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Carbon Based Nanomaterials for Detection of Heavy Metals and Water Treatment

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ABSTRACT

This report explores the use of carbon nanoparticles for the detection of heavy metals, highlighting their potential in environmental and industrial applications. Various carbon nanomaterials, such as graphene-based materials, carbon nanotubes, and fullerenes, are employed for the extraction of heavy metals and wastewater treatment. Carbon nanoparticles have gained significant attention as heavy metal detectors and water purifiers due to their high reactivity, large surface area, and unique properties. These characteristics make them ideal for detecting and removing toxic heavy metals from contaminated environments. However, the widespread application of carbon nanoparticles is hindered by challenges such as high production costs, complex synthesis methods, and environmental concerns. Despite these limitations, ongoing research is focused on optimizing the use of carbon nanoparticles in several promising domains. These include nanoelectronics, smart materials, biomedical applications, energy storage and conversion, advanced water treatment systems, and sensing technologies. By addressing the existing challenges and exploring emerging opportunities, carbon nanoparticles have the potential to revolutionize various industries. With continued advancements in their production and functionality, carbon nanoparticles could provide more sustainable solutions for environmental pollution, particularly in the fields of water purification and heavy metal detection. As these technologies evolve, carbon nanoparticles are poised to contribute to a more technologically advanced and environmentally friendly future. Their successful integration into multiple industries could lead to breakthroughs in water treatment and pollution control, further improving environmental sustainability and human health. Carbon nanoparticles offer substantial promise, but overcoming the current challenges is key to unlocking their full potential.

INTRODUCTION

Water is one of the most critical environmental stresses since supplies are finite, and usage is expected to increase in the future. Common methods for treating wastewater include membrane processes, ion exchange, reverse osmosis, oxidation, adsorption, flocculation, ultrafiltration, sedimentation, and advanced oxidation processes (AOPs). Bioprocesses, activated carbon adsorption, ozonation, and ultraviolet light photolysis/photocatalysis are some wastewater treatment methods that have successfully removed organic contaminants and other water impurities (Venkateswara Raju et al., 2023).

Nanomaterials have several potential applications in removing organic pollutants and bioactive molecules; they include filtration, photocatalysis, advanced oxidation processes (AOPs), and adsorption. It is well-established that wastewater contains a wide variety of contaminants, and an increasing number of them are being identified as potential health hazards. Some examples of substances that fall into this category include pesticides, plasticizers, disinfection byproducts, perfluoroalkyl compounds (PFOA, PFOS), PCBs, PAHs, endocrine disruptors, pharmaceuticals, and personal care items. As adsorbents, carbonaceous nanoparticles are used to remove per- and poly-fluoroalkyl compounds (PFASs) from water. Many mechanisms, including electrostatic and hydrophobic interactions, hydrogen bonding, and ligand exchange, among others, cause the adsorption of PFOS and PFOA materials (Song et al., 2022). Because of their large surface areas and remarkable reactivities, recently synthesized nanomaterials hold great promise for removing these dangerous contaminants (Deshmukh et al., 2018).

There has been a recent push to find more environmentally friendly and "greener" ways of doing things, such as reducing harmful solvents, chemical reagents, precursors, and catalysts and streamlining production processes. Innovative and appropriate methods for the safer elimination of harmful pollutants and contaminants are essential, and green chemistry and nanotechnology may be used to solve new and pressing problems caused by different kinds of microbes and toxins (Song et al., 2022). Using renewable energy and hydrogen to purify water is one way that green nanotechnology might make processes that are today associated with negative externalities more environmentally sustainable. Nanoscale filtration methods, contaminant adsorption on nanoparticles (NPs), and contaminant elimination by nanocatalysts hold great promise for cost-effective and efficient wastewater treatment and prevention (Li et al., 2020).

Many micropollutants are contaminating water sources, and there is a dramatic rise in the demand for potable freshwater in both industrialized and developing nations. Ozonation and chlorination are two of the most used modern decontamination methods; however, they can be quite toxic due to the high concentrations of chemicals utilized. Water treatment and remediation applications are well-suited to nanoparticles because of their mechanical properties, low power consumption, economic feasibility, and extraordinary chemical reactivity (Li et al., 2020). These materials may be good adsorbents since their morphologies are easily defined and manipulable. Their size and porosity are both satisfactory. In addition to their extensive usage in effluent treatment, prevention, and cleanup, nanomaterials are finding increasing applications in the development of efficient, cost-effective water treatment systems with real-time quality monitoring capabilities (Pandey et al., 2016).

Using these biodegradable polymers, industrial, municipal, or anthropogenic waste can be consistently monitored for biological and chemical contamination. They can also keep the water supply operational, accessible, and of high quality throughout time. The following section will focus on nanoparticles used to cleanse wastewater and remove pharmaceutical contaminants. These nanoparticles comprise carbon nanotubes, graphene nanomaterials, and quantum dots composed of carbon and graphene (Buledi et al., 2020). In order for these nanoparticles to be widely used as effective alternatives for treating wastewater, we must first overcome a number of challenges, even when the advantages are obvious. Some of the things that come under this category are inadequate selectivity, potential health risks, increased production costs, concerns about sustainability, and problems with recyclability. Toxicological concerns, environmental impacts of pertinent nanomaterials, standardized analytical methods, removal kinetics, simulation models, and the environmental behaviours of dangerous contaminants all necessitate further in-depth investigation (Deshmukh et al., 2018).

Research on eco-friendly and economically viable nanomaterials for wastewater and aquatic system cleaning has thus been a priority for the scientific community. Pharmacological, endocrine-disrupting, pesticide, toxic organic dye, P.C., detergent, and other new and persistent pollutant-contaminated wastewater and systems are particularly at risk. Utilizing carbon-based nanomaterials for water purification is the focal point of this effort. Some examples of these nanomaterials are quantum dots made of carbon and graphene, graphene, and graphene oxide (Buledi et al., 2020).

Wastewater

Water that has been used up is called sewage. It contains chemicals, oils, soaps, food scraps, and human excrement. This category includes the water that flows from domestic appliances such as sinks, showers, toilets, washing machines, and dishwashers. Much of the treated wastewater originates from various commercial and industrial sources. Because wastewater is a complex problem caused by human activities, it requires thorough research and stringent regulation. It includes any water types that humans have polluted in some way. It encompasses industrial and agricultural effluent and wastewater from homes and businesses (Pandey et al., 2016).

The collection of domestic wastewater occurs in homes, schools, and companies. It contains organic waste, bacteria from human waste, chemicals from cleaning products, and prescription residues. Depending on the specific company, industrial process effluent can include a broad range of contaminants, from heavy metals and solvents to oils and other compounds. Due to the contamination of water sources with garbage, fertilizers, and pesticides, runoff from agricultural land is a major cause. Because these pollutants can travel through natural and artificial habitats, they threaten ecosystems and human health (Venkateswara Raju et al., 2023).

Untreated or inadequately treated wastewater has several significant and far-reaching effects. One of the most serious problems with environmental degradation is the disturbance of biological equilibrium brought about by the discharge of pollutants into aquatic systems. This imbalance then causes eutrophication, oxygen depletion, and the loss of ecosystems. Polluted water devastates aquatic life, causing certain species to see their populations decline or perhaps go extinct (Deshmukh et al., 2018). Waterborne diseases threaten public health because they can spread more quickly in contaminated water sources. Cholera, typhoid, and gastroenteritis are just some of these diseases. In countries deemed poor, the already heavy burden of waterborne illnesses caused by inadequate sanitation facilities is much heavier for children and the elderly (Buledi et al., 2020).

An integral part of a comprehensive strategy for wastewater management includes the treatment, collection, disposal, and reuse of wastewater. Wastewater treatment facilities employ various physical, chemical, and biological methods to remove contaminants. Methods including screening, sedimentation, filtering, and disinfection are part of this set of procedures. New pollutants, such as microplastics and medicines, are increasing the demand for sophisticated treatment methods. Membrane filtering and UV disinfection are two of these methods. Decentralized treatment systems and built wetland systems are two more eco-friendly options for wastewater management, especially in outlying or rural areas.

