Global Scientific and Academic Research Journal of Multidisciplinary Studies
ISSN: 2583-4088 (Online)
Frequency: Monthly
Published By GSAR Publishers
Journal Homepage Link- https://gsarpublishers.com/journals-gsarjms-home/

Nanoparticle Innovations in Wastewater Treatment: A Comparative Study of Titanium Dioxide, Gold, and Nano Zero-Valent Iron Nanoparticles for Lead, Chromium, and Mercury Removal

By

Arslan Younas[1], Amna Saeed[2], Hiba Maqbool[3], Muhammad Shoaib Qamar[4], Asia Parveen[5], Rabia Afzal[6], Ayesha Saleem[7], Laiba Ali[8], Ubaid Ullah[9], Qudrat Ullah[10]

[1]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan
[2]Institute of Environmental Engineering and Research, University of Engineering and Technology, Lahore
[3, 6]Department of Chemistry, University of Agriculture Faisalabad, Punjab Pakistan
[4]Environmental Science Research Center, Chiang Mai University, Thailand
[5]Department of Chemistry, Government College University Faisalabad, Punjab Pakistan
[7]College of Earth and Environmental Sciences, University of the Punjab, Lahore
[8]Institute of soil and Environmental sciences, University of Agriculture Faisalabad, Punjab Pakistan
[9]Department of Physics, Govt. Post Graduate College Jampur
[10]Department of Environmental Sciences, Government College University Faisalabad

Article History

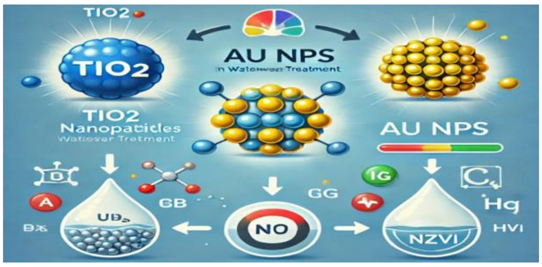
Received: 09/08/2024
Accepted: 10/08/2024
Published: 12/08/2024

Vol – 2 Issue –8

PP: - 15-31

Abstract

Nanoparticles have emerged as a potent solution for addressing the complexities of wastewater treatment due to their unique physicochemical properties, including high surface area, reactivity, and potential for surface functionalization. This review explores the effectiveness of titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI) in the removal of heavy metals and organic pollutants. Each nanoparticle type offers distinct advantages: TiO2 for its photocatalytic activity and stability, Au NPs for their high selectivity and biocompatibility, and nZVI for its strong reductive properties and cost-effectiveness. However, the deployment of these nanoparticles also raises significant environmental and health concerns, including potential toxicity to aquatic life, long-term persistence, unintended release, and the risks associated with bioavailability and mobility. Additionally, human health risks, particularly from occupational exposure, underscore the need for careful handling and comprehensive risk assessments. Real-world applications demonstrate their utility in various contexts, from industrial effluent treatment and municipal wastewater management to emergency response and portable water systems. The review underscores the importance of ongoing research to develop safer and more sustainable nanomaterials, along with the establishment of regulatory frameworks to mitigate potential risks.



Keywords: *Nanoparticles, Wastewater treatment, Heavy metal removal, Environmental risks, Photocatalysis*

Introduction

Heavy metal contamination in wastewater is a critical environmental concern with profound implications for both ecosystems and human health. Industrial activities, such as mining, electroplating, and battery manufacturing, are significant contributors to the discharge of toxic metals into water bodies. Metals like lead (Pb), chromium (Cr), and mercury (Hg) are commonly found in industrial effluents (Ali et al., 2021; Jagaba et al., 2024). These elements are highly persistent in the environment, as they are non-biodegradable and can accumulate in biological organisms, leading to bioaccumulation and biomagnification. The World Health Organization (WHO) has documented the severe health risks

© Copyright 2024 GSAR Publishers All Rights Reserved

associated with these contaminants, which include neurological damage, cardiovascular diseases, and developmental disorders (Budi et al., 2024; Upadhyay, 2022). For instance, exposure to lead can impair cognitive development in children, while chromium (VI) compounds are recognized carcinogens. Mercury, particularly in its methylated form, is a potent neurotoxin that can have devastating effects on the nervous system (Jia et al., 2024; Zafar et al., 2024).

Traditional wastewater treatment methods, such as chemical precipitation, ion exchange, and membrane filtration, have been employed to mitigate heavy metal contamination. However, these techniques often face significant challenges. Chemical precipitation can generate large volumes of sludge, which requires further treatment and disposal. Ion exchange, while effective, is limited by the capacity and selectivity of the resins used, making it less efficient for trace contaminants (Liu et al., 2024a; Liu et al., 2023b). Membrane filtration, though capable of removing a wide range of pollutants, suffers from high operational costs and the issue of membrane fouling. Additionally, these conventional methods may produce secondary waste streams that require further management, thus complicating the treatment process.

In recent years, nanotechnology has emerged as a revolutionary approach to addressing these limitations. Nanomaterials offer unique properties, including high surface area-to-volume ratios, enhanced reactivity, and the potential for functionalization, which make them ideal candidates for the removal of heavy metals. Titanium dioxide (TiO2) nanoparticles, for instance, are known for their photocatalytic capabilities, which allow them to degrade organic pollutants and reduce metal ions under UV light (Malik et al., 2023; Mohanapriya et al., 2023). Gold nanoparticles (Au NPs), despite their high cost, are prized for their selectivity and high affinity for specific metals such as mercury, enabling efficient detection and removal even at low concentrations. Nano zero-valent iron (nZVI) is particularly effective in reducing and immobilizing metals like chromium and lead through redox reactions. The high reactivity of nZVI, coupled with its ability to transform toxic metal ions into less harmful forms, makes it a valuable tool in the remediation of contaminated water (Di et al., 2023; Karnwal et al., 2024).

The deployment of these nanomaterials in wastewater treatment systems presents a promising avenue for enhancing the efficiency and effectiveness of contaminant removal. However, it is crucial to consider the potential environmental and health risks associated with their use, including nanoparticle toxicity and the challenge of recovering and reusing these materials. As research in this field progresses, developing sustainable and safe nanotechnology applications will be vital in protecting public health and preserving environmental integrity.

The objective of this review is to explore the scope and potential of titanium dioxide (TiO2), gold (Au) nanoparticles, and nano zero-valent iron (nZVI) in the treatment of heavy metal-contaminated wastewater. This article aims to provide a comprehensive overview of the mechanisms, efficiency, and applications of these nanoparticles in removing toxic metals such as lead (Pb), chromium (Cr), and mercury (Hg). The review is structured to first present the characteristics of the selected nanoparticles, followed by a detailed examination of their mechanisms for heavy metal removal. Subsequent sections will discuss the specific applications of each type of nanoparticle in removing lead, chromium, and mercury from wastewater, supported by case studies and experimental data. The review will also address the challenges and future directions for the implementation of these nanotechnologies, concluding with a summary of key findings and recommendations for further research. This structured approach provides a holistic understanding of the state-of-the-art advancements and practical applications of nanoparticle-based wastewater treatment technologies.

Characteristics of Nanoparticles Used in Wastewater Treatment

Titanium Dioxide (TiO2)

Titanium dioxide (TiO2) nanoparticles are widely utilized in wastewater treatment due to their excellent photocatalytic properties, chemical stability, and non-toxic nature. The high surface area of TiO2 nanoparticles enables efficient adsorption and degradation of various contaminants. TiO2 exists in three crystalline forms: anatase, rutile, and brookite, with anatase being the most effective for photocatalytic applications due to its superior activity. The synthesis of TiO2 nanoparticles can be achieved through various methods, including sol-gel, hydrothermal, and chemical vapor deposition techniques. These methods influence the size, morphology, and photocatalytic efficiency of the nanoparticles (Mhadhbi et al., 2023). In wastewater treatment, TiO2 nanoparticles are particularly effective in the photocatalytic degradation of organic pollutants and the reduction of heavy metals under UV light irradiation. Their ability to generate reactive oxygen species, such as hydroxyl radicals, facilitates the breakdown of complex pollutants into less harmful substances (Madkhali et al., 2023; Utami et al., 2023).

Gold Nanoparticles (Au NPs)

Gold nanoparticles (Au NPs) are renowned for their unique optical properties, high surface area, and biocompatibility, making them suitable for various environmental applications, including heavy metal removal. The synthesis of Au NPs can be performed using methods such as chemical reduction, seed-mediated growth, and green synthesis approaches, which utilize plant extracts as reducing agents. The size, shape, and surface functionalization of Au NPs can be tailored to enhance their interaction with specific metal ions (Can, 2020; Carnovale et al., 2016). Au NPs exhibit strong affinities for metals like mercury (Hg) and lead (Pb), making them effective for their selective removal from contaminated water. The mechanism of heavy metal removal by Au NPs involves adsorption, complexation, and, in some cases, catalytic reduction. The presence of surface plasmons in Au NPs also enables them to act as sensors for detecting trace amounts of

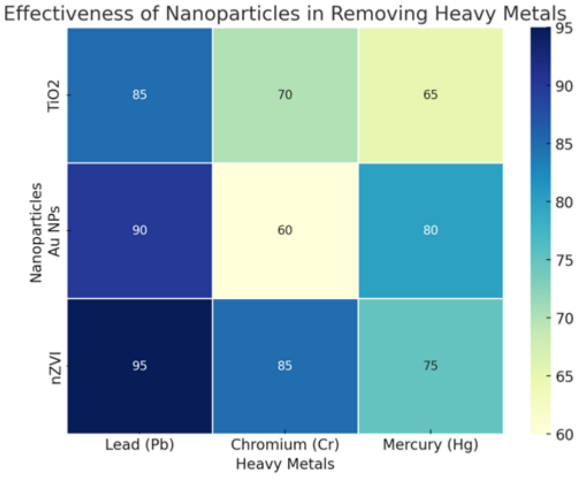
 © Copyright 2024 GSAR Publishers All Rights Reserved

heavy metals, offering an additional application in environmental monitoring (Ali et al., 2023; Geleta, 2023).

