials endows them with exceptional physical, mechanical, and chemical characteristics, driving them to the forefront of materials research. Their appeal lies in their efficacy as superior adsorbents and their exceptional thermal resistance, making them versatile in various applications. The present review extensively explores a range of carbon-based nanomaterials, delving into their synthesis methods and examining their multifaceted applications in addressing environmental pollutants. It is crucial to emphasize that the popularity of carbon-based nanomaterials arises from their potential to serve as superior adsorbents, coupled with their outstanding thermal resistance properties. These attributes contribute to their applicability in diverse environmental contexts. Looking ahead, carbon-based nanomaterials are poised to emerge as environmentally friendly and cost-effective materials, representing promising and potential avenues for the advancement of sustainable technology.

INTRODUCTION

Nanotechnology, a convergence of science, engineering, and technology dedicated to manipulating materials at the nanoscale, where structures or devices range from 1 to 100 nanometers in size (Guldi & Prato 2000), is a transformative domain that employs nanotechnological methods to manipulate the molecular structure of materials. This manipulation serves to alter their intrinsic properties, unlocking a plethora of revolutionary applications (Ghorbani et al. 2020). The broad scope of nanotechnology extends to environmental applications, contributing to environmental protection by comprehending and regulating emissions from diverse sources. It acts as a catalyst for the development of green technologies, minimizing the generation of undesirable by-products. Moreover, nanotechnology not only offers solutions for addressing current waste and polluted sites but also demonstrates remarkable capabilities in the targeted elimination of minute contaminants from the soil, water, and air ecosystems (Lucky et al. 2015, Qin et al. 2021).

The historical deployment of nanoscale materials traces back millions of years (Aris et al. 2020). In contemporary times, nanotechnology stands as an emerging applied technology in the developing world, addressing challenges in environmental and human health mitigation (Hao et al. 2021). Present-day scientists and engineers are exploring diverse avenues to create novel materials at the nanoscale, aiming to enhance properties such as strength and chemical activities. A prominent example of materials at the nanoscale is found in carbon-based nanomaterials, also referred to as organic nanomaterials. This category includes fullerene, carbon dots, graphene, carbon nanoparticles (CNP), and carbon nanotubes, among others. These structured nanomaterials are distinguished by the presence of sp2-bonded carbon atoms, further classified based on their dimensions (Testa et al. 2019). The unique properties of carbonaceous- nanomaterials and their application in the environment are listed in Table 1.

This comprehensive review synthesizes various applications and fields where modern carbon-based nanoscience technology can be harnessed for environmental pollution mitigation. Its applications span the removal of dyes, heavy metals, pesticides, hydrocarbons, and radioactive compounds, showcasing the diverse potential of this cutting-edge technology in contributing to environmental sustainability.

Table 1: The unique properties of carbonaceous- nanomaterials and their application in the environment (Meagan et al. 2008).

The unique properties	Pollution prevention	Absorbents	Composite filters	Sensors	Energy Storage
Size	-	√	√	√	-
Surface Area	√	√	√		
Molecular Specificity	-	√	-	√	√
Hydrophobicity	-	√	√	-	-
Thermal Conductivity	√	-	-	-	√
Electrical Conductivity	-	-	-	√	√
Optical Activity	-	√	-	-	-

SYNTHETIC STRATEGIES FOR CARBON-BASED NANOMATERIALS

Carbon-based nanomaterials showcase distinctive characteristics stemming from their nanoscale dimensions, extensive surface area, and quantum effects. Carbon is the building block of choice for a wide variety of carbon-based nanomaterials at this scale. Notable examples of these nanomaterials are carbon nanotubes, graphene, fullerenes, and carbon nanodots, all of which will be discussed in more detail next.

Carbon Nanotubes

A novel class of nanomaterials known as carbon nanotubes (CNTs) are made of concentric graphite carbons arranged in one or more tubular forms. Within the CNT classification, both single-walled nanotubes (SWNT) and multiple-walled nanotubes (MWNT) demonstrate extraordinary three-dimensional and thermally stable features along with unique chemical activities (Derakhshi et al. 2022). These nanomaterials hold significant potential for the remediation of various hydrocarbons, including chemical pesticides. The presence of a wide range of surface-accessible functional groups and the pore structure of CNTs are closely related to their adsorption capacity for contaminants. Enhancing the performance of CNTs for specific applications requires the customization of functional groups through chemical or thermal methodologies.

The synthesis of CNTs can be achieved through diverse methods, with three noteworthy approaches, including:

Arc Discharge

An arc voltage is applied in this technique between two graphite electrodes that are placed across from one another. As temperatures rise to about 6000ºC, carbon directly transitions from a solid to a gaseous form without passing through a liquid phase. Nanotube formation occurs on the cathode as atoms migrate toward colder regions within the chamber (Karimi et al. 2015). The electric arc discharge method is also called as Plasma Arcing method. The electrodes are made to strike each other under these conditions, it produces an electric arc.