However, many more entities than treatment plants contribute to wastewater management. Using source management strategies makes it feasible to significantly decrease both the quantity of wastewater produced and the quantity of pollutants discharged at the source. Examples of such tactics are frameworks for regulation, programs to reduce pollution, and public awareness drives. Recycling wastewater and recovering resources are gaining popularity because treated wastewater is used for irrigation, industrial activities, and to supplement drinkable water in water-scarce areas (Liu et al., 2016).

Pollution by Wastewater

Water pollution is a complicated and widespread environmental problem that endangers ecosystems and human health. The presence of several pollutants in wastewater leads to its release without treatment or with insufficient treatment, degrading rivers, lakes, and oceans. A drop in oxygen levels in aquatic habitats results from eutrophication, which happens when organic pollutants, including fertilizers in sewage and agricultural runoff, generate an overabundance of algae. Because of this, aquatic ecosystems are upended, which causes habitat degradation, biodiversity loss, and fish extinction. Untreated wastewater contains germs that can contaminate water supplies and lead to epidemics of water-transmitted diseases in regions with poor sanitation, endangering the public's health (Anitha et al., 2015).

Industrial wastewater discharges exacerbate water contamination because they typically contain many chemical contaminants, including heavy metals, toxic organic compounds, and industrial wastes. The persistence of harmful compounds in the environment, their buildup in aquatic life, and their subsequent biomagnification in food webs make them a danger to animal and human health. The carcinogenic and neurological effects of heavy metals, including cadmium, lead, and mercury, are well-documented. Dioxins and polychlorinated biphenyls (PCBs) are well-known persistent organic pollutants (POPs) that can linger in the environment, build up in living things, and spread widely (Farghali et al., 2017).

The depletion of terrestrial ecosystems and the impairment of soil quality are additional consequences of wastewater pollution beyond its effects on aquatic ecosystems. In both cases, the contaminated wastewater is to blame. Agricultural runoff with an overabundance of nutrients and agrochemicals has the potential to contaminate groundwater and reduce soil biodiversity. Inappropriate disposal of untreated wastewater, such as in an open landfill or an unlined lagoon, can lead to the poisoning of groundwater aquifers, which in turn endangers ecosystems and human health (Liu et al., 2016).

Nanomaterials

Nanoscale dimensions, on the order of one to one hundred nanometers, are a defining feature of nanomaterials. The characteristics of each nanomaterial are distinct and interesting in their way. The physical, chemical, and biological characteristics of materials at this size scale differ from those of their bulk equivalents. The manufacturing of such materials can make use of a wide range of ingredients. Materials such as metals, polymers, and semiconductors are among these. Carbon-based materials like graphene and carbon nanotubes are also among them (Farghali et al., 2017).

One defining feature of nanoparticles is their extremely high surface area-to-volume ratio. Because of this ratio, nanomaterials have surface-related characteristics and increased reactivity. Due to their enormous surface area, nanoparticles have a vast array of possible uses. Their enhanced ability to engage with their surroundings is the reason behind this. The chemical sciences are an area where this trait is highly valued (Venkateswara Raju et al., 2023).

Nanomaterials have increased the effectiveness and number of catalysts used in chemical processes, transforming catalysis in the chemical sciences. Due to their enormous surface area and unrestricted ability to adjust their surface properties, nanoparticles—like metal oxides—are exceptional catalysts. Chemical reactions like hydrogenation, oxidation, and the formation of carbon-carbon bonds rely on these materials because of their higher catalytic activity and selectivity compared to their bulk counterparts (Deshmukh et al., 2018).

Nanoparticles play an essential role in the detection and sensing sectors. Due to their unusual electrical, optical, or magnetic characteristics and increased surface-to-volume ratio, sensors built around nanoparticles are extremely sensitive to the analytes they are intended to detect. These sensors are highly valuable in many areas, including food safety, medical diagnostics, and environmental monitoring, due to their capacity to detect extremely minute amounts of chemicals, biomolecules, or contaminants in the environment (Nabisab Mujawar Mubarak et al., 2014).

In nanomedicine, nanomaterials play a crucial role, especially in the delivery of drugs, imaging, and treatment. Liposomes, dendrimers, and polymeric nanoparticles are just a few examples of nanoparticles that can transport medicinal compounds to targeted organs and tissues without compromising their stability. Cancer treatments like photothermal and photodynamic therapy are made possible by nanomaterials with unique optical, magnetic, or thermal characteristics. Furthermore, biomedical imaging can use nanomaterials to enhance high-resolution viewing of tissues and disease markers.

Nanomaterials in Water treatment

Nanoparticles, with their unique properties and capacities, could greatly enhance water treatment in many ways. These materials provide innovative solutions to issues including disinfection, water purification, and pollutant removal, aiding in the creation of more efficient and eco-friendly water treatment systems.

There are several uses for nanomaterials in water treatment, but the primary one is the removal of pollutants. Nanoparticles best accomplish the adsorption, oxidation, or reduction of water contaminants due to their large surface area and high reactivity. It includes carbon nanotubes, graphene, and metal oxides (such as iron oxide and titanium dioxide). Adsorption, catalysis, and photocatalysis are some of the techniques that these materials use to effectively remove organic compounds, microorganisms, and heavy metals, among many other contaminants. One such example is the extensive research into the efficacy of nanoscale zero-valent iron (nZVI) nanoparticles as adsorbents and reductants of chlorinated organic compounds and heavy metals (Farghali et al., 2017).

In order to disinfect water, nanomaterials are essential. Nanoparticles made of antimicrobial materials, such as copper and silver, can be incorporated into water treatment systems to inhibit the proliferation of pathogenic bacteria, viruses, and other organisms. Upon contact with bacteria, these nanoparticles sterilise water by producing reactive oxygen species or antimicrobial ions. For drinking and other uses, this means the water is perfectly fine to drink. In order to disinfect water more effectively and with less environmental harm, one may use photocatalysts made of nanomaterials, like titanium dioxide nanoparticles, which could be triggered by either visible or ultraviolet light.

The permeability and separation efficiency of membrane-based water treatment systems can be greatly enhanced with the use of nanoparticles. Nanocomposite membranes containing nanoparticles such as graphene oxide or zeolites can be advantageous in applications including reverse osmosis, ultrafiltration, and nanofiltration. Improved fouling resistance, selectivity, and flux are characteristics of these membranes. This membrane technology efficiently removes organic molecules, dissolved ions, and particles from water, leaving behind potable water fit for human consumption or other uses. Meanwhile, they let molecules of pure water pass through (Malode et al., 2024).

Furthermore, more studies are needed to determine whether nanoparticles can effectively clean contaminated groundwater and wastewater. Polluted water sources can have persistent contaminants removed using nanoparticle remediation treatments. These are two examples of systems that use nanotechnology to enhance filtration and in-situ groundwater treatment. Some examples of such toxins include emerging contaminants, chlorinated solvents, and heavy metals. Recently, methods that use the unique features of nanomaterials to improve the sorption, degradation, and transport of contaminants have made cleaning up polluted water resources more efficient and inexpensive (Nabisab Mujawar Mubarak et al., 2014).

Heavy Metals

When an element has metal-like properties, an atomic number greater than 20, and an atomic density greater than 5 grams per cubic centimetre, it is classified as a heavy metal (HM). Some heavy metals are necessary for human survival, whereas others are irritating. Crucial heavy metals are required for the basic physiological processes of all living things, including the development of organs, metabolism, and growth. Many biological processes rely on these metals. Plants cannot develop without certain heavy metals, including copper, iron, manganese, cobalt, zinc, and nickel, which are part of enzymes and other proteins. Micronutrients, or important elements, are typically needed in extremely low concentrations, anywhere from tens of parts per million to hundreds of parts per million. No metabolic mechanism shown in Figure 1 necessitates even trace amounts of non-essential heavy metals like cadmium, lead, mercury, chromium, or aluminium.

Among the most harmful water contaminants are the ions of heavy metals. "Heavy metals" encompass a wide range of elements, including transition metals (Cd, Hg, and Cr), elements from the bottom left quadrant of the periodic table (Pd and Sn), and even certain metalloids (As, for example). These elements can bond with many different functional groups in biomolecules, including sulphur-containing, amino, and carboxylic acids, which could be dangerous. Consequently, they can attach to proteins and enzymes, making these molecules less effective. They facilitate the precipitation or decomposition of phosphate biomolecules. Most heavy metals in wastewater originate from human activities, such as farming, manufacturing, and other industrial processes (Anitha et al., 2015). Contrarily, even trace levels of several metals can negatively affect human health. People and other kinds of life are particularly vulnerable to the toxic effects of a few chemicals. Because of this, heavy metal removal is becoming more important to many wastewater treatment plants. Several methods for completely removing heavy metal pollution have emerged from this immediate outcome. Many nanomaterials have shown that they can successfully filter out most heavy metals from water, and this area has made great use of nanotechnology.

