



# Nanochemistry-Driven Nanotechnology Approaches for Enhanced Water Purification through Adsorption

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**Abstract:** Water contamination by heavy metals, dyes, pharmaceuticals, and emerging pollutants presents critical challenges to public health and the environment worldwide. Nanochemistry-driven nanotechnology offers promising solutions by enabling the design of highly efficient nanoadsorbents with tailored surface properties, high surface area, and selective adsorption capabilities. This review comprehensively explores the fundamentals of nanochemistry as applied to adsorption processes, the synthesis and functionalization of various nanoadsorbents, including carbon-based materials, metal and metal oxide nanoparticles, polymer hybrids, and green bio-inspired nanomaterials and their mechanisms of interaction with pollutants at the nanoscale. Key performance parameters such as adsorption capacity, kinetics, isotherms, regeneration, and reusability are analyzed, along with applications in real water and wastewater treatment scenarios. Additionally, environmental, health, and safety considerations, challenges related to scale-up, stability, and cost, as well as future research directions involving smart nanoadsorbents and AI-assisted design, are discussed. This review highlights the significant potential and ongoing challenges of nanochemistry-enabled water purification technologies to advance sustainable and efficient water treatment

## 1. Introduction

Access to clean and safe water is essential for human health, socioeconomic development, and environmental sustainability. However, rapid industrialization, urbanization, and intensive agricultural activities have led to the continuous discharge of hazardous contaminants, including heavy metals, synthetic dyes, pharmaceuticals, pesticides, and emerging pollutants, into natural water systems. These contaminants are often persistent, non-biodegradable, and capable of bioaccumulation, posing serious risks to aquatic ecosystems and public health (Singh *et al.*, 2024a; Bakare-Abidola and Olaoye, 2025). Conventional water treatment technologies such as chemical precipitation, coagulation–flocculation, membrane filtration, and biological treatment frequently suffer from limitations, including high operational costs, secondary waste generation, and reduced treatment efficiency, particularly at low contaminant concentrations (Siddique *et al.*, 2025).

Among existing remediation strategies, adsorption has gained increasing attention due to its operational simplicity, high removal efficiency, cost-effectiveness, and adaptability to a wide range of

pollutants. Traditional adsorbents such as activated carbon, zeolites, and natural clays have been widely employed in water treatment; however, their performance is often constrained by limited adsorption capacity, slow adsorption kinetics, poor selectivity, and difficulties associated with regeneration and reuse (Rezania *et al.*, 2024; Yang *et al.*, 2024). These drawbacks have intensified research efforts toward the development of advanced adsorbent materials with improved surface properties and tunable chemical functionalities.

Nanochemistry-driven nanotechnology offers promising solutions to overcome these limitations by enabling precise control over material composition, structure, and surface chemistry at the nanoscale. Nanomaterials exhibit unique physicochemical properties, including exceptionally high surface area-to-volume ratios, abundant active sites, and enhanced surface reactivity, which significantly improve adsorption capacity and kinetics compared to conventional bulk materials (Azzaoui *et al.*, 2022; De Silva *et al.*, 2025a). Through nanochemical approaches such as surface functionalization, heteroatom doping, and hybrid nanostructure formation, nanoadsorbents can be rationally designed for selective and efficient removal of specific contaminants (Nasraddi, 2025).

Recent research has demonstrated the effectiveness of a wide range of nanoadsorbents, including carbon-based nanomaterials, metal and metal oxide nanoparticles, polymer-based nanocomposites, and bio-inspired nanostructures, for water purification applications. These advanced materials have shown remarkable potential for the removal of heavy metals, organic pollutants, and emerging contaminants across diverse water matrices and environmental conditions (Tariq and Gull, 2025a; Jan *et al.*, 2025). In this context, the present paper reviews recent advances in nanochemistry-driven nanotechnology approaches for enhanced water purification through adsorption, with particular emphasis on nanoadsorbent design strategies, adsorption mechanisms, performance evaluation, and future research directions toward sustainable, safe, and scalable water treatment technologies.

## **2. Fundamentals of Nanochemistry in Adsorption**

### ***2.1 Role of Surface Chemistry and Functionalization***

Surface chemistry is a decisive factor in determining the adsorption performance of nanomaterials. At the nanoscale, a significant proportion of atoms are located on the surface, making surface functional groups highly active in pollutant binding. Functionalization with specific chemical groups, such as hydroxyl, carboxyl, amine, and thiol moieties, enhances the affinity of nanoadsorbents toward targeted contaminants. These functional groups promote selective interactions with pollutants through coordination, electrostatic attraction, or hydrogen bonding, thereby improving adsorption capacity and selectivity in water purification applications (Makvandi *et al.*, 2021; Akartasse *et al.*, 2022; Chinnakoti *et al.*, 2025).

### ***2.2 Influence of Particle Size, Morphology, and Surface Energy***

Particle size directly affects adsorption efficiency, as nanoscale materials possess exceptionally high surface area-to-volume ratios, providing more active sites for contaminant uptake. In addition to size, the morphology of nanoadsorbents such as nanoparticles, nanorods, nanosheets, or porous nanostructures plays a crucial role in determining adsorption behavior. Morphology influences mass transfer, accessibility of adsorption sites, and interaction time between pollutants and the adsorbent. High surface energy, a characteristic feature of nanomaterials, enhances surface reactivity and adsorption potential but may also lead to particle aggregation, which can be mitigated through

surface modification or composite design (Joudeh and, Linke, 2022; Khdair *et al.*, 2025; Tariq and Gull, 2025b).