The energy produced in the arc is transferred to the anode, which ionizes the carbon atoms of a pure graphite anode, produces C^+ ions, and forms plasma (Plasma is atoms or molecules in a vapor state at high temperature). These positively charged carbon ions move towards the cathode, get reduced and deposited, and grow as CNTs on the cathode.

Chemical Vapor Deposition

Chemical vapor deposition is a technique in which the vaporized reactants react chemically and form a nanomaterial product that is deposited on the substrate. Substrates are materials on which the carbon nanotube is grown. Zeolite, silica, and silicon plates coated with iron particles are commonly used substrates in chemical vapor deposition.

Hydrocarbons play a pivotal role in this method, serving as both a carbon source and a catalyst (utilizing iron, nickel, or cobalt nanoparticles) for nanotube growth on its surface (Okai et al. 2000).

Laser Ablation

The laser ablation method is also called as physical vapor deposition method. In this technique, graphite is vaporized with a laser in the presence of Ni or Co catalysts. When the laser interacts with a graphite surface, the vaporized carbon atoms coalesce to form soot, which is then collected by a cooled copper collector (Bota et al. 2014).

The graphite target is vaporized by either a continuous laser source or a pulsed laser source. The vaporized target atoms (carbon) are swept toward the cooled copper collector by the flow of argon gas. The carbon atoms are deposited and grown as CNTs on a cooled copper collector. By this method, multi-walled carbon nanotubes are synthesized, and to synthesize single-walled carbon nanotubes, catalyst nanoparticles of Fe, Co, and Ni are used. At last, the obtained carbon nanotubes are further purified to get the pure form of carbon nanotubes.

Graphene Nanomaterials

With its unique two-dimensional atomic crystal structure, graphene is a breakthrough in the field of carbon-based nanomaterials. It is essential for the removal of heavy metals from wastewater. When it comes to the removal of heavy metals from contaminated water and wastewater, graphene oxide (GO) and reduced graphene oxide (RGO) are both very useful (Okai et al. 2000). A variety of oxygen-based functional groups, including hydroxyls, carboxyls, epoxides, and carbonyl functionalities, are included in graphene oxide, an oxidative derivative of graphene. Its capacity to extract heavy metals from tainted wastewater is enhanced by these functional groups (Derakhshi et al. 2022). The fundamental process by which they are effective in removing heavy metals can be attributed to their large specific surface area and diverse functional groups. Synthesis techniques like Scotch tape, Chemical Vapor Deposition (CVD), laser-assisted methods, or exfoliation are employed to produce graphene sheets, with the oxidation of GO contributing to chemical exfoliation (Ye & Tour 2019).

The utilization of graphene-based materials, such as GO/RGO, for the removal of heavy metals from wastewater has been extensively studied. Variables like temperature, ion coexistence, adsorbent dosage, contact time, and pH have all been examined. According to earlier research, the adsorption process closely resembles the second pseudo-second-order kinetics and Langmuir isothermal models. GO was proven to be a highly effective adsorbent for zinc [II], with a maximum adsorption capacity of 246 $mg.g^{-1}$. The present research trajectory emphasizes the application of nanomaterials based on graphene for the removal of heavy metals from wastewater and water. To remove heavy metals, for example, calcium alginate (CA) beads embedded in graphene oxide and further decreased by polyethyleneimine significantly increase the adsorption capacity. The nanocomposite is superior in eliminating Pb [II], Hg [II], and Cd [II] ions, as evidenced by the Langmuir isotherm, which shows that it reaches high adsorption capacities for these ions at 602 $mg.g^{-1}$, 374 $mg.g^{-1}$, and 181 $mg.g^{-1}$, respectively. Functionalized beads, often reduced by polyethyleneimine, exhibit even higher adsorption abilities due to a synergistic effect.

Beyond the realm of heavy metal removal, graphene nanomaterials find diverse applications in gene/drug delivery, tissue engineering, and photodynamic therapies, leveraging their exceptional Surface Enhanced Raman Scattering (SERS), mechanical and electrical compatibility, aqueous processability, among other attributes (Ghosal & Sarkar 2018).

Carbon Dots

Carbon dots (CDs) represent carbon-based nanomaterials synthesized through advanced methods such as chemical oxidation, electrochemical processes, microwave treatment, microplasma techniques, and solvothermal/hydrothermal methods. Carbon Dots (CDs) are classified into discrete categories, including Carbonized Polymer Dots (CPDs), Graphene Quantum Dots (GQDs), and Carbon Quantum Dots (CQDs), every one of which has a different structure and set of properties due to the different synthesis techniques used. Because CDs have a large surface area, stability, and a variety of functional groups, they are very desirable for managing environmental pollution because of their exceptional sorption capacity for contaminants. CDs have found practical applications as nano-photocatalytic and nano-organocatalytic platforms, showcasing their versatility and effectiveness in addressing environmental challenges (Rosso et al. 2020).