Here heavy metals and their toxicity are discussed below;

Toxicity of Mercury (Hg)

Under typical circumstances, the d-block element mercury (Hg) is most often seen in its liquid form. Its atomic number is 80. The presence of mercuric sulphide in cinnabar makes it a potential mercury source. Many different types of industries contribute to mercury pollution. Some examples are pharmaceutical manufacturing, caustic soda production, pulp and paper preservation, and agriculture. Mercury exposure can cause a condition called acrodynia, which is also called pink sickness. Mercury is the most harmful heavy metal that nature has to offer. Whether a chemical is organic or inorganic, it can produce a mercury complex. All kinds of mercury risk many organs when exposure levels are high enough. These include the kidneys, brain, developing fetus, and many more. The EPA has classified methyl mercury and mercuric chloride as carcinogenic on their respective lists. Mercury exposure can cause various harmful effects, including dermatitis, cognitive impairment, skin rashes, and lung damage. Regarding human water intake, the World Health Organization (WHO) has established a safe limit of 0.01 mg/l for mercury (Zhang et al., 2012).

Toxicity of Lead (Pb)

Heavy metal with an atomic number of 82, lead (Pb), initially appears silvery-blue but, when exposed to air, oxidizes to a dull grey hue while retaining its initial hue. The most prevalent sources of lead pollution include chemical fertilizers and pesticides, metal plating and finishing processes, vehicle emissions, fuel additives, paint for automobiles, and processed ores. Because of its widespread use, this toxic heavy metal is causing increasing worry for human and environmental health around the world. Lead (Pb) is a chemical that can cause cancer, according to the EPA. Acute or chronic lead poisoning are two possible outcomes of exposure to toxic lead. Lead poisoning can cause a variety of negative health effects, such as mental retardation, allergies, dyslexia, paralysis, brain damage, kidney damage, and even death (Anitha et al., 2015).

Toxicity of Arsenic (As)

Arsenic, a metalloid with the atomic number 33, exists in two forms: an element and a mixture of minerals. The salts of copper, iron, calcium, and sodium also contain arsenic. Furthermore, it is present in sulphur-containing minerals and minerals containing other metals. Pollutants in water sources include arsenic-containing herbicides, naturally occurring mineral deposits, and incorrectly disposing of arsenic-containing chemicals or compounds. Arsenate and arsenite are poisonous arsenic compounds that harm ecosystems and the creatures living in them. Arsenic disrupts mitosis, cellular enzymes, and respiration via interacting with the sulfhydryl group in cells, disrupting protoplasm (Kumar et al., 2014).

Toxicity of the Cadmium (Cd)

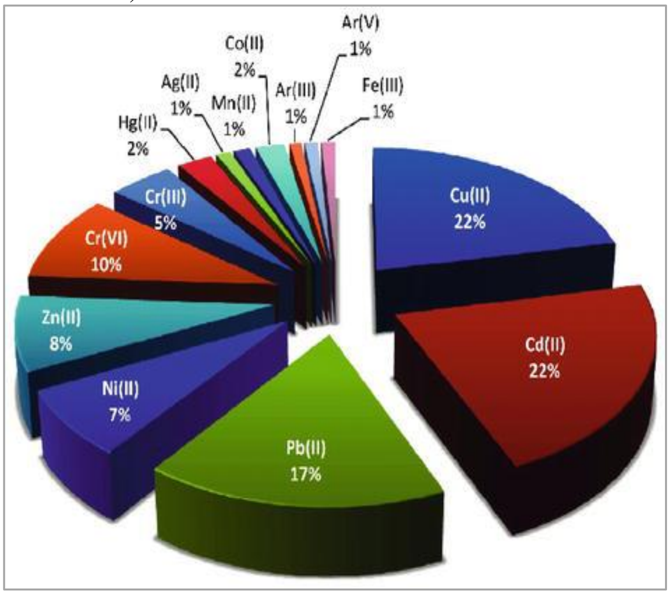
Besides being a malleable metal with a bluish-white hue, cadmium also has an atomic number of 48. Its chemical composition is similar to that of group 12 metals like mercury and zinc. Nuclear power, cigarette smoke, additions to plastic, metal alloys, batteries, electroplating, and melting ore are some of the many sources that go into their creation. Although naturally occurring cadmium levels in the environment are extremely low, industrial waste has caused them to rise substantially. Cancer, kidney disease, bone and joint damage, and pulmonary impairment are some of the negative health effects of cadmium on humans. In terms of metal toxicity, cadmium is ranked sixth according to the ATSDR.

Toxicity of Chromium (Cr)

Chromium, with an atomic number of 24, is a metal easily identifiable by its steely grey colour. The most stable forms of chromium are trivalent and hexavalent, although the element can also exist in other states, including pentavalent. The most stable forms are these. Supplemental chromium (III) foods are necessary for the continued existence of all forms of life on Earth. In contrast, chromium (VI) is very dangerous and may induce cancer. Chromium is found in soil, water, and wastewater, the main environmental matrices. Industries engaged in metallurgy and chemical production are the primary dischargers of chromium into the atmosphere and aquatic systems. Research in humans has demonstrated that hexavalent chromium (Cr VI) and other industrial pollutants can cause tumours to grow. There is a 50 µg/L limit for chromium (VI) in both surface and underground water sources set by the World Health Organization (WHO). At the moment, this level is being surpassed (Liu et al., 2016).

Figure 1

Adsorption of heavy metals from industrial waste (Liu et al., 2016)



Removal of Heavy Materials by Nanomaterials

Heavy metal removal from water sources is a topic that is generating significant global concern. Many methods have been devised to extract heavy metals from their respective environments. The fast-expanding subject of nanotechnology encompasses a wide range of nanomaterials that may be able to remove heavy metals from polluted water sources. The extraordinary optical properties, compact size, and high adsorption capacity define nanoparticles. These are all qualities that are highly prized. As a result of its rapid progress over the past two decades, nanotechnology has found numerous uses in numerous scientific and technological fields. Thanks to their large pore volume and enhanced specific surface area, many nanomaterials have been developed and used to remove heavy metal pollutants from wastewater. Nanomaterials include graphene-based materials, carbon nanotubes, nanoscale zerovalent particles, and nanometal-oxide supports. An increase in nanoparticles' adsorption capability is mostly attributable to their unsaturated surfaces. Stable compounds are formed when additional atoms in the aqueous solution can establish bonds more easily on these surfaces. In addition, nanoparticle-enhanced membranes have better hydrophilicity, antifouling, and heavy metal adsorption capabilities.

Table 1

Shows Some Examples of NMs used in Heavy Metal Removal and their Mechanism of Action.