### **2.3 Chemical Bonding and Interaction Mechanisms**

Adsorption at the nanoscale involves multiple interaction mechanisms depending on the chemical nature of both the pollutant and the nanoadsorbent. These interactions include electrostatic attraction between oppositely charged species, surface complexation via coordination bonds, ion exchange processes, hydrogen bonding,  $\pi$ - $\pi$  stacking interactions, and van der Waals forces. Nanochemistry enables the rational design of adsorbent surfaces to favor specific interaction pathways, allowing for enhanced selectivity and stronger binding of contaminants such as heavy metals, dyes, and organic pollutants (Abdullah and Ahmed, 2025; Siddique *et al.*, 2025).

### **2.4 Thermodynamics and Kinetics of Nanoscale Adsorption**

Thermodynamic and kinetic considerations are essential for understanding and optimizing adsorption processes involving nanomaterials. Thermodynamic parameters such as Gibbs free energy change indicate the spontaneity of adsorption, while enthalpy and entropy changes provide insight into the nature of adsorbent-adsorbate interactions. Kinetically, adsorption on nanoadsorbents is often rapid due to the abundance of active sites and reduced diffusion distances at the nanoscale. The evaluation of adsorption kinetics helps in identifying rate-controlling steps and designing efficient nanoadsorbents for practical water treatment applications (Abolghasemi *et al.*, 2025; Yang *et al.*, 2024).

## **3. Types of Nanoadsorbents for Water Purification**

### **3.1 Carbon-Based Nanomaterials**

Carbon-based nanomaterials such as graphene oxide, carbon nanotubes, and carbon dots have gained significant attention for water purification applications. These materials offer exceptionally high surface areas, providing abundant active sites for adsorption. Additionally, their unique  $\pi$ - $\pi$  interactions facilitate the strong binding of aromatic organic pollutants, including dyes and various organic compounds. Due to their chemical stability and ease of surface modification, carbon-based nanomaterials are widely applied for the removal of dyes, pharmaceuticals, and other organic contaminants from wastewater (Li *et al.*, 2024; Piaskowski *et al.*, 2025; Latifi *et al.*, 2025).

### **3.2 Metal and Metal Oxide Nanoparticles**

Metal and metal oxide nanoparticles, including iron oxide, titanium dioxide, zinc oxide, and manganese oxide, are commonly employed as nanoadsorbents due to their multifunctional properties. These nanoparticles can be engineered to exhibit magnetic properties, enabling facile separation and recovery from treated water through magnetic fields. Moreover, many of these metal oxides possess photocatalytic abilities that synergize with adsorption processes, enhancing the degradation and removal of contaminants. Their high affinity for heavy metals and arsenic makes them particularly useful for addressing toxic metal pollution in water systems (Bouri *et al.*, 2012; Aldwayyan *et al.*, 2013; Benmassaoud *et al.*, 2017; Yang and Shen, 2025; Olawade *et al.*, 2024).

**Table 1.** Fundamentals of Nanochemistry and Adsorption Mechanisms

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Adsorption mechanisms at nanoscale	Detailed mechanisms including electrostatic, chelation, ion exchange	Adsorption kinetics, surface functionalization	Spectroscopy, surface analysis, modeling	<a href="#">De Silva <i>et al.</i> (2025a)</a>
Influence of particle size and morphology on adsorption	Particle size and morphology strongly affect adsorption efficiency	Surface area, pore size, particle size distribution	SEM, BET, adsorption isotherms	<a href="#">Xu <i>et al.</i>, (2024)</a>
Adsorption mechanisms of bio-adsorbents with AI optimization	Explores bio-adsorbent mechanisms, modeling with ANN and RSM	Adsorption kinetics, surface interactions	Spectroscopy, adsorption tests, AI modeling	<a href="#">Discover Sustainability (2025)</a>
Molecular-level adsorption and thermodynamics	Insights into adsorption energetics and thermodynamic parameters at nanoscale	Adsorption enthalpy, Gibbs free energy	Calorimetry, computational modeling	<a href="#">Li <i>et al.</i> (2023)</a>
Surface chemistry impact on nanoparticle adsorbents	Functional groups and surface charge control adsorption selectivity	Surface charge density, ligand chemistry	FTIR, zeta potential measurements	<a href="#">Nguyen and Lee (2024)</a>
Mechanistic insights into nanoscale adsorption	Advanced spectroscopic techniques reveal adsorption pathways	Surface speciation, pollutant affinity	XPS, Raman spectroscopy, modeling	<a href="#">Gómez <i>et al.</i> (2023)</a>

### 3.3 Polymer-Based and Hybrid Nanomaterials

Polymer-based nanomaterials, often functionalized with specific chemical groups, serve as versatile adsorbents with enhanced selectivity and stability. These materials include functionalized polymer nanoparticles and nanocomposites formed by integrating polymers with metal oxides or carbon-based nanomaterials. The hybridization improves mechanical strength and structural integrity, making them more durable in water treatment processes. These composites combine the advantages of each

component, providing tailored adsorption properties for specific pollutants and improved regeneration capabilities (Abdullah and Ahmed, 2025).

### 3.4 Bio-Inspired and Green Nanoadsorbents

Bio-inspired and green nanoadsorbents focus on sustainable and environmentally friendly synthesis approaches, utilizing natural materials such as chitosan nanoparticles and plant-derived biogenic nanomaterials. Chitosan, a biopolymer derived from chitin, offers biodegradability, biocompatibility, and abundant functional groups that enhance pollutant binding. Plant-based nanomaterials, synthesized through green chemistry methods, minimize the use of toxic chemicals and energy-intensive processes. These eco-friendly nanoadsorbents present a promising alternative for sustainable water purification, aligning with circular economy principles and reducing environmental impact (El-Shanshoury *et al.*, 2025; Hussein *et al.*, 2025a).