Carbon Fibers

During the 1960s, carbon fibers (CNFs) emerged as a significant focus in industrial applications and scientific research, primarily synthesized through the melt-spinning of carbon precursors, as detailed by Rodriguez in 1993. An essential precursor was polyacrylonitrile (PAN), which underwent several changes, such as low-temperature oxidation stabilization, addition of additives, stretching during stabilization, and carbonization after that. A key factor in the creation of vapor-grown carbon fibers (VGCFs) was the catalytic chemical vapor deposition (CVD) technique. Two predominant methods for CNF synthesis, as outlined by Ruiz-Cornejo et al. (2020), involve:

a) Carbonization and electrospinning of polymers.
b) Catalytic decomposition of carbon precursors.

In carbon nanofibers (CNFs) synthesis by using catalytic chemical vapor deposition (CVD), carbon-containing gas undergoes decomposition, and it is catalyzed by metal particles. The most commonly employed metal catalysts for the development of CNF include Ni, Co, and Fe, with additional investigations into the catalytic capabilities of metals such as V, Ni, Cr, and Mo (Ashok et al. 2010). In groundbreaking research led by Zhou et al. (2016), an environmentally friendly approach was adopted for carbon fiber manufacturing.

Traditionally, carbon fibers are derived from fossil fuels as starting materials. However, waste cotton linter was used in this experiment as a raw material, enabling the cost-effective production of crude Cellulose Carbamate (CC) fibers through the innovative Carba Cell technology, incorporating carbonization and wet-spinning methods. This sustainable and resource-efficient method signifies a departure from the conventional reliance on fossil fuels for carbon fiber production, as testified by Zhou et al. (2015) in their study.

Fullerenes

Discovered in 1985, Buckminsterfullerene (C60) has gained widespread acknowledgment for its unique photochemical and photophysical attributes, extensively elucidated by Arbogast et al. (1991). As a representative of spherical fullerenes, C60 exhibits a distinctive propensity to serve as a sensitizer in the photo-induced generation of singlet oxygen (1O2) reactive oxygen species (ROS), as discussed by Sharma et al. (2011). This specific property of fullerenes has been strategically applied in practical domains such as photodynamic cancer therapy and blood sterilization, as emphasized by the research works of Arbogast et al. (1991), Sharma et al. (2011), and Accorsi et al. (2010).

Initially, the synthesis of fullerenes involved a controlled environment utilizing laser vaporization of carbon. However, methodologies for C60 fullerene production have advanced, encompassing techniques like arc heating of graphite as a carbonization source and laser irradiation of polyaromatic hydrocarbons, as meticulously detailed by Nimibofa et al. (2018). Sinitsa et al. (2017) conducted an exhaustive exploration into the formation of fullerenes from amorphous carbon clusters, delineating a two-step process. The initial phase involves rapid reactions leading to the transformation of the amorphous structure into hollow sp2 structures. Subsequently, the remaining carbon chains are concurrently integrated into the sp2 structure during the formation of the fullerene shell.

Carbon Nanodiamond [NDs]

Nanodiamonds, belonging to the nanocarbon family, are carbon nanoparticles characterized by truncated octahedral structures with a diameter ranging from 2 to 8 nm. This structural feature facilitates the effective delivery of proteins, nucleic acids, and small molecules, as demonstrated by Chen et al. (2008) and Zhang et al. (2009). The distinctive optical, chemical, and biological properties, in conjunction with their non-toxic nature and expansive surface area attributes, render diamond nanoparticles a subject of significant interest, especially in the fields of drug and gene delivery, as expounded by Mengesha in 2013.

The production of Nanodiamonds (NDs) involves various methodologies, including hot filament chemical vapor deposition, laser ablation, high-energy ball millings, microwave plasma-enhanced chemical vapor deposition, irradiation of graphite with high-energy ions at room temperature, low-temperature neutral beam-enhanced chemical vapor deposition, and electrical irradiation of carbon ions, as comprehensively detailed by Pandey et al. (2021).

Activated Carbons (ACs)

AC is a carbonic substance distinguished by well-defined micropores, presenting a substantial internal surface area, pore volume, and notable adsorption capabilities (Galvão et al. 2021). Its versatile applicability is evident across diverse domains, particularly in water treatment, purification processes, organic dye removal, and gas adsorption, spanning industries such as petroleum, cosmetics, textiles, and automobiles (Lima et al. 2016, Tadda et al. 2016). The predominant commercially available forms of AC include powdered activated carbons (PACs) and granular activated carbons (GACs) (Deng et al. 2015).

PACs typically exhibit superior adsorption capacities compared to GACs, attributed to their increased specific surface area and microporosity (Alslaibi et al. 2013). GAC can result from rigid biomass materials like palm kernel shells and coconut shells, undergoing activation through physical or chemical methods of producing GAC (Jjagwe et al. 2021). Alternatively, GAC can be synthesized from soft biomass waste materials, utilizing low-density granulation or PAC granulation with binders to create pellets or granules with enhanced adsorption capacity (Deshannavar et al. 2018).