Nanomaterial	Mechanism	Metal	Reference
Zero-valent iron	Catalyzed reduction	Cr^{6+}	(Buledi et al., 2020)
	Adsorption	As^{3+} and As^{4+}	(Liu et al., 2016)
Iron oxides (Fe_3O_4, γ-Fe_2O_3) and oxy-hydroxides (FeOOH)	Adsorption electrostatic attractions	As^{3+} and As^{4+}	(Farghali et al., 2017)
Functionalized Fe_3O_4 nanoparticles	Adsorption	Cu^{2+}, Cd^{2+}, Pb^{2+}, Ni^{2+}, Cr^{6+}, U^{6+}, Hg^{2+}	(Anitha et al., 2015)
Metal oxides (Al_2O_3, TiO_2, MnO_2, ZrO_2, ZnO, MgO, CeO_2)	Adsorption	Zn^{2+}, Cu^{2+}, Cd^{2+}, Pb^{2+}, Ni^{2+}, Cr^{6+}, U^{6+}, Hg^{2+}	(Zhang et al., 2012)
TiO_2	Photocatalyst	Pb^{2+}, Cu^{2+}, As^{3+}, Cr^{6+}, Se	(Tian et al., 2012)
Carbon nanotubes	Adsorption	Pb^{2+}, Cu^{2+}, Th^{4+}, Zn^{2+}, Ni^{2+}, Cr^{6+}, Sn^{2+}	(Yan et al., 2016)
Graphene oxide	Adsorption	As^{3+}, As^{5+}, Hg^{2+}, Cu^{2+}, Cd^{2+}, Pb^{2+}	(Garrido et al., 2020)
MgO	Cation exchange	Cd^{2+}, Pb^{2+}	(M. Królikowski et al., 2024)
Bio-based nanomaterials chitosan, cellulose	Adsorption and chelation	Cd^{2+}, Pb^{2++}, Cu^{2+}	(Krasley et al., 2024)

Heavy metals can be extracted from wastewater by using the adsorption method on nanomaterial surfaces. Nanomaterials must meet certain requirements to effectively remove heavy metal ions from wastewater: A perfect nanoparticle would be completely safe for humans to swallow, highly selective for very small amounts of pollutants, very adsorbent, surface-removable, and very recyclable. In order to extract heavy metals from wastewater, new developments have enabled nanomaterials such as zeolite, carbonaceous substances, chitosan, magnetic materials, bimetallic complexes, metal oxides, and metallic elements. The use of nanomaterials has enabled this to happen. This section will delve into various nanomaterials, studying their properties and function in heavy metal cleanup. Our focus will be on the fundamentals of these materials (Zhang et al., 2012).

Carbon-Based Nanomaterials

The predominant approach to treating wastewater with carbon-based compounds involves using activated carbon. Additionally, this method is the most efficient. An exceptionally porous structure, a high surface reaction affinity, and a massive surface area characterize activated carbon. Activated carbon's many desirable properties make it a top pick for purifying water of various contaminants. Many carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene oxide (GO), and carbon-based nanocomposites, have recently entered the market, impeding research on activated carbon. Moreover, this is so even though activated carbon has extensive applications in treating wastewater. Functionalizing carbon-based nanomaterials offers an attractive method for efficiently extracting hazardous metals from wastewater. It is possible to use carbon-based nanosorbents for wastewater purification due to their distinctive physical and chemical characteristics. Carbon nanotubes' (CNTs') electrical conductivity, tiny size, cylindrical hollow shape, and huge surface area attract engineers. There are two main carbon nanotubes, or allotropes: those with one wall and those with multiple walls (Tian et al., 2012).

Their ability to extract heavy metals from water-containing environments is second to none. Carbon nanotubes (CNTs) effectively remove heavy metal ions from water using sorption-precipitation, electrostatic attraction, physical adsorption, and chemical interaction. Carbon nanotubes (CNTs) in all their forms have been the subject of a plethora of research that has shown promise in the elimination of heavy metals like cadmium, chromium, copper, arsenate, nickel, lead, zinc, cerium, strontium, and mercury. More adsorption sites per mass of carbon nanotubes (CNTs) and intraparticles do not have to travel as far. Carbon nanotubes' (CNTs') adsorption capability depends on many variables. The number of distinct adsorption sites and open to activated nanotubes ratio are crucial morphological factors. Compared to capped CNT bundles, those exposed to the environment have more active sites. To be more precise, there are four potential sites for carbon nanotube (CNT) adsorption: surfaces, grooves, interstitial channels, and the material itself. Compared to the interstitial channels and internal sites, the adsorbent material reaches equilibrium considerably faster when exposed to the grooves and adsorption sites on the surrounding surface. Carbon nanotube (CNT) purity is crucial because carbon-based contaminants, like soot and carbon-catalyst particles, cover the surfaces of CNT bundles, reducing the number of active adsorption sites (Tian et al., 2012).

According to the research, electromagnetic interactions, surface acid treatment, and functional group grafting can increase carbon nanotubes' (CNTs') adsorption ability. Changing the chemical makeup of the CNTs will achieve this goal. The adsorption of metal ions onto the surface functional groups of carbon nanotubes (CNTs) causes the release of hydrogen ions, which in turn causes the pH of water to fall. Rhodium, carboxyl, and phenol are examples of such functional groups. Carbon nanotubes (CNTs) have far better metal adsorption capabilities after surface oxidation than activated carbons. Oxidation enhances carbon nanotubes' (CNTs') cation exchange capability by creating surface negative charges (Kumar et al., 2014).

Surface functional acid sites and negative zeta potential on single-walled carbon nanotubes (SWCNTs) have increased the adsorption of Ni2+ and Zn2+. Carbon nanotubes were important in making this happen. Heavy metals such as manganese dioxide, iron oxide, and aluminum oxide have been effectively removed by modifying carbon nanotubes with metal oxide. A separate experiment confirmed that lead ions have an adsorption capability of 70.2 mg/g in water (Yan et al., 2016).

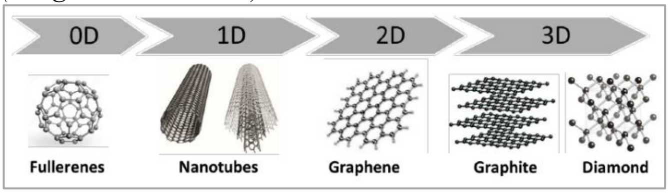
Manganese dioxide was applied to oxidized MWCNTs with an adsorption capacity of 41.7 mg/g to efficiently remove cadmium ions from water. We do not yet know the exact processes that cause the synergistic effects of metal oxides and carbon nanotubes (CNTs) to boost the adsorption capacity of these composites. Scientists have just created a new carbon nanocomposite, which differs from traditional carbon nanomaterials in important ways. A composite of montmorillonite and carbon modified with nano adsorbents was made and used to remove lead ions. This composite showed a low environmental impact due to its 247.86 mg/g adsorption capacity (Tian et al., 2012).

Classification of Carbon Nanomaterials Based on their Dimensions

The zero-dimensional nanomaterial fullerenes, sometimes called quantum dots, is one example. The defining feature of these nanomaterials is their extremely small size—less than 100 nanometers in all three dimensions. Nanoparticles with just one dimension larger than 100 nanometers and two dimensions smaller than that are called one-dimensional (1-D) nanomaterials. Such nanomaterials include carbon and titanium nanotubes, for instance. One well-known example of a two-dimensional nanomaterial is graphene. The picture clearly shows that the dimensions of graphene are larger than 100 nanometers. As shown in Figure 2, three-dimensional (3-D) materials include graphite and other nanomaterial composites. More than 100 nanometers is the entire size of these materials.

Figure 2

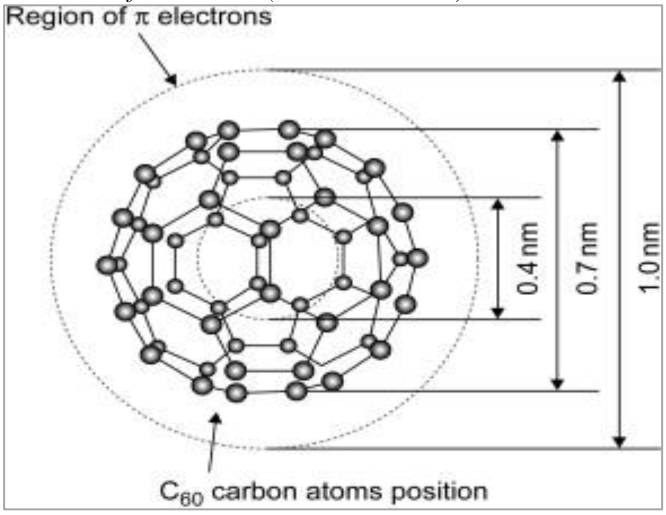
Carbon Nanomaterials based on their dimensions (Farghali et al., 2017)



Fullerene (0-D)

Fullerenes such as C60 and C70 are easily accessible. In its natural condition, C60 has an electrical structure that is icosahedral, symmetrical and identical to graphene. While fullerenes can be made using the carbon arc technique, a more exact and controlled approach is to burn a hydrocarbon feedstock with a well-controlled oxygen supply. When fullerenes dissolve, they leave behind soot, which is another name for "amorphous carbon" and has the potential to be recovered. Endohedral atom inclusion, surface functionalization, and substitutional doping of the carbon lattice (with boron, for example) are some alterations that fullerenes can undergo. These changes can be shown in Figure 3. As a result, fullerenes have a lot more potential uses.

Figure 3
Structure of Fullerene (Yan et al., 2016)



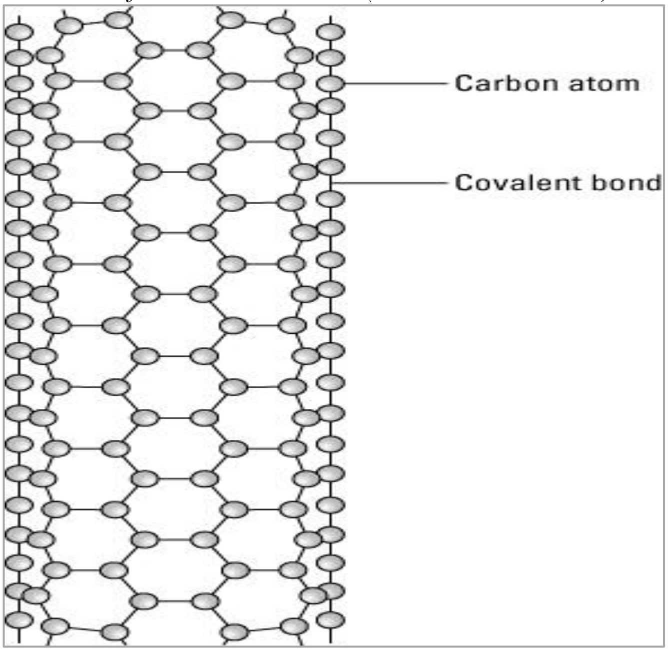
Carbon-Nanotubes (1-D)

There have been many studies on carbon nanotubes (CNTs) over the last several decades. These nanotubes exhibit various characteristics, from optical and electrical to vibrational, mechanical and thermal. There has been much coverage of these methods' use in heavy metal removal from wastewater. Two main carbon nanotubes are single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). These materials are made of carbon and can be hundreds to thousands of nanometers long and one to three nanometers wide. Carbon nanotubes are the way to go when it comes to cleaning up heavy metal-contaminated wastewater due to their large specific surface area, increased adsorption capacity, and fast adsorption kinetics. Carbon nanotubes are shown to have good adsorption properties for several metals, including but not limited to Mn (VII), Tl (I), Cu (II), Pb (II), and Cr (VI). The surface, interior, interstitial channels, and external grooves of carbon nanotubes can all contain adsorption active sites. As seen in Figure 4, these locations are ideal for adsorption bundles of single-walled carbon nanotubes (SWNTs) (Yan et al., 2016).

It is standard practice to chemically modify, thermally treat, or endohedral fill carbon nanotubes (CNTs) with functional groups like -COOH, -NH2, and -OH to increase their adsorption capacity for heavy metals. Carbon nanotubes (CNTs) can have their surface modified by oxidants, including KMnO4, HNO3, H2SO4, and NaOCl, which increases their adsorption capacity, according to research. In order to recover mercury (II), Mohamed et al. utilized a functionalized carbon nanotube absorbent. Innovative functionalized carbon nanotubes (CNTs) were synthesized by sonicating pre-oxidized CNTs with a deep eutectic solvent (DES) composed of allyl triphenyl phosphonium bromide and glycerol. Results from the batch adsorption experiment at 28 minutes of contact time and a pH of 5.5 aligned with predictions. The Freundlich isotherm model, based on pseudo-second-order kinetics, showed that the maximum adsorption capacity for mercury (II) was 186.97 mg/g (Malode et al., 2024).

Although there are several advantages to using carbon nanotubes (CNTs) to remove heavy metals from wastewater, there are also several downsides. The high initial cost of carbon nanotubes (CNTs) prevents their widespread application in industry. It takes much work to develop CNTs that are practical and affordable. Secondary contamination is a real concern, and treatment costs go up when post-adsorption carbon nanotubes (CNTs) from wastewater are difficult to separate. Last, research into the toxicity of carbon nanotubes (CNTs) is urgently needed.

Figure 4
Structure of Carbon Nanotube (Malode et al., 2024)



Graphene Nanomaterials (2-D)

For example, graphene, the first two-dimensional atomic crystal, is a carbon-based nanomaterial that can remove heavy metals from drains. The material's exceptional features, including its mechanical strength, flexibility, electrical and thermal conductivity, and many more, make it versatile and ideal for various uses. Graphene oxide (GO) and reduced graphene oxide (RGO), two nanomaterials derived from graphene, may also be useful in treating wastewater for heavy metals. The byproduct of graphene's oxidation, graphene oxide (GO), has many oxygen-containing functional groups. Heavy metal removal is made easier by these groupings! Carboxyl and epoxide groups are among them, along with carbonyl and hydroxyl. Compared to pure graphene, the byproduct of graphene oxide reduction, reduced graphene oxide (RGO), is more susceptible to changes in functional groups (-OH, -COOH, etc.) and typically contains a higher number of impurities. The reason is that reduced graphene oxide (RGO) results from that process. The remarkable properties of these graphene-based nanomaterials allow them to remove heavy metals. These properties include a high negative charge density, apparent hydrophilicity, many functional groups (CH(O), CH-, -OH, and -COOH), and large specific surface areas.

Many different chemicals fit inside graphene's two-dimensional structure. Because of the grey zone, which indicates that these nano allotropes belong to other families, they are not considered graphene-family nanomaterials (GFNs).

Graphene and materials based on GO/RGO have proven time and time again that they can successfully filter out heavy metals from wastewater. It is important to take into account the findings of Wang et al., who performed batch tests to examine how factors such as pH, adsorbent dosage, contact length, temperature, and coexisting ions affected the effectiveness of graphene oxide adsorption for heavy metal removal. Results showed that the pseudo-second-order kinetic model and the Langmuir isotherm accurately predicted the adsorption process. In addition, it was found that GO has an impressive ability to adsorb zinc (II), with a maximal capacity of 246 $mg{\bullet}g^{-1}$. Using a modified Hummers approach, Zhao et al. synthesized few-layered graphene oxide nanosheets. As a further step, these nanosheets were employed to remove Cd (II) and Co (II) from water through batch adsorption. The adsorption of Cd (II) and Co (II) was shown to be reduced when humic acid was added to water, with pH playing a significant role in this process. The maximum amount of Cd (II) detected on GO was 106.3 $mg{\bullet}g^{-1}$, whereas the highest amount of Co (II) was 68.2 $mg{\bullet}g^{-1}$. Thermodynamic parameters of this adsorption process were computed, and it was found that Cd (II) and Co (II) adsorption on GO nanosheets is endothermic and spontaneous (Tian et al., 2012).

METHODOLOGY

Detection of Heavy Metals by Carbon Nanomaterials

As mentioned earlier, using different types of carbon nanostructures allows for the detection of heavy metals. In this section, we will examine each technique for heavy metal detection and wastewater treatment separately.

Fullerenes

The characteristic closed-cage configuration characterizes fullerene forms. With an integer m, they are expressed as C20 + m. In 1985, fullerenes were initially detected in interplanetary dust. In addition to being hydrophobic, these materials have a high electron affinity, a relatively large surface area relative to their volume, and surface imperfections. These materials have unique physicochemical properties that make them useful in many industries. A few examples of these areas of study are electronics, solar cells, biomedicine, cosmetics, surface coatings, and artificial photosynthesis. Brunet et al. showed that hydrophilic functionalized fullerenes (C60) may effectively photocatalyze the eradication of hazardous bacteria in water (Garrido et al., 2020).

Because of their rapid transition from C-C to C-H bonds, fullerene molecules are an ideal clean material for hydrogen storage. Hydrogen's binding energies are the lowest of any element compared to carbon. Fullerenes can store the largest quantity of hydrogen (6.1%), which is made feasible by their molecular chemistry and cage-like structure. The higher the C-C bond energy, the easier it is for the fullerene structure to be reversible. Supercapacitors' capacitance is proportional to the electrodes' electrical conductivity, surface area, and pore size distribution. The carbon conductive layers used in supercapacitors are placed on the surface of the electrodes (Yien Jun Lau et al., 2019).