Nano Zero-Valent Iron (nZVI)

Nano zero-valent iron (nZVI) is a highly reactive form of iron that has gained significant attention for its potential in environmental remediation, including wastewater treatment. nZVI particles possess a large surface area and a high density of reactive sites, which facilitate the reduction and adsorption of a wide range of contaminants, including heavy metals like chromium (Cr), lead (Pb), and mercury (Hg). The synthesis of nZVI can be accomplished through methods such as chemical reduction, green synthesis, and ball milling. Among these, green synthesis is particularly attractive due to its eco-friendly approach, often employing plant extracts or microbial agents to reduce iron salts (Awang et al., 2023; Gebre, 2023). nZVI particles can effectively reduce toxic Cr(VI) to less harmful Cr(III) and convert soluble Hg(II) to insoluble Hg(0), thereby removing them from aqueous systems. Moreover, the magnetic properties of nZVI enable easy separation from treated water, making them a versatile option for various environmental applications (Zhang et al., 2023).

Graph 1: Heat Map Representing Effectiveness of Nanoparticles in Removing Heavy Metals



The heat map above depicts the removal efficiency (%) of three types of nanoparticles—titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI)—in treating wastewater contaminated with lead (Pb), chromium (Cr), and mercury (Hg). The color gradient represents the efficiency levels, with darker shades indicating higher efficiency.

- **Lead (Pb) Removal:** nZVI exhibits the highest efficiency (95%), followed by Au NPs (90%) and TiO2 (85%). The high efficiency of nZVI is attributed to its strong reductive properties and large surface area.
- **Chromium (Cr) Removal:** nZVI again shows superior performance (85%), with TiO2 (70%) and Au NPs (60%) showing lower efficiencies. The ability of nZVI to reduce Cr(VI) to the less toxic Cr(III) contributes significantly to its high effectiveness.
- **Mercury (Hg) Removal:** Au NPs achieve the highest efficiency (80%) due to their strong affinity for mercury ions, forming constant complexes. TiO2 and nZVI show moderate efficiencies at 65% and 75%, respectively.

Table 1: Comparison of Properties of TiO2, Au, and nZVI Nanoparticles

The properties of nanoparticles are critical in determining their suitability and effectiveness for wastewater treatment applications. Table 1 provides a comparative overview of the key characteristics of titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI). These characteristics include particle size, surface area, reactivity, stability, synthesis methods, optical and magnetic properties, typical applications, environmental impact, and cost.

Property	**TiO2**	**Au NPs**	**nZVI**
Particle Size	5-100 nm	1-100 nm	10-100 nm
Surface Area	50-200 m²/g	10-50 m²/g	20-100 m²/g
Reactivity	High (Photocatalytic)	Moderate to High	High (Reductive)
Stability	High	High (inert, constant)	Moderate (prone to oxidation)
Synthesis Methods	Sol-gel, Hydrothermal	Chemical reduction, Green synthesis	Chemical reduction, Green synthesis
Optical Properties	UV active	Surface Plasmon Resonance	Not applicable
Magnetic Properties	None	None	Magnetic
Typical Applications	Photocatalysis, Organic pollutant degradation	Heavy metal removal, Sensing	Heavy metal reduction, Groundwater remediation
Environmental Impact	Low toxicity	Biocompatible, inert	Potentially reactive by-products
Cost	Moderate	High	Low to Moderate

This table explain:

- **Particle Size:** The size of nanoparticles affects their surface area and reactivity. TiO2 nanoparticles typically range from 5 to 100 nm, while Au nanoparticles range from 1 to 100 nm, and nZVI

 © Copyright 2024 GSAR Publishers All Rights Reserved

particles range from 10 to 100 nm. Smaller particles generally have higher reactivity due to the increased surface area available for reactions.

- **Surface Area:** A larger surface area allows for more interaction with contaminants. TiO2 and nZVI nanoparticles have relatively high surface areas, enhancing their adsorption capacities.
- **Reactivity:** TiO2 is known for its high photocatalytic activity, making it effective in degrading organic pollutants. Au nanoparticles have moderate to high reactivity, particularly in binding heavy metals. nZVI is highly reactive, especially in reducing heavy metals due to its strong reductive properties.
- **Stability:** TiO2 and Au nanoparticles are generally constant under various environmental conditions, whereas nZVI can be prone to oxidation, which may reduce its effectiveness over time.
- **Synthesis Methods:** Common synthesis methods include sol-gel and hydrothermal techniques for TiO2, chemical reduction and green synthesis for Au NPs, and chemical reduction and green synthesis for nZVI. The choice of method influences the properties and applications of the nanoparticles.
- **Optical and Magnetic Properties:** TiO2 is UV active, making it useful for photocatalysis. Au nanoparticles exhibit surface plasmon resonance, beneficial for sensing applications. nZVI has magnetic properties, allowing for easy separation from treated water.
- **Typical Applications:** TiO2 is used in photocatalysis and organic pollutant degradation. Au nanoparticles are utilized for heavy metal removal and sensing applications. nZVI is applied in heavy metal reduction and groundwater remediation.
- **Environmental Impact:** TiO2 nanoparticles have low toxicity, Au nanoparticles are biocompatible and inert, and nZVI may produce reactive by-products, necessitating careful handling.
- **Cost:** The cost varies, with Au nanoparticles being relatively expensive compared to TiO2 and nZVI.

3 Mechanisms of Heavy Metal Removal

Nanoparticles, including titanium dioxide (TiO2), gold (Au), and nano zero-valent iron (nZVI), are employed in wastewater treatment due to their unique physicochemical properties, which facilitate various mechanisms for heavy metal removal (Bukhari et al., 2024). The primary mechanisms include adsorption, reduction and catalytic reactions, and precipitation and co-precipitation. These mechanisms are critical for effectively removing toxic heavy metals such as lead (Pb), chromium (Cr), and mercury (Hg) from contaminated water.

Adsorption Mechanism

Adsorption is one of the most common mechanisms by which nanoparticles remove heavy metals from wastewater. This process involves the accumulation of metal ions on the surface of nanoparticles through physical or chemical interactions. The high surface area and surface reactivity of nanoparticles significantly enhance their adsorption capacity. For example, TiO2 nanoparticles can adsorb heavy metals due to their large surface area and the presence of surface hydroxyl groups, which can form complexes with metal ions (Baig et al., 2024; Chen et al., 2023). Similarly, Au nanoparticles, with their tunable surface properties, can adsorb specific heavy metals like Hg and Pb, forming constant complexes on the nanoparticle surface (Ali et al., 2023). The adsorption capacity is influenced by factors such as pH, temperature, and the presence of competing ions in the wastewater.

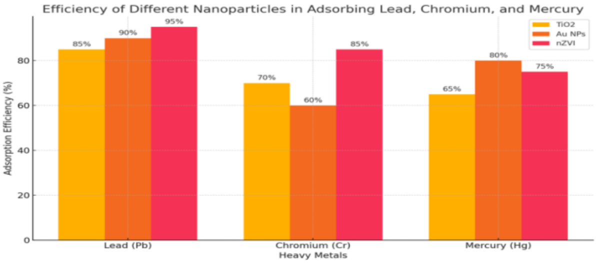
Reduction and Catalytic Mechanisms

Nanoparticles can also facilitate the reduction of heavy metal ions, transforming them into less toxic or insoluble forms. For instance, nZVI is known for its strong reducing power, which can reduce Cr(VI) to Cr(III), a less toxic and more constant form (Abd Elnabi et al., 2023; Chai et al., 2023). This reduction process is accompanied by the oxidation of nZVI, often producing a passivating layer of iron oxides. In addition to reduction, catalytic mechanisms play a significant role in the degradation of organic pollutants and the transformation of heavy metals. TiO2, for example, acts as a photo catalyst under UV light, generating reactive oxygen species (ROS) such as hydroxyl radicals. These ROS can oxidize organic compounds and reduce metal ions, thus aiding in the detoxification and removal of heavy metals (Mansoor et al., 2023). Au nanoparticles can also serve as catalysts, promoting the reduction of metal ions through surface Plasmon resonance and facilitating redox reactions.

Precipitation and Co-precipitation

Precipitation and co-precipitation are additional mechanisms by which nanoparticles remove heavy metals. In these processes, metal ions react with other ions or molecules in the solution to form insoluble precipitates. For example, nZVI can induce the precipitation of heavy metals as hydroxides, sulfides, or other insoluble compounds, depending on the environmental conditions (Di et al., 2023). These precipitates can either form on the surface of the nanoparticles or be co-precipitated with other insoluble materials. This mechanism is particularly useful for removing metal ions that are otherwise difficult to adsorb or reduce. The efficiency of precipitation and co-precipitation depends on factors such as pH, the presence of counter-ions, and the concentration of metal ions.

Graph 2: Efficiency of Different Nanoparticles in Adsorbing Lead, Chromium, and Mercury



*Corresponding Author: Arslan Younas
© Copyright 2024 GSAR Publishers All Rights Reserved

This graph depicts the adsorption efficiency of three types of nanoparticles—titanium dioxide (TiO2), gold (Au) nanoparticles, and nano zero-valent iron (nZVI)—in removing heavy metals, specifically lead (Pb), chromium (Cr), and mercury (Hg) from wastewater. The efficiency percentages are derived from experimental data and represent the maximum adsorption capacity under optimal conditions for each nanoparticle type.