Various granulation processes, such as vibration dropping, spray coating, extrusion, or manual application on raw precursors, contribute to the synthesis of GAC (Mustafa & Asmatulu, 2020), PAC (Nagalakshmi et al. 2019), and/or carbonized precursors (Aransiola et al. 2019). Moreover, activated carbon can be produced from diverse waste materials, including agricultural, fruits, vegetables, plastic, and electronic waste (e-waste). E-waste, encompassing discarded electronic gadgets such as mobile phones, CPUs, and refrigerators, especially non-metallic segments like printed circuit boards (PCBs), serves as a valuable resource for nano-activated carbon production. Activated carbon generated from e-waste demonstrates significant potential as an adsorbent for the removal of Cu^{+2}, Zn^{+2}, Cd^{+2}, and Pb^{+2} metals from wastewater (Hadi et al. 2014).

APPLICATIONS FOR CARBON-BASED NANOMATERIALS

Using carbon-based nanomaterials for ecological remediation is a useful way to promote sustainable development and reduce pollution, and it provides a workable alternative to current approaches. Fig. 1 explains the various uses of carbon-based nano-materials.

Removal of Synthetic Dyes

Dyes are widely used in a variety of industries, including textiles, leather, cosmetics, and pigments. However, when

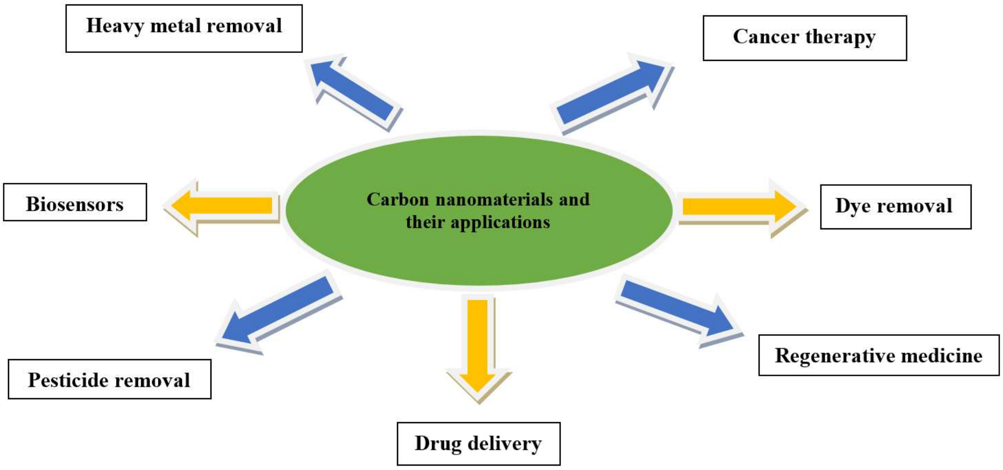


Fig. 1: Various applications of carbon nano-materials.

they are disposed of into wastewater, they provide serious health and environmental hazards. Mitigating these risks necessitates careful consideration due to their potential hazards. Recent years have witnessed significant efforts devoted to addressing this issue through the implementation of conventional biological, chemical, and physical methods for the elimination of colorants from water. Amid these methods, adsorption, acknowledged for its efficiency and cost-effectiveness in dye removal (Wang et al. 2012a), has gained prominence, particularly with the emergence of Carbon Nanotechnology as a rapidly advancing field. As thoroughly covered in a review offering a wealth of literature information on diverse dye removal techniques, including dyes, classification, toxicity, and the use of carbon-based nanomaterials, the use of carbon-based nanomaterials for dye removal has proven beneficial (Ghaedi et al. 2012).

Azo dyes, constituting a significant group of organic compounds extensively used in textiles, leather, and various industries, present a considerable environmental challenge, with an estimated global production of one million tonnes annually. These synthetic compounds, characterized by azo groups (-N = N-) as chromophores, contribute to substantial wastewater discharge during dyeing, accounting for 10-15% of the applied dye. This discharge poses severe problems globally, as the inefficiency of immobilizing dyes to substrates, dependent on the immobilization method or affinity, results in the formation of colored water, thereby deteriorating water quality (Rajabia et al. 2017). Azo dyes, being water-soluble, enter the environment through runoff, exhibiting mutagenic and carcinogenic effects on various living organisms and impacting the photosynthetic activity of plants by limiting sunlight penetration. Furthermore, the toxic effects of these dyes lead to tumors, cancers, and allergies in humans, inhibiting the growth of algae, bacteria, protozoa, plants, and various animals (Ghaedi et al. 2012).

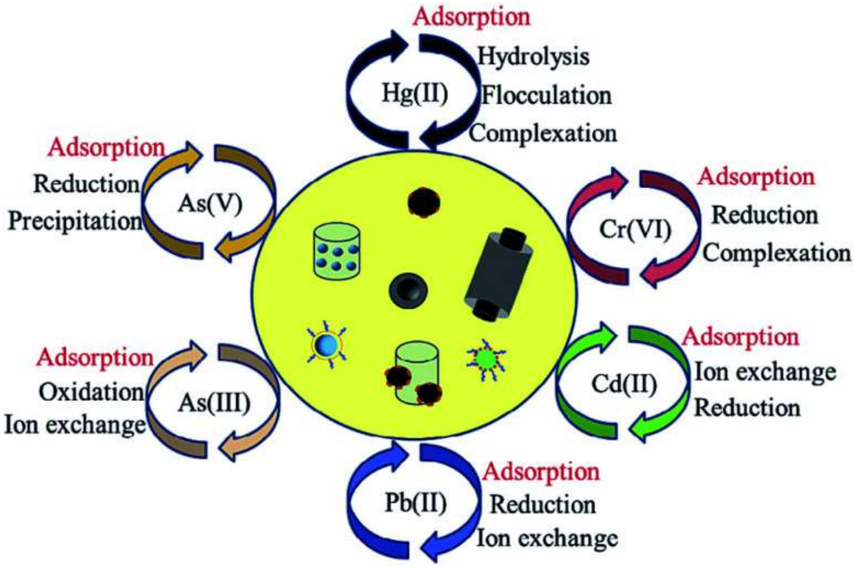
A wide range of methodologies, including physical, chemical, and biological approaches, have been utilized in the elimination of azo dyes. Microbial degradation, especially bacterial degradation, is a highly effective way to remove pollutants from the environment (Kaizar & Ismail 2015, Kaizar et al. 2016). While molds and algae primarily discolor contaminated dyes in wastewater through adsorption rather than decomposition, bacteria can destroy the dye under specific conditions, producing intermediate by-products such as aromatic amines with the help of hydroxylase and oxygenase enzymes. Carbon-based nanomaterials, notably carbon nanotubes, have garnered attention for their efficacy in removing dyes and treating wastewater through adsorption (Mashkoor & Nasar 2020). Noteworthy studies involve low-cost graphene-based nano adsorbers, such as sulfonated magnetic graphene oxide (SGMO), demonstrating efficacy in eradicating methylene blue from aqueous solutions. After seven cycles of eliminating cationic pollutants, numerous reuse and regeneration analyses revealed that SGMO's efficacy was consistently maintained above 80%, making it a viable option for wastewater treatment (Kumari et al. 2023). Table 2 in various studies underscores the potential of carbon nanotubes as adsorbents, showcasing their capacity to effectively remove synthetic dyes from waste, providing a promising avenue for sustainable and efficient dye removal processes.

Removal of Heavy Metals

Nowadays, the burgeoning challenge of metal pollution has emerged as a formidable concern within environmental ecosystems, necessitating immediate and concerted efforts to mitigate severe threats. The urgency for proficient heavy metal processing emanates from the potential enduring

Table 2: Types of carbon adsorbents and their adsorption capacity.

Adsorbent	Dye	Adsorption capacity [mg.g^{-1}]	Reference
MWCNT	Methyl Blue	57.6	Wang et al. (2012)
MWCNT	Reactive Blue 4	309.2	Machado et al. (2012)
Carbon nanotubes	Methylene blue	188.68	Royer et al. (2009)
SWCNT-COOH	Basic red 46	49.45	Rajabia et al. (2017)
HNO_3/NaClO/MWCNTs	Bromothymol blue	55.25	Ghaedi et al. (2012)



(Source from Xu et al. 2018)

Fig. 2: The Pathways for removal of heavy metal ions by functionalized nanomaterials in aqueous solution.

consequences on sustainability and environmental resilience (Tanveer et al. 2018). A variety of approaches to the removal of heavy metals from wastewater have been thoroughly examined. Conventional procedures include flotation, coagulation-coagulation, adsorption, membrane filtration, ion exchange, chemical precipitation, and electrochemical processes. (Lihua et al. 2018). The comprehensive analysis of the literature highlights the critical role that nanoscale materials play in the treatment of wastewater contaminated with heavy metals, with a focus on ion exchange, adsorption, and membrane filtration (Tanveer et al. 2018).

While nanomaterials have demonstrated efficacy in water treatment, challenges pertaining to stability, toxicity, and recovery have spurred innovative solutions. In the realm of heavy metal removal, this review provides an updated panorama of key technologies and materials, with specific emphasis on nanoscale materials and processes. Surprisingly, certain carbon-based nanomaterials, such as graphene and its derivatives, activated carbon, and carbon nanotubes (SWCNTs and MCWNTs), have gotten a lot of interest because of their outstanding characteristics and efficacy in heavy metal removal (Alekseeva et al. 2016, Dehghani et al. 2015).

In recent decades, a great deal of research has been conducted on carbon-based nanomaterials, which have demonstrated high adsorption properties, especially for heavy metal ions like arsenic, chromium, zinc, lead, nickel, and mercury. Due to these metals' lack of biodegradability, there are significant dangers to both human health and the food chain. (Farghali et al. 2017). Table 3 summarizes a comprehensive summary of the adsorption capacities of various carbon nanomaterials for eliminating heavy metal ions from wastewater. The intricate relationship between surface functional groups and heavy metal ions is intimately linked to the surface properties of the nanomaterials. Carbon nanomaterials can absorb metal ions primarily through physical adsorption, precipitation, reduction/sorption, ion exchange, and electrostatic interactions. (Fig. 2). A complete understanding of these mechanisms is crucial to designing and implementing carbon-based nanomaterials to remove heavy metals from wastewater as effectively as possible.

Removal of Pesticides

Globally, pesticides play a pivotal role in safeguarding agricultural crops against the detrimental impact of pests,

Table 3: Metal ion adsorption capacity of carbon nanomaterials.

Adsorbent	Metal ions	Adsorption capacity [mg.g^{-1}]/efficiency %	Reference
Fullerene [C6]	Cu^{+2}	14.6 mmol.g^{-1}	Alekseeva et al. (2016)
Porous graphene	As^{+3}	90%	Tanveer et al. (2018)
SWCNTs	Cr^{+6}	2.35 mg.g^{-1}	Dehghani et al. (2015)
Functionalized MWCNTs	Pb^{+2} Ni^{+2} Cd^{+2} Cu^{+2}	93% 83% 15% 78%	Farghali et al. (2017)
Spent activated carbon	Pb^{+2} Cd^{+2}	95%	Lihua et al. (2018)

Table 4: The adsorbent capacity of graphene-based materials of pesticides.

Adsorbent	Pesticide	Adsorption capacity [mg.g^{-1}]	Reference
Cellulose/Graphene composite	Triazine pesticides, Prometryn, Simeton, Cyprazine, Altrazine, Ametryn	30	Zhou and Fang (2015)
Graphene quantum dots [GQD]	Carbamate pesticide oxamyl	0.6	Aris et al. (2020)
Graphene oxide [GO] and iron oxide magnetic nanoparticles [MNPs]	Dieldrin and Endrin	Dieldrin-28 mg.L^{-1} En drin-99 mg.L^{-1}	Suo et al. (2018)
Reduced graphene oxide-silver nanocomposite [rGO@Ag]	Endosulfan, Dichlorodiphenyl dichloroethylene, Chloropyrifos	1534	Sen Gupta et al. (2015)
Sieve-like cellulose/ Graphene oxide composites [ACCE/G]	Chloropyrifos	152.5	Wanjeri et al. (2018)

weeds, and fungi, thereby significantly contributing to enhanced agricultural productivity (Suo et al. 2018). Nevertheless, the extensive utilization of pesticides has resulted in the widespread dispersion of their residues in critical environmental reservoirs, including drinking water, groundwater, and soil. The pervasive environmental pollution caused by pesticides is attributed to multiple pathways, including dust, agricultural runoff, direct spraying, and industrial waste streams. This omnipresent presence poses substantial environmental threats to aquatic ecosystems and diverse life forms (Aris et al. 2020).

Acknowledging the environmental repercussions of pesticide residues, regulatory agencies have implemented stringent limits to mitigate their impact. For instance, the drinking water directive establishes a threshold of 0.1 µg.L^{-1} for individual drugs and pesticides and 0.5 µg.L^{-1} for all pesticides detected during follow-ups (Sen Gupta et al. 2015). Regulatory mandates necessitate the identification of pesticides in soil and water, prompting swift actions to eradicate them from contaminated sites. Various technologies, including adsorption, photocatalysis, membrane separation, and biodegradation, are deployed for pesticide removal, with their effectiveness contingent on the material properties and chemistry of the contaminants. Advanced water and wastewater treatment methods, particularly those leveraging nanotechnology and nanomaterials, have gained prominence, bolstering the overall efficiency of the system (Wanjeri et al. 2018).

Operating at the molecular scale, ranging from 1 nm to approximately 100 nm, nanotechnology introduces novel physical properties, chemistry, and biology distinct from their bulk counterparts. Nanomaterials, characterized by their microscopic size, high surface area-to-volume ratio, surface-modifying capabilities, and exceptional magnetic properties, prove more effective and efficient in pesticide removal.

The physicochemical attributes of nanomaterials, coupled with their specific targeting capabilities and environmental friendliness, position them as ideal candidates for pesticide removal. Functionalization with diverse chemical groups is a common strategy to enhance nanomaterials' efficiency in removing targeted compounds. This paper aims to provide a comprehensive overview of recent advances in nanotechnology applied to pesticide removal, spanning adsorption, filtration, and decomposition (Zhou & Fang 2015).

A groundbreaking method introduced by Xu et al. (2019) involves the preparation of Magnetic Porous Carbon Materials (MPMs) comprising porous carbon and iron nanoparticles, showcasing exemplary pesticide removal efficacy in rice fields. Adsorption emerges as a predominant application in pesticide removal, offering advantages such as low initial cost, flexibility, design simplicity, ease of use, and insensitivity to toxic pollutants. Importantly, the adsorption process does not generate additional toxic by-products post-treatment. This surface phenomenon hinges on factors like porosity, the availability of adsorption sites, diverse interactions, and the specific surface area of the adsorbent.

Shifting focus to India, a region extensively employing pesticides like lindane and malathion, the utilization of low-cost adsorbents such as graphene and its derivatives (graphene oxide, graphene quantum dots, and reduced graphene oxide) presents a promising avenue for reducing pesticide levels in water. Table 4 provides a detailed insight into the adsorption capacity of graphene-based materials for removing pesticides.

Various physicochemical factors, including initial concentration level (mg.L^{-1}), average time of contact (min), pH value, operating temperature (°C), and efficiency of removal (%), undergo variation to attain their optimal values in the interaction between sorbate and sorbent. This optimization is crucial for achieving the maximum efficiency of adsorption of carbon-based nanomaterials in the reduction of pesticides, and the pertinent details are consolidated in Table 5.

Removal of Hydrocarbons

Hydrocarbon pollutants represent a substantial environmental hazard, predominantly emanating from sources such as crude oil, petroleum-based derivatives, pesticides, and the discharge of diverse hazardous organic compounds into aquatic ecosystems via sewage channels (Fasfous et al. 2010). In the concerted effort to confront the challenges posed by environmental contamination, nanotechnology emerges as a propitious solution, capitalizing on technological advancements and ongoing progress (Tóth et al. 2012). Carbon-based nanomaterials (CNM) assume significance in this domain, comprising a category of materials distinguished by distinctive physical and chemical attributes, including expansive surface areas, elevated mechanical strength, conductivity, and stability (Yao et al. 2014). Noteworthy examples of carbon-based nanomaterials encompass fullerenes, carbon nanotubes, graphene, and graphene derivatives, each characterized by a specific array of properties. To provide a comprehensive elucidation of their capabilities, Table 6 furnishes an overview of the hydrocarbon removal capacities exhibited by various carbon adsorbents.

Removal of Radioactive Waste

Radioactive waste, predominantly originating from domestic and industrial activities, represents a significant concern for environmental integrity and human well-being (Mubarak et al. 2016, Zhang et al. 2013, Tan et al. 2016, Yılmaz et al. 2020). Effective management of radioactive waste is imperative due to the inherent risks associated with radioactive materials. The ionizing nature of these materials leads to the generation of free radicals, instigating oxidative stress that detrimentally impacts proteins, membranes, and nucleic acids. The interaction between free radicals and DNA plays a pivotal role in cancer development, disrupting molecular processes and fostering mutations that may result in malignant tumors.

Table 5: Optimized physiochemical parameters of different pesticides for adsorption during removal of Pesticides using carbon-based nanocomposite materials.

Carbon-Based Nanocomposite Materials	Name of pesticide	Initial concentration level [mg.L^{-1}]	Average time of contact [min]	pH value	Operating temperature [°C]	Efficiency of removal [%]	Reference
Graphene-coated	Bifenthrin, Cyhalothrin, Permethrin, Cypermethrin, Phenvalerate & Deltamethrin	0.01	90	-	270	-	Chen et al. (2010)
Graphene-based	Thiamethoxam	5×10^{-7}	10	6	30 ± 2	55	Wang et al. (2012)
	Imidacloprid	5×10^{-7}	10	6	30 ± 2	78	
	Acetamiprid	5×10^{-7}	10	6	30 ± 2	72	
Graphene-based magnetic nanocomposite	Atrazine	0.01	30	6–7	25 ± 2	84-96.4	Wu et al. (2011)
	Prometon	0.01	30	6–7	25 ± 2	84-96.4	
	Ametryn	0.01	30	6–7	25 ± 2	84-96.4	
	Prometryn	0.01	30	6–7	25 ± 2	84-96.4	
Graphene-coated silica	Thiacloprid	10–7	10	6	30 ± 2 5	70	Liu et al. (2013)
cellulose/graphene composite	Atrazine	1	0	9	25-45	98	Zhang et al. (2013), (2015)

Table 6: Hydrocarbon removal capacity of carbon adsorbents.

Adsorbent	Hydrocarbon	Removal capacity [%]	Reference
MWCNTs	Tetrabromobisphenol [TBBPA]	90	Fasfous et al. (2010)
Oxidized SWNTs	p-Nitrophenol	97.9	Yao et al. (2014)
MWCNT-COOH	3-chlorophenol	95%	Tóth et al. (2012)
HNO_3 and $KMnO_4$ functionalized MWCNTs	Phenol	88%	Mubarak et al. (2016)
Graphene oxide[GO]	TBBPA	70 - 90%	Zhang et al. (2013)

Table 7: The adsorptive capability of carbon nanomaterials for radioactive compounds.