**Table 2.** Types of Nanoadsorbents

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Carbon-based and metal oxide nanomaterials	High adsorption for dyes and heavy metals	Surface chemistry, pollutant concentration, pH	Chemical synthesis, batch adsorption tests	Rezania <i>et al.</i> (2024)
Cellulose-based bioadsorbents for wastewater treatment	Effective removal of heavy metals and dyes	Adsorption capacity, contact time	Biosynthesis, FTIR, batch experiments	Yang <i>et al.</i> (2024)
Bio-based nanocomposites for dye removal	Eco-friendly nanocomposites with improved kinetics and selectivity	Adsorption kinetics, pollutant type	Polymer synthesis, adsorption experiments	Al-Gethami <i>et al.</i> (2024)
Carbon nanotubes for cadmium removal	Effective Cd adsorption mechanisms and capacity	Adsorbent dosage, contact time	Adsorption experiments, characterization	Irshad <i>et al.</i> (2025)
Metal-organic frameworks (MOFs) for water purification	MOFs show excellent adsorption selectivity and capacity	Surface area, pore size distribution	Hydrothermal synthesis, batch adsorption	Singh <i>et al.</i> (2023)
Magnetic nanoparticles for heavy metal recovery	Magnetic properties facilitate easy separation after adsorption	Magnetic saturation, adsorption capacity	Co-precipitation synthesis, magnetic characterization	Wang <i>et al.</i> (2023)
Polymer-functionalized	Enhanced selectivity and	Polymer type, functional group	Polymer grafting, adsorption tests	Chen and Zhao (2023)

nanoadsorbents	mechanical stability	density		
Green-synthesized nanoparticles for wastewater treatment	Eco-friendly synthesis improves biocompatibility	Precursor type, synthesis time	Plant extract synthesis, characterization	Patel <i>et al.</i> (2023)

## 4. Adsorption Mechanisms at the Nanoscale

### 4.1 Electrostatic Attraction: Charge-Based Interactions

Electrostatic attraction is a key mechanism governing adsorption at the nanoscale, involving the interaction between charged nanoadsorbent surfaces and oppositely charged pollutant ions or molecules. The surface charge of nanomaterials depends largely on their surface functional groups and the environmental pH, which influences ionization states. Positively charged surfaces preferentially adsorb negatively charged species such as anionic dyes and heavy metals, whereas negatively charged surfaces attract cationic contaminants. This charge-driven binding plays a pivotal role in defining adsorption efficiency and specificity (Chen *et al.*, 2025).

### 4.2 Surface Complexation and Chelation: Chemical Binding

Surface complexation involves the formation of strong coordination bonds between pollutant molecules and active sites on the nanoadsorbent surface. Functional groups such as hydroxyl, carboxyl, amine, and thiol groups act as ligands binding to metal ions or organic contaminants. Chelation is a particular form where one pollutant ion binds to multiple sites on the adsorbent, creating stable ring-like structures that enhance the stability and strength of adsorption, especially for toxic heavy metals (Gupta and Ali, 2024).

### 4.3 Hydrogen Bonding and van der Waals Forces: Weak but Crucial Interactions

Though individually weak, hydrogen bonding and van der Waals forces contribute significantly to the overall adsorption process, especially for neutral and organic molecules. Hydrogen bonds form between hydrogen atoms attached to electronegative atoms and lone electron pairs on the adsorbent or adsorbate. Van der Waals forces result from transient dipoles between molecules. These interactions enhance the adsorption of organic pollutants such as pharmaceuticals, pesticides, and dyes by providing additional binding forces that increase overall adsorption capacity and selectivity (Liu and Zhao, 2024).

### 4.4 Ion Exchange: Reversible Adsorption through Ion Replacement

Ion exchange is characterized by the reversible replacement of ions on the adsorbent surface with pollutant ions from the aqueous solution. This mechanism depends on the affinity of functional groups like sulfonates, carboxylates, or amines for specific ions, as well as the ionic concentrations in solution. Ion exchange enables selective removal of heavy metals and charged contaminants, while also allowing for adsorbent regeneration by replacing adsorbed ions with regenerant solutions (Singh and Singh, 2025).

**Table 3.** Adsorption Mechanisms at the Nanoscale

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Detailed adsorption interactions	Hydrogen bonding, van der Waals forces, ion exchange analyzed	pH, temperature, ionic strength	Isotherm modeling, spectroscopic characterization	<a href="#">De Silva <i>et al.</i> (2025b)</a>
Kinetic and thermodynamic modeling of adsorption	Pseudo-first/second order kinetics and thermodynamics studied	Time, temperature, adsorbent dosage	Kinetic modeling, thermodynamic studies	<a href="#">Tariq and Gull (2025a)</a>
Adsorption mechanisms and AI optimization for bio-adsorbents	Bio-adsorbent interaction mechanisms optimized by AI methods	Adsorbate/adsorbent interaction parameters	Spectroscopy, AI modeling, adsorption tests	<a href="#">Discover Sustainability (2025)</a>
Role of electrostatic interactions in nanoparticle adsorption	Charge-based attraction/repulsion governs adsorption efficiency	Zeta potential, pH dependency	Zeta potential analysis, adsorption isotherms	<a href="#">Chen <i>et al.</i> (2023)</a>
Ion exchange dynamics in functionalized nanoparticles	Mechanistic study of ion exchange processes with heavy metals	Ion exchange capacity, selectivity	Batch ion exchange tests, spectroscopic analysis	<a href="#">Kumar and Patel (2024)</a>
Thermodynamics of nanoadsorbent-pollutant systems	Enthalpy and entropy changes characterize adsorption spontaneity	Thermodynamic parameters, temperature	Van't Hoff analysis, calorimetry	<a href="#">Martinez <i>et al.</i> (2024)</a>

## 4.5 Environmental Factors Affecting Adsorption Efficiency

### 4.5.1 pH Effects

pH is a critical parameter influencing adsorption by affecting both the surface charge of nanoadsorbents and the speciation of pollutants. Changes in pH alter the protonation state of functional groups, thereby modulating electrostatic interactions and surface complexation. For example, acidic conditions may enhance adsorption of anions by protonating surface groups, whereas alkaline conditions favor cation adsorption ([Wang and Chen, 2025](#)).

### **4.5.2 Temperature Influence**

Temperature impacts adsorption kinetics and thermodynamics. Increased temperatures often enhance the rate of adsorption by providing the necessary energy for interactions but may reduce adsorption capacity if the process is exothermic or promotes desorption. Understanding temperature effects is essential for optimizing adsorption under varying operational conditions (Wang and Chen, 2025).

### **4.5.3 Ionic Strength and Competing Ions**

Ionic strength, reflecting the concentration of salts and other ions in solution, influences adsorption by affecting the electrical double layer around charged surfaces and ions. High ionic strength can shield electrostatic interactions, reducing adsorption efficiency, and cause competition between pollutant ions and background ions, affecting selectivity and capacity (Wang and Chen, 2025).

## **5. Synthesis and Functionalization Strategies**

### **5.1 Chemical Precipitation and Sol–Gel Methods**

Chemical precipitation is a widely used method for synthesizing nanomaterials, where metal ions in solution react to form insoluble compounds that precipitate as nanoparticles. This method allows control over particle size, shape, and composition by adjusting parameters such as pH, temperature, and concentration. The sol–gel process is another versatile technique involving the transition of a solution (sol) into a solid gel phase. It offers advantages in producing highly uniform and pure nanomaterials with controlled porosity and surface area. Both methods are cost-effective and scalable, making them popular for preparing nanoadsorbents used in water purification (Zakir *et al.*, 2025).

### **5.2 Hydrothermal and Solvothermal Synthesis**

Hydrothermal and solvothermal techniques involve crystallizing materials from aqueous or non-aqueous solvents under high temperature and pressure within sealed vessels. These methods facilitate the formation of highly crystalline nanomaterials with controlled morphology and phase purity. By carefully tuning reaction conditions such as temperature, time, and solvent type, researchers can tailor particle size and surface characteristics. These techniques are especially beneficial for synthesizing metal oxide nanoparticles and composites with enhanced adsorption properties (Zakir *et al.*, 2025).

### **5.3 Surface Modification Using Ligands and Functional Groups**

Surface functionalization is critical for enhancing the adsorption performance and selectivity of nanomaterials. It involves attaching specific ligands or chemical groups onto the nanoparticle surface to introduce active sites that interact strongly with target pollutants. Common functional groups include amines, carboxyls, thiols, and hydroxyls, which can be grafted onto nanoadsorbents through covalent bonding or physical adsorption. Functionalization also improves stability, dispersibility, and reusability of the adsorbents, enabling customized solutions for different contaminants (Sanni *et al.*, 2025).

## 5.4 Green Synthesis Approaches Using Biological Agents

Green synthesis methods utilize biological organisms or their extracts such as bacteria, fungi, algae, and plant extracts to produce nanomaterials through eco-friendly and sustainable routes. These biological agents act as natural reducing and stabilizing agents, eliminating the need for hazardous chemicals and reducing energy consumption. Green-synthesized nanomaterials often possess biocompatibility and unique surface chemistries that enhance adsorption efficiency. This approach aligns with sustainable development goals by minimizing environmental impact during nanoparticle production (Liu *et al.*, 2024a; Zhou *et al.*, 2024; Yang *et al.*, 2024).

**Table 4.** Synthesis and Functionalization Strategies

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Nanomaterial synthesis methods	Chemical precipitation, hydrothermal, green synthesis enhance adsorption	Surface modification, functional groups	Hydrothermal, sol-gel, chemical precipitation	<a href="#">Siddique <i>et al.</i> (2025)</a>
Recent synthesis advances of nanoparticles and nanocomposites	Explores solvothermal and green synthesis routes improving adsorption	Synthesis temperature, precursor concentration	Hydrothermal, solvothermal, green synthesis	<a href="#">Advances in nanoparticles (2024)</a>
Green synthesis using plant extracts	Eco-friendly synthesis improves biocompatibility and adsorption	Extract concentration, reaction time	Biological synthesis, UV-Vis, FTIR	<a href="#">Ahmad <i>et al.</i> (2023)</a>
Ligand functionalization for enhanced selectivity	Surface ligands tailored for specific pollutant adsorption	Ligand type, binding affinity	Surface chemistry analysis, adsorption tests	<a href="#">Singh and Gupta (2024)</a>
Microwave-assisted synthesis of nanoadsorbents	Rapid and uniform synthesis with controlled morphology	Microwave power, synthesis duration	Microwave synthesis, characterization	<a href="#">Liu <i>et al.</i> (2024b)</a>

## 6. Performance Evaluation of Nanoadsorbents

### 6.1 Adsorption Capacity and Efficiency

Adsorption capacity is a critical measure representing the maximum amount of pollutant that a nanoadsorbent can capture per unit mass, usually expressed in milligrams per gram (mg/g). This parameter reflects the effectiveness and potential utility of the adsorbent in water purification

applications. Adsorption efficiency, often expressed as a percentage, indicates the fraction of the pollutant removed from the solution relative to its initial concentration. These metrics are influenced by various factors such as the nanomaterial's surface area, pore size distribution, surface chemistry, and the specific nature of the pollutant. Environmental conditions including solution pH, temperature, and initial contaminant concentration also play important roles in determining adsorption performance. Together, adsorption capacity and efficiency provide essential insights for designing and scaling up water treatment systems (Li and Zhao, 2025; Husaini *et al.*, 2025a-d; Adebisi *et al.*, 2024).

## **6.2 Kinetic Models: Adsorption Rates and Mechanisms**

Kinetic models are essential tools for understanding the rate at which adsorption occurs and identifying the mechanisms controlling the process. The pseudo-first-order kinetic model assumes the adsorption rate is proportional to the number of available adsorption sites and typically describes the initial adsorption phase where the contaminant concentration is high. Conversely, the pseudo-second-order kinetic model often provides a better fit for many adsorption systems, assuming that chemisorption through valence forces involving electron sharing or exchange is the rate-limiting step. Analyzing kinetic data using these models helps optimize contact times and operational conditions, enabling more efficient pollutant removal in practical applications (Adebisi *et al.*, 2024; Husaini *et al.*, 2024a-b; Husaini and Ibrahim, 2025; Rabiou *et al.*, 2023).

## **6.3 Isotherm Models: Adsorption Equilibrium**

Isotherm models describe the relationship between the amount of pollutant adsorbed and its concentration in solution at equilibrium. The Langmuir isotherm model assumes monolayer adsorption onto a surface with a finite number of identical and energetically equivalent sites, with no interaction between adsorbed molecules. It is widely used to estimate the maximum adsorption capacity and understand adsorption saturation. In contrast, the Freundlich isotherm model is an empirical model suitable for heterogeneous surfaces, allowing for multilayer adsorption and varying binding affinities. Applying these isotherm models to experimental data provides critical insights into adsorption mechanisms, surface heterogeneity, and adsorbent performance under varying pollutant concentrations (Gomez and Singh, 2024; Husaini *et al.*, 2023a-f; Li and Zhao, 2025).

## **6.4 Regeneration and Reusability Studies**

For nanoadsorbents to be sustainable and economically viable, their regeneration and reusability are crucial. Regeneration involves restoring the adsorbent's capacity by removing adsorbed contaminants, commonly achieved through thermal treatment, chemical desorption (using acids, bases, or solvents), or advanced techniques like microwave and ultrasonic-assisted methods. Reusability studies assess the adsorbent's ability to maintain its adsorption capacity over multiple adsorption-desorption cycles, revealing its structural stability and resistance to fouling or degradation. Efficient regeneration minimizes waste production, reduces operational costs, and extends the functional lifespan of nanoadsorbents, making them more attractive for large-scale water treatment applications (Chen *et al.*, 2025b; Hamza *et al.*, 2025).

**Table 5.** Performance Evaluation of Nanoadsorbents

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Adsorption capacity and reusability	Regeneration and isotherm model fitting key for practical use	Adsorption capacity, cycle number, pollutant concentration	Batch tests, Langmuir and Freundlich models	<a href="#">Hussein <i>et al.</i> (2025a)</a>
Kinetic modeling of novel adsorbents	Comparative study of kinetic models on new nanoadsorbents	Time, concentration, temperature	Experimental batch adsorption, kinetic fitting	<a href="#">Patel <i>et al.</i> (2023)</a>
Effect of regeneration methods on adsorbent stability	Chemical and thermal regeneration impacts performance and lifespan	Number of cycles, adsorption efficiency	Regeneration experiments, characterization	<a href="#">Zhang <i>et al.</i> (2024)</a>
Comparative performance of carbon and metal oxide adsorbents	Differences in adsorption efficiency for organics and metals	Adsorption isotherms, regeneration cycles	Batch adsorption, reusability tests	<a href="#">Singh and Sharma (2024)</a>

## 7. Applications in Water and Wastewater Treatment

### 7.1 Removal of Heavy Metals ( $Pb^{2+}$ , $Cd^{2+}$ , $Hg^{2+}$ , $As^{3+}$ )

Heavy metals such as lead ( $Pb^{2+}$ ), cadmium ( $Cd^{2+}$ ), mercury ( $Hg^{2+}$ ), and arsenic ( $As^{3+}$ ) are among the most hazardous contaminants in water systems, originating from industrial effluents, mining operations, and agricultural runoff. These metals are non-biodegradable and can accumulate in living organisms, leading to severe health risks including neurological damage and organ failure. Nanoadsorbents provide a promising solution due to their exceptionally high surface area and customizable surface chemistry, which facilitate strong interactions with metal ions through mechanisms like surface complexation, ion exchange, and electrostatic attraction. Additionally, the development of magnetic nanoadsorbents enables easy separation and recovery from treated water, enhancing process efficiency and allowing for multiple reuse cycles, which is critical for sustainable water treatment ([Hussein \*et al.\*, 2025b](#); [Jain, 2025](#)).

### 7.2 Adsorption of Dyes and Textile Effluents

Wastewater from textile industries often contains a complex mixture of synthetic dyes that are highly visible even at low concentrations and toxic to aquatic life. Conventional treatment methods are often ineffective at completely removing these dyes due to their chemical stability and diverse molecular structures. Nanomaterials such as graphene oxide, carbon nanotubes, and metal oxide nanoparticles offer superior adsorption capabilities thanks to their large surface areas, porosity, and functional groups that interact with dye molecules. These interactions occur through  $\pi$ - $\pi$  stacking, hydrogen

bonding, and electrostatic forces, allowing for efficient decolorization and detoxification of textile effluents. Furthermore, certain nanoadsorbents exhibit photocatalytic properties that can degrade dyes under light irradiation, further enhancing treatment performance (Rezania *et al.*, 2024; Abdelhamid, 2024).

### 7.3 Elimination of Pharmaceutical Residues and Pesticides

Pharmaceutical compounds and pesticides are emerging contaminants increasingly detected in water bodies due to their extensive use and persistence. These pollutants pose significant ecological and human health risks, including endocrine disruption and antibiotic resistance. Nanoadsorbents have demonstrated remarkable efficiency in adsorbing these organic micropollutants due to their tailored surface properties, which facilitate hydrogen bonding, hydrophobic interactions, and chemical complexation with pharmaceutical and pesticide molecules. Moreover, some nanomaterials can catalyze the degradation of these contaminants via advanced oxidation processes, breaking them down into less harmful substances. This dual adsorption and degradation capability make nanotechnology-based approaches highly attractive for addressing complex wastewater matrices (Aziz *et al.*, 2025).

### 7.4 Pathogen and Microbial Contaminant Control

Waterborne pathogens, including bacteria, viruses, and protozoa, remain a major concern for water safety worldwide, causing diseases such as cholera, dysentery, and hepatitis. Nanomaterials such as silver, copper, and zinc oxide nanoparticles possess intrinsic antimicrobial properties that disrupt microbial membranes and inhibit growth. In addition, functionalized nanoadsorbents can capture microbial cells through adsorption, preventing their spread. Some nanomaterials exhibit photocatalytic or oxidative activity under light exposure, generating reactive oxygen species that inactivate pathogens, thereby combining physical removal with disinfection. These multifunctional nanoadsorbents offer a comprehensive solution to microbial contamination, improving water quality and public health protection (Sabbahi *et al.*, 2022; Darwesh *et al.*, 2024; Rezania *et al.*, 2024).

**Table 6.** Applications in Water and Wastewater Treatment

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Bio-nanocomposites for dye and micropollutant removal	Eco-friendly, effective adsorption of dyes and micropollutants	Pollutant type, adsorption time	Synthesis, batch adsorption studies	<a href="#">Al-Gethami <i>et al.</i> (2024)</a>
Nano-adsorbents for pharmaceutical contaminants	Critical review of removal efficiency and challenges	Pollutant type, adsorbent dosage	Batch adsorption, mechanism study	<a href="#">Perumal <i>et al.</i> (2024)</a>
Hybrid membrane-nanoparticle	Enhanced dye rejection and antifouling	Dye concentration, membrane flux	Membrane synthesis, filtration tests	<a href="#">Scientific Reports (2025)</a>

systems for water purification	performance			
Removal of pesticide residues using nano-adsorbents	Efficient adsorption and degradation of pesticides	Adsorption capacity, degradation rates	Batch adsorption, photocatalysis	<a href="#">Garcia et al. (2023)</a>
Pathogen control via functionalized nanoparticles	Nanoparticles inhibit microbial contaminants effectively	Microbial reduction, contact time	Microbial assays, surface functionalization	<a href="#">Lee et al. (2024)</a>
Heavy metal removal by nano-zero valent iron	High removal efficiency and cost-effectiveness	Iron dosage, contact time	Synthesis, batch adsorption	<a href="#">Chen and Zhang (2023)</a>

## 8. Environmental, Health, and Safety Considerations

### 8.1 Nanomaterial Toxicity and Environmental Fate

Nanomaterials exhibit distinct physicochemical properties such as increased surface area, enhanced reactivity, and novel electronic behaviors that differ significantly from their bulk counterparts. These unique features, while beneficial for water purification, also raise concerns about their potential toxicity. Once released into the environment, nanoparticles can interact with biological organisms at cellular and molecular levels, potentially causing oxidative stress, inflammation, and DNA damage. Their small size enables easy penetration into biological membranes, increasing bioavailability and toxicity risks. Additionally, nanomaterials may undergo transformations such as aggregation, dissolution, or surface modification, which influence their environmental persistence, mobility, and bioaccumulation. Comprehensive studies on the environmental fate and transport of nanoparticles are essential to predict their long-term ecological impacts and to inform risk assessments ([Liu et al., 2025b](#); [Chavez-Hernandez et al., 2024](#)).

### 8.2 Risks Associated with Nanoparticle Release

Nanoparticles can be unintentionally released during various stages, including synthesis, application, and disposal. Occupational exposure during manufacturing poses inhalation and dermal risks, which have been linked to respiratory disorders, cytotoxicity, and immunological responses in workers. In consumer settings, release from products or treatment processes may result in human exposure through air, water, or food chains. Environmental release of nanoparticles may adversely affect microbial communities crucial for ecosystem functioning, disrupt aquatic food webs, and accumulate in sediments, affecting both fauna and flora. Understanding the pathways and mechanisms of nanoparticle release is vital to establish effective containment, exposure mitigation, and environmental monitoring protocols ([Hussein et al., 2025b](#); [Singh et al., 2024b](#)).

### 8.3 Safe-by-Design Approaches in Nanochemistry

The safe-by-design strategy aims to proactively incorporate safety considerations during the development of nanomaterials, reducing potential risks before commercialization. This involves tailoring nanoparticle size, shape, surface chemistry, and composition to minimize toxicity while maintaining functional performance. Approaches include surface coating with biocompatible polymers, use of naturally derived materials, and engineering nanoparticles that degrade into non-toxic substances under environmental conditions. Incorporating green synthesis methods also aligns with this philosophy by reducing hazardous reagents and energy consumption. The safe-by-design framework encourages a balance between innovation and safety, fostering sustainable nanotechnology development in water treatment applications (National Nanotechnology Initiative, 2024; Chavez-Hernandez *et al.*, 2024).

### 8.4 Regulatory Perspectives

The rapid growth of nanotechnology has prompted regulatory bodies worldwide to develop frameworks addressing the safe production, use, and disposal of nanomaterials. Regulatory challenges include the lack of standardized testing methods, varying definitions of nanomaterials, and limited toxicological data. Agencies such as the U.S. Environmental Protection Agency (EPA), European Chemicals Agency (ECHA), and others have issued guidelines focusing on risk assessment, labeling requirements, and environmental monitoring. There is an increasing emphasis on life cycle analysis and post-market surveillance to evaluate long-term impacts. Collaboration between scientists, industry stakeholders, and regulators is critical to harmonize standards and ensure that nanotechnology advances in a manner protective of human health and the environment (National Nanotechnology Initiative, 2024; Singh *et al.*, 2024b).

Table 7. Environmental, Health, and Safety Considerations

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Nanoparticle toxicity and environmental fate	Discusses toxicity, environmental persistence, and safe design	Toxicity assays, environmental persistence	Ecotoxicology, environmental monitoring	Khair <i>et al.</i> (2025)
Bio-adsorbent sustainability and environmental impact	Focus on eco-friendly adsorbents with minimal environmental harm	Toxicity, biodegradability	Environmental impact assessment, life cycle analysis	Discover Sustainability (2025)
Toxicological effects of nano-adsorbents in aquatic systems	Assessment of bioaccumulation and chronic toxicity	Toxicity endpoints, bioaccumulation	Aquatic toxicity tests, biochemical assays	Wu <i>et al.</i> (2023)
Regulatory	Overview of	Safety standards,	Policy analysis,	Johnson and

frameworks for nanomaterials in water treatment	international regulations and guidelines	permissible limits	literature review	Smith (2024)
Environmental risk assessment of nanomaterials	Quantitative risk analysis of environmental release	Exposure concentration, toxicity	Risk modeling, experimental validation	Lee and Park (2024)

## 9. Challenges and Limitations

### 9.1 Aggregation and Stability Issues

One of the primary challenges in using nanoadsorbents is their tendency to aggregate due to high surface energy and magnetic or van der Waals forces. Aggregation decreases the effective surface area available for adsorption, thereby reducing the overall efficiency of pollutant removal. Furthermore, aggregated nanoparticles can settle out of suspension more quickly, limiting their dispersion and interaction with contaminants. Stabilizing nanoadsorbents often involves surface functionalization with polymers, surfactants, or other agents that enhance colloidal stability. However, these stabilizers may introduce new variables such as potential toxicity or interference with adsorption mechanisms, requiring careful optimization to maintain a balance between stability and performance (Khdaier *et al.*, 2025).

### 9.2 Scale-Up and Cost Constraints

Translating laboratory-scale successes to industrial-scale applications remains a significant hurdle. The cost of producing high-quality nanomaterials at scale is often prohibitive due to expensive precursors, energy-intensive synthesis methods, and complex purification steps. Maintaining consistency in nanoparticle size, morphology, and surface functionality during large-scale manufacturing is technically challenging but crucial for ensuring reliable performance. Additionally, the economic feasibility of nanoadsorbents must compete with established water treatment technologies, necessitating the development of more cost-effective synthesis approaches, such as green or bio-inspired methods, to lower production costs and facilitate wider adoption (Chinnakoti *et al.*, 2025).

### 9.3 Recovery and Disposal of Spent Nanoadsorbents

After water treatment, recovering nanoadsorbents is essential to prevent their release into the environment and to enable reuse. Magnetic nanoadsorbents provide a promising route for facile separation using external magnetic fields, but this option is limited to materials with magnetic properties. Non-magnetic nanomaterials require alternative recovery methods such as filtration or centrifugation, which may be less efficient or more resource-intensive. Moreover, the disposal of spent nanoadsorbents raises environmental and health concerns, particularly if contaminants remain adsorbed or if nanoparticles themselves pose toxicity risks. Developing sustainable regeneration techniques, safe disposal protocols, and recycling strategies is critical to minimizing secondary pollution and enhancing the overall sustainability of nanoadsorbent-based water treatment (Akhtar *et al.*, 2024; Abolghasemi *et al.*, 2025).

## 9.4 Long-Term Environmental Impacts

Despite their advantages, the long-term ecological consequences of deploying nanomaterials in water treatment are not yet fully understood. Persistent nanoparticles can accumulate in sediments, soils, and aquatic organisms, potentially disrupting microbial communities and natural biogeochemical cycles. Chronic exposure to low concentrations of nanoparticles may induce toxicological effects such as oxidative stress, genetic damage, or hormonal disruption in various organisms. Furthermore, the potential for nanoparticles to bioaccumulate and biomagnify through food chains poses risks to both environmental and human health. Comprehensive life cycle assessments, environmental monitoring programs, and toxicological studies are necessary to assess these risks accurately and inform regulations that ensure the responsible use of nanotechnology in water purification (Liu *et al.*, 2025; Khdair *et al.*, 2025).

**Table 8.** Challenges and Limitations

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Practical challenges in nanoadsorbent use	Issues with aggregation, cost, recovery, and environmental impacts	Stability, cost analysis	Review and modeling studies	Tariq and Gull (2025b)
Limitations in pharmaceutical contaminant removal	Challenges due to complex wastewater matrices	Pollutant diversity, adsorbent stability	Experimental studies, comparative analysis	Perumal <i>et al.</i> (2024)
Scale-up challenges in nanomembrane systems	Practical performance, fouling, and scalability	Membrane flux, fouling rates	Pilot-scale testing	Scientific Reports (2025)
Disposal and lifecycle impacts of spent nanoadsorbents	Discusses environmental risks of disposal and recycling methods	Environmental impact, degradation	Life cycle assessment, experimental evaluation	Chen <i>et al.</i> (2023)
Economic feasibility of large-scale nanoadsorbent production	Cost analysis and market barriers	Production cost, market demand	Economic modeling, case studies	Zhang <i>et al.</i> (2024)

## 10. Future Perspectives and Research Directions

### 10.1 Smart and Stimuli-Responsive Nanoadsorbents

The development of smart nanoadsorbents capable of responding to external stimuli such as pH changes, temperature variations, light exposure, or magnetic fields represents a transformative approach in water purification. These materials can alter their surface properties or structural configurations dynamically, enabling selective adsorption and controlled release of targeted contaminants. This functionality not only improves adsorption efficiency but also facilitates easier

regeneration and reuse of the adsorbents, minimizing operational costs and environmental impact. Advances in polymer chemistry and surface engineering will be instrumental in designing such multifunctional and adaptive nanoadsorbents tailored for specific pollutant profiles (Al Amri *et al.*, 2024).

### 10.2 Integration with Membrane and Photocatalytic Systems

Integrating nanoadsorbents with established water treatment technologies such as membrane filtration and photocatalysis offers a powerful strategy to tackle complex and diverse water contaminants. Membrane-nano hybrid systems can enhance filtration selectivity, reduce fouling tendencies, and extend the operational lifespan of membranes by providing additional adsorption sites. Photocatalytic nanocomposites combine adsorption with catalytic degradation under light irradiation, effectively breaking down organic pollutants into harmless products. The synergy achieved through these hybrid systems enables comprehensive treatment of wastewater streams, improving both efficiency and sustainability (Zakir *et al.*, 2025).

### 10.3 AI-Guided Nanomaterial Design

Artificial intelligence (AI) and machine learning (ML) techniques are increasingly being employed to accelerate the design, optimization, and discovery of novel nanomaterials for water purification. By analyzing large datasets and simulating molecular interactions, AI algorithms can predict the adsorption performance, stability, and environmental impact of nanoadsorbents before synthesis. This data-driven approach reduces experimental trial-and-error, shortens development timelines, and enables customization of nanomaterials for specific pollutants or treatment conditions. Incorporating AI tools also facilitates the identification of safe-by-design strategies to balance efficacy with environmental and health safety (Tabassam *et al.*, 2025a).

### 10.4 Field-Scale and Real-Water Applications

While laboratory studies have demonstrated the potential of nanoadsorbents, validating their effectiveness in field-scale and real-world conditions is crucial for practical implementation. Future research should focus on pilot-scale projects involving industrial effluents, groundwater, and municipal wastewater with complex pollutant mixtures and varying water chemistries. Such studies will provide insights into the operational challenges, stability, regeneration potential, and ecological impacts of nanoadsorbents in diverse environments. Addressing economic feasibility, regulatory compliance, and public acceptance will also be vital to facilitate the transition from laboratory innovation to commercial-scale water treatment solutions (Hussein *et al.*, 2025a).

Table 9. Future Perspectives and Research Directions

Subject	Key Findings	Key Studied Parameters	Methods Used	Reference
Smart and stimuli-responsive nanoadsorbents	Improved selectivity and regeneration via stimuli response	pH, temperature, magnetic field responsiveness	Synthesis, material characterization	Al Amri <i>et al.</i> (2024b)

Integration with hybrid water treatment systems	Enhanced efficiency combining membranes, photocatalysis	Pollutant degradation, membrane fouling	Hybrid system experiments	<a href="#">Siddique <i>et al.</i> (2025)</a>
AI-guided nanomaterial design	Accelerates discovery and optimization of nanoadsorbents	Adsorption performance prediction	Machine learning, computational modeling	<a href="#">Tabassam <i>et al.</i> (2025b)</a>
AI for nanomembrane design in water treatment	Future integration of AI for optimized nanomaterial systems	Desalination performance, fouling prediction	AI algorithms, experimental validation	<a href="#">Krishnan <i>et al.</i> (2024)</a>
Pilot-scale and real water application challenges	Highlights scale-up and field implementation issues	Real water matrices, cost-effectiveness	Field trials, scale-up studies	<a href="#">Hussein <i>et al.</i> (2025b)</a>
Circular economy in nanoadsorbent recycling	Emphasizes sustainable reuse and recycling of spent nanoadsorbents	Recycling efficiency, environmental impact	Techno-economic analysis, pilot studies	<a href="#">Kumar and Das (2023)</a>
Emerging trends in nanoadsorbent multifunctionality	Focus on combined adsorption, catalysis, sensing	Multifunctional activity, stability	Experimental and computational studies	<a href="#">Gupta <i>et al.</i> (2024)</a>

## Conclusion

Nanochemistry-driven nanotechnology has revolutionized the field of water purification by enabling the development of highly efficient and selective nanoadsorbents. Advances in understanding surface chemistry, adsorption mechanisms, and material synthesis have allowed tailoring nanoadsorbents to target a wide range of contaminants, including heavy metals, dyes, pharmaceuticals, and microbial pathogens. Despite promising laboratory-scale performance, challenges remain in translating these technologies to large-scale applications, particularly regarding nanoparticle stability, aggregation, regeneration, cost-effectiveness, and environmental safety. Integrating nanoadsorbents with complementary treatment methods and employing smart, stimuli-responsive materials alongside AI-guided design are promising strategies to overcome current limitations. Future research should emphasize sustainable synthesis, lifecycle assessment, and real-world validation to realize the full potential of nanochemistry-enabled nanotechnology for global water security and environmental protection.

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*Compliance with Ethical Standards:* This article does not contain any studies involving human or animal subjects.

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