Biological and Clinical Sciences Research Journal
eISSN: 2708-2261; pISSN: 2958-4728
www.bcsrj.com
DOI: https://doi.org/10.54112/bcsrj.v2024i1.1052
Biol. Clin. Sci. Res. J., Volume, ***2024****: 1052*
Review Article

ADSORPTION OF ORGANIC COMPOUNDS AND HAZARDOUS MICROORGANISMS FROM SEWAGE AND SURFACTANT-CONTAINING WASTEWATER USING CARBON-BASED NANOMATERIALS: A FOCUS ON GRAPHENE OXIDE AND CARBON NANOTUBE

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(Received, 25th May 2024, Revised 18th August 2024, Published 24th August 2024)

Abstract: *This review comprehensively examines the utilization of carbon-based nanomaterials, specifically graphene oxide (GO) and carbon nanotubes (CNTs), in advanced wastewater treatment applications. GO and CNTs demonstrate exceptional efficacy in adsorbing a broad spectrum of organic compounds and hazardous microorganisms due to their unique physicochemical properties, such as large specific surface areas, high aspect ratios, and versatile chemical modifications enabled by functional groups. GO is characterised by abundant oxygen-containing groups, including hydroxyl, carboxyl, and epoxy, which enhance its hydrophilicity and adsorption potential for cationic pollutants. Meanwhile, CNTs, available as single-walled (SWCNTs) and multi-walled (MWCNTs), are noted for their tubular structure, high tensile strength, and significant electrical conductivity, making them highly effective in adsorbing organic molecules and heavy metals. The review explores the mechanisms of action of these nanomaterials, which encompass physical adsorption through van der Waals forces and π-π interactions, as well as chemical adsorption involving covalent or ionic bond formation with contaminants. Recent innovations in hybrid systems that integrate GO and CNTs with other technologies, such as photocatalysis and membrane filtration, are highlighted for enhancing contaminant removal and energy efficiency in water purification processes. The review addresses critical challenges related to nanoparticle stability, recovery, production costs, and the environmental and health impacts of deploying these nanomaterials in practical applications. Crucial issues, such as nanoparticle aggregation, reusability, and the safe disposal of used materials, are identified, with potential solutions including surface modifications to improve dispersion and the incorporation of magnetic nanoparticles for easier recovery. The findings emphasise the significant potential of GO and CNTs in advancing environmental remediation technologies, offering promising avenues for developing cleaner and more efficient water treatment solutions. As the field progresses, the continued exploration and interdisciplinary collaboration promise substantial water purification and environmental protection advancements.*

Keywords: Graphene Oxide, Carbon Nanotubes, Wastewater Treatment, Adsorption, Nanotechnology

Introduction

The contamination of water resources with diverse pollutants is a critical global issue, posing substantial risks to both environmental integrity and human health; among the vast array of contaminants, organic compounds and hazardous microorganisms found in sewage and surfactant-containing wastewater present significant removal challenges due to their complex chemical structures and intricate interactions with aqueous matrices (Fida et al., 2023; Kotun et al., 2023). These pollutants originate from various sources, including industrial effluents, agricultural runoff, and household discharges. Surfactants, in particular, represent a class of amphiphilic compounds extensively utilised in detergents, emulsifiers, and dispersants. They play a critical role in stabilising and mobilising other pollutants, thereby complicating their extraction through conventional water treatment methods (Ganesan et al., 2024; Khalfallah, 2023; Ullah et al., 2024a). Sewage and surfactant-laden effluents typically harbour a heterogeneous mixture of pharmaceuticals, personal care products, endocrine-disrupting chemicals (EDCs), and pathogenic microorganisms, such as bacteria, viruses, and protozoa (Fatima et al., 2024; Priyadarshini et al., 2022). For instance, common organic pollutants include pharmaceuticals like acetaminophen and ibuprofen, present in concentrations up to 10 µg/L and 1.0 mg/L, respectively. Endocrine disruptors, such as bisphenol A (BPA), can be found at concentrations up to 0.5 mg/L, while surfactants like linear alkylbenzene sulfonates (LAS) may reach levels as high as 30 mg/L (Das et al., 2023; Waseem et al., 2023). These contaminants can cause severe ecological disruptions, including the alteration of aquatic ecosystems, interference with reproductive functions in wildlife, and the proliferation of antibiotic-resistant microbial strains.

The presence of these contaminants in aquatic environments poses serious public health risks. Exposure to contaminated water can lead to a range of adverse health outcomes, from acute conditions like gastrointestinal infections to chronic

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diseases, including endocrine disorders and antibiotic-resistant infections. The increasing prevalence of such contaminants highlights the urgent need for effective water treatment solutions (Haidri et al., 2024).

In recent years, nanotechnology has emerged as a transformative approach to environmental remediation, particularly in water treatment applications (Mondal et al., 2023). Carbon-based nanomaterials, such as graphene oxide (GO) and carbon nanotubes (CNTs), have gained prominence due to their exceptional physicochemical properties (Ali et al., 2023; Ummer et al., 2023). GO and CNTs exhibit high adsorption capacities, attributable to their extensive specific surface areas, which can exceed 1000 m^2/g in the case of CNTs. These nanomaterials also possess significant mechanical strength. CNTs demonstrate tensile strengths up to 100 GPa and excellent chemical stability, ensuring their durability in harsh environmental conditions (Leroy, 2023; Ullah et al., 2024b).

Furthermore, the surface chemistry of these nanomaterials can be precisely tailored through functionalisation, allowing for the introduction of various chemical groups that enhance their affinity for specific contaminants (Baig et al., 2024; Batool et al., 2024). For example, GO can be functionalised with carboxyl (-COOH) and hydroxyl (-OH) groups, increasing its hydrophilicity and adsorption potential for cationic pollutants. Similarly, CNTs can be functionalised with amine groups ($-NH_2$) to improve their interaction with anionic contaminants. These versatile functionalisation capabilities, combined with their intrinsic properties, position GO and CNTs as potent tools in advancing water purification technologies, offering innovative solutions for addressing complex contamination challenges (Kanani-Jazi & Akbari, 2024; Kumar et al., 2023). This review aims to comprehensively assess the application of graphene oxide and carbon nanotubes in treating sewage and surfactant-containing wastewater. The focus will be on the adsorption mechanisms and the nanomaterials' efficacy in removing a range of organic compounds and hazardous microorganisms. Specifically, the review will explore the structural properties and functionalisation of GO and CNTs, the adsorption kinetics and isotherms, and the challenges associated with their use, including environmental and safety concerns.

The review will also provide an in-depth analysis of recent advancements in the field, highlighting critical studies and data demonstrating these nanomaterials' potential in practical water treatment applications. Furthermore, the review will discuss the limitations and challenges faced in implementing these technologies, such as nanoparticle recovery, reusability, and regulatory hurdles. By presenting a detailed overview of the current state of research and future directions, this review aims to provide valuable insights into the potential of carbon-based nanomaterials in addressing the pressing issue of water pollution.

Characterisation of Sewage and Surfactant-Containing Wastewater

Contaminant Profiles

Common Organic Compounds:

Sewage and surfactant-containing wastewater are complex mixtures laden with various organic compounds. These include detergents, pharmaceuticals, personal care products, endocrine-disrupting chemicals (EDCs), and other household and industrial chemicals. The concentration of these compounds can vary significantly depending on the source and level of industrialisation. For example, detergents containing surfactants are ubiquitously present in wastewater due to their extensive use in domestic cleaning products. Anionic surfactants like linear alkylbenzene sulfonates (LAS) are particularly common, with concentrations ranging from 1 to 30 mg/L in municipal wastewater (Wang et al., 2024; Zhu et al., 2023).

Pharmaceuticals, another significant group of organic pollutants, enter wastewater streams primarily through human excretion and the improper disposal of unused medications. These substances include antibiotics, analgesics, hormones, and other medications. Concentrations of pharmaceuticals in wastewater can vary widely; for instance, acetaminophen has been detected at concentrations up to 10 µg/L, while certain antibiotics can reach one µg/L levels. These compounds pose a risk of developing antibiotic-resistant bacteria and potential disruptions to aquatic organisms' endocrine systems (Gorgaslidze et al., 2024; Khan & Barros, 2023). *Table 1* presents a comprehensive overview of major organic compounds typically found in wastewater and their concentration ranges. The compounds are categorised into various classes: detergents/surfactants, pharmaceuticals, personal care products, endocrine disruptors, and other organic compounds. The concentration ranges indicate the typical levels at which these contaminants can be found in wastewater, highlighting the variability depending on the source and composition of the effluent. For instance, surfactants like LAS can be present at concentrations ranging from 1 to 30 mg/L, while pharmaceuticals such as acetaminophen can range from 0.01 to 10 mg/L.

Table 1: Major Organic Compounds in Wastewater and Their Typical Concentrations

Compound Class	Example Compounds	Typical Concentration Range (mg/L)
Detergents/Surfactants	Linear Alkylbenzene Sulfonates (LAS)	1 - 30
	Sodium Dodecyl Sulfate (SDS)	0.5 - 20
Pharmaceuticals	Acetaminophen	0.01 - 10
	Ibuprofen	0.05 - 1.0
	Antibiotics (e.g., Ciprofloxacin)	0.001 - 1.0
Personal Care Products	Triclosan	0.001 - 0.1
	Parabens (e.g., Methylparaben)	0.01 - 0.5
Endocrine Disruptors	Bisphenol A (BPA)	0.01 - 0.5
	Phthalates (e.g., Diethyl Phthalate)	0.01 - 0.2
Other Organic Compounds	Polycyclic Aromatic Hydrocarbons (PAHs)	0.001 - 0.1
	Pesticides (e.g., Atrazine)	0.001 - 0.05

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Presence of Hazardous Microorganisms:
In addition to chemical pollutants, sewage and surfactant-laden wastewater are reservoirs of various pathogenic microorganisms. These include bacteria, viruses, protozoa, and helminths, which can pose severe public health risks if not adequately treated. Common bacterial pathogens in wastewater include Escherichia coli, Salmonella spp., and Vibrio cholerae. Viral contaminants can range from enteric viruses such as norovirus and rotavirus to more concerning agents like hepatitis A and enteroviruses (Abbas et al.). Protozoan pathogens, such as Giardia lamblia and Cryptosporidium parvum, are also frequently present and are known for their resilience to conventional disinfection methods (Jena et al., 2023; Siddique et al., 2024). *Table 2* provides a detailed overview of hazardous microorganisms commonly found in wastewater and their characteristics and typical concentrations. The microorganisms are categorised into four main types: bacteria, viruses, protozoa, and helminths. Each type is further exemplified by specific species known to pose health risks. The table includes critical characteristics such as gram staining for bacteria, enveloped or non-enveloped nature for viruses, and cysts or oocysts for protozoa. Typical concentration ranges, expressed in colony-forming units per millilitre (CFU/mL), indicate the prevalence of these microorganisms in wastewater.

Table 2: Types and Characteristics of Hazardous Microorganisms in Wastewater

Microorganism Type	Example Species	Characteristics	Typical Concentration (CFU/mL)
Bacteria	*Escherichia coli*	Gram-negative indicator of faecal contamination	10^3 - 10^6
	Salmonella spp.	Gram-negative, pathogenic, causes foodborne illness	10^1 – 10^4
	Vibrio cholera	Gram-negative, causes cholera	10^0 - 10^2
Viruses	Norovirus	Non-enveloped, highly contagious, causes gastroenteritis	10^0 - 10^3
	Enteroviruses	Non-enveloped, includes poliovirus	10^0 - 10^3
	Hepatitis A	Non-enveloped, causes liver infection	10^0 - 10^2
Protozoa	*Giardia lamblia*	Cyst-forming causes giardiasis	10^0 - 10^2
	Cryptosporidium parvum	Oocyst-forming, resistant to chlorination, causes cryptosporidiosis	10^0 – 10^1
Helminths	*Ascaris lumbricoides*	Nematode causes ascariasis, eggs are highly resistant	10^0 - 10^2
	Taenia spp.	Tapeworm causes taeniasis	10^0 – 10^1

Impact of Surfactants
Surfactants, as amphiphilic molecules, significantly influence the physicochemical behaviour of contaminants in wastewater. They reduce surface tension and facilitate the emulsification and solubilisation of hydrophobic organic compounds, thus affecting their transport and fate in aquatic environments. The presence of surfactants can alter other contaminants' stability, mobility, and bioavailability. For example, surfactants can increase the solubility of hydrophobic compounds, such as polycyclic aromatic hydrocarbons (PAHs) and pesticides, enhancing their dispersion in the water column and potentially increasing their uptake by aquatic organisms (Bolan et al., 2023; Hartal et al., 2023).
Moreover, surfactants can impact the adsorption behaviour of contaminants on particulate matter and treatment media, influencing the efficiency of removal processes. Anionic surfactants, for instance, can form complexes with cationic pollutants, potentially facilitating their co-precipitation or, conversely, hindering their adsorption on negatively charged surfaces (Luo et al., 2023). Furthermore, surfactants can be resistant to biodegradation, leading to toxic degradation products that can further complicate wastewater treatment processes.
Overall, the complex interplay between organic compounds, microorganisms, and surfactants in sewage and surfactant-containing wastewater underscores the need for advanced treatment technologies. Carbon-based nanomaterials like graphene oxide and carbon nanotubes offer promising solutions due to their unique adsorption properties and ability to interact with various contaminants.

Properties and Functionalization of Carbon-Based Nanomaterials

Graphene Oxide

Structural Properties:
Graphene oxide (GO) is a single-layered material derived from graphene, which consists of carbon atoms arranged in a hexagonal lattice. Unlike pristine graphene, GO is heavily oxidised, resulting in various oxygen-containing functional groups. These functional groups include hydroxyl (-OH), epoxide (-O-), carbonyl (C=O), and carboxyl (-COOH) groups, which are randomly distributed across the basal plane and edges of the graphene sheet. The introduction of these groups disrupts the sp2 hybridised carbon network, creating a sp3 hybridised structure that imparts hydrophilicity to GO. This modification significantly alters graphene's electrical, mechanical, and chemical properties, making GO an excellent candidate for various applications, including water treatment (PAYYAPPILLY et al., 2024; Qiu et al., 2023).
The typical interlayer spacing of GO is larger than that of graphite, often in the range of 0.6-1.2 nm, due to the presence of oxygen groups and water molecules. This increased spacing allows GO to exhibit unique adsorption properties, such as the ability to intercalate ions and molecules, enhancing its potential as an adsorbent for various contaminants in wastewater.

Functional Groups and Reactivity:

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The oxygen-containing functional groups increase its hydrophilicity and provide active sites for chemical reactions. These groups can interact with various pollutants through hydrogen bonding, electrostatic interactions, and π-π stacking. For example, carboxyl groups can form strong ionic bonds with cationic pollutants, while aromatic rings can interact with organic molecules through π-π interactions. This interaction versatility enables GO to adsorb various contaminants, including heavy metals, organic dyes, and pharmaceuticals (Kong et al., 2023; Zhao et al., 2024).

Synthesis Methods:

Graphene Oxide groups are typically synthesised from graphite using the Hummers' method, a widely adopted chemical oxidation process (Omar et al., 2023). This method involves the oxidation of graphite with a mixture of potent oxidising agents, such as potassium permanganate (KMnO4) and concentrated sulfuric acid (H2SO4). The process generates highly oxidised GO sheets that can be exfoliated into individual layers. Variations of the Hummers' method have been developed to improve the yield and quality of GO, such as the modified Hummers' method, which uses phosphoric acid (H3PO4) to reduce the formation of toxic gases and improve the oxidation efficiency.

Carbon Nanotubes

Structural Variants:

Carbon nanotubes (CNTs) are cylindrical nanostructures composed of rolled-up graphene sheets. They are classified into two primary types based on the number of graphene layers: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs). SWCNTs consist of a single graphene cylinder with a diameter typically ranging from 0.6 to 2 nm. In contrast, MWCNTs comprise multiple concentric graphene cylinders, with diameters ranging from 2 to 100 nm and interlayer distances similar to the spacing in graphite (~0.34 nm) (Rudyak et al., 2024; Sacco & Vollebregt, 2023). The unique tubular structure of CNTs endows them with extraordinary mechanical strength, electrical conductivity, and thermal stability.

Synthesis Techniques:

CNTs are commonly synthesised using chemical vapour deposition (CVD), arc discharge, and laser ablation methods. CVD is the most widely used among these due to its scalability and ability to produce high-purity CNTs with controlled diameters and lengths. In the CVD process, a carbon-containing gas, such as methane (CH4), is decomposed at high temperatures (600-1200°C) in the presence of a metal catalyst, typically iron (Fe), cobalt (Co), or nickel (Ni). The carbon atoms precipitate on the catalyst surface, forming CNTs. Adjusting the reaction parameters, such as temperature, gas flow rate, and catalyst composition, the properties of the resulting CNTs can be fine-tuned (Khovavko et al., 2024). *Table 3* compares the physical and chemical properties of graphene oxide (GO) and carbon nanotubes (CNTs). The table highlights key differences in structure, thickness, surface area, oxygen content, functional groups, electrical conductivity, thermal conductivity, mechanical strength, chemical reactivity, hydrophilicity, and typical applications. For instance, GO is characterised by its single-layered structure, high oxygen content, and various functional groups, which make it highly hydrophilic and chemically reactive. In contrast, CNTs, available as single-walled (SWCNTs) and multi-walled (MWCNTs) variants, possess cylindrical structures, low oxygen content, and exceptional electrical and thermal conductivity, making them suitable for electronic and composite applications. The differences in these properties underscore each nanomaterial's unique capabilities and potential applications in various fields, including water treatment, electronics, and material science.

Table 3: Comparison of Physical and Chemical Properties of Graphene Oxide and Carbon Nanotubes

Property	Graphene Oxide (GO)	Carbon Nanotubes (CNTs)
Structure	Single-layered, hexagonal carbon lattice	Cylindrical, rolled graphene sheets
Layer Thickness	0.6 - 1.2 nm	SWCNTs: 0.6 - 2 nm, MWCNTs: 2 - 100 nm
Surface Area	150 - 300 m^2/g	200 - 1000 m^2/g
Oxygen Content	High, due to functional groups (up to 50% by weight)	Low, typically less than 1%
Functional Groups	Hydroxyl, epoxy, carbonyl, carboxyl	Primarily inert; can be functionalised (e.g., -COOH)
Electrical Conductivity	Insulating to semi-conductive	Conductive (metallic and semiconducting)
Thermal Conductivity	~ 0.5 W/mK (depends on reduction level)	SWCNTs: 2000 - 6000 W/mK, MWCNTs: 3000 W/mK
Mechanical Strength	Tensile strength ~ 130 MPa	SWCNTs: 50 - 200 GPa, MWCNTs: up to 100 GPa
Chemical Reactivity	High, due to the presence of oxygen-containing groups	Low, unless functionalised
Hydrophilicity	High, due to polar functional groups	Low, but can be increased with functionalisation
Typical Applications	Adsorption, catalysis, sensors	Electronics, composites, water treatment

Functionalisation:

The surface of CNTs is chemically inert, necessitating functionalisation to enhance their dispersibility in aqueous solutions and their ability to interact with contaminants (Krishna et al., 2023). Functionalisation can be achieved through covalent or non-covalent methods. Covalent functionalisation involves attaching functional groups to the CNT surface via chemical reactions, such as acid treatment, which introduces carboxyl and hydroxyl groups. This process increases the hydrophilicity of CNTs and provides

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active sites for pollutant adsorption. Non-covalent functionalisation, on the other hand, involves the adsorption of surfactants, polymers, or biomolecules onto the CNT surface through van der Waals forces or π-π interactions, preserving the inherent electronic properties of CNTs.
Functionalised CNTs exhibit enhanced adsorption capacities for various pollutants due to the increased availability of binding sites and improved dispersion in water. For instance, CNTs functionalised with amine groups can effectively remove anionic dyes through electrostatic attraction, while those with carboxyl groups can adsorb heavy metal ions (Krishna et al., 2023). Functionalisation's versatility makes CNTs highly effective in removing many contaminants from wastewater. *Table 4* outlines standard functionalisation techniques for modifying carbon-based nanomaterials, such as graphene oxide and carbon nanotubes, and their effects on adsorption capabilities. The table briefly describes each technique, the primary functional groups introduced, and the resultant impact on the nanomaterials' adsorption properties. For instance, acid treatment introduces carboxyl and hydroxyl groups, enhancing the material's hydrophilicity and adsorption capacity for heavy metals and organic pollutants. Amination introduces amine groups, which improve the adsorption of anionic species through electrostatic interactions. Other methods, such as silane functionalisation and polymer grafting, enhance the stability and dispersibility of nanomaterials in aqueous solutions, making them suitable for various applications like catalysis and targeted adsorption. Non-covalent functionalisation, which involves the adsorption of molecules onto the nanomaterial surface, maintains the material's intrinsic properties while improving dispersion and interaction with target pollutants.

Table 4: Common Functionalization Techniques and Their Effects on Adsorption Capabilities

Functionalization Technique	Description	Target Functional Groups	Effect on Adsorption Capabilities	Applications
Acid Treatment	Oxidation using strong acids (HNO3</sub>, H2SO4)	-COOH, -OH, -CO	Increases hydrophilicity and introduces carboxyl groups; enhances adsorption of heavy metals and organic molecules	Water purification, sensors
Amination	Grafting amine groups onto the surface	$-NH_2$	Introduces positive charges; improves adsorption of anionic pollutants through electrostatic attraction	Removal of dyes, pharmaceuticals
Silane Functionalization	Attachment of silane compounds to the surface	$-Si(OEt)_3$-SiCl	Provides a platform for further functionalisation; enhances stability and dispersibility in aqueous solutions	Catalysis, drug delivery
Polymer Grafting	Covalent attachment of polymers (e.g., PEG, PVP)	-PEG, -PVP	Increases dispersibility in water; can tailor surface properties for specific adsorption interactions	Targeted adsorption, biocompatibility
Plasma Treatment	Exposure to plasma to modify surface chemistry	Various (depends on gas used)	Introduces various functional groups; can selectively alter surface energy and reactivity	Surface modification, sensors
Non-Covalent Functionalization	Adsorption of surfactants or aromatic compounds	-COOH, -NH2, π-π stacking	Maintains the intrinsic properties of the	Stabilisation in composites, electronics

			nanomaterial; enhances dispersion and adsorption through π-π interactions	

Overall, the unique structural properties and functionalisation capabilities of graphene oxide and carbon nanotubes make them highly suitable for applications in water treatment. Their ability to adsorb a diverse array of contaminants and their high surface area and reactivity offers significant advantages in removing organic compounds and hazardous microorganisms from wastewater. As research progresses, further optimisation of synthesis and functionalisation techniques will continue to enhance the efficacy of these nanomaterials in environmental remediation.

Adsorption Mechanisms and Efficacy

Mechanisms

Physical Adsorption:

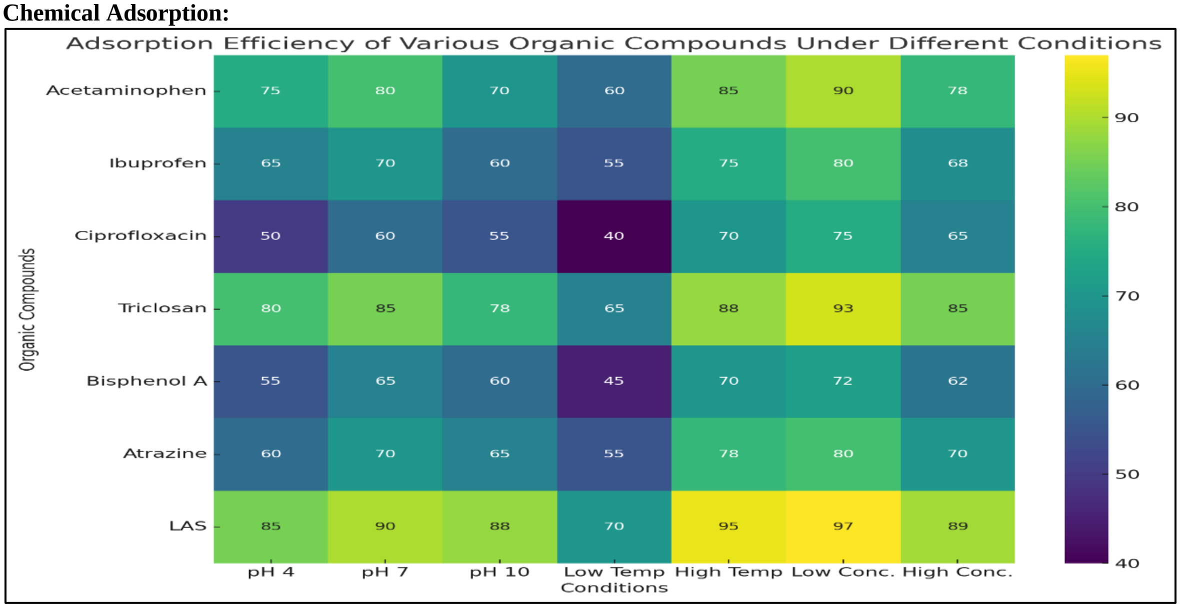
Physical adsorption, or physisorption, involves the adherence of contaminants to the surface of a nanomaterial through weak van der Waals forces. This type of adsorption is typically non-specific and reversible, making it dependent on the surface area and porosity of the adsorbent. In the context of carbon-based nanomaterials like graphene oxide (GO) and carbon nanotubes (CNTs), the extensive surface area and unique surface structures facilitate the adsorption of various organic and inorganic molecules (Krishna et al., 2023). The physisorption process is often favoured at lower temperatures, as increased thermal energy can desorb the adsorbed molecules.

Chemical Adsorption:

Chemical adsorption, or chemisorption, involves the formation of strong chemical bonds between the adsorbate and the adsorbent. This process is generally more specific than physisorption and often involves functional groups present on the surface of the nanomaterials. For instance, oxygen-containing groups on GO, such as carboxyl, hydroxyl, and epoxy groups, can form covalent or ionic bonds with pollutants like heavy metals or organic compounds. Chemisorption is characterised by higher adsorption energy and typically occurs at specific active sites on the nanomaterial's surface (Alcolea-Rodriguez et al., 2024). This type of adsorption is less reversible due to the stronger interactions involved.

Electrostatic Interactions:

Electrostatic interactions play a crucial role in adsorption, mainly when dealing with charged pollutants. Carbon-based nanomaterials can acquire surface charges, either naturally or through functionalisation, influencing their interaction with ionic species in wastewater. For example, GO functionalised with carboxyl groups can adsorb cationic pollutants through electrostatic attraction. Conversely, amine-functionalized CNTs can adsorb anionic species (Gul et al., 2021). The efficiency of electrostatic interactions depends on factors such as pH, ionic strength, and the surface charge density of the nanomaterials.



Graph 1: Heatmap Showing Adsorption Efficiency of Various Organic Compounds under Different Conditions

Graph 1 presents a heatmap that visually represents the adsorption efficiency of various organic compounds under different conditions using graphene oxide (GO) and carbon nanotubes (CNTs). The organic compounds examined include Acetaminophen, Ibuprofen, Ciprofloxacin, Triclosan, Bisphenol A, Atrazine, and LAS (Linear et al.). The conditions vary across pH levels (pH 4, pH 7, pH 10), temperature settings (Low et al.), and concentration ranges (Low Conc., High Conc.).

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The colour gradient indicates the percentage of adsorption efficiency, with darker shades representing higher efficiency. The data reveals significant adsorption performance variations based on the type of organic compound and the specific environmental conditions. For instance, LAS demonstrates high adsorption efficiency across all conditions, particularly at high temperatures and concentrations. In contrast, Ciprofloxacin shows lower adsorption efficiencies, especially under low temperatures and acidic conditions.

This heatmap highlights the complex interplay between the adsorbents' and adsorbates' properties and the influence of environmental factors on adsorption processes. It is a valuable tool for identifying optimal conditions for removing specific contaminants.

Performance Metrics

Adsorption Capacity:

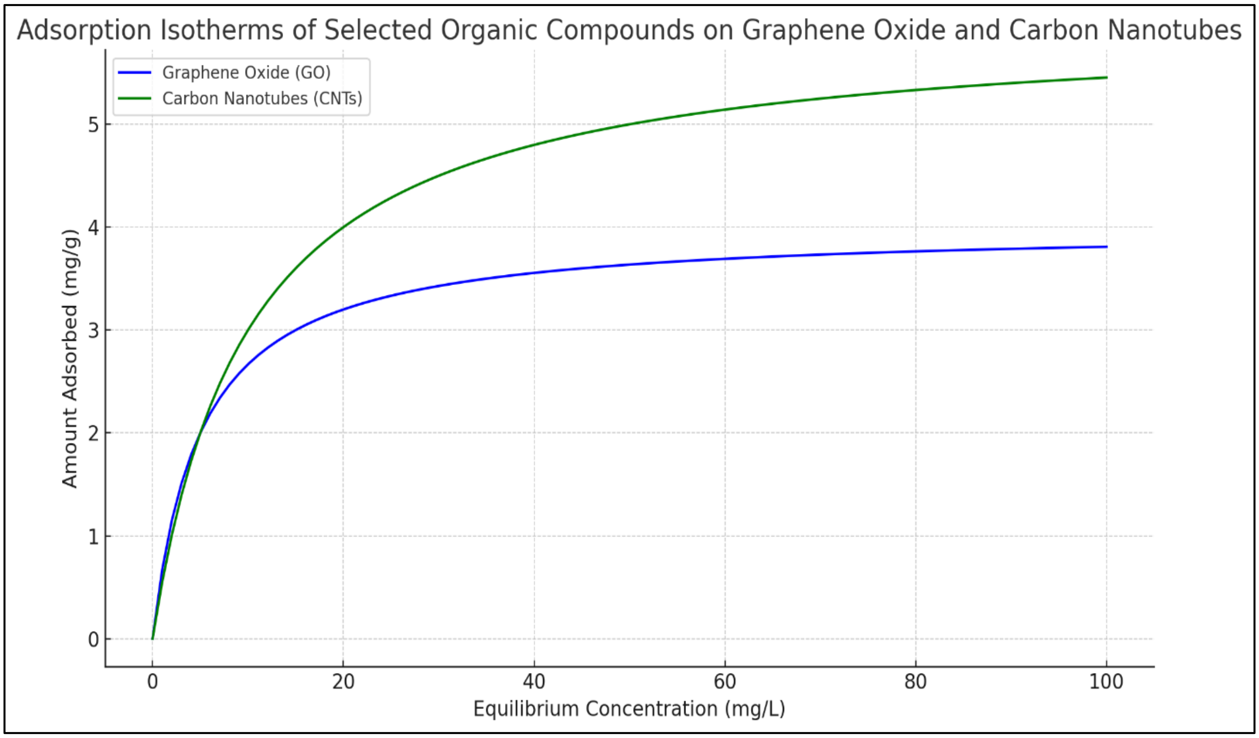
Adsorption capacity is a critical metric that quantifies the maximum amount of contaminant that can be adsorbed per unit weight of the adsorbent. It is typically expressed in milligrams of adsorbate per gram of adsorbent (mg/g). The nanomaterials' surface area, porosity, and functional groups influence the adsorption capacity. For instance, the high surface area of CNTs allows for the adsorption of a substantial amount of organic pollutants. At the same time, the functional groups on GO can provide specific binding sites for metal ions.

Kinetics:

Adsorption kinetics describes the rate at which contaminants are removed from the solution and adsorbed onto the nanomaterial's surface. Kinetic studies provide insight into adsorption mechanisms and help identify the rate-limiting steps. Standard kinetic models include the pseudo-first-order, pseudo-second-order, and intraparticle diffusion models. The pseudo-second-order model, which assumes that chemisorption is the rate-limiting step, often provides a better fit for the adsorption of contaminants onto functionalised nanomaterials (Mohamed Nasser et al., 2024; Sahoo & Prelot, 2020). The rate constants derived from these models can help predict the efficiency and time required for complete adsorption.

Equilibrium Studies:

Equilibrium studies involve the analysis of adsorption isotherms, which describe the relationship between the amount of adsorbate adsorbed and its equilibrium concentration in the solution at a constant temperature. Isotherm models, such as the Langmuir, Freundlich, and Temkin models, are commonly used to analyse the adsorption data. The Langmuir model, which assumes monolayer adsorption on a homogeneous surface, is beneficial for describing the adsorption of single species onto nanomaterials with uniform surface properties (Hu et al., 2023; Lima et al., 2015). The Freundlich model, which accounts for heterogeneous surface adsorption, applies to systems with multiple adsorbate species or varying surface characteristics. These models provide parameters such as the maximum adsorption capacity and the adsorption affinity, which are essential for designing and optimising adsorption processes.



Graph 2: Adsorption Isotherms of Selected OrganicCompounds on Graphene Oxide and Carbon Nanotubes

Graph 2 illustrates the adsorption isotherms of selected organic compounds on graphene oxide (GO) and carbon nanotubes (CNTs). The graph depicts the relationship between the equilibrium concentration of the organic compounds in the solution (mg/L) and the amount adsorbed onto the nanomaterial (mg/g). The isotherms are modelled using the Langmuir adsorption model, which assumes monolayer adsorption on a homogeneous surface.

The data indicates that graphene oxide (represented by the blue curve) exhibits a higher adsorption capacity than carbon nanotubes (represented by the green curve) at lower equilibrium concentrations. This difference is attributed to oxygen-containing functional groups on GO, which provide additional binding sites for organic molecules. As the equilibrium concentration increases, the adsorption capacity of both materials reaches a plateau, indicating saturation of the available adsorption sites.

Therefore, carbon-based nanomaterials' adsorption mechanisms and efficacy are governed by a combination of physical adsorption, chemical adsorption, and electrostatic interactions. The performance of these materials as adsorbents is evaluated through metrics such as adsorption capacity, kinetics, and equilibrium studies. These factors are crucial for understanding the behaviour of contaminants in wastewater and developing effective treatment strategies.

Removal of Hazardous Microorganisms

Antimicrobial Activity

Mechanisms of Action against Bacteria and Viruses: Graphene oxide (GO) and carbon nanotubes (CNTs) exhibit potent antimicrobial properties due to several mechanisms. The antimicrobial activity primarily targets the structural integrity of microbial cells and the disruption of vital biological processes.

1. **Physical Disruption:** The sharp edges of GO and the needle-like structure of CNTs can physically damage bacterial cell membranes. This "nano knife" effect leads to the cell envelope's disruption, resulting in cellular contents' leakage and eventual cell death (Hu et al., 2021). This mechanism is particularly effective against Gram-negative bacteria, which possess a thinner peptidoglycan layer than Gram-positive bacteria.
2. **Oxidative Stress:** The presence of oxygen-containing functional groups on GO can generate reactive oxygen species (ROS), such as superoxide anions and hydroxyl radicals. These ROS can induce oxidative stress in microbial cells, damaging cellular components such as lipids, proteins, and nucleic acids (Ghulam et al., 2022). The oxidative stress mechanism is also observed with CNTs, especially when they are functionalised with oxidative groups.
3. **Electron Transfer Interference:** GO and CNTs can interfere with microbial electron transfer processes. These nanomaterials can disrupt ATP production by interacting with the electron transport chain, leading to energy depletion and cell death. This mechanism is particularly relevant for aerobic microorganisms that rely heavily on oxidative phosphorylation (Dong et al., 2023; Naaz et al., 2023).
4. **DNA Interaction:** GO and CNTs can adsorb and intercalate with DNA molecules, inhibiting replication and transcription. This interaction can lead to genetic mutations or inhibit the expression of essential genes, further contributing to microbial lethality (Mascarenhas et al., 2023).
5. **Metal Ion Release:** When functionalised with metal nanoparticles (e.g., silver, copper), CNTs can release metal ions that possess intrinsic antimicrobial properties. These ions can bind to thiol groups in proteins, disrupting their function or generating additional ROS, enhancing the antimicrobial effect (Skłodowski et al., 2023).

Case Studies

Graphene Oxide: A study by Lavrikova et al. (2024) demonstrated the efficacy of GO in inactivating *Escherichia coli* and *Staphylococcus aureus*. The study reported a significant reduction in bacterial viability, with a complete inactivation observed within two hours at a concentration of 1 mg/mL GO. The primary mechanisms were physical disruption and oxidative stress induced by GO.

Another study by Kwiatkowska and Granicka (2023) focused on the antiviral activity of GO against enteric viruses. The results indicated that GO could adsorb viral particles, reducing their infectivity. The antiviral mechanism was attributed to the physical entrapment of viruses on the GO surface and the subsequent inhibition of viral attachment to host cells.

Carbon Nanotubes: Maksimova et al. (2023) investigated the antibacterial activity of SWCNTs against *E. coli*. The study found that SWCNTs at a 10 µg/mL concentration could reduce bacterial viability by over 90% within 30 minutes. The primary mechanisms were identified as membrane damage and oxidative stress.

CNTs have also been explored for their antiviral properties. In a study examining the inactivation of the influenza virus, MWCNTs functionalised with silver nanoparticles showed enhanced antiviral activity. The metal ions released from the MWCNTs contributed to the inactivation of the viral particles, demonstrating the potential of hybrid nanomaterials in pathogen control.

Applications and Implications: The antimicrobial properties of GO and CNTs make them promising candidates for various applications, including water disinfection, medical devices, and surface coatings. However, using these nanomaterials in real-world applications must consider potential cytotoxicity to human cells and the environmental impact of nanomaterial release. *Graph 3* presents a radar chart comparing the efficiency of graphene oxide (GO) and carbon nanotubes (CNTs) in removing microorganisms, evaluated across five key factors: Antimicrobial Efficiency, Stability, Reusability, Environmental Impact, and Cost. The ratings for each factor are plotted on a scale from 0 to 10, with higher values indicating better performance.

- **Antimicrobial Efficiency:** GO scores higher (8) than CNTs (7), indicating superior effectiveness in inactivating microorganisms.
- **Stability:** CNTs exhibit better stability (8) under varying conditions than GO (7), suggesting greater resilience during usage.
- **Reusability:** Both materials have moderate reusability, with GO rated at six and CNTs at 5.
- **Environmental Impact:** GO has a slightly lower environmental impact (5) than CNTs (4), possibly due to lesser concerns regarding cytotoxicity and persistence.
- **Cost:** CNTs are relatively more expensive (5) than GO (4), reflecting the current market prices and synthesis complexities.

The filled areas represent the overall performance of each nanomaterial across these criteria. GO shows a balanced profile with strong antimicrobial properties and lower cost,

[Citation: Younas, A., Rashad, M., Rafaqat, A., Maqbool, H., Gul, K., Ahmad, M., Shahbaz, J., Kanwal, K.U., Umair, M. (2024). Adsorption of organic compounds and hazardous microorganisms from sewage and surfactant-containing wastewater using carbon-based nanomaterials: a focus on graphene oxide and carbon nanotube. *Biol. Clin. Sci. Res. J.*, **2024**: 1052. doi: https://doi.org/10.54112/bcsrj.v2024i1.1052]

while CNTs excel in stability but have a higher environmental impact.

Therefore, graphene oxide and carbon nanotubes exhibit multifaceted antimicrobial activities against various microorganisms, including bacteria and viruses. The combination of physical disruption, oxidative stress, and other mechanisms provides a comprehensive approach to microbial control. The case studies presented highlight the effectiveness of these nanomaterials in laboratory settings, offering insights into their potential for broader applications in antimicrobial treatments.

Environmental and Safety Considerations

Toxicological Concerns

Deploying carbon-based nanomaterials, such as graphene oxide (GO) and carbon nanotubes (CNTs), in water treatment and other applications raises significant toxicological concerns. The unique properties that make these materials effective in contaminant removal also pose potential risks to aquatic life and human health.

Aquatic Toxicity:

Studies have shown that GO and CNTs can exhibit toxicity to aquatic organisms, including algae, crustaceans, and fish. The mechanisms of toxicity vary depending on the organism and the specific properties of the nanomaterial. For instance, the sharp edges of GO sheets can cause physical damage to cell membranes, while the oxidative potential of both GO and CNTs can generate reactive oxygen species (ROS), leading to oxidative stress (Gamoń et al., 2023; Shinde et al., 2023). This stress can result in lipid peroxidation, protein denaturation, and DNA damage, ultimately causing cell death. The acute toxicity of these nanomaterials is often concentration-dependent, with higher doses leading to more severe effects.

In algae, for example, exposure to high concentrations of GO (e.g., >10 mg/L) has been associated with inhibited growth, chlorophyll degradation, and reduced photosynthetic efficiency. In crustaceans such as Daphnia magna, CNTs have been observed to accumulate in the gut, causing physical obstruction and impairing feeding (Ahmed et al., 2023; You et al., 2023). Fish exposed to CNTs have shown signs of gill inflammation, oxidative stress, and changes in liver enzyme activity, indicating potential systemic toxicity.

Human Health Risks:

The potential human health risks associated with exposure to carbon-based nanomaterials are an active research area. Inhalation, dermal contact, and ingestion are humans' primary routes to exposure. Inhalation of airborne CNTs, for example, can lead to pulmonary inflammation and fibrosis, similar to the effects observed with asbestos fibres. The high aspect ratio and persistence of CNTs contribute to their potential to cause respiratory issues (Seidel et al., 2023).

When ingested or injected, GO has shown some level of biocompatibility but can still cause immune responses, oxidative stress, and cytotoxicity at high concentrations. The interactions between GO and biological membranes, proteins, and DNA are complex and can result in various biochemical perturbations (Ayreen et al., 2024; Fantini et al., 2024). While the toxicity profile of GO is generally considered lower than that of CNTs, the risk assessment must consider factors such as dose, exposure duration, and the specific functionalisation of the nanomaterials. *Table 5* comprehensively summarises toxicity studies related to graphene oxide (GO) and carbon nanotubes (CNTs), focusing on various organisms and test models. The table outlines the observed toxicological effects, exposure concentrations, duration of exposure, and key findings for each study.

For instance, GO has been shown to cause reduced mobility and oxidative stress in *Daphnia magna* at concentrations ranging from 0.1 to 10 mg/L over 48 hours. In zebrafish (*Danio rerio*), exposure to GO concentrations of 0.5 to 5 mg/L for 96 hours resulted in gill inflammation and altered liver enzyme activity, suggesting potential systemic toxicity. Additionally, studies on human lung cells (A549) indicate that GO can induce cytotoxicity and DNA damage at 1 to 50 µg/mL concentrations over 24 hours.

Similarly, CNTs have been associated with membrane damage and growth inhibition in *Escherichia coli* at 5 to 50 µg/mL concentrations within 24 hours. In *Daphnia magna*, CNT exposure at 0.1 to 5 mg/L for 72 hours led to gut obstruction and oxidative stress. Human bronchial epithelial cells (BEAS-2B) exposed to CNTs at 0.1 to 10 µg/mL for 48 hours showed increased inflammation and oxidative stress.

These findings highlight the potential risks of using carbon-based nanomaterials, emphasising the need to consider their environmental and health impacts carefully.

Table 5: Summary of Toxicity Studies Related to Graphene Oxide and Carbon Nanotubes

Nanomaterial	Organism/Test Model	Toxicological Effects	Exposure Concentration	Duration	Key Findings
Graphene Oxide	*Daphnia magna*	Reduced mobility, oxidative stress	0.1 - 10 mg/L	48 hours	GO induces oxidative stress and physical damage to the exoskeleton, impairing mobility.
Graphene Oxide	*Danio rerio* (zebrafish)	Gill inflammation, altered liver enzyme activity	0.5 - 5 mg/L	96 hours	GO causes inflammation in gill tissues and alters liver enzyme levels, indicating

[Citation: Younas, A., Rashad, M., Rafaqat, A., Maqbool, H., Gul, K., Ahmad, M., Shahbaz, J., Kanwal, K.U., Umair, M. (2024). Adsorption of organic compounds and hazardous microorganisms from sewage and surfactant-containing wastewater using carbon-based nanomaterials: a focus on graphene oxide and carbon nanotube. *Biol. Clin. Sci. Res. J.*, **2024***: 1052*. doi: https://doi.org/10.54112/bcsrj.v2024i1.1052]

					potential systemic toxicity.
Graphene Oxide	Human lung cells (A549)	Cytotoxicity, DNA damage	1 - 50 µg/mL	24 hours	GO induces cytotoxic effects and DNA damage in a dose-dependent manner.
Carbon Nanotubes	*Escherichia coli*	Membrane damage, growth inhibition	5 - 50 µg/mL	24 hours	CNTs cause significant damage to bacterial cell membranes, leading to reduced cell viability.
Carbon Nanotubes	*Daphnia magna*	Gut obstruction, oxidative stress	0.1 - 5 mg/L	72 hours	CNTs accumulate in the gut, causing physical obstruction and oxidative stress.
Carbon Nanotubes	Human bronchial epithelial cells (BEAS-2B)	Inflammation, oxidative stress	0.1 - 10 µg/mL	48 hours	CNT exposure leads to increased inflammatory response and oxidative stress in lung cells.

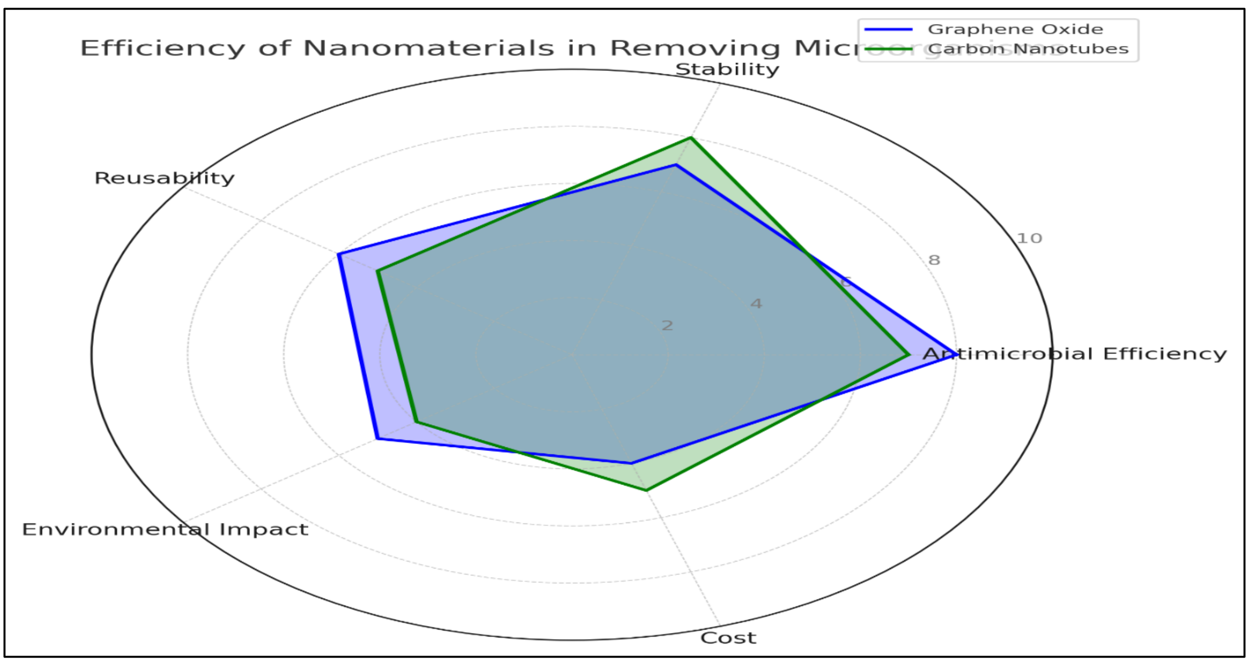
Graph 3: Radar Chart Illustrating the Efficiency of Nanomaterials in Removing Different Types of Microorganisms, Showing Factors like Antimicrobial Efficiency, Stability, Reusability, Environmental Impact, and Cost

Environmental Impact

The environmental impact of GO and CNTs is multifaceted, encompassing their persistence, mobility, and potential for bioaccumulation in the ecosystem.

Persistence and Degradation:

GO and CNTs are highly stable materials, which raises concerns about their persistence in the environment. The chemical inertness of CNTs, particularly in their pristine form, makes them resistant to biodegradation (Darvishi et al., 2023; Ibrahim et al., 2023). However, functionalisation can enhance their degradation under specific conditions, such as exposure to UV light or oxidative agents. Being more chemically reactive, GO has a relatively higher potential for transformation and degradation in natural environments, especially under oxidative conditions.



[Citation: Younas, A., Rashad, M., Rafaqat, A., Maqbool, H., Gul, K., Ahmad, M., Shahbaz, J., Kanwal, K.U., Umair, M. (2024). Adsorption of organic compounds and hazardous microorganisms from sewage and surfactant-containing wastewater using carbon-based nanomaterials: a focus on graphene oxide and carbon nanotube. *Biol. Clin. Sci. Res. J.*, **2024***: 1052*. doi: https://doi.org/10.54112/bcsrj.v2024i1.1052]

Nonetheless, the byproducts of such degradation processes can still pose ecological risks (Ahmadi & Kim, 2024).

Mobility and Bioaccumulation:

The mobility of these nanomaterials in water systems is influenced by their surface charge, size, and the presence of natural organic matter. GO, being hydrophilic, tends to remain dispersed in water, while CNTs can aggregate, reducing their mobility. The potential for bioaccumulation is a significant concern, particularly for CNTs, which can adsorb onto biological tissues and accumulate along the food chain (Li et al., 2024). This bioaccumulation can lead to biomagnification, where higher concentrations of nanomaterials are found in organisms at higher trophic levels, posing risks to predators, including humans.

Long-term Ecological Effects:

The long-term ecological effects of GO and CNTs are still not fully understood. The potential for chronic toxicity, disruption of food webs, and alteration of microbial communities are areas that require further investigation. The release of these nanomaterials into the environment, whether through direct discharge or due to product degradation, necessitates a comprehensive understanding of their life cycle and environmental fate (Mubeen et al., 2023).

While carbon-based nanomaterials hold promise for various applications, including environmental remediation, their potential toxicity and environmental impact cannot be overlooked. Developing safe and sustainable nanotechnology requires rigorous risk assessment, including understanding the mechanisms of toxicity, environmental persistence, and bioaccumulation potential. Regulatory frameworks and guidelines must also evolve to address the unique challenges posed by nanomaterials, ensuring their responsible use and minimising unintended consequences (Fatima & Mushtaq, 2023).

Regulatory Considerations

Overview of Regulatory Standards and Guidelines

The rapid advancement and widespread application of nanotechnology, particularly in carbon-based nanomaterials like graphene oxide (GO) and carbon nanotubes (CNTs), necessitate a robust regulatory framework to ensure safety and environmental protection. However, the unique properties of nanomaterials present challenges for traditional regulatory approaches, which are often designed for bulk materials with different physicochemical characteristics (Fatima & Mushtaq, 2023; Hsu et al., 2023). This section provides an overview of the current regulatory standards and guidelines governing the use of these nanomaterials, highlighting key aspects and areas of concern.

International Guidelines and Frameworks

1. **OECD (Organisation for Economic Co-operation and Development):** The OECD has been at the forefront of developing guidelines for the safety testing and risk assessment of nanomaterials. The OECD's Working Party on Manufactured Nanomaterials (WPMN) has established a series of testing guidelines, known as the "OECD Test Guidelines," which are used to evaluate the safety of chemicals, including nanomaterials (Doak et al., 2023; Hristozov et al., 2024). These guidelines include physical-chemical properties, environmental fate, ecotoxicology, and human health effects. For instance, the OECD has emphasised the importance of assessing the bioavailability, bioaccumulation, and ecotoxicological effects of nanomaterials like GO and CNTs.
2. **ISO (International Organization for Standardization):** The ISO has developed standards specific to nanotechnologies, focusing on terminology, metrology, and safety practices. ISO standards such as ISO/TR 13014:2012 guide the physicochemical characterisation of engineered nanoscale materials (Labuda et al., 2023). Additionally, ISO/TR 13329:2012 offers guidelines for labelling manufactured nanoparticles and products containing them, aiming to inform consumers and regulators about the presence of nanomaterials (Demirbaş & Çevik, 2020).

Regional Regulations

1. **European Union:** In the European Union, the regulation of nanomaterials falls under the REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) framework. Under REACH, manufacturers and importers must register substances, including nanomaterials, with the European Chemicals Agency (ECHA) (Bleeker et al., 2023; Rovida et al., 2023). The regulation requires specific information on substances' properties, uses, and potential risks, including those at the nanoscale. The EU has also implemented the Biocidal Products Regulation (BPR), which mandates the evaluation of nanomaterials used in biocidal products for their potential health and environmental risks.
2. **United States:** In the United States, the Environmental Protection Agency (EPA) regulates nanomaterials under the Toxic Substances Control Act (TSCA). The EPA requires manufacturers to notify the agency before producing new chemicals, including nanoscale materials and provides a framework for evaluating potential risks. Additionally, the Food and Drug Administration (FDA) oversees the use of nanomaterials in products regulated under the Federal Food, Drug, and Cosmetic Act (FDCA), including food additives, drugs, and cosmetics. The FDA has issued guidance documents addressing the safety and labelling of nanomaterials in these products (Chávez-Hernández et al., 2024).
3. **Asia-Pacific Region:** In countries like Japan, South Korea, and Australia, regulatory frameworks for nanomaterials are often integrated into existing chemical safety regulations. Japan's Chemical Substances Control Law (CSCL) and South Korea's Chemical Control Act (CCA) include provisions for the management of nanomaterials (Kim et al., 2023; Subhan et al., 2024). Australia, through its National Industrial Chemicals Notification and Assessment Scheme (NICNAS), requires notification and assessment of nanomaterials used in industrial applications (Isibor, 2024; Kumari et al., 2023).

[Citation: Younas, A., Rashad, M., Rafaqat, A., Maqbool, H., Gul, K., Ahmad, M., Shahbaz, J., Kanwal, K.U., Umair, M. (2024). Adsorption of organic compounds and hazardous microorganisms from sewage and surfactant-containing wastewater using carbon-based nanomaterials: a focus on graphene oxide and carbon nanotube. *Biol. Clin. Sci. Res. J.*, **2024***: 1052*. doi: https://doi.org/10.54112/bcsrj.v2024i1.1052]

Challenges and Future Directions

The regulation of nanomaterials, including GO and CNTs, is still evolving. One of the main challenges is the lack of standardised methods for characterising nanomaterials' unique properties, such as size, shape, surface chemistry, and reactivity. These characteristics can significantly influence nanomaterials' toxicity and environmental behaviour, making risk assessment complex.

Another challenge is the limited data on the long-term effects of nanomaterials on human health and the environment. The lack of comprehensive life cycle assessments (LCAs) further complicates the evaluation of potential risks. As a result, regulatory agencies often adopt a precautionary approach, requiring thorough testing and safety evaluations before approving the use of nanomaterials in commercial products.

To address these challenges, ongoing international collaboration and research are essential. Regulatory agencies, industry stakeholders, and academic researchers must work together to develop harmonised guidelines and testing methodologies. This collaboration will ensure that nanomaterials are used safely and responsibly, balancing technological innovation with health and environmental protection. *Table 6* provides an overview of the regulatory frameworks governing the use of nanomaterials in water treatment across different regions. The table highlights vital regulatory bodies, relevant legislation, the scope and requirements of these regulations, and specific focus areas related to nanomaterials.

In the European Union, the REACH Regulation, managed by the European Chemicals Agency (ECHA), covers the registration, evaluation, authorisation, and restriction of chemicals, including nanomaterials. Specific provisions exist for nanoscale substances, requiring separate registration and detailed safety data (Chávez-Hernández et al., 2024). The European Food Safety Authority (EFSA) also provides guidelines for the risk assessment of nanomaterials in food and feed (Schoonjans et al., 2023).

In the United States, the Environmental Protection Agency (EPA) regulates nanomaterials under the Toxic Substances Control Act (TSCA), which includes pre-manufacture notifications and risk evaluations. The Food and Drug Administration (FDA) has issued guidance for the safety evaluation of nanomaterials in FDA-regulated products, encouraging manufacturers to consult with the agency and submit safety data.

Other regions, such as Japan, South Korea, Australia, and China, have established regulatory frameworks to manage the risks associated with nanomaterials. These frameworks often include specific guidelines for the characterisation, safety assessment, and environmental impact evaluation of nanomaterials used in industrial applications, including water treatment.

Table 6: Overview of Regulatory Frameworks for Nanomaterials in Water Treatment across Different Regions

Region	Regulatory Body	Relevant Legislation/Guidelines	Scope and Key Requirements	Specific Focus on Nanomaterials
European Union	European Chemicals Agency (ECHA)	REACH Regulation (EC No 1907/2006)	Registration, evaluation, authorisation, and restriction of chemicals include safety data and risk assessment.	Specific provisions for nanomaterials; separate registration requirements for nanoscale substances.
	European Food Safety Authority (EFSA)	Guidance on risk assessment of nanomaterials in food and feed	Risk assessment for food additives and feed-containing nanomaterials includes toxicity and exposure assessment.	Detailed guidelines for nanomaterial characterisation and safety evaluation in food and feed products.
United States	Environmental Protection Agency (EPA)	Toxic Substances Control Act (TSCA)	Pre-manufacture notification for new chemicals, including nanomaterials; evaluation of risks and regulatory actions.	Nanomaterial-specific reporting and testing requirements; focus on human health and environmental impacts.
	Food and Drug Administration (FDA)	FDA Guidance for Industry: Safety of Nanomaterials in FDA-Regulated Products	Guidelines for the safety evaluation of nanomaterials in drugs, cosmetics, and food products.	Encourages manufacturers to consult with the FDA regarding nanomaterial use; safety data submission is required.
Japan	Ministry of Health, Labour and Welfare (MHLW)	Chemical Substances Control Law (CSCL)	Regulation of chemical substances, including nanomaterials; safety assessment and	It includes guidelines for the safety evaluation of manufactured nanomaterials, focusing on

			notification requirements.	environmental and human safety.
South Korea	Ministry of Environment	Chemical Control Act (CCA)	Regulation of chemicals, including hazardous substances and nanomaterials; safety management and reporting.	Specific provisions for nanomaterials include a detailed evaluation of potential risks and environmental impact.
Australia	National Industrial Chemicals Notification and Assessment Scheme (NICNAS)	Industrial Chemicals Act (2019)	Notification and assessment of new industrial chemicals, including nanomaterials; risk assessment and control measures.	Nanomaterial-specific guidance; requirements for detailed characterisation and risk assessment.
China	Ministry of Ecology and Environment	Measures for the Environmental Management of New Chemical Substances	Registration and evaluation of new chemical substances, including nanomaterials; environmental risk assessment.	Nanomaterial-specific regulations under the general chemical management framework; emphasis on environmental safety.

While significant progress has been made in regulating nanomaterials, including GO and CNTs, much work remains to be done. The unique properties of these materials necessitate specialised testing and risk assessment approaches. As the field of nanotechnology continues to evolve, so must the regulatory frameworks that govern its use, ensuring that the benefits of these advanced materials are realised without compromising safety and environmental integrity.

Challenges and Future Directions

Technical and Practical Challenges

Nanoparticle Stability:

One of the primary technical challenges in the application of carbon-based nanomaterials, such as graphene oxide (GO) and carbon nanotubes (CNTs), is ensuring their stability in various environmental conditions (Fatima & Mushtaq, 2023). Nanoparticle stability is crucial for maintaining their efficacy in contaminant adsorption. Factors such as pH, ionic strength, and the presence of natural organic matter can influence these nanomaterials' dispersion and aggregation behaviour. For instance, in high ionic strength environments, CNTs may aggregate due to the reduction in electrostatic repulsion, leading to a decrease in active surface area and adsorption capacity. Similarly, GO may undergo structural changes or reduction, altering its functional groups and reactivity. Ensuring stable dispersion in aqueous systems remains a significant challenge that impacts the consistency and effectiveness of these materials in practical applications.

Recovery and Reusability:

The recovery and reusability of nanomaterials are critical for the economic and environmental sustainability of water treatment processes. Nanomaterials' small size and high surface area pose challenges to their recovery post-treatment. Traditional filtration methods may not be effective, necessitating the development of novel separation techniques. Magnetic nanomaterials, such as iron oxide-functionalized CNTs, have been explored as a solution, allowing for magnetic recovery. However, the repeated use of nanomaterials can lead to the degradation of their structure and a reduction in adsorption capacity. For instance, repeated adsorption and desorption cycles may strip away functional groups or cause structural defects, impacting performance. Developing methods to enhance the durability and regeneration of nanomaterials is essential for their practical deployment.

Cost Considerations:

The cost of synthesising and functionalising nanomaterials remains a significant barrier to their widespread adoption in water treatment applications. Producing high-quality GO and CNTs requires advanced techniques and costly precursors, contributing to the overall expense. Additionally, the functionalisation processes, necessary to enhance adsorption properties and selectivity, further increase costs. The scalability of these processes and the availability of cost-effective raw materials are critical factors that must be addressed. To make nanomaterials economically viable for large-scale water treatment, research efforts must focus on developing cost-effective synthesis methods and optimising functionalisation processes.

Research Gaps

Long-Term Studies:

There is a notable lack of long-term studies assessing carbon-based nanomaterials' environmental and health impacts. While short-term toxicity studies provide valuable insights, they may not fully capture the potential chronic effects and bioaccumulation risks. Long-term exposure studies are essential to understand the persistence of these materials in the environment, their degradation products, and their potential to bioaccumulate in the food chain. To provide a comprehensive risk assessment, such studies should encompass various ecological compartments, including soil, water, and biota.

Standardised Protocols:

The absence of standardised protocols for the characterisation and testing nanomaterials poses a significant challenge for researchers and regulators.

Variability in experimental methods can lead to inconsistent results and hinder data comparison across studies. Standardised protocols are needed for the synthesis, functionalisation, and characterisation of nanomaterials, as well as for toxicity testing and environmental impact assessments. These protocols should include guidelines for measuring particle size distribution, surface chemistry, zeta potential, and other critical properties. Establishing standardised testing methodologies will facilitate more reliable and reproducible research outcomes and support regulatory decision-making.

Emerging Applications and Innovations:

While significant progress has been made in the application of GO and CNTs for water treatment, numerous emerging applications warrant further exploration. For example, integrating nanomaterials with membrane technologies could enhance the selectivity and permeability of filtration systems. Developing hybrid nanomaterials, combining carbon-based nanomaterials with other materials (e.g., metals, polymers), could offer synergistic properties for enhanced adsorption, catalytic activity, or antimicrobial action. Research into these innovative approaches could lead to new, more efficient water treatment technologies.

Future Directions:

The future of nanomaterials in water treatment lies in overcoming these challenges and addressing the identified research gaps. Efforts should focus on developing more stable, efficient, and cost-effective nanomaterials. Advancements in synthesis and functionalization techniques will be crucial, as will the establishment of comprehensive, long-term studies and standardised testing protocols. Additionally, interdisciplinary collaborations among chemists, materials scientists, toxicologists, and engineers will be essential to drive innovation and ensure the safe and effective use of nanomaterials in water treatment.

In summary, while carbon-based nanomaterials hold significant promise for water treatment applications, several technical, practical, and research challenges must be addressed. The continued exploration of these materials, combined with advancements in technology and regulatory frameworks, will play a pivotal role in shaping the future landscape of water treatment technologies.

Innovative Approaches

Emerging Trends and Potential Future Applications

The field of nanotechnology is rapidly evolving, offering innovative approaches for water treatment that go beyond traditional methods. Among these, developing hybrid systems that combine nanomaterials with other technologies is particularly promising. These hybrid systems leverage the unique properties of nanomaterials, such as graphene oxide (GO) and carbon nanotubes (CNTs), to enhance the efficiency, selectivity, and multifunctionality of water treatment processes. This section explores some of these hybrid systems' emerging trends and potential future applications.

1. Nanocomposite Membranes

One of the most promising nanomaterials applications is the fabrication of nanocomposite membranes. By incorporating GO or CNTs into polymeric matrices, researchers can create membranes with enhanced mechanical strength, permeability, and selectivity. GO's hydrophilic nature and large surface area can improve water flux while providing a barrier to contaminants. CNTs, with their unique electronic properties and high aspect ratio, can create pathways that facilitate the selective transport of water molecules, thus enhancing the rejection of pollutants.

For instance, GO-polyamide nanocomposite membranes have been shown to exhibit superior antifouling properties and higher water flux compared to conventional reverse osmosis membranes. Incorporating CNTs in ultrafiltration membranes has also demonstrated improved rejection rates for organic compounds and pathogens. Developing such advanced membranes could revolutionise desalination, wastewater treatment, and potable water production.

2. Photocatalytic Systems

Hybrid systems that integrate nanomaterials with photocatalytic materials offer an innovative solution for the degradation of organic pollutants. GO and CNTs can support photocatalysts like titanium dioxide (TiO_2), enhancing light absorption and charge separation. This synergy improves the efficiency of photocatalytic reactions, leading to the rapid degradation of contaminants.

For example, GO-TiO_2 nanocomposites have been utilised to degrade organic dyes and pharmaceutical residues under UV or visible light. The high surface area of GO provides ample active sites for photocatalytic reactions, while the oxygen-containing groups can act as electron traps, reducing recombination rates. Similarly, CNT-TiO_2 composites have shown enhanced photocatalytic activity due to the efficient electron transport properties of CNTs, which facilitate the separation of photogenerated electron-hole pairs.

3. Electrochemical Systems

Integrating nanomaterials into electrochemical water treatment systems represents another exciting avenue for innovation. GO and CNTs can enhance the performance of electrodes in electrochemical oxidation, capacitive deionisation, and electrosorption processes. The excellent conductivity and large surface area of these nanomaterials make them ideal for electrode applications, where they can increase charge storage capacity and improve the efficiency of electrochemical reactions.

In capacitive deionisation, for instance, GO-modified electrodes have demonstrated improved salt removal efficiency due to their high surface charge density and hydrophilicity. CNT-based electrodes have also been used in electrochemical oxidation systems to degrade persistent organic pollutants, such as phenolic compounds and pharmaceuticals, through advanced oxidation processes (AOPs). These hybrid electrochemical systems offer a sustainable and energy-efficient alternative for water purification.

4. Nanomaterial-Enhanced Adsorbents

Developing nanomaterial-enhanced adsorbents is a promising approach for the selective removal of specific contaminants. By functionalising GO or CNTs with targeted chemical groups, researchers can create adsorbents with high selectivity for heavy metals, organic pollutants, or emerging contaminants such as microplastics and endocrine-disrupting chemicals.

For example, GO functionalised with amino groups has shown high selectivity for anionic dyes and heavy metals. In contrast, CNTs functionalised with thiol groups can effectively adsorb mercury ions from contaminated water. These tailored adsorbents can be used in various water treatment processes, including fixed-bed columns and batch adsorption systems, offering a versatile solution for targeted contaminant removal.

5. Biologically-Inspired Systems

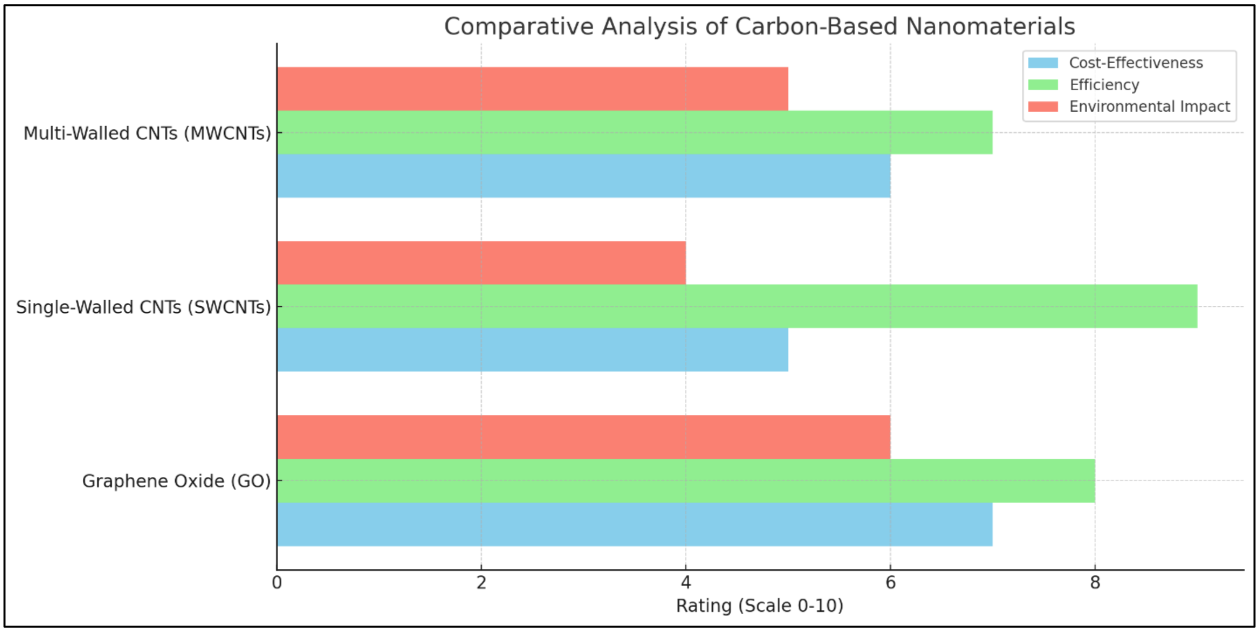
Biologically inspired systems that mimic natural processes are gaining traction in water treatment. Integrating nanomaterials with biological components, such as enzymes or microbial cells, can create hybrid systems with unique functionalities. For instance, GO can be used as a platform for enzyme immobilisation, enhancing enzyme stability and activity for the degradation of organic pollutants.

Another innovative approach involves using CNTs as conductive scaffolds in microbial fuel cells (MFCs). These hybrid systems utilise electroactive bacteria to convert organic matter into electrical energy, while CNTs enhance electron transfer and improve power output. Such biologically-inspired systems not only treat wastewater but also offer the potential for energy recovery, making them attractive for sustainable water management.

Future Directions

The continued exploration and development of hybrid systems combining nanomaterials with other technologies hold great promise for the future of water treatment. Key areas of focus include optimising the design and fabrication of nanocomposites, improving the scalability and cost-effectiveness of synthesis methods, and ensuring the environmental safety and sustainability of these advanced materials.

Interdisciplinary collaborations between chemists, engineers, biologists, and environmental scientists will be crucial in driving innovation and overcoming the technical and practical challenges associated with these systems. Furthermore, establishing standardised testing protocols and regulatory frameworks will ensure nanomaterials' safe and responsible use in water treatment applications.



Graph 4: Comparative Analysis of Various Carbon-Based Nanomaterials in Terms of Cost-Effectiveness, Efficiency, and Environmental Impact

Graph 4 illustrates a comparative analysis of three carbon-based nanomaterials—Graphene Oxide (GO), Single-Walled Carbon Nanotubes (SWCNTs), and Multi-Walled Carbon Nanotubes (MWCNTs)—evaluating them based on cost-effectiveness, efficiency, and environmental impact. The ratings are on a scale from 0 to 10, with higher values indicating better performance for cost-effectiveness and efficiency. In contrast, a lower value indicates a lower environmental impact, which is preferable.

- **Cost-Effectiveness:** GO scores the highest (7), indicating a relatively lower cost than CNTs. SWCNTs, being more expensive to produce, score lower (5), while MWCNTs are in between (6).
- **Efficiency:** SWCNTs exhibit the highest efficiency (9), followed by GO (8) and MWCNTs (7). The high efficiency of SWCNTs is attributed to their superior electrical and thermal properties.
- **Environmental Impact:** GO has a moderate environmental impact rating (6), while SWCNTs have a lower impact (4), reflecting concerns over their potential toxicity and persistence. MWCNTs have a slightly higher impact rating (5).

This comparative analysis helps highlight the trade-offs associated with each nanomaterial, providing valuable insights for their selection in specific applications.

In summary, integrating carbon-based nanomaterials with other technologies offers a versatile and powerful approach to addressing the complex challenges of water pollution. As research in this field progresses, developing innovative hybrid systems can significantly enhance water treatment processes' efficiency, selectivity, and sustainability, paving the way for cleaner and safer water resources**.**

[Citation: Younas, A., Rashad, M., Rafaqat, A., Maqbool, H., Gul, K., Ahmad, M., Shahbaz, J., Kanwal, K.U., Umair, M. (2024). Adsorption of organic compounds and hazardous microorganisms from sewage and surfactant-containing wastewater using carbon-based nanomaterials: a focus on graphene oxide and carbon nanotube. *Biol. Clin. Sci. Res. J.*, **2024***: 1052*. doi: https://doi.org/10.54112/bcsrj.v2024i1.1052]

Conclusion

Graphene oxide (GO) and carbon nanotubes (CNTs) exhibit significant potential and effectiveness in wastewater treatment applications, owing to their unique structural properties, high surface area, and versatile functionalisation capabilities. These nanomaterials demonstrate impressive adsorption capacities for various organic compounds and hazardous microorganisms, facilitated by physical adsorption, chemical adsorption, and electrostatic interactions. Integrating GO and CNTs into hybrid systems, including nanocomposite membranes, photocatalytic systems, and electrochemical setups, has further expanded their applicability, offering innovative solutions for complex water treatment challenges. However, practical considerations such as nanoparticle stability, recovery, cost, and potential toxicity must be addressed to ensure their safe and sustainable use. Future research should focus on long-term studies, standardised protocols, and the development of cost-effective synthesis methods to fully realise the potential of these materials. As the field of nanotechnology continues to evolve, the advancements in GO and CNT applications could significantly enhance environmental remediation efforts, offering promising pathways for cleaner and more efficient water treatment technologies. The continued exploration of these advanced materials, combined with interdisciplinary collaboration, holds the promise of driving significant progress in environmental science and engineering.

Declarations

Data Availability statement
All data generated or analysed during the study are included in the manuscript.
Ethics approval and consent to participate
Approved by the department concerned.
Consent for publication
Approved
Funding
Not applicable

Conflict of interest

The authors declared the absence of a conflict of interest.

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[Citation: Younas, A., Rashad, M., Rafaqat, A., Maqbool, H., Gul, K., Ahmad, M., Shahbaz, J., Kanwal, K.U., Umair, M. (2024). Adsorption of organic compounds and hazardous microorganisms from sewage and surfactant-containing wastewater using carbon-based nanomaterials: a focus on graphene oxide and carbon nanotube. *Biol. Clin. Sci. Res. J.,* **2024***: 1052*. doi: https://doi.org/10.54112/bcsrj.v2024i1.1052]