Adsorbent	Radioactive material	Adsorption capacity [mg.g^{-1}]/Removal efficiency %	Reference
Graphene oxide	^{137}Cs	55%	Nagalakshmi et al. (2019), Yin et al. (2016), Tan et al. (2016)
Graphene	Iodine-131	0.878 mg.g^{-1}	Yılmaz and Gürol (2020)
SWCNTs	Iodine-131	1.356 g.g^{-1}	Yılmaz and Gürol (2020)
MWCNTs	^{137}Cs	45 %	Delgado et al. (2014), Yavari et al. (2011)
Pristine graphene	^{137}Cs	41 %	Kaewmee et al. (2017)

Primarily generated as a byproduct of nuclear power plants and various nuclear applications, including research and medical treatments, radioactive waste presents formidable challenges (Yılmaz et al. 2020). In therapeutic applications, specific radionuclides are pre-diluted before administration. The domain of nanotechnology, particularly the utilization of nanostructured materials, emerges as a promising avenue for effectively mitigating the oxidative damage associated with radioactive waste (Yavari et al. 2011). Diverse carbon nanomaterials, such as single-walled carbon nanotubes (SWCNTs), carboxyl-functionalized SWCNTs (SWCNT-COOH), graphene, and graphene oxide, find application in the removal of radioactive compounds such as iodine-131 and cesium.

Cesium, a radioactive byproduct resulting from nuclear power plant fission, contains highly toxic isotopes like 137Cs and 134Cs, capable of contaminating water, air, and soil. The half-life of 134Cs is approximately two years, 137Cs is 30.4 years, and Iodine-131 has a half-life of eight days (Rauwel & Rauwel 2019, Kaewmee et al. 2017). Table 7 provides a comprehensive overview of the adsorption capacity of various carbon adsorbents for radioactive materials.

Carbon-Based Nano-remediation of Air Pollutants

The most common and harmful outdoor air pollutants are particle matter (PM_{10} and $PM_{2.5}$), carbon monoxide, lead, nitrogen oxides, sulfur dioxide, and ground-level ozone, i.e., forming by chemical reactions between nitrogen oxides and volatile organic compounds (VOCs). To mitigate this problem, few researchers have investigated and got good results that include the use of graphene oxides (GOs), graphite oxides, and CNTs with highly reactive surface sites and surface area, large pore volume, mesoporous silica materials with ordered and tunable porous structure and thermal stability. More oxygen-containing functional groups are there on the surface of graphite oxide, which can be controlled by changing the reaction temperature with the addition of water (Yeh et al. 2010). These nanomaterials can be used for ammonia gas sensors operating at different temperatures. The graphene oxides and zirconium hydroxide/graphene composites have been applied for the adsorption of SO_2 (Luo et al. 2018)

Graphene oxide was also used as a photocatalyst to degrade VOCs under ultraviolet light irradiation through photoreduction. Continuous pore structure and large specific surface area Graphene oxide membrane were used to capture PM2.5. These properties help to enhance the adsorption capacity when it's used on CNTs (Weiwu et al. 2019)

CONCLUSION

In conclusion, nanotechnology emerges as a potent tool, providing inventive solutions to a range of environmental challenges. The current landscape witnesses the rise of novel toxic substances, evolving alongside the changing toxicology of e-waste due to advancements in electronics. The distinct properties of artificial nanomaterials position them as pivotal facilitators of sustainable environmental solutions, encompassing pollution reduction, water treatment, environmental monitoring, remediation, and cost-effective alternative energy sources. This review extensively explores the ecological applications of engineered carbon nanomaterials, emphasizing their integral role in sustainable practices. It also underscores the future potential of these materials within natural environmental systems. A notable observation from the comprehensive review is the relatively limited quantity of research dedicated to toxin removal from the environment within the broader field of nanotechnology. While the emphasis on the sustainability of carbon nanotechnology is frequent, it is essential to address any unwarranted expectations associated with its potential. Carbon-based nanotechnology significantly contributes to enhancing environmental quality sustainably, particularly in mitigating pollutants like dyes, e-waste, and pesticides, among others. The widespread adoption of carbon-based nanomaterials in diverse industries underscores their popularity, attributed to their non-toxic nature, expansive surface area, and cost-effectiveness. As these materials have become integral to numerous sectors, their enduring popularity is expected to persist in the years to come. Proceeding forward, the conclusion recognizes the wide range of uses for carbon-based nanomaterials and emphasizes their great potential for further studies. This ongoing research aims to establish carbon-based nanomaterials as a key component in the field of environmental pollution remediation and to play a pivotal role in attaining environmental sustainability.

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