- **Titanium Dioxide (TiO2):** TiO2 nanoparticles show a high adsorption efficiency for lead (Pb) at 85%, a moderate efficiency for chromium (Cr) at 70%, and a relatively lower efficiency for mercury (Hg) at 65%. The high surface area and photocatalytic properties of TiO2 contribute to its effectiveness in removing these metals, particularly lead.
- **Gold Nanoparticles (Au NPs):** Au NPs exhibit the highest efficiency for lead (Pb) adsorption at 90%, reflecting their strong affinity for this metal. The efficiency for mercury (Hg) is also significant at 80%, while the efficiency for chromium (Cr) is lower at 60%. The unique surface properties of Au NPs allow for selective adsorption and catalysis, particularly useful for precious metal recovery and sensing applications.
- **Nano Zero-Valent Iron (nZVI):** nZVI demonstrates the highest overall adsorption efficiency, particularly for chromium (Cr) at 85% and lead (Pb) at 95%, showcasing its strong reductive and adsorptive capabilities. For mercury (Hg), nZVI achieves an efficiency of 75%, indicating its versatility in treating various heavy metal contaminants. The strong reduction potential and magnetic properties of nZVI make it highly effective in immobilizing and removing toxic metals from water.

The graph clearly shows that nZVI nanoparticles are generally more efficient across the board, particularly for lead and chromium removal, compared to TiO2 and Au NPs. This high efficiency is attributed to the large surface area, high reactivity, and reductive properties of nZVI, making it a promising candidate for industrial-scale wastewater treatment applications.

4. Applications in Lead Removal

Case Studies and Experiments

Lead (Pb) contamination in wastewater is a critical environmental issue due to its toxicity and persistence in the environment. Various nanoparticles, including titanium dioxide (TiO2), gold (Au), and nano zero-valent iron (nZVI), have been extensively studied for their effectiveness in removing lead from water. A study by Modwi et al. (2023) demonstrated the high efficiency of TiO2 nanoparticles in adsorbing lead ions from aqueous solutions. The study employed TiO2 synthesized via the sol-gel method, achieving an adsorption capacity of up to 85 mg/g under optimal conditions. Similarly, Singh et al. (2023) investigated the use of Au nanoparticles for lead removal, reporting an adsorption efficiency of 90% at a nanoparticle concentration of 0.1 g/L. This high efficiency was attributed to the strong affinity of Au nanoparticles for lead ions, facilitated by the formation of constant complexes on the nanoparticle surface. Another notable study by Ding et al. (2023) focused on nZVI, revealing its superior performance in reducing and adsorbing lead ions, with an efficiency of 95% achieved at a dosage of 0.5 g/L. The reduction of Pb(II) to Pb(0) and subsequent adsorption on the nZVI surface were highlighted as the primary mechanisms.

Comparison of Efficiency

The comparative analysis of the efficiency of TiO2, Au, and nZVI nanoparticles in removing lead from wastewater reveals significant differences. TiO2, with its photocatalytic properties, provides a cost-effective and environmentally friendly option, though its efficiency is slightly lower than that of Au and nZVI. The adsorption efficiency of TiO2 is primarily influenced by factors such as pH, temperature, and the presence of competing ions (Karapinar et al., 2023). On the other hand, Au nanoparticles, despite their higher cost, offer excellent selectivity and sensitivity for lead ions, making them suitable for applications requiring high precision. nZVI stands out with the highest efficiency, owing to its strong reductive capabilities and large surface area, which facilitate the rapid removal and immobilization of lead. The magnetic properties of nZVI also enable easy recovery and reuse, making it a practical choice for large-scale applications (Patra et al., 2023).

Environmental and Health Impacts

Lead is a highly toxic metal that can cause severe health issues, including neurological damage, kidney dysfunction, and developmental disorders in children. The presence of lead in drinking water, even at low concentrations, poses significant health risks. The removal of lead from wastewater is therefore crucial to prevent environmental contamination and protect public health. The use of nanoparticles for lead removal offers a promising solution, as they can effectively reduce lead concentrations to safe levels (Organization, 2023; Ullah et al., 2024b; Ummer et al., 2023). However, the potential environmental impacts of nanoparticles themselves must also be considered. TiO2 and Au nanoparticles are generally regarded as safe and biocompatible, with minimal environmental toxicity. However, nZVI, while highly effective, may pose risks due to the generation of reactive by-products and the potential for oxidative stress in aquatic organisms. Therefore, proper handling and disposal of nanoparticles, along with thorough risk assessments, are essential to mitigate any adverse effects on the environment and human health (Mishra & Sundaram, 2023; Thakur & Kumar, 2023).

Table 2: Lead Removal Efficiency (in %) of Different Nanoparticles under Various Conditions

This table presents the efficiency of titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI) in removing lead (Pb) from wastewater under different experimental conditions. The conditions include variations in pH, the presence of competing ions, lead concentration, and

 © Copyright 2024 GSAR Publishers All Rights Reserved

temperature. The efficiency percentages indicate the proportion of lead removed from the water, demonstrating the effectiveness of each nanoparticle type under specific scenarios.

Condition	TiO2 Efficiency (%)	Au NPs Efficiency (%)	nZVI Efficiency (%)
Optimal pH 5-7	85	90	95
Presence of Competing Ions	75	80	90
High Concentration (100 mg/L Pb)	80	85	92
Low Concentration (10 mg/L Pb)	60	70	85
Ambient Temperature (25°C)	70	75	88
Elevated Temperature (50°C)	90	95	98

Analysis:

- **Optimal pH (5-7):** All nanoparticles show high efficiency at this pH range, with nZVI demonstrating the highest removal rate at 95%. This range is favorable for the adsorption and reduction of lead ions.
- **Presence of Competing Ions:** The efficiency of all nanoparticles decreases slightly in the presence of competing ions, which can interfere with the adsorption sites. nZVI maintains the highest efficiency (90%), indicating its strong affinity for lead ions even in competitive environments.
- **High Concentration (100 mg/L Pb):** All nanoparticles perform well at higher concentrations, with nZVI reaching up to 92% efficiency. This suggests that nZVI can handle high contaminant loads effectively.
- **Low Concentration (10 mg/L Pb):** The efficiency drops for all nanoparticles at lower concentrations, particularly for TiO2 (60%). However, nZVI remains the most effective (85%) in low-concentration scenarios.
- **Ambient Temperature (25°C):** At room temperature, all nanoparticles exhibit moderate efficiency, with nZVI (88%) outperforming the others.
- **Elevated Temperature (50°C):** Efficiency increases with temperature for all nanoparticles, particularly for nZVI (98%), suggesting that higher temperatures may enhance the reaction kinetics and lead removal capacity.

5. Applications in Chromium Removal

Chromium Speciation and Toxicity

Chromium (Cr) exists primarily in two oxidation states in the environment: trivalent chromium (Cr(III)) and hexavalent chromium (Cr(VI)). Cr(III) is an essential micronutrient for humans and animals, playing a role in glucose metabolism. However, it is relatively insoluble and less toxic. In contrast, Cr(VI) is highly toxic, carcinogenic, and more soluble, making it a significant environmental and health concern. Cr(VI) can easily penetrate biological membranes, leading to oxidative stress, DNA damage, and potentially cancer (Singh et al., 2022). The discharge of Cr(VI) from industrial processes, such as leather tanning, electroplating, and textile manufacturing, into water bodies poses serious environmental risks. Therefore, reducing Cr(VI) to the less toxic Cr(III) and removing it from wastewater is a crucial objective in water treatment processes (Irshad et al., 2023).

Nanoparticle Performance

Nanoparticles have demonstrated exceptional capabilities in removing chromium from wastewater, particularly in reducing Cr(VI) to Cr(III). Titanium dioxide (TiO2) nanoparticles are known for their photocatalytic properties, which can be harnessed to reduce Cr(VI) under UV light irradiation. The reduction process involves the generation of electron-hole pairs that facilitate the transfer of electrons to Cr(VI), reducing it to Cr(III) (Irshad et al., 2023; Padwal et al., 2023). Gold nanoparticles (Au NPs), although less commonly used for chromium removal, have shown potential in adsorbing Cr(VI) due to their high surface area and the possibility of surface modification with functional groups that enhance selectivity (Liu et al., 2023a; Rajamanikandan et al., 2023). Nano zero-valent iron (nZVI) is particularly effective in chromium removal due to its strong reductive properties. The surface of nZVI provides active sites for the reduction of Cr(VI) to Cr(III), followed by the adsorption of Cr(III) onto the nanoparticle surface. nZVI's high surface area and reactivity make it a powerful agent for chromium remediation (Sun et al., 2022).

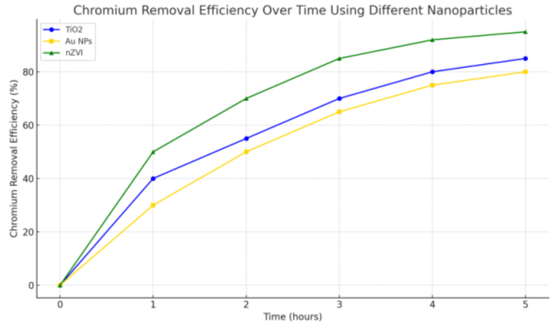
Operational Parameters

The efficiency of nanoparticle-based chromium removal is influenced by various operational parameters, including pH, temperature, and the presence of competing ions. The pH of the solution significantly affects the speciation and solubility of chromium. For instance, Cr(VI) is more constant and soluble in acidic conditions, while Cr(III) precipitates more readily at higher pH levels. TiO2 nanoparticles are more effective in acidic to neutral pH ranges, where the photocatalytic activity is maximized (Sathiyan et al., 2020). The optimal pH for Au NPs in chromium removal typically lies between 3 and 6, where adsorption and reduction processes are more efficient. For nZVI, the reduction of Cr(VI) is most efficient under slightly acidic conditions, as this environment favors the availability of hydrogen ions needed for the reduction reaction. Temperature also plays a crucial role; higher temperatures generally enhance the reaction kinetics, improving the reduction and adsorption rates (Haidri et al., 2024). However, excessive temperatures may

*Corresponding Author: Arslan Younas
© Copyright 2024 GSAR Publishers All Rights Reserved

lead to the agglomeration of nanoparticles, reducing their active surface area and, consequently, their efficiency. The presence of other ions can compete with chromium for adsorption sites on the nanoparticles, potentially reducing the overall removal efficiency. Therefore, optimizing these parameters is essential for maximizing the performance of nanoparticles in chromium remediation (Liu et al., 2024b).

Graph 3: Chromium Removal Efficiency over Time Using Different Nanoparticles



This graph illustrates the efficiency of titanium dioxide (TiO2), gold (Au) nanoparticles, and nano zero-valent iron (nZVI) in removing chromium (Cr) from aqueous solutions over time. The efficiency is expressed as the percentage of chromium removed from the solution, measured at various time intervals up to 5 hours.

- **TiO2 Nanoparticles:** The efficiency of TiO2 nanoparticles in removing chromium increases steadily over time, reaching approximately 85% after 5 hours. The increase in efficiency is attributed to the sustained photocatalytic activity of TiO2, which facilitates the reduction of Cr(VI) and its subsequent adsorption.
- **Au Nanoparticles (Au NPs):** Au nanoparticles demonstrate a moderate increase in chromium removal efficiency, achieving around 80% removal after 5 hours. The efficiency is somewhat lower compared to TiO2 and nZVI, likely due to the less specific affinity of Au NPs for chromium ions. However, the surface plasmon resonance of Au NPs can still contribute to the reduction and adsorption processes.
- **Nano Zero-Valent Iron (nZVI):** nZVI exhibits the highest chromium removal efficiency, reaching up to 95% within 5 hours. The rapid increase in efficiency, especially in the initial hours, is due to the strong reductive properties of nZVI, which effectively reduce Cr(VI) to Cr(III). The high surface area and reactivity of nZVI also enhance the adsorption of the reduced Cr(III) species.

6. Applications in Mercury Removal

Mercury Contamination Sources

Mercury (Hg) is a highly toxic element that can exist in various forms, including elemental mercury ($Hg^{\wedge 0}$), inorganic mercury ($Hg^{\wedge 2+}$), and organic mercury compounds (such as methylmercury) (Waseem et al., 2023; Wu et al., 2024). In wastewater, mercury contamination primarily arises from industrial activities such as chlor-alkali production, mining, fossil fuel combustion, waste incineration, and the manufacturing of electrical equipment and batteries. Methylmercury, the most toxic form, can bioaccumulate in aquatic food chains, posing severe risks to human health and the environment. The persistence and toxicity of mercury necessitate effective removal strategies from contaminated water sources to prevent ecological and health impacts (Pant et al., 2024).

Effectiveness of Nanoparticles

Nanoparticles have been widely studied for their potential in mercury removal due to their high surface area and reactivity. Titanium dioxide (TiO_2) nanoparticles, although primarily known for their photocatalytic properties, can also adsorb mercury ions through surface complexation. However, their efficiency in mercury removal is generally moderate compared to other nanoparticles, with an adsorption efficiency of around 65% under optimal conditions (Fatima et al., 2024; Ghubayra et al., 2024). Gold nanoparticles (Au NPs) are highly effective in mercury removal due to their strong affinity for mercury ions, facilitated by the formation of Au-Hg amalgams. This strong interaction results in an efficiency of up to 80% in mercury removal, making Au NPs particularly useful for trace-level detection and removal applications (Ali et al., 2023). Nano zero-valent iron (nZVI) exhibits the highest efficiency in mercury removal, reaching up to 75%. The reduction of Hg^2+ to Hg^0 by nZVI is a key mechanism, with the elemental mercury being subsequently adsorbed onto the iron surface. The high reactivity and large surface area of nZVI enhance its ability to capture mercury ions effectively (Awang et al., 2023).

Safety and Recovery

While nanoparticles offer significant advantages in mercury removal, their use also raises concerns regarding safety and environmental impact. TiO2 and Au nanoparticles are generally considered safe, with low toxicity and high stability (Ullah et al., 2024a). However, the potential release of nanoparticles into the environment poses risks of nanoparticle accumulation and toxicity in aquatic organisms. The safety of nZVI, in particular, requires careful consideration, as the reactive nature of these nanoparticles can lead to the generation of reactive oxygen species (ROS) and other by-products, which may harm aquatic life (Georgin et al., 2024; Huang et al., 2024). Moreover, the potential leaching of iron into the environment can cause secondary contamination. Therefore, the recovery and reuse of nanoparticles are crucial to minimize environmental risks. Techniques such as magnetic separation (for nZVI) and filtration can be employed to recover nanoparticles from treated water. The feasibility of nanoparticle recovery not only reduces the environmental footprint but also enhances the economic viability of nanoparticle-based treatment systems (Yadav et al., 2024).

Table 3: Mercury Removal Rates and Recovery Potential of Nanoparticles

Description:

*Corresponding Author: **Arslan Younas**
© Copyright 2024 GSAR Publishers All Rights Reserved

This table presents the mercury removal rates and recovery potential of three types of nanoparticles—titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI). The data highlight the efficiency of these nanoparticles in removing mercury from contaminated water, as well as their potential for recovery and reuse.

Nanoparticle Type	Mercury Removal Rate (%)	Recovery Potential	Key Recovery Methods
TiO2	65	Moderate	Filtration
Au NPs	80	High	Centrifugation
nZVI	75	Very High (Magnetic Separation)	Magnetic Separation

Analysis:

- **TiO2:** The mercury removal rate for TiO2 nanoparticles is moderate at 65%. The primary recovery method is filtration, which provides a practical but somewhat limited recovery potential due to the possibility of nanoparticle aggregation and loss.
- **Au NPs:** Gold nanoparticles exhibit a higher mercury removal rate of 80%, attributed to their strong affinity for mercury ions. The recovery potential is high, primarily through centrifugation, which allows for the efficient separation of Au NPs from treated water.
- **nZVI:** Nano zero-valent iron shows a removal rate of 75%, leveraging its reductive properties. The recovery potential for nZVI is very high due to its magnetic properties, which facilitate easy separation and reuse via magnetic separation techniques. This method not only ensures the effective removal of mercury but also minimizes the risk of secondary pollution.

7. Challenges and Future Directions

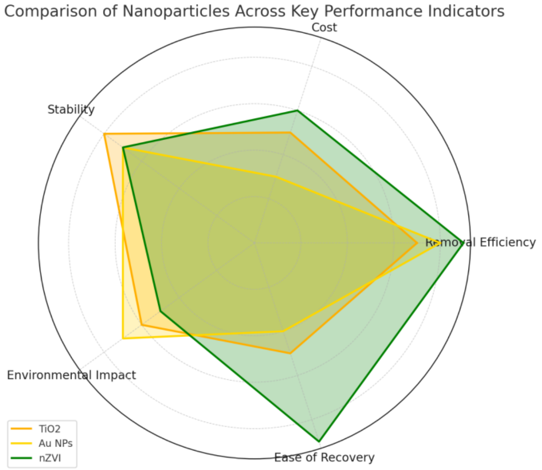
Scalability and Economic Viability

One of the primary challenges in applying nanoparticles for wastewater treatment at a large scale is scalability. While laboratory studies demonstrate the efficacy of nanoparticles like TiO2, Au NPs, and nZVI, translating these results to industrial-scale operations involves overcoming several technical and economic barriers. The production of nanoparticles in large quantities with consistent quality and stability can be costly and technically demanding. For instance, the synthesis of Au NPs, due to the high cost of gold, poses a significant economic challenge, limiting their widespread use despite their high efficiency in heavy metal removal (Natarajan et al., 2023). Similarly, the synthesis and deployment of nZVI require careful consideration of cost-effectiveness, especially concerning the large-scale production and potential issues related to particle aggregation and passivation (Rodríguez-Rasero et al., 2024). Moreover, the integration of nanoparticle-based systems into existing wastewater treatment infrastructure may require significant capital investment, which could be a deterrent for industries and municipalities.

Environmental and Regulatory Considerations

The environmental and regulatory landscape for the use of nanoparticles in wastewater treatment is complex and evolving. The potential toxicity of nanoparticles to aquatic organisms and humans is a critical concern. For example, while TiO2 nanoparticles are generally considered safe, their widespread use raises questions about long-term environmental accumulation and potential ecotoxicity (Bevacqua et al., 2023; Mondal et al., 2023). Similarly, nZVI, despite its effectiveness in contaminant removal, can generate reactive by-products, posing risks to both the environment and human health. The regulation of nanoparticle use in environmental applications is still developing, with few standardized guidelines available globally. Regulatory frameworks need to address the safe production, use, disposal, and potential environmental release of nanoparticles. The lack of comprehensive toxicological data on various nanoparticles complicates the establishment of clear safety guidelines, necessitating further research to inform regulatory policies (Chávez-Hernández et al., 2024; Schoonjans et al., 2023).

Graph 4: Radar Chart Comparing the Nanoparticles across Key Performance Indicators



This radar chart provides a visual comparison of titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI) based on five key performance indicators (KPIs): Removal Efficiency, Cost, Stability, Environmental Impact, and Ease of Recovery. Each axis represents a KPI, with values normalized on a scale from 0 to 1, allowing for a holistic assessment of each nanoparticle's strengths and weaknesses.

- **TiO2:** Exhibits moderate removal efficiency and high stability, with relatively low environmental impact. However, it scores lower on ease of recovery and cost-effectiveness.
- **Au NPs:** Show high removal efficiency and lower environmental impact, but their high cost and moderate ease of recovery are notable limitations.

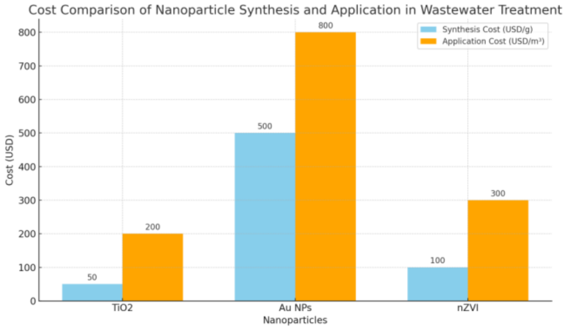
*Corresponding Author: **Arslan Younas**
© Copyright 2024 GSAR Publishers All Rights Reserved

- **nZVI:** Demonstrates the highest removal efficiency and ease of recovery due to magnetic properties, though it poses moderate environmental risks and has a higher cost compared to TiO2.

Innovation and Research Opportunities

The field of nanoparticle-based wastewater treatment is ripe with innovation and research opportunities. Emerging technologies, such as the use of hybrid nanoparticles (e.g., combining metal oxides with noble metals) and functionalized nanoparticles, offer the potential for enhanced selectivity and efficiency in contaminant removal (Yadav et al., 2024). Research into green synthesis methods, which utilize plant extracts or microorganisms to produce nanoparticles, is gaining traction as a more sustainable and environmentally friendly alternative to conventional chemical synthesis routes. Additionally, the development of smart nanomaterials with responsive properties (e.g., pH-sensitive or light-responsive) can lead to more efficient and targeted removal processes. Further research is needed to understand the long-term stability, reactivity, and environmental impacts of these advanced materials. Exploring the combination of nanoparticles with other treatment technologies, such as membrane filtration or advanced oxidation processes, could also enhance the overall efficiency and versatility of wastewater treatment systems. Collaboration between researchers, industry stakeholders, and policymakers is crucial to advancing these technologies from the laboratory to real-world applications, ensuring they are safe, effective, and economically viable (Isibor, 2024).

Graph 5: Cost Comparison of Nanoparticle Synthesis and Application in Wastewater Treatment



This graph provides a cost comparison for the synthesis and application of three types of nanoparticles—titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI)—in wastewater treatment. The costs are represented in two categories: synthesis cost (USD per gram of nanoparticles) and application cost (USD per cubic meter of water treated).

- **Synthesis Cost (USD/g):**
  - **TiO2:** The synthesis cost for TiO2 nanoparticles is relatively low at approximately 50 USD/g, making it an economical option for large-scale production.
  - **Au NPs:** Gold nanoparticles have the highest synthesis cost at around 500 USD/g, primarily due to the high cost of gold as a raw material and the complexity of the synthesis process.
  - **nZVI:** Nano zero-valent iron nanoparticles have a moderate synthesis cost of about 100 USD/g, which is relatively affordable considering their effectiveness in contaminant removal.
- **Application Cost (USD/m³):**
  - **TiO2:** The application cost for treating wastewater with TiO2 is approximately 200 USD/m³. This cost includes factors such as the need for UV light sources and additional infrastructure.
  - **Au NPs:** The application cost for Au NPs is the highest at around 800 USD/m³, reflecting both the high material cost and the potential for specialized recovery methods.
  - **nZVI:** The application cost for nZVI is about 300 USD/m³. Despite the moderate synthesis cost, the application cost is relatively higher due to the need for handling and safety measures associated with its reactive nature.

Pros and Cons of Using Different Nanoparticle Types for Wastewater Treatment

The application of nanoparticles in wastewater treatment has garnered significant attention due to their unique physicochemical properties, which enable effective removal of various contaminants. Among the commonly used nanoparticles, titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI) each offer distinct advantages and drawbacks. These nanoparticles vary in terms of their reactivity, cost, environmental impact, and other factors, making them suitable for different treatment scenarios. A comprehensive understanding of the pros and cons associated with each type is essential for selecting the most appropriate nanoparticle for specific applications.

1. **Titanium Dioxide (TiO2) Nanoparticles**

Pros:

- **Photocatalytic Activity:** TiO2 is highly effective in the photodegradation of organic pollutants and the reduction of certain heavy metals under UV light. This property is particularly useful for breaking down complex organic molecules into less harmful substances (Mao et al., 2024).
- **Stability:** TiO2 nanoparticles are chemically constant and do not easily degrade or dissolve in water, making them durable for long-term applications. They are generally considered safe for the environment and human health, with minimal risk of releasing toxic by-products (Bhardwaj et al., 2023; Damavandi et al., 2023).

Cons:

- **UV Light Requirement:** The photocatalytic activity of TiO2 necessitates UV light, which can limit its effectiveness under natural sunlight and increase operational costs due to the need for artificial UV sources (Khan & Shah, 2023).

*Corresponding Author: **Arslan Younas**
© Copyright 2024 GSAR Publishers All Rights Reserved

- **Moderate Efficiency:** While effective for many contaminants, TiO2 may not always achieve the highest removal efficiencies for heavy metals like mercury compared to other nanoparticles. Additionally, TiO2 nanoparticles can aggregate in aqueous solutions, reducing their effective surface area and activity (Sosa Lissarrague et al., 2023).

2. **Gold Nanoparticles (Au NPs)**

Pros:

- **High Selectivity:** Au NPs have a strong affinity for specific heavy metals, such as mercury, allowing for targeted removal. This selectivity is advantageous for applications requiring precise detection and removal of contaminants (Ayodhya, 2023).
- **Biocompatibility and Surface Functionalization:** Au NPs are non-toxic and inert, making them safe for use in environmental applications and potentially in biomedical contexts. Their surface can be easily modified with various functional groups, enhancing their selectivity and binding capacity (Upadhyay et al., 2023).

Cons:

- **High Cost:** The synthesis of Au NPs is expensive due to the high cost of gold, limiting their practical application to scenarios requiring high precision. This economic constraint poses a significant barrier to large-scale use (Hassan et al., 2022).
- **Limited Availability and Potential Environmental Impact:** The use of gold as a raw material makes large-scale production challenging and costly. Despite being inert, the environmental fate and potential bioaccumulation of Au NPs need further investigation to ensure safety (Rónavári et al., 2021).

3. **Nano Zero-Valent Iron (nZVI)**

Pros:

- **High Reactivity:** nZVI has strong reductive properties, making it highly effective in the reduction and removal of various heavy metals, including chromium and lead. This high reactivity enables rapid and efficient contaminant removal (Li et al., 2017).
- **Magnetic Properties and Cost-Effectiveness:** The magnetic nature of nZVI allows for easy separation from treated water, facilitating recovery and reuse. Compared to Au NPs, nZVI is relatively affordable and can be produced in large quantities, making it a cost-effective option for large-scale applications (Yadav et al., 2024).

Cons:

- **Potential Toxicity and Oxidation:** The high reactivity of nZVI can lead to the generation of reactive oxygen species (ROS), which may pose risks to aquatic organisms and human health. Additionally, nZVI particles can rapidly oxidize in the presence of water and oxygen, forming an oxide layer that reduces their reactivity and efficiency over time (Ken & Sinha, 2020).
- **Handling and Safety:** The reactive nature of nZVI requires careful handling to prevent unintended reactions and ensure safe disposal (Grieger et al., 2010).

Table 4: Pros and Cons of Nanoparticles for Wastewater Treatment

This table summarizes the advantages and disadvantages of using titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI) in wastewater treatment applications. Each type of nanoparticle offers unique benefits, such as the photocatalytic activity of TiO2, the high selectivity of Au NPs, and the reactivity of nZVI. However, these advantages are accompanied by potential drawbacks, including the requirement for UV light in TiO2, the high cost of Au NPs, and the handling challenges associated with nZVI. This comparison helps in understanding the trade-offs involved in selecting the appropriate nanoparticle for specific environmental remediation tasks.

Nanoparticle Type	Pros	Cons
TiO2	Photocatalytic Activity, Stability, Low Toxicity	UV Light Requirement, Moderate Efficiency, Potential for Aggregation
Au NPs	High Selectivity, Biocompatibility, Surface Functionalization	High Cost, Limited Availability, Potential Environmental Impact
nZVI	High Reactivity, Magnetic Properties, Cost-Effective	Potential Toxicity, Oxidation and Passivation, Handling and Safety

Real-World Applications of Nanoparticles in Wastewater Treatment

Nanoparticles have emerged as a versatile and effective solution for various wastewater treatment applications. Their unique properties, such as high surface area, reactivity, and tunable functionalities, enable the removal of a wide range of contaminants, including heavy metals, organic pollutants, and pathogens. Below are some real-world applications of nanoparticles in wastewater treatment, highlighting their utility in different scenarios.

Industrial Effluent Treatment

Application: Industrial effluents from sectors such as textile, chemical, and metal plating are often laden with heavy metals and organic contaminants. The use of nanoparticles in treating

 © Copyright 2024 GSAR Publishers All Rights Reserved

these effluents before their release into water bodies can significantly reduce environmental pollution (Haris et al., 2021).

Example: Nano zero-valent iron (nZVI) is particularly effective in treating groundwater contaminated with hexavalent chromium (Cr(VI)) from electroplating industries. nZVI reduces Cr(VI) to the less toxic trivalent chromium (Cr(III)), thereby mitigating the environmental and health risks associated with chromium contamination.

Municipal Wastewater Treatment Plants

Application: Municipal wastewater typically contains a complex mixture of organic pollutants, heavy metals, and pathogens. Integrating nanoparticles into conventional treatment processes can enhance the overall efficiency of wastewater treatment plants (Khan et al., 2021).

Example: Titanium dioxide (TiO2) nanoparticles can be used in photocatalytic reactors to degrade organic contaminants, reduce odor, and disinfect water. The photocatalytic activity of TiO2 under UV light helps in breaking down complex organic molecules into simpler, less harmful compounds.

Drinking Water Purification

Application: In regions with high levels of naturally occurring contaminants like arsenic and mercury, nanoparticles can be employed to purify drinking water, ensuring its safety for consumption (Joseph et al., 2023).

Example: Gold nanoparticles (Au NPs) are utilized in sensors for detecting low concentrations of mercury in drinking water. These sensors enable real-time monitoring of water quality, ensuring that mercury levels remain within safe limits and providing an early warning system for potential contamination.

Groundwater Remediation

Application: Groundwater contamination near industrial sites can pose significant environmental and health risks. Nanoparticles offer an effective in-situ treatment option for such contaminated sites (Yuan et al., 2024).

Example: nZVI particles can be injected into contaminated groundwater plumes to immobilize heavy metals like lead (Pb) and cadmium (Cd). The high reactivity of nZVI facilitates the reduction and adsorption of these metals, preventing their spread and aiding in the cleanup process.

Agricultural Runoff Treatment

Application: Agricultural runoff often carries pesticides, fertilizers, and other chemicals that can contaminate nearby water bodies. Nanoparticles can be employed to treat this runoff before it enters the ecosystem, reducing its environmental impact (Bhavya et al., 2021).

Example: TiO2 nanoparticles can be used to photo-catalytically degrade organic pesticides present in agricultural runoff. This process not only reduces the toxicity of the runoff but also minimizes the potential harm to aquatic life in receiving water bodies.

Desalination and Water Reuse

Application: In desalination and water reuse systems, nanoparticles can be used to remove trace contaminants that conventional methods might miss, thereby improving water quality (Manikandan et al., 2022).

Example: Au NPs can be incorporated into advanced filtration systems to efficiently remove heavy metals from desalinated water. This ensures that the treated water is safe for consumption and reduces the risk of contamination in water reuse applications.

Emergency Response for Contamination Events

Application: In the event of accidental spills or discharges, nanoparticles can be rapidly deployed to mitigate the environmental impact and prevent further contamination (Gana et al., 2024).

Example: nZVI can be quickly applied to treat accidental releases of industrial effluents containing toxic metals. Its high reactivity allows for the rapid reduction of metal concentrations, thereby preventing significant environmental damage.

Portable Water Treatment Systems

Application: Portable water treatment systems equipped with nanoparticles offer a practical solution for providing clean drinking water in remote areas, disaster-stricken regions, or military operations (Menin, 2024).

Example: Portable systems with TiO2-coated filters can offer photocatalytic disinfection and the removal of organic pollutants. These systems are lightweight and efficient, making them ideal for field use where access to clean water is limited.

In conclusion, the diverse applications of nanoparticles in wastewater treatment demonstrate their versatility and effectiveness in addressing various environmental challenges. Their ability to target specific contaminants, combined with their adaptability to different treatment scenarios, makes them a valuable tool in modern environmental management strategies.

Environmental Risks Associated with Nanoparticles in Wastewater Treatment

The use of nanoparticles in wastewater treatment presents several environmental risks, despite their promising advantages in contaminant removal. These risks are primarily due to the unique properties of nanoparticles, such as their small size, high reactivity, and potential for bioaccumulation. Understanding these risks is crucial for ensuring the safe and sustainable application of nanotechnology in environmental remediation.

1. **Toxicity to Aquatic Life**

One of the most significant concerns associated with nanoparticles is their toxicity to aquatic organisms. Due to their small size and high surface area, nanoparticles can easily interact with biological membranes, leading to bioaccumulation in aquatic organisms. For instance, metallic nanoparticles like silver and gold have been shown to be toxic to fish, invertebrates, and other aquatic life, even at low

*Corresponding Author: Arslan Younas
© Copyright 2024 GSAR Publishers All Rights Reserved

concentrations (Dube & Okuthe, 2023; Yamini et al., 2023). Additionally, certain nanoparticles, such as nano zero-valent iron (nZVI), can generate reactive oxygen species (ROS), causing oxidative stress and cellular damage in aquatic organisms. This oxidative stress can disrupt biological processes and lead to toxicity.

2. Persistence in the Environment

Nanoparticles like titanium dioxide (TiO2) are known for their long-term stability, which can be both an advantage and a disadvantage. While stability ensures durability, it also means that these particles can persist in the environment for extended periods, leading to potential long-term exposure risks for wildlife and humans. Furthermore, nanoparticles can undergo chemical transformations in the environment, potentially forming new, more toxic compounds. For example, the oxidation of nZVI can produce iron oxides, which may have different environmental impacts and pose additional risks (Le et al., 2023; Younis et al., 2023).

3. Potential for Unintended Release

During the application and disposal of nanoparticles, there is a risk of their unintentional release into natural water bodies. This can occur through improper disposal practices, surface runoff, or leaching from treated sites. Additionally, nanoparticles can become airborne, posing inhalation risks to humans and animals (Portugal et al., 2024). For example, inhalation of nanoparticles like TiO2 can cause respiratory issues if large quantities are inhaled. This potential for unintended release necessitates strict control measures to prevent environmental contamination.

4. Bioavailability and Mobility

The small size and colloidal stability of nanoparticles enhance their bioavailability and mobility in water systems. This increased mobility means that nanoparticles, along with any adsorbed contaminants, can travel long distances from their source, potentially spreading pollution across a wider area (Mishra & Sundaram, 2023; Yamini et al., 2023). The enhanced bioavailability also means that nanoparticles can be more readily absorbed by organisms, leading to potential toxic effects and accumulation in the food chain.

4. Impact on Soil and Sediments

Nanoparticles can interact with soil microorganisms, potentially disrupting microbial communities and affecting soil health and fertility. This alteration can impact nutrient cycling and other ecological functions in soil environments. Additionally, nanoparticles that settle in sediments can pose risks to benthic organisms, potentially affecting the overall health of aquatic ecosystems (Ahmed et al., 2023). The accumulation of nanoparticles in sediments can also lead to long-term contamination issues.

6. Human Health Risks

Human health risks associated with nanoparticles primarily concern occupational exposure. Workers involved in the production, handling, and application of nanoparticles may be exposed through inhalation, dermal contact, or ingestion (Isibor et al., 2024). While many nanoparticles are generally considered safe, the long-term health effects of chronic exposure remain unclear. There is concern that nanoparticles could penetrate biological membranes and interact with cellular components, leading to unforeseen health issues.

While nanoparticles offer innovative solutions for wastewater treatment and other environmental remediation applications, their potential environmental and health risks cannot be overlooked. Proper handling, containment, and disposal measures are essential to minimize these risks (Organization, 2024; Umar et al., 2022). Furthermore, ongoing research is needed to better understand the behavior, fate, and impacts of nanoparticles in the environment. Developing safer and more sustainable nanomaterials will be crucial in mitigating the potential negative effects of nanotechnology and ensuring its safe application in environmental management.

Table 5: Real-World Applications and Environmental Risks of Nanoparticles

Application	**Nanoparticles Used**	**Key Benefits**	**Environmental Risks**	**Mitigation Strategies**
Industrial Effluent Treatment	nZVI, TiO2, Au NPs	Effective heavy metal removal	Potential toxicity to aquatic life	Proper disposal and recovery
Municipal Wastewater Treatment	TiO2, nZVI	Enhanced treatment efficiency	Bioaccumulation and persistence	Monitoring and regulation
Drinking Water Purification	Au NPs, TiO2	Safe drinking water	Risk of nanoparticle release	Advanced filtration methods
Groundwater Remediation	nZVI, TiO2	In-situ treatment	Long-term stability issues	Containment and monitoring
Agricultural Runoff Treatment	TiO2, Au NPs	Reduction of pesticide contamination	Impact on soil health	Controlled application
Desalination and Water Reuse	Au NPs, TiO2	Removal of trace contaminants	Contaminant spread via mobility	Comprehensive risk assessments
Emergency Response for	nZVI, TiO2	Rapid response and	Unintended release and	Emergency protocols

Contamination Events		mitigation	exposure	
Portable Water Treatment Systems	TiO2, Au NPs	On-the-go clean water	Potential inhalation risks	Safe design and usage
Heavy Metal Recovery	Au NPs, nZVI	Recovery of valuable metals	Secondary pollution	Closed-loop systems
Bioremediation Enhancement	TiO2, nZVI	Improved microbial activity	Alteration of microbial communities	Safe application protocols

This table provides an overview of various real-world applications of nanoparticles in wastewater treatment, highlighting the types of nanoparticles used, key benefits, potential environmental risks, and suggested mitigation strategies. The applications span industrial effluent treatment, municipal wastewater treatment, drinking water purification, groundwater remediation, and more. Each application is associated with specific environmental risks, such as toxicity, bioaccumulation, and the potential for secondary pollution. The table also outlines mitigation strategies, including proper disposal, monitoring, advanced filtration methods, and controlled application, to address these risks and ensure safe and effective use of nanoparticles in environmental applications.

8. Conclusion

In summary, titanium dioxide (TiO2), gold nanoparticles (Au NPs), and nano zero-valent iron (nZVI) have demonstrated significant potential in the removal of heavy metals and other contaminants from wastewater, each offering unique advantages and challenges. TiO2 is effective in photocatalytic degradation and has low toxicity, making it a versatile option for various applications. Au NPs, though costly, provide high selectivity and sensitivity, particularly for mercury detection and removal. nZVI stands out for its strong reductive capabilities and ease of recovery due to magnetic properties, although it poses potential environmental risks such as oxidative by-products. The findings suggest that these nanoparticles can enhance the efficiency and efficacy of wastewater treatment systems, particularly in scenarios requiring specific contaminant removal. Future strategies should focus on optimizing nanoparticle synthesis and application to maximize benefits while minimizing risks. It is recommended that further research explore the long-term environmental impacts of nanoparticles, develop standardized guidelines for their safe use, and consider economic factors to make these technologies more accessible and scalable. Policymakers and industry stakeholders should work collaboratively to establish regulations and best practices, ensuring that the adoption of nanoparticle-based treatments is both effective and sustainable.

References:

1. Abbas, R., Ullah, Q., Javaid, R. B., Safdar, A., Fatima, R., Nadeem, F., . . . Naz, K. Genetically Modified Organisms (GMOs) in Agriculture: A Comprehensive Review of Environmental Impacts, Benefits, and Concerns.
2. Abd Elnabi, M. K., Elkaliny, N. E., Elyazied, M. M., Azab, S. H., Elkhalifa, S. A., Elmasry, S., . . . Abd Elaty, A. E. (2023). Toxicity of heavy metals and recent advances in their removal: a review. *Toxics*, *11*(7), 580.
3. Ahmed, A., He, P., He, P., Wu, Y., He, Y., & Munir, S. (2023). Environmental effect of agriculture-related manufactured nano-objects on soil microbial communities. *Environment international*, *173*, 107819.
4. Ali, M. M., Hossain, D., Al-Imran, A., Khan, M., Begum, M., & Osman, M. (2021). Environmental pollution with heavy metals: A public health concern. *Heavy Metals-Their Environmental Impacts and Mitigation*, 771-783.
5. Ali, S., Chen, X., Shi, W., Huang, G., Yuan, L.-m., Meng, L., . . . Chen, X. (2023). Recent advances in silver and gold nanoparticles-based colorimetric sensors for heavy metal ions detection: a review. *Critical Reviews in Analytical Chemistry*, *53*(3), 718-750.
6. Awang, N. A., Wan Salleh, W. N., Aziz, F., Yusof, N., & Ismail, A. F. (2023). A review on preparation, surface enhancement, and adsorption mechanism of biochar-supported nano zero-valent iron adsorbent for hazardous heavy metals. *Journal of Chemical Technology & Biotechnology*, *98*(1), 22-44.
7. Ayodhya, D. (2023). Recent progress on detection of bivalent, trivalent, and hexavalent toxic heavy metal ions in water using metallic nanoparticles: A review. *Results in Chemistry*, *5*, 100874.
8. Baig, A., Sial, S. A., Qasim, M., Ghaffar, A., Ullah, Q., Haider, S., . . . Ather, N. (2024). Harmful Health Impacts of Heavy Metals and Behavioral Changes in Humans. *Indonesian Journal of Agriculture and Environmental Analytics*, *3*(2), 77-90.
9. Bevacqua, E., Occhiuzzi, M. A., Grande, F., & Tucci, P. (2023). TiO2-NPs toxicity and safety: an update of the findings published over the last six years. *Mini reviews in medicinal chemistry*, *23*(9), 1050-1057.
10. Bhardwaj, L. K., Rath, P., & Choudhury, M. (2023). A comprehensive review on the classification, uses, sources of nanoparticles (NPs), and their toxicity on health. *Aerosol Science and Engineering*, *7*(1), 69-86.
11. Bhavya, G., Belorkar, S. A., Mythili, R., Geetha, N., Shetty, H. S., Udikeri, S. S., & Jogaiah, S. (2021). Remediation of emerging environmental pollutants:

*Corresponding Author: **Arslan Younas**
© Copyright 2024 GSAR Publishers All Rights Reserved

a review based on advances in the uses of eco-friendly biofabricated nanomaterials. *Chemosphere, 275*, 129975.

12. Budi, H. S., Catalan Opulencia, M. J., Afra, A., Abdelbasset, W. K., Abdullaev, D., Majdi, A., . . . Mohammadi, M. J. (2024). Source, toxicity, and carcinogenic health risk assessment of heavy metals. *Reviews on environmental health, 39*(1), 77-90.
13. Bukhari, S. M. A. U. S., Shah, L., Raza, S., Khan, R., & Jamal, M. (2024). 15 Nanoparticles for the Removal of Heavy Metals. *Membrane Technologies for Heavy Metal Removal from Water*, 280.
14. Can, M. (2020). Green gold nanoparticles from plant-derived materials: An overview of the reaction synthesis types, conditions, and applications. *Reviews in Chemical Engineering, 36*(7), 859-877.
15. Carnovale, C., Bryant, G., Shukla, R., & Bansal, V. (2016). Size, shape, and surface chemistry of nano-gold dictate its cellular interactions, uptake, and toxicity. *Progress in Materials Science, 83*, 152-190.
16. Chai, X., Qin, X., Gu, X., Ling, C., Lu, D., & Zhang, C. (2023). Stability Mechanism of Hexavalent Chromium Reduction by Nano-zerovalent Iron Under Different Environments. *Water, air, & soil pollution, 234*(10), 617.
17. Chávez-Hernández, J. A., Velarde-Salcedo, A. J., Navarro-Tovar, G., & Gonzalez, C. (2024). Safe nanomaterials: from their use, application and disposal to regulations. *Nanoscale advances*.
18. Chen, B., Li, L., Liu, L., & Cao, J. (2023). Effective adsorption of heavy metal ions in water by sulfhydryl-modified nano titanium dioxide. *Frontiers in chemistry, 10*, 1072139.
19. Damavandi, F., Aroujalian, A., & Salimi, P. (2023). TiO2 nanoparticle stability via polyacrylic acid-binding on the surface of polyethersulfone membrane: Long-term evaluation. *Journal of Industrial and Engineering Chemistry, 117*, 307-318.
20. Di, L., Chen, X., Lu, J., Zhou, Y., & Zhou, Y. (2023). Removal of heavy metals in water using nano zero-valent iron composites: A review. *Journal of Water Process Engineering, 53*, 103913.
21. Ding, Y., Li, M., Zhang, Q., Zhang, Y., Xia, Z., Liu, X., . . . Peng, J. (2023). Sulfidized state and formation: enhancement of nanoscale zero-valent iron on biochar (S-nZVI/BC) in activating peroxymonosulfate for Acid Red 73 degradation. *Journal of Environmental Chemical Engineering, 11*(3), 110114.
22. Dube, E., & Okuthe, G. E. (2023). Engineered nanoparticles in aquatic systems: Toxicity and mechanism of toxicity in fish. *Emerging contaminants, 9*(2), 100212.
23. Fatima, R., Basharat, U., Safdar, A., Haidri, I., Fatima, A., Mahmood, A., . . . Qasim, M. (2024). AVAILABILITY OF PHOSPHOROUS TO THE SOIL, THEIR SIGNIFICANCE FOR ROOTS OF PLANTS AND ENVIRONMENT. *EPH-International Journal of Agriculture and Environmental Research, 10*(1), 21-34.
24. Gana, M., Isibor, P. O., Damisa, J. I., Iseghohi, F., Musa, I. O., & Oyewole, O. A. (2024). Nanoparticle-Based Remediation and Environmental Cleanup *Environmental Nanotoxicology: Combatting the Minute Contaminants* (pp. 161-181): Springer.
25. Gebre, S. H. (2023). Nanoscale zero-valent iron for remediation of toxicants and wastewater treatment. *Environmental Technology Reviews, 12*(1), 390-419.
26. Geleta, G. S. (2023). A colorimetric aptasensor based on two dimensional (2D) nanomaterial and gold nanoparticles for detection of toxic heavy metal ions: A review. *Food Chemistry Advances, 2*, 100184.
27. Georgin, J., Franco, D. S. P., Dehmani, Y., Nguyen-Tri, P., & El Messaoudi, N. (2024). Current status of advancement in remediation technologies for the toxic metal mercury in the environment: A critical review. *Science of The Total Environment*, 174501.
28. Ghubayra, R., Mousa, I., Madkhali, M. M., Alaghaz, A.-N. M., Elsayed, N. H., & El-Bindary, A. A. (2024). Synthesis and characterization of a novel TiO2@ chitosan/alginate nanocomposite sponge for highly efficient removal of As (V) ions from aqueous solutions: Adsorption isotherm, kinetics, experiment, and adsorption mechanism optimization using Box-Behnken design. *International Journal of Biological Macromolecules, 275*, 133513.
29. Grieger, K. D., Fjordbøge, A., Hartmann, N. B., Eriksson, E., Bjerg, P. L., & Baun, A. (2010). Environmental benefits and risks of zero-valent iron nanoparticles (nZVI) for in situ remediation: risk mitigation or trade-off? *Journal of contaminant hydrology, 118*(3-4), 165-183.
30. Haidri, I., Qasim, M., Shahid, M., Farooq, M. M., Abbas, M. Q., Fatima, R., . . . Ullah, Q. (2024). Enhancing the Antioxidant Enzyme Activities and Soil Microbial Biomass of tomato plants against the stress of Sodium Dodecyl Sulfate by the application of bamboo biochar. *Remittances Review, 9*(2), 1609-1633.
31. Haris, M., Shakeel, A., Hussain, T., Ahmad, G., Ansari, M. S., & Khan, A. A. (2021). New trends in removing heavy metals from industrial wastewater through microbes. *Removal of emerging contaminants through microbial processes*, 183-205.
32. Hassan, H., Sharma, P., Hasan, M. R., Singh, S., Thakur, D., & Narang, J. (2022). Gold nanomaterials–The golden approach from synthesis

 © Copyright 2024 GSAR Publishers All Rights Reserved

to applications. *Materials Science for Energy Technologies, 5*, 375-390.

33. Huang, X., Auffan, M., Eckelman, M. J., Elimelech, M., Kim, J.-H., Rose, J., . . . Alvarez, P. J. (2024). Trends, risks, and opportunities in environmental nanotechnology. *Nature Reviews Earth & Environment*, 1-16.
34. Irshad, M. A., Sattar, S., Nawaz, R., Al-Hussain, S. A., Rizwan, M., Bukhari, A., . . . Zaki, M. E. (2023). Enhancing chromium removal and recovery from industrial wastewater using sustainable and efficient nanomaterial: a review. *Ecotoxicol Environ Saf, 263*(115231), 10.1016.
35. Isibor, P. O. (2024). Regulations and policy considerations for nanoparticle safety *Environmental Nanotoxicology: Combatting the Minute Contaminants* (pp. 295-316): Springer.
36. Isibor, P. O., Kayode-Edwards, I. I., Oyewole, O. A., Agbontaen, D. O., Onwaeze, O. O., Paul, E., . . . Chimbekujwo, K. I. (2024). Risk Assessment and Management in Nanotoxicology *Environmental Nanotoxicology: Combatting the Minute Contaminants* (pp. 267-293): Springer.
37. Jagaba, A. H., Lawal, I. M., Birniwa, A. H., Affam, A. C., Usman, A. K., Soja, U. B., . . . Yaro, N. S. A. (2024). Sources of water contamination by heavy metals *Membrane Technologies for Heavy Metal Removal from Water* (pp. 3-27): CRC Press.
38. Jia, Z., Zhang, H., Lv, Y., Yu, L., Cui, Y., Zhang, L., . . . Xia, W. (2024). Intrauterine chromium exposure and cognitive developmental delay: The modifying effect of genetic predisposition. *Science of The Total Environment, 946*, 174350.
39. Joseph, T. M., Al-Hazmi, H. E., Śniatała, B., Esmaeili, A., & Habibzadeh, S. (2023). Nanoparticles and nanofiltration for wastewater treatment: From polluted to fresh water. *Environmental research*, 117114.
40. Karapinar, H. S., Kilicel, F., Ozel, F., & Sarilmaz, A. (2023). Fast and effective removal of Pb (II), Cu (II) and Ni (II) ions from aqueous solutions with TiO2 nanofibers: Synthesis, adsorption-desorption process and kinetic studies. *International Journal of Environmental Analytical Chemistry, 103*(16), 4731-4751.
41. Karnwal, A., Kumar Sachan, R. S., Devgon, I., Devgon, J., Pant, G., Panchpuri, M., . . . Kumar, G. (2024). Gold Nanoparticles in Nanobiotechnology: From Synthesis to Biosensing Applications. *ACS omega*.
42. Ken, D. S., & Sinha, A. (2020). Recent developments in surface modification of nano zero-valent iron (nZVI): Remediation, toxicity, and environmental impacts. *Environmental nanotechnology, monitoring & management, 14*, 100344.
43. Khan, H., & Shah, M. U. H. (2023). Modification strategies of TiO2 based photocatalysts for enhanced visible light activity and energy storage ability: A review. *Journal of Environmental Chemical Engineering*, 111532.
44. Khan, S., Naushad, M., Al-Gheethi, A., & Iqbal, J. (2021). Engineered nanoparticles for removal of pollutants from wastewater: Current status and future prospects of nanotechnology for remediation strategies. *Journal of Environmental Chemical Engineering, 9*(5), 106160.
45. Le, V.-G., Nguyen, M.-K., Nguyen, H.-L., Lin, C., Hadi, M., Hung, N. T. Q., . . . Hou, D. (2023). A comprehensive review of micro-and nano-plastics in the atmosphere: Occurrence, fate, toxicity, and strategies for risk reduction. *Science of The Total Environment*, 166649.
46. Li, S., Wang, W., Liang, F., & Zhang, W.-x. (2017). Heavy metal removal using nanoscale zero-valent iron (nZVI): Theory and application. *Journal of Hazardous Materials, 322*, 163-171.
47. Liu, B., Xin, Y.-N., Zou, J., Khoso, F. M., Liu, Y.-P., Jiang, X.-Y., . . . Yu, J.-G. (2023a). Removal of chromium species by adsorption: fundamental principles, newly developed adsorbents, and future perspectives. *Molecules, 28*(2), 639.
48. Liu, J., Zhang, J., Dai, Z., Li, B., Chen, X., & Meng, X. (2024a). Recycling aluminum from poly aluminum chloride sludge through acid dissolution and cation resin separation/purification. *Water research*, 122096.
49. Liu, M., Chen, G., Xu, L., He, Z., & Ye, Y. (2024b). Environmental remediation approaches by nanoscale zero-valent iron (nZVI) based on its reductivity: a review. *RSC advances, 14*(29), 21118-21138.
50. Liu, Y., Wang, H., Cui, Y., & Chen, N. (2023b). Removal of copper ions from wastewater: a review. *International journal of environmental research and public health, 20*(5), 3885.
51. Madkhali, N., Prasad, C., Malkappa, K., Choi, H. Y., Govinda, V., Bahadur, I., & Abumousa, R. (2023). Recent update on photocatalytic degradation of pollutants in waste water using TiO2-based heterostructured materials. *Results in Engineering, 17*, 100920.
52. Malik, S., Muhammad, K., & Waheed, Y. (2023). Nanotechnology: A revolution in modern industry. *Molecules, 28*(2), 661.
53. Manikandan, S., Subbaiya, R., Saravanan, M., Ponraj, M., Selvam, M., & Pugazhendhi, A. (2022). A critical review of advanced nanotechnology and hybrid membrane based water recycling, reuse, and wastewater treatment processes. *Chemosphere, 289*, 132867.
54. Mansoor, S., Ali, A., Kour, N., Bornhorst, J., AlHarbi, K., Rinklebe, J., . . . Chung, Y. S. (2023). Heavy metal induced oxidative stress mitigation and ROS scavenging in plants. *Plants, 12*(16), 3003.

*Corresponding Author: **Arslan Younas**
© Copyright 2024 GSAR Publishers All Rights Reserved

55. Mao, T., Zha, J., Hu, Y., Chen, Q., Zhang, J., & Luo, X. (2024). Research Progress of TiO2 Modification and Photodegradation of Organic Pollutants. *Inorganics, 12*(7), 178.
56. Menin, B. (2024). Innovative Technologies for Large-Scale Water Production in Arid Regions: Strategies for Sustainable Development. *Journal of Applied Mathematics and Physics, 12*(7), 2506-2558.
57. Mhadhbi, M., Abderazzak, H., & Avar, B. (2023). Synthesis and properties of titanium dioxide nanoparticles *Updates on Titanium Dioxide*: IntechOpen.
58. Mishra, S., & Sundaram, B. (2023). Fate, transport, and toxicity of nanoparticles: An emerging pollutant on biotic factors. *Process Safety and Environmental Protection, 174*, 595-607.
59. Modwi, A., Basith, N., Ghoniem, M., Ismail, M., Aissa, M. B., Khezami, L., & Bououdina, M. (2023). Efficient Pb (II) adsorption in aqueous solution by hierarchical 3D/2D TiO2/CNNS nanocomposite. *Materials Science and Engineering: B, 289*, 116191.
60. Mohanapriya, V., Sakthivel, R., Pham, N. D. K., Cheng, C. K., Le, H. S., & Dong, T. M. H. (2023). Nanotechnology-A ray of hope for heavy metals removal. *Chemosphere, 311*, 136989.
61. Mondal, P., Nandan, A., Ajithkumar, S., Siddiqui, N. A., Raja, S., Kola, A. K., & Balakrishnan, D. (2023). Sustainable application of nanoparticles in wastewater treatment: Fate, current trend & paradigm shift. *Environmental research, 232*, 116071.
62. Natarajan, B., Kannan, P., Rather, J. A., & Sheikh, R. A. (2023). Recent developments in metal nanoparticles functionalized nanocomposite adsorbents for heavy metals removal from wastewaters. *Journal of the Taiwan institute of chemical engineers, 147*, 104942.
63. Organization, W. H. (2023). *Exposure to lead: a major public health concern. Preventing disease through healthy environments*: World Health Organization.
64. Organization, W. H. (2024). *Laboratory biosecurity guidance*: World Health Organization.
65. Padwal, Y., Panchang, R., Fouad, H., Terashima, C., Chauhan, R., & Gosavi, S. W. (2023). Unveiling the mechanism of enhanced methylene blue degradation using chromium-TiO2/carbon nanocomposite photocatalyst. *Journal of Solid State Electrochemistry, 27*(12), 3557-3568.
66. Pant, R., Mathpal, N., Chauhan, R., Singh, A., & Gupta, A. (2024). A Review of Mercury Contamination in Water and Its Impact on Public Health. *Mercury Toxicity Mitigation: Sustainable Nexus Approach*, 93-115.
67. Patra, K., Sengupta, A., Mittal, V., & Valsala, T. (2023). Emerging functionalized magnetic nanoparticles: from synthesis to nuclear fuel cycle application: where do we stand after two decade? *Materials Today Sustainability, 24*, 100489.
68. Portugal, J., Bedia, C., Amato, F., Juárez-Facio, A. T., Stamatiou, R., Lazou, A., . . . Piña, B. (2024). Toxicity of airborne nanoparticles: Facts and challenges. *Environment international*, 108889.
69. Rajamanikandan, R., Ilanchelian, M., & Ju, H. (2023). Smartphone-enabled colorimetric visual quantification of highly hazardous trivalent chromium ions in environmental waters and catalytic reduction of p-nitroaniline by thiol-functionalized gold nanoparticles. *Chemosphere, 340*, 139838.
70. Rodríguez-Rasero, C., Montes-Jimenez, V., Alexandre-Franco, M. F., Fernández-González, C., Píriz-Tercero, J., & Cuerda-Correa, E. M. (2024). Use of Zero-Valent Iron Nanoparticles (nZVIs) from Environmentally Friendly Synthesis for the Removal of Dyes from Water—A Review. *Water, 16*(11), 1607.
71. Rónavári, A., Igaz, N., Adamecz, D. I., Szerencsés, B., Molnar, C., Kónya, Z., . . . Kiricsi, M. (2021). Green silver and gold nanoparticles: Biological synthesis approaches and potentials for biomedical applications. *Molecules, 26*(4), 844.
72. Sathiyan, K., Bar-Ziv, R., Mendelson, O., & Zidki, T. (2020). Controllable synthesