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APPLICATION OF NANOMATERIALS FOR THE REMOVAL OF TOXIC ELEMENTS FROM WATER

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Abstract

The water crisis which has been intensified by rapid industrialization and population explosion of the globe, has rendered conventional water treatment technologies such as coagulation and chemical precipitation inefficient, owing to the high cost of operation and the inability to remove trace amounts of non-biodegradable heavy metals. This article aims to review the tremendous potential of nanotechnology, which has been recognized as efficient, eco-friendly and cost effective water purification technology compared to conventional methods. This technology utilizes the physicochemical properties of nanomaterials such as their high surface area to volume ratio, high durability and surface properties, to enable efficient water purification mechanism such as physical and chemical Adsorption, surface complexion, ion exchange and electrostatic interactions. This article aims to discuss the potential of nanomaterials, ranging from metallic and metal oxide nanoparticles, carbon nanostructures like 0D, 1D, 3D and hybrid nanocomposites, which are capable of achieving water high purification efficiency rates of water contaminants such as chromium and lead etc. Additionally, critically operational factors such as pH, contact time and nanomaterials dosage are also reviewed along with environmental factors such as cytotoxicity, bioaccumulation and oxidative stress. Despite the challenges facing scalability and ecotoxicity, nanotechnology has emerged as cornerstone for achieving future water security by moving from filtration to molecular engineering.

INTRODUCTION

Access to clean water is a fundamental necessity to all living organisms and human development. However, the world currently faces a critical water crisis driven by rapid population growth, climate change, and accelerating industrialization. While freshwater is essential, its availability is increasingly limited, with billions of people lacking access to safe drinking water, leading to millions of annual deaths from waterborne diseases and contamination (Karnwal & Malik, 2024).

Water pollution by heavy metals such as, mercury, lead, chromium, arsenic, and cadmium has become a worldwide crisis. These toxic elements are primarily introduced into water bodies through: Industrial waste and poor waste management practices, poorly managed landfills, pharmaceutical residues and hazardous materials (Ethaib et al., 2022). Because these heavy metals are non- biodegradable and tend to accumulate within food chain, they pose severe risk to public health and environment causing conditions such as cancer and gastrointestinal problems (Yang et al., 2019). Traditional water treatment processes including coagulation, chemical precipitation, and membrane filtration are increasingly viewed as inadequate for modern challenges. These conventional methods are often economically burdening, faced with high operational costs ,ineffective often showing low efficiency in removing trace contaminants, or simply converting pollutants in another form rather than removing them entirely, unsustainable, lacking the environmentally friendly profile needed for long term industrial development (Baby et al., 2022). Nanomaterial based adsorption has been recognized as a superior, cost-effective and eco-friendly alternatives. Nanomaterials possess unique properties that make them suitable for wastewater treatment, including high surface area to volume ratios, superior porosity and extreme durability (De Silva et al., 2025). Carbon based nanomaterials and functionalized mesoporous nanospheres, for instance, offer stable and technically feasible options for protecting public health (Usman et al., 2023). This review aims to discuss the role of nanotechnology in addressing the global water crisis specifically it evaluates the efficiency of these nanomaterials by examining the effects of operational factors such as pH, temperature, and contact time on their ion removal capacity.

World is facing a water crisis, which is systemic failure because of rapid industrialization and population growth that has made the existing treatment methods obsolete because of their high operational costs and inability to remove trace amounts of non-biodegradable heavy metals. These heavy metals are toxic and pose a serious biological hazards because of their ability to bioaccumulation in food chain, making nanomaterial based adsorption a necessary alternative. This is purposed to be superior, eco-friendly alternative because of high surface area to volume ratio and ability to control chemical stability of nanospheres, which makes them highly efficient and cost effective.

Mechanism

The removal of toxic elements from aqueous solutions by utilizing nanomaterials is a complex phenomenon based on the large surface area to volume ratio of nanomaterials. This phenomenon occurs mainly through adsorption, which can be either physical adsorption (physisorption) or chemical adsorption (chemisorption). Physisorption occurs through weak Van der Waals forces, which become very efficient owing to the huge number of available active sites on the surface of the nanomaterial. Chemisorption occurs through the sharing or transfer of electrons from metal ions to the surface of the adsorbent, resulting in a strong chemical bond. This phenomenon occurs through the Langmuir isotherm, which states that adsorption occurs on a monolayer surface, and pseudo-second-order kinetics, which states that chemisorption occurs as a rate-controlling step (Hussein et al., 2025). Apart from adsorption, complexation and chelating action play a major role in surface engineering. Nanoparticles are functionalized using specific functional groups such as amino NH_2, carboxyl –COOH, hydroxyl –OH and thiol –SH, these functional groups are known as chelating claws, which react with metal ions such as Pb^{+2} , Cu^{+2}, Cd^{+2} etc., to form insoluble complexes (Karnwal & Malik, 2024). Furthermore, electrostatic interaction is another way of removing metal ions from wastewater using nanomaterials. The point of zero charge (PZC) of the nanomaterials is used to attract metal ions in wastewater. The nanomaterial's surface is made negative at a specific pH value; as a result, metal ions with a positive charge are attracted to the negative surface of the nanomaterial. In addition, a positive surface can be used to attract metal ions (Raul et al., 2022). Ion exchange mechanisms also help in purification by the use of materials such as carbon nanotubes or layered double hydroxides that can exchange ions, such as Na^{+} or Ca^{+2} with heavy metal ions such as Cr^{+6}, As^{+5} and Pb^{+2} which are all toxic to the environment. Some adsorbents, such as MgO, help in precipitation by reacting with heavy metal ions to produce hydroxides that can be separated from the solution at higher pH levels (Usman et al., 2023).

The effectiveness of the adsorption process is enhanced by the fact that the reaction is spontaneous, as suggested by the Gibbs free energy change ΔG^0, which is negative for the reaction. The stability of the adsorption process is enhanced by the use of magnetic adsorbents such as Fe_3O_4 that can be separated from the solution by the use of an external magnetic field. The adsorbents are sustainable in that they can be regenerated by washing with NaOH to remove captured metals to reuse (De Silva et al., 2025).

Metallic and Metal Oxide Nanoparticles category is based on natural reactivity and metal oxides where they are nanoparticles in size (Alhalili, 2023; Siddeeg et al., 2020). Zero Valent Ion (nZVT) are one of the most popular nanoparticles for their reducing ability, particularly in decolorizing and removing synthetic dyes like methyl blue (Alhalili, 2023; Baby et al., 2022). Biogenically synthesized silver oxide nanoparticles, produced by microbial processes like *Bacillus thuringiensis*, are very effective antimicrobial agents. They are particularly effective against waterborne bacteria like *E.coli* and *S. aureus*. (Fiorati et al., 2020; Siddeeg et al., 2020). Copper nanoparticles are used to improve the structural properties (surface area and porosity) of polymeric support beads. Copper oxide nanoparticles $(\approx 11.4nm)$ with high antimicrobial properties are highly valued (Alhalili, 2023; Siddeeg et al., 2020).

Carbon-based nanomaterials signify the structural vanguard of the current water remediation techniques and are mainly classified on the basis of their spatial dimensionality. This mode of classification is not only related to their shapes and sizes but also determines their specific surface area, electronic properties, and ligand binding kinetics (Nasrollahzadeh et al., 2021).Zero-Dimensional (0D) Carbon-Based Nanomaterials Fullerene is a spherical and hollow polyhedral structure composed of an interconnected network of hexagonal and pentagonal rings of carbon atoms. The geometry of Florence's is such that it not only enables the encapsulation of guest molecules within its structure but also separates them from an aqueous medium (Mohapatra et al., 2023).

The unique feature of 1D nanomaterials, which is based on their dimensionality, makes single-walled or multi-walled carbon nanotubes prime candidates for remediation purposes. This is because of their aspect ratio, which is beneficial for enhancing transport efficiency (Gul et al., 2022). The tubular framework is beneficial for chemical modification of 1D CNTs. The incorporation of oxygenated nitrogenous groups, such as carboxyl or amide groups, enables the tuning of CNTs for selective chelation of divalent heavy metals, especially lead, via coordination bonds (Sarfraz et al., 2025). The graphene family, including graphene, Graphene Oxide, and reduced Graphene Oxide, is considered to have the highest theoretical surface area. This is beneficial for interactions (Dhiman et al., 2022; Kumar et al., 2023). Graphene Oxide is specifically valued for its dense population of oxygen-bearing functional groups (hydroxyl, carboxyl, and epoxy). These groups serve as active coordination sites, enabling high-capacity ion exchange and surface complexion with both inorganic ions and polar organic contaminants (Dhiman et al., 2022; Kumar et al., 2023). To mitigate the inherent tendency of 2D sheets to restack due to van de Waals forces, which significantly reduces accessible surface area, researchers have developed 3D Graphene Architectures (Ansari et al., 2025; Zhang et al., 2024).

Synergistic is a foam-like macrostructures preserve the high flux pathways of 2D graphene while providing a rigid, three-dimensional porous network. When hybridized with transition metal oxides$(e.g. TiO_2\ or\ ZnO)$, 3DG frame works act as high efficiency platforms for the solar mediated photocatalytic degradation of persistent organic pollutants (Zhang et al., 2024; Yu et al., 2022) Hybrid nanocomposites are designed to take advantage of the strengths of more than one material and overcome the limitations of individual materials (e.g., non-selectivity or instability (Baby et al., 2022).

The combination of Metal Organic Frameworks (MOFs) and CNTs has resulted in the creation of nanocomposites that have adsorption capacities beyond those of normal MOFs. These nanocomposites are very effective in the removal of phenols and complex dyes from aqueous solutions (Baby et al., 2022).These nanocomposites are formed by the doping of semiconductors to enhance their properties. Mn Doped Zinc and oxide graphene nanocomposites are used for the photocatalytic removal of herbicides, while multi-component nanocomposites such as CuS, ZnO, ZnS are designed for efficient dye removal (Araujo et al., 2023; Tripathy et al., 2024).Polymer nanocomposite is concerned with sustainability and membrane technology, where biodegradable matrices are used (Adeola & Nomngongo, 2022).

Natural polymers such as proteins, lipids, and polysaccharides are used as the host material. The matrices are filled with nanoscale active materials to create highly selective filtration membranes. This nanocomposite is critical in the development of eco-friendly water treatment technologies that ensure the remediation process has little environmental impact (Kayani & Mohammed, 2025).The effectiveness of removing nanomaterials from water depends on their physicochemical characteristics, ambient factors, and process variables. In contrast to PVP coatings that imitate uncoated versions, surface coatings like citrate or gum arabic extend liquid-phase presence for minerals like CeO and Ag; core kinds like pure TiO or CeO achieve near-total elimination (Hussein et al., 2025).

Negative zeta potentials decrease settling by resisting solids, but smaller particles dissolve more quickly, skewing apparent efficiency. Higher total suspended solids and biomass in secondary treatment encourage heteroaggregation for better capture; pH changes surface charges, increasing surfactant removal by magnetite at pH 9 or zeolite at pH 10. Scavenging strength is increased by dosage, contact times reach their maximum effectiveness in 10–60 minutes (or longer for specialties like benzethonium chloride), and processes like bacterial attachment promote settling. Stability is changed by transformations like Ce(IV) reduction or Ag sulfidation. Additionally, integrating photocatalysis with biodegradation into hybrid treatment models provides a highly effective method for the elimination of surfactants (Barton, 2014; Ciurcanu, 2023; Popescu et al., 2018).

Challenges and limitations of nanomaterial-based water treatment

Although nanomaterial-based water treatment has a lot of potential, there are significant obstacles in the areas of technical performance, environmental safety, and regulatory frameworks that need to be addressed before it can be widely used. The materials' propensity to clump together or destabilize in water, which reduces their efficacy in capturing pollutants and makes recovery more difficult due to their small size, are major problems. There are also gaps in dependable long-term trials and scalable production for actual wastewater scenarios. Better energy use is required by photocatalytic variations, such as switching from UV to sunlight while reducing inefficient electron reactions (Karnwal & Malik, 2024).

As demonstrated by graphene oxide stressing algae, carbon nanotubes stunting marine larvae and increasing mortality, or silver particles harming bottom-dwellers, leaked nanoparticles endanger aquatic life through oxidative damage, cell rupture, and DNA harm. However, their interaction with other toxins can unpredictably increase or decrease hazards, such as amplifying copper harm or lessening lead effects. Because of its novelty, nanotechnology lacks standardized testing procedures, precise safety standards, and comprehensive understanding of long-term hazards. As a result, regulatory bodies such as the European Commission struggle with the elusive behavior of nanotechnology in comparison to larger-scale materials (Saleem & Zaidi, 2020).

Health and Environmental Concerns

Nanomaterials display cytotoxicity because of their high surface area to volume ratio, making them chemically hyper-reactive compared to their bulk material counterparts. If such a material comes into contact with a biological system, it is capable of physically puncturing the cell membrane or to be swallowed by the cell through a process called endocytosis as shown in fig 1, effectively hijacking the cell's natural transport system. Once inside the cell's cytoplasm, it is capable of moving to the mitochondria or nucleus and physically interfering with the cell's vital protein folding of vital proteins (Sun et al., 2020).

Furthermore, certain particles like silver or copper-based nano-oxides can undergo lysosomal sonication, where they dissolve within the acidic environment of the cell to release a flood of toxic metal ions. This internal chemical warfare often triggers a cascade of signaling pathways that lead to apoptosis, or programmed cell death, even if the particle itself isn't inherently poisonous in a larger form. Over time, persistent cytotoxic exposure can lead to tissue atrophy and the failure of high-turnover organs like the lining of the gut or the skin (Kuruva Nandyal, 2022).

Oxidative stress is arguably the most pervasive mechanism of nano-toxicity, stemming from the fact that the active surfaces of nanoparticles often act as catalysts for the production of Reactive Oxygen Species (ROS). When these particles enter a cell, they can trigger an imbalance where the production of free radicals, such as superoxide (O_2) and hydroxyl radicals (OH), far outpaces the cell's natural antioxidant defenses like glutathione. This state of chemical friction causes immediate damage to the cell's lipid membranes through a process called lipid peroxidation, which effectively turns the cell's protective fatty acids rancid (Kuruva Nandyal, 2022).

Unlike larger particles that the body can filter out through the kidneys or process via the liver's enzymatic pathways, many nanomaterials are simply too small or too chemically inert to be efficiently captured or broken down. This leads to a process of internal bioaccumulation, where the concentration of the material within an organism increases steadily over time because the rate of intake exceeds the rate of excretion (Kuruva Nandyal, 2022).This becomes particularly dangerous when these particles cross the blood-brain barrier or the placental barrier, reaching protected areas of the body that are usually shielded from toxins. (Environ. 2024; 912, Sep. Purif. Technol. 2023).

The bioaccumulation of the large nanoparticles or nanostructures (> 100nm) can be specifically tailored to sequester or neutralize toxins. (Environ. Chem. Lett. 2020), Mater Adv. 2020). Nanoparticles have the ability to adsorb on the toxins present in the environment, such as in water or soil, or even inside the body, thus forming large aggregates (Sun et al., 2020). In Biomimetic nanosponges, which may consist of a polymeric core surrounded by a layer of cell membrane material such as red blood cells, can specifically attract the toxins away from the healthy cells. In Intracellular Immobilization Nanoparticles have the ability to sequester toxins inside the cells of organisms such as mussels and worms, thus effectively sequestering the toxins away from the vital cells? (Chem. Lett 2020, Purif. Technol. 2023).While Trojan Horse Effect mechanism often describes the release of toxic ions, it can be utilized in reverse. Nanoparticles can be designed to deliver a neutralizing agent (an antidote) directly into a cell or bind a toxin and, due to their size, be excreted via the hepatobiliary route in feces. (Purif. Technol. 2023).

While designed for removal, the accumulation of non-degradable nanoparticles can lead to long-term persistence in tissues, potentially causing inflammation or oxidative stress. The ultimate goal in using large nanoparticles for detoxification is to ensure they are excreted after binding the toxin, rather than accumulating permanently (Kuruva Nandyal, 2022).

The unintended and often irreversible effects of these materials are referred to as ecotoxicity, the consequences of which are felt when these inevitably leach into the the earth's soil, water, and air. In the water, nanoparticles do not settle like sand; rather, they remain suspended in a colloidal form, capable of binding to the sensitive gill structure of fish or coating the cell walls of algae, essentially choking the bottom of the aquatic food chain. On land, they may be capable of toxicity to beneficial microbes in the soil, which are essential for the proper cycling of nitrogen and the production of healthy crops (Karnwal & Malik, 2024).The transport of nanoparticles is so unusual that they may be carried by wind or water flows. There is also the concern of Trojan Horse effects, where nanoparticles bind to other pollutants like heavy metals or pesticides and carry them into organisms that would otherwise be protected from those toxins. This unpredictability makes it nearly impossible for current environmental regulations to accurately map the long-term impact of nanotechnology on biodiversity and planetary health (Sadegh et al., 2021).

Regulatory bodies such as the European Commission have identified that nanomaterials are difficult to regulate because of their inherent complexity and a general lack of knowledge about their long-term effects (Saleem & Zaidi, 2020). Table 01 shows the unique physicochemical properties of nanomaterials allowing for transformative applications across diverse sectors, ranging from enhanced industrial coatings to precision medicine. By manipulating material characteristics at the nanoscale, researchers can optimize surface-to-volume ratios and quantum effects to solve complex engineering and biological challenges (Smith et al., 2023).

Table 01: Properties and Environmental Applications of Nanomaterials for Toxic Element Removal

Property	Regional History & Context	Practical App.	Research Strategy	References
Optical & Photonic	Significant history in Germany (Max Planck) and China, where photonic crystal research is a national priority.	Anti-reflective coatings & cancer detection	Focus on Surface Plasmon Resonance (SPR) to tune light-matter interaction at the nanoscale.	Jones & Wang, 2024)
Magnetic	Japan and the USA have led this since the 1980s, originating with the development of magnetic recording heads.	High-density storage & MRI contrast agents.	Utilizing superparamagnetism in nanoparticles to prevent data loss while maintaining high sensitivity.	(Miller, 2022)
Thermal	High research density in the Middle East (UAE/Saudi Arabia) for solar efficiency and Scandinavia for industrial cooling.	Solar collectors & transformer cooling	Enhancing Nanofluid thermal conductivity using carbon nanotubes or metallic oxides to bypass bulk limits.	(Brown et al., 2023)
Mechanical	Strong roots in UK (Manchester) following the discovery of Graphene, and US Aerospace hubs for carbon-fiber tech.	Lightweight, ultra-strong composites.	Engineering dislocation pinning and grain-boundary strengthening to create lighter than steel materials.	(Davis, 2025)
Electronic	Centered in South Korea (Samsung) and Taiwan (TSMC), driving the global nano-electronics shift since 2010.	Miniaturized mobile devices & efficient displays.	Transitioning from Silicon to 2D materials (like MoS2) to overcome quantum tunneling in smaller chips.	(Wilson, 2023)
Energy & Fuel	North America and Europe have focused here via the Green Deal; Japan led early hydrogen fuel cell history.	High-capacity batteries & fuel cells	Developing electrocatalysts with high surface-to-volume ratios to speed up hydrogen redox reactions.	(Taylor, 2024)
Biomedical	Early breakthroughs in USA (MIT/Harvard); recent rapid growth in India and Brazil for affordable medical nano-tech.	Antibacterial dressings & smart drug delivery.	Using functionalized ligands to ensure nanoparticles only release drugs when they reach a specific tumor pH.	(Garcia & Lee, 2024)
Surface Science	Inspired by natural studies in Southeast Asia; industrialized by French and German chemical giants (e.g., BASF).	Self-cleaning glass & active catalysts	Mimicking the Lotus Effect (super hydrophobicity) to create surfaces that repel pollutants naturally.	(Clark, 2022)
Personal Care	Market-driven research primarily in France (L'Oreal) and USA, dating back to the late 1990s.	Transparent inorganic UV filters in sunscreens	Particle size reduction of Zinc Oxide/Titanium Dioxide to eliminate the white cast while increasing UV absorption.	(Adams, 2023)

Recent Advances

Expanding on these cutting-edge developments requires looking at how researchers are moving away from simple particles toward intelligent systems that solve complex problems in medicine, electronics, and environmental science (Sadegh et al., 2020; Sun et al., 2020).

This advance involves chemically modifying the surface of graphene oxide sheets by attaching specific functional groups, such as polymers, proteins, or small molecules. The third innovation involves chemically modifying the surface of graphene oxide sheets to incorporate specific chemical groups. This allows chemists to tailor the chemical properties of graphene oxide to achieve specific purposes, such as making it extremely soluble in water to facilitate drug delivery or making it extremely attractive to heavy metals to facilitate water purification. This also prevents graphene oxide sheets from clumping or sticking to each other, which would eliminate the extremely large surface area. This has been used to target cancer cells to prevent chemotherapy side effects (Usman et al., 2023).

Bio-inspired nanotechnology is based on mimicking naturally occurring phenomena. This includes mimicking the hydrophobicity of a lotus leaf or the structural properties of a sea shell. This has been achieved by developing nanoparticles that can avoid being detected by the human immune system by mimicking a red blood cell membrane (Fu, L., & Yang, H. 2024). This is more biocompatible and less toxic because it utilizes building blocks that are naturally recognized by the body or environment. This has also been used to develop nanoparticles that can heal themselves when damaged, much like biological tissue (J. Clean. Prod. 2023).

The traditional method of nanoparticle formation involves the use of chemical reagents, which are harmful to the environment, and high energy consumption, whereas the green method uses natural biological extracts obtained from plants, fungi, or bacteria. For example, the leaves' natural extract can be used to reduce metal ions to produce silver or gold nanoparticles at room temperature without the formation of harmful byproducts. This not only reduces the carbon footprint of nanotechnology but the nanoparticles are also capped with a natural material, making them safe for use, for example, in the food industry or medicine (Da Silva Júnior, A. H. Alam, G. Ehsanullah, I. Naushad 2023).

The central hub of the graphic centers around Photocatalytic Nanomaterials, which utilize light to initiate a chemical reaction. This intelligent nanomaterial is designed to target four major categories of pollutants. (De Silva, M., Cao, G., & Tam, K. C. 2025) Pesticides: chemicals used in agriculture that have a tendency to persist in the soil and water. (Environ. Chem. Lett. 2020). Biphenyl a chemical commonly used in the manufacturing of plastics, known to disrupt the body's natural endocrine system. (Environ. Chem. Lett. 2020). Antibiotics & Drugs: waste byproduct of prescription drugs, often unable to be filtered out by traditional water treatment plants. Dyes: often byproduct of the textile industry, these chemicals are often bright in color and extremely dangerous to waterways. (De Silva, M., Cao, G., & Tam, K. C. 2025)

These nanomaterials are intelligent in the sense that their composition will alter physically or chemically in response to an outside stimulus, such as a change in pH, a rise in temperature, or the presence of a magnetic field. For example, a smart nanocarrier will seal tight during transport through the bloodstream, but unzip to deliver the medication when it detects the specific acidic environment of a tumor cell, allowing the potent drug to have maximum therapeutic effect while limiting the risk of systemic toxicity (Sahoo, D. K., Yadav, V. K., & Patel, A. 2023)

Future Perspectives

The future of the field relies on the ability to transition away from expensive, rare-earth metals and toward more affordable, earth-rich precursors such as carbon, silica, and cellulose. There has been a focus on the scaling down of the production costs such that nanotechnology-based solutions such as high-efficiency solar cells or water purification systems can be implemented in developing nations. By utilizing agricultural waste such as rice husks or coconut shells to create nanostructures composed of carbon, the field has the potential to become a cornerstone of the circular economy. (Umar, K., & Mohamad Ibrahim, M. N. 2020).

The transition from a lab scale gram to an industrial scale ton is the largest hurdle to the field of nanotechnology over the next ten years. Future perspectives include the ability to create a continuous flow manufacturing system whereby every single nanoparticle created in a massive factory is identical in size and shape. This is important, especially in regulated industries such as pharmaceuticals or microchip manufacturing, where a 1% variance can lead to complete failure of the product (Chand, S., Rout, P. R., & Shahid, M. K. 2024)).

The future of water treatment is likely to feature a new generation of hybrid membranes that actually incorporate nanoparticles into the membrane. This membrane is considered an active membrane because it is able to not only filter impurities physically but also kill bacteria on contact and chemically remove toxins such as arsenic or lead. This dual-action approach prevents befouling (the buildup of slime and bacteria on filters), which currently costs the water industry billions of Dollars in maintenance (Thangavelu, L., & Veeraragavan, G. R. 2022).

The persistence of organic/inorganic pollutants in the water has become a serious environmental issue. Among the different pollutants, dyes and heavy metal pollution in waterways are viewed as a global ecological problem that can have an impact on humans, plants, and animals. The necessity to develop a sustainable and environmentally acceptable approach to remove these toxic contaminants from the ecosystem has been raised. (Saleem, H., & Zaidi, S. J. 2020).

In the past two decades, rapid industrialization and anthropogenic activities in developed countries have aggravated environmental pollution. Industrial effluents that are discharged directly into the natural environment taint the water, which has consequences for the water resources. Magnetic nanohybrids are broadly investigated materials used in the adsorption and photocatalytic degradation of poisonous pollutants present across water effluents. Usman, S. O., & Ajisafe, O. (2024).

Using nanoparticles to generate heat and cook cancer cells. Using metallic nanoparticles as contrast agents for clearer imaging. The title Reusable and Recyclable Nanoadsorbents and the text below suggest a focus on environmental safety. It addresses the risk of bioaccumulation and waste, indicating that the next generation of nanomaterials is being designed to be more sustainable or easily cleared from the body environment. E., Karakasidis, T. E., & Sarris, I. E. (2021).

To address the risk of bioaccumulation and waste, future nanomaterials must be designed for end-of-life recovery. Magnetic nanoadsorbents are a prime example: once they have soaked up pollutants from a contaminated lake, they can be pulled back out of the water using a large magnet. Future research is focused on making these particles regenerative, meaning the captured toxins can be stripped off and the nanoparticles reused hundreds of times, making them a more sustainable and cost-effective option than single-use filters . (Kamyab, H., & Taghavijeloudar, M. 2024).

Rather than replacing current infrastructure, the future lies in retrofitting existing water plants with nano-enhanced modules. This involves creating plug-and-play units that use nano-catalysts or nano-sensors to detect and destroy emerging contaminants like micro plastics and pharmaceutical residues that traditional plants are not equipped to handle (Tripathy et al., 2024).

Conclusion

Nanomaterials mark a leap from passive filtration to active molecular engineering to remove toxic elements from water. Unlike traditional activated carbon or sand filters, which use a simple mechanism of trapping, nanomaterials use their enormous surface area to volume ratio to offer a huge density of active sites to form chemical bonds. This allows the trapping of trace contaminants such as endocrine disruptors and micro-pollutants, which pass through the traditional municipal systems untouched. Their magnetic properties and catalytic abilities also offer superior performance compared to traditional techniques because they allow for the active destruction of pollutants as well as the recovery of the material itself. Even though the results obtained from laboratory testing are revolutionary, the way to full commercialization is currently blocked by a number of key challenges. At present, for example, the high energy cost required to obtain pristine graphene or carbon nanotubes makes it difficult to utilize them in low-income countries, which is where they are most urgently required. Additionally, we need to close the so-called knowledge gap regarding the long-term environmental fate of these particles to avoid any potential ecotoxicity or health risks. Finally, moving to industrial-scale techniques involves a paradigm shift to continuous manufacturing techniques rather than small-scale batch processing, to ensure that every single milligram of material meets the same stringent standards required for public. These socioeconomic issues and technical challenges are the main prerequisite to the full commercialization of these advanced materials. The ultimate potential of nanotechnology is to offer a sustainable, decentralized solution to water purification and environmental remediation in the future. The future of nanotechnology is based on a philosophy of Benign by Design to ensure that nanoparticles are synthesized from green sources and are recyclable via a magnetic recovery process. If we can successfully align the performance of nanotechnology with environmental safety via risk assessment and safe disposal, then nanotechnology is poised to become a cornerstone of water security on a global scale. Nanotechnology has a strong potential to offer a sustainable solution to water purification and environmental remediation, ensuring access to clean water for the 21st century and beyond. Thangavelu, L., & Veeraragavan, G. R. (2022).

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