Since carbon nanoparticles have a larger surface area than commonly available materials, they are better able to conduct electricity. Compared to pure graphene, which lacks fullerene hybridization, composite materials, including fullerene, have a higher specific capacitance. These composite materials have a specific capacitance of 135.36 Fg^{-1}. A fullerene-based composite material demonstrated exceptional retention time performance, which preserved 92.35% even after 1000 charging and discharging cycles. The manufacturing of lithium-ion batteries has used fullerenes as an anode material. Compared to non-biodegradable metallic anodes, these are more effective and better for the environment (Krasley et al., 2024).

Fullerenes have unique physicochemical properties that make them promising candidates for the remediation of many aquatic species. Following the lead of Pickering et al., the team created fullerene compounds that dissolve in water and used them as sensitizers to produce reactive oxygen species (ROS) in water-based environments when exposed to UV and visible light. Because of their antioxidant and photodegradation properties, reactive oxygen species (ROS) and water-soluble fullerenes (fullers) can break down organic contaminants in water, respectively. Additionally, fullerenes can decompose organic pollutants. The primary concern in this procedure is the effectiveness of fuller photodegradation in removing the chemical from water. Fullerenes are appealing nanomaterials for heavy metal ion extraction from water due to their enormous surface area, low tendency to combine, and capacity to adsorb species from the interstitial spaces and flaws among carbon nanoclusters. The high surface area of fullerenes is the reason behind this.

Despite Fullerenes' promise for usage in water adsorption applications, their high cost prevents them from being fully employed. Materials like activated carbon, lignin, and zeolites can enhance adsorption efficiency by adding a small amount of fullerenes during production. Materials with higher hydrophobicity are better suited for adsorption and recycling during fullerene synthesis. One possible way to enhance water disinfection is to create an antibacterial material by grafting fullerene C60 with polyvinylpyrrolidone (PVP). Membranes are increasingly used to remove pollutants, particles, organic compounds, gases, and other substances from water. The use of membrane extraction is on the rise. Mechanical strength, selectivity, and reactivity are all affected by the material's composition, affecting the membrane's performance. Thanks to their malleability, strength, size tunability, ease of functionalization, and strong electron affinity, fullerenes are excellent prospects for membrane technology applications. Fullerenes are a great contender because of these qualities. Grafting fullerenes onto nano-adsorbents may increase their adsorption efficiency (Krasley et al., 2024).

Biocompatibility of Fullerenes

Multiple studies have confirmed that fullerene-based nanomaterials used in the biomedical industry are biocompatible. Its biomedical engineering uses extend beyond its roles as a biosensor and bioreceptor. According to reports, it does not harm living systems. Fullerene is a non-toxic compound with several applications in water and environmental treatment, and it has many potential uses. Membrane materials, adsorbents, and filtration are among these uses (Yan, Cohen, et al., 2016).

Carbon Nanotubes

Carbon nanotubes with one or more walls, known as SWCNTs and MWCNTs, were discovered by Iijima in 1999, and their presence is plain to see. In contrast to the latter, which consists of numerous rolled carbon nanotubes, the former consists of a single layer of rolled graphene. Because of their unique physicochemical properties, carbon nanotubes have captivated nanotechnology researchers since their inception. Among the many potential uses for these carbon allotropes with cylindrical nanostructures are electronics, semiconductors, field emission, energy storage, catalysis, biomedicine, and air and water purification. They are perfect for heavy metal ion adsorption due to their big specific surface area (150-1500 m2/g), mesopores, and diameter (ranging from 1 nm to several nanometers). Not only that but carbon nanotubes (CNTs) can be functionalized with a broad range of organic molecules, making them more selective for adsorbates and improving their adsorption properties. A carbon nanotube (CNT) heavy metal sorption mechanism is based on surface characteristics, electrochemical potential, and the ion exchange process.

CNT in Photocatalysis for Wastewater Treatment

Photocatalysis employs semiconductors and is one of the most advanced wastewater treatment approaches. Various other semiconductor materials are used as part of this production method, including Fe3O4, ZnO, and TiO2. However, these materials react slowly to UV light and have a low quantum efficiency. Carbon nanotubes (CNTs) are promising new catalytic materials due to their large specific surface area, improved quantum efficiency, smaller size, exceptional chemical stability, and tubular structure. Success was achieved in the development and application of the ultrathin network photocatalysts for water extraction from oil by Gao et al. Park et al. utilized titanium-coated SWCNT aerogel to efficiently remove methylene blue from water. The development of MWCNTs-TiO2 was initiated by Zhao et al. to photodegrade methylene blue. Xu and colleagues developed photocatalysts to efficiently remove pyridine from water by combining hydroxy MWCNTs with a PbO2 nanocrystalline anode (M. Królikowski et al., 2024).

SWCNTs in the Purification of Heavy Metal-Contaminated Water

One-dimensional carbon nanomaterials with a hollow structure and only one atom thick walls are called super-wall carbon nanotubes (SWCNTs). This one-dimensional substance's remarkable physicochemical features are due to its peculiar configuration. Numerous sectors are investigating potential new uses for single-walled carbon nanotubes (SWCNTs), such as electronics, biosensors, medical fields, and semiconductors. Many environmental pollution prevention efforts focus on single-walled carbon nanotubes (SWCNTs) due to their tiny size, large surface area, ease of surface functionalization, and porous structure. Because of their unique properties, SWCNTs have the potential to revolutionize water filtration. After making single-walled carbon nanotubes (SWCNTs) with magnetite cobalt sulphide, Alijani and colleagues created a nanocomposite. Afterwards, they extracted mercury using these nanocomposites, demonstrating an adsorption efficacy of over 99.56% in as little as seven minutes. Alternatively, SWCNTs autonomously absorbed 45.39 per cent of the mercury (Yan, Cohen, et al., 2016).

Anitha and colleagues used molecular dynamics to forecast the adsorption characteristics of functionalized single-walled carbon nanotubes (SWCNTs), including SWCNTs-OH, SWCNTs-NH2, and SWCNTs-COOH, in comparison to unmodified SWCNTs, in order to extract Cd^{2+}, Cu^{2+}, Pb^{2+}, and Hg^{2+} from water-based solutions. The results show that compared to naked SWCNTs, the adsorption capacities of SWCNTs-COOH are around 150-230 per cent higher. I can confirm that. Nevertheless, it was demonstrated that SWCNTs-OH and SWCNTs-NH lacked adequate adsorption capacities, showing only a 10-47% improvement in adsorption compared to SWCNTs. In contrast, SWCNTs-COOH had an adsorption capacity of 96.02 mg/g for Pb^{2+} ions, 77.00 mg/g for Cu^{2+} ions, and 55.89 mg/g for Cd^{2+} ions. Regarding lead, copper, and cadmium ions, unfunctionalized SWCNTs may adsorb 33.55 mg/g, 24.29 mg/g, and 24.07 mg/g, respectively (Malode et al., 2024).

By functionalizing SWCNTs with L-cysteine, Zazouli and coworkers created nanocomposites. Using the nanocomposites they had made, they accomplished eliminating mercury from water. The synthesized SWCNTs-cysteine exhibits an impressive adsorption effectiveness of 95%. Gupta and colleagues created a membrane of SWCNTs and polysulfone nanocomposites to filter out heavy metals. When SWCNTs were incorporated into the membrane, the surface smoothness and pore size were both enhanced. By effectively removing 96.8% of Cr^{+6}, 87.6% of As^{+3}, and 94.2% of Pb^{+2} ions, the modified membrane was proven to have enhanced metal ion rejection efficacy. There was a total rejection rate of 30.3% for Cr^{+6}, 28.5% for As^{+3}, and 28.3% for Pb^{+2} ions in the SWCNT-free membrane.

The results showed that the membrane's efficacy was enhanced once SWCNTs were incorporated. Dehghani and colleagues studied the effect of various parameters on adsorption capacity to successfully remove Cr^{+} 6 ions from water using single-walled carbon nanotubes (SWCNTs). Time of contact, starting pH, and initial concentration of Cr^{+} 6 ions were among these factors. According to the Langmuir isotherm model, the adsorption process is carried out, and the effectiveness of adsorption became increasingly pH-dependent, peaking at 2.5. Research has demonstrated that heavy metal-contaminated water can be effectively remedied by employing single-wall carbon nanotubes.

Biocompatibility of CNTs

Carbon nanotubes (CNTs) might soon be used in many different sectors. Some examples of these areas of study are environmental cleanup, biosensors, electronics, semiconductors, diagnostics, and medicine. CNTs have been extensively used in many biological fields, and as a result, numerous studies have shown that they are biocompatible. Carbon nanotubes (CNTs) and other carbon-based materials provide no health risks and have numerous potential uses, such as in water purification and environmental cleanup.

Graphene Based Carbon Nanomaterial

Since carbon dioxide (CO_2) is a major contributor to climate change, it has been the focus of considerable environmental concern. Nanoparticles outperform traditional materials in terms of efficiency and cost-effectiveness, as shown by studies. The utilization of graphene-based materials has enabled the adsorption of gaseous pollutants. Nanomaterials made of graphene can be used to absorb carbon dioxide and hydrogen, according to Gosh et al. Some studies have shown that just one graphene layer may capture 37-93% of CO_2. Another interesting property of graphene is its ability to selectively absorb carbon dioxide (CO_2) rather than nitrogen (N_2) or methane (CH_4). Graphene oxide is selective for carbon dioxide with a greater dipole moment because its polar oxygenated functional groups are more easily engaged by carbon dioxide with a higher dipole moment. The prospect of enhancing graphene's selectivity for gaseous pollutants through chemical composition modification has been the subject of more investigation (Lim et al., 2021).

Graphene Oxide in Removal of Organic Dyes from Water

Because of their nanoscale size, large surface area, and capacity to interact through pi-pi stacking, hydrogen bonding, and electrostatic interactions, nano-adsorbents based on graphene are great for removing organic pollutants from water. Graphite showed poorer adsorption capabilities than graphene oxide, according to experiments using methylene blue and malachite green as reference organic dyes. Graphene oxide (GO) has been used to remove cationic dyes from water, such as crystal violet (CV), rhodamine B (RhB), and methylene blue (MB). The results showed that as the starting dye concentrations were raised, the adsorption capabilities of MB, CV, and RhB—199.2, 195.4, and 154.8 mg g^{-1}, respectively—increased. Anionic dyes can be efficiently removed from water-based solutions by using graphene oxide (GO). Direct Red 23 and Acid Orange 8 are two of these colors (Yan, Cohen, et al., 2016).

Graphene and Graphene Oxide-Based Adsorbents for the Purification of Heavy Metal-Contaminated Water

A one-atom-thick hexagonal lattice of carbon atoms makes up graphene, the strongest material that humanity has found so far. Its one-atom thickness belies its 200-fold strength compared to steel. In 2010, the Nobel Prize in Physics was bestowed upon Andre Geim and Konstantin Novoselov. Their 2002 discovery of graphene was the reason for this accolade. Touch screens, mobile phones, LCDs, semiconductors, computer chips, batteries, energy generation, water filtration, supercapacitors, solar cells, and many more areas of study, including biomedicine and environmental science, are just a few of graphene's countless uses (Lim et al., 2021).

Due to their distinct physicochemical properties, these two-dimensional graphene-based materials are garnering more and more attention in the water treatment industry. These qualities include electrical properties, thermal mobility, exceptional mechanical strength, and adjustable surface chemistry. Tabish and colleagues' porous graphene was an adsorbent that filtered out heavy metal ions and other pollutants from water. They achieved an efficiency of 80% in removing silver ions from water by using this porous graphene material. Regarding the material's ability to handle water, regeneration and recycling had no detrimental effect. Guo et al. could remove lead ions from water by using the in situ co-precipitation approach to synthesize a nanocomposite of partially reduced graphene oxide and Fe3O4. The reported nanocomposite proved quite functional, able to adsorb lead ions in an aqueous solution with an impressive 373.14 mg/g capacity. Zhang et al. functionalized reduced graphene oxide with 4-sulfophenylizazo to remove several heavy metal ions from water. The maximum adsorption capabilities of the produced material for lead2+, copper2+, nickel2+, cadmium2+, and chromium 3+ were 689, 59, 66, 267, and 191 mg/g, respectively (Sasaki et al., 2024).

Diana and her colleagues in the lab constructed a microbot system out of microscopic multilayers of graphene oxide, nickel, and platinum that can propel itself. The engine's capacity to self-propel is enabled by platinum, graphene oxide binds to Pb2+ ions, and nickel controls microbots via an external magnetic field. Eight per cent of the lead ion (Pb2+) in the water-based solution was extracted using the specified method. Zheng and colleagues synthesized nanocomposites by combining tea polyphenol with reduced graphene oxide to produce zinc oxide (TPG-ZnO). In addition to effectively removing heavy metal ions, the developed material has antimicrobial properties. The adsorption efficiency of 98.9% for the removal of Pb2+ ions from an aqueous solution was achieved using this material. The adsorbent was also shown to have antibacterial properties, which allowed it to eliminate 99 per cent of Streptococcus mutans (Yien Jun Lau et al., 2019).

Mousavi et al. showed that graphene oxide/iron oxide magnetite nanoparticles (Fe3O4) nanocomposites could remove 126.6 mg/g of lead ions from water with a 90% removal efficiency (Yien Jun Lau et al., 2019). When tested at a pH of 5.0, functionalized graphene could extract a maximum of 406.6 mg/g of lead ions from water-based solutions. All of this was finished in about forty minutes. An exceedingly polar surface was produced by oxygenated functional groups in graphene-hydrogel lingo sulfonate functionalized nanocomposites, which enhanced the adsorption rate of lead2+ ions. The materials reached equilibrium after forty minutes and reached a maximum effectiveness of 1,38 mg/g. Awad and colleagues modified graphene oxide by incorporating chloroacetic acid (GO-COOH) and ethylenediamine (GO-amino). When tested for Hg2+ removal from water, the adsorption capacities of the manufactured systems were determined to be 122 mg/g for the GO-COOH nanocomposites and 230 mg/g for the GO amino nanocomposites. It was a major accomplishment that the produced systems kept their adsorption efficiency even after recycling. An optimized magnetic graphene oxide was created by Yan et al. to aid in the quick removal of iron (II) and manganese (II) from water that had been micropolluted. Ali et al. successfully removed dangerous impurities like copper (II), lead (II), iron (II), and manganese (II) by creating an efficient adsorbent using graphene technology.

Biocompatibility of Graphene-Based Nanomaterial

Nanomaterials generated from graphene can benefit electrodes, chemical sensors, biosensors, drug delivery, theranostics, and a host of other biological contexts. This research explains the cytocompatibility of graphene-based materials through in vitro and in vivo animal investigations. Since these materials are designed for graphene-based environmental cleanup applications and not for human ingestion, they are safe to use (Sasaki et al., 2024).

Advantages of using Carbon Nanomaterials

Carbon nanomaterials offer a plethora of advantages across various fields, owing to their unique properties and versatility. Some key advantages of using carbon nanomaterials include:

I. **Exceptional Mechanical Strength**: Carbon nanostructures, such as graphene and carbon nanotubes, have higher mechanical strengths than other materials. Because of this, they are perfect for use as composite reinforcements, which improve the mechanical characteristics of a wide variety of materials.

II. **High Electrical Conductivity**: Carbon nanotubes and graphene are two examples of carbon-based materials with electrical conductivities on par with or higher than those of metals like copper. This feature is useful for various technologies, including electronics, conductive coatings, batteries, and supercapacitors.

III. **Tunable Optical Properties**: Carbon nanomaterials' optical characteristics can be manipulated over a broad frequency range, from the visible to the near-infrared. Multiple industries, including sensors, photonics, and optoelectronics, can benefit from their remarkable light-manipulation capabilities.

IV. **Large Surface Area**: The increased surface area-to-volume ratio and small size of nanoscale carbon particles give them a plethora of sensing, adsorption, and catalytic active sites. Because of how well they work in gas sensing, cleaning up pollutants, and heterogeneous catalysis, this is what happens.

V. **Chemical Stability and Inertness**: Nothing beats carbon nanoparticles when it comes to protecting materials from oxidation, corrosion, and chemical deterioration. They're chemically stable and dead-end, which improves their stability and longevity in a variety of settings, making them useful in situations calling for strong materials.

VI. **Biocompatibility**: Carbon nanostructures have great promise for use in biomedicine because of their low cytotoxicity and high biocompatibility. Medicines, biosensors, and tissue engineering all fall under this umbrella. Their unique properties allow for high-resolution imaging, accurate medicine administration, and control of biological processes.

VII. **Environmental Friendliness**: Carbon nanoparticles may be efficiently and scale synthesized from easily accessible carbon sources like carbon dioxide and graphite. Environmental cleanup and the use of renewable energy sources could reduce pollution and emissions of greenhouse gases (Sasaki et al., 2024).

VIII. **Versatility and Customizability**: Carbon nanostructures have a wide range of applications and characteristics. Some examples are fullerenes, graphene, carbon dots, and nanotubes. They have many potential applications because their properties can be changed by structural changes, functionalization, and hybridization (M. Królikowski et al., 2024).

Disadvantages of Using Carbon Nanomaterials

While carbon nanomaterials offer numerous advantages for heavy metal detection and water treatment, they also present certain limitations and challenges. Some disadvantages include:

I. **Cost of Production**: Carbon nanotubes and graphene, two of the most common types of carbon nanomaterials, can be quite energy and money-consuming to synthesize. In settings with few resources or a high volume of industrial activity, the costs of the synthesis, purification, and functionalization processes may be too high.

II. **Synthesis Complexity and Scalability**: Synthesis and characterization of nanomaterials are typically required when working with carbon nanomaterials. Carbon nanomaterial production is an intricate process requiring cutting-edge technology and tools. One possible barrier to broad adoption is the difficulty of increasing production to meet commercial demands without compromising quality or reproducibility.

III. **Environmental and Health Concerns**: It is common practice to produce and characterize carbon nanoparticles before studying them. Carbon nanomaterial synthesis is an intricate process that requires state-of-the-art machinery. The difficulty of meeting business needs for increased output without lowering quality or reproducibility is a potential barrier to wider adoption.

IV. **Limited Selectivity and Specificity**: Some people are worried that carbon nanomaterials, such as graphene oxide and carbon nanotubes, could harm people and the environment. This is still the case even though these materials might be useful in some situations. We need new risk assessments and more studies to determine the potential long-term impacts on ecosystems and human health from breathing, eating, or getting skin-deep exposure.

V. **Interference from Matrix Components**: The reactive carbon nanoparticles possess a large surface area. However, their selectivity and accuracy may be insufficient for heavy metal detection. In complex matrices, non-specific adsorption or interference from other components might reduce detection accuracy and reliability. Based on the results, additional steps in signal amplification or sample preparation may be required.

VI. **Regulatory and Safety Considerations**: It is fascinating how carbon nanoparticles used for water treatment could interact with matrix components in real water samples. Organic molecules, ions, and dissolved solids compete fiercely for adsorption sites on nanoparticle surfaces. Removing impurities and purifying water is crucial.

VII. **Long-term Stability and Durability**: Few studies have investigated how carbon nanoparticles fare in continuous operational settings or under harsh conditions. As nanomaterials agglomerate, degrade, or leach with time, the effectiveness of heavy metal detection and water treatment may be reduced.

VIII. **Ethical and Social Implications**: We must evaluate the social and ethical implications of carbon nanoparticles before they are extensively used for water treatment and heavy metal detection. Societal issues such as fair access, unforeseen effects, and public opinion may impact the acceptance and use of nanotechnology.

Future Prospects

The future prospects of carbon nanomaterials are highly promising, with ongoing research and development efforts aimed at unlocking their full potential across diverse fields. Some key future prospects include:

I. **Advanced Sensing Technologies**: Then, nanoparticles are an encouraging step forward. Analytes in the development of sensitive and selective sensing systems approaches can detect analytesogical molecules, organic pollutants, and heavy metals and can be detection-based sensors with faster response times, specificity, and greater sensitivity that might revolutionise medical diagnostics, food safety verification, and environmental monitoring.

II. **Innovative Water Treatment Solutions**: Carbon nanotube water filtration techniques' effectiveness in removing contaminants is approaching a tipping point. Exciting new avenues for research include developing nanomaterial-enhanced filtration membranes with improved fouling resistance, selectivity, and water permeability and studying novel photocatalytic and adsorptive materials for effective contamination removal from water sources.

III. **Energy Storage and Conversion Devices**: Fuel cells, batteries, and supercapacitors are examples of energy storage and conversion devices that can use carbon nanomaterials. This has the potential to significantly change the sector's operational dynamics. Investigating ways to improve carbon-based electrodes' nanostructure, electrochemical properties, and surface chemistry could lead to increased energy densities, faster charging speeds, and longer cycle lifetimes. This would make it easier for more people to use renewable energy devices (M. Królikowski et al., 2024).

IV. **Biomedical Applications**: Potential biological uses for carbon nanoparticles include imaging, drug delivery, and tissue engineering, among many others. Theranostic imaging, site-specific medication delivery, and cellular and molecular-level management of biological processes are all areas that might lead to medical breakthroughs. Another perk of this development is that regenerative and personalised treatments are now easier to obtain.

V. **Environmental Remediation Technologies**: Nanostructured carbon has the potential to help clean up contaminated groundwater, soil, and air. Combining nanomaterials with chemical or biological treatments might be synergistic for researchers looking to create cleansers with improved lifetime and effectiveness. The scientific community ought to follow this course of action. Future research and development efforts may aim to advance nanotechnology-driven cleanup solutions. Poisons like per- and polyfluoroalkyl substances (PFAS) are becoming an increasingly serious problem, and this measure could be implemented to help.

VI. **Smart and Functional Materials**: Carbon nanoparticles are only one example of the many smart and useful materials that may be created by chemical synthesis. The properties and use of these materials vary widely. Nanocomposites with enhanced electrical, thermal, or mechanical characteristics might be the subject of future study to meet the demands of high-tech engineering. Research into creating materials that can repair themselves, clean themselves, or respond to stimuli is also possible.

VII. **Nanoelectronics and Quantum Technologies**: Graphene, carbon nanotubes, and other carbon nanostructures have remarkable properties that might lead to quantum computing and nanoelectronics breakthroughs. Graphene sensors and the connections between transistors are potentially game-changing for future electronics. Quantum sensing, communication, and computation are the main research areas for carbon-based materials. The materials can be added in the usual way.

Carbon nanoparticles could be useful in several fields, such as computing, ecology, medicine, and energy storage. Their exciting and complex adventure is just around the corner. Engineers and scientists may use these traits to create a better, more interdependent, and more advanced future while solving big social problems.

Summary

Carbon nanoparticles' large surface area and great reactivity have made them highly desirable for water filtration and heavy metal detection applications. Despite the many benefits, making use of these resources is difficult. In the early stages of production, nanomaterials, particularly high-quality ones like graphene and carbon nanotubes, can be expensive and energy-consuming. Complex synthesis methods hinder scalability in commercial applications since they require specialized equipment and skilled workers' knowledge. Additional research and risk evaluations are required to fully comprehend the ecological and human health effects of carbon nanotubes and graphene oxide in the long run.

Matrix components may diminish the effectiveness of carbon nanoparticles in water treatment, and they may not have the necessary selectivity and specificity to detect heavy metals. In addition to the challenges presented by legislation and safety concerns, the implementation process is further complicated by the need to adhere to health and environmental laws. This could lead to an increase in both the time and money needed for the treatment. Extreme conditions pose significant risks to the stability and durability of materials, making continuous operating scenarios extremely challenging. Despite the present challenges, carbon nanomaterials nevertheless have promising prospects. Their full potential in various domains is the target of present-day R&D efforts. Carbon nanoparticles have the potential to greatly enhance detection capabilities when combined with current sensing technologies. This could have far-reaching benefits for food safety, medical diagnostics, and environmental monitoring.

Modern water treatment systems use nanoparticle filtration membranes and new adsorbent materials to improve disinfection, purification, and pollution removal. Researchers are actively using carbon nanoparticles to improve the performance and efficiency of several energy storage systems, including fuel cells and supercapacitors. They may improve personalized and regenerative biomedical treatments through targeted drug delivery, theranostic imaging, and tissue engineering. Using carbon nanoparticles in environmental remediation offers new ways to deal with recently discovered toxins and could work with other treatments, such as chemical and biological ones.

Quantum technology, nanoelectronics, and the incorporation of carbon nanoparticles into novel and practical materials could revolutionize electronics, sensing, and communication. As a result of this revolution, programs will soon be able to fix themselves, respond to outside stimuli, and clean themselves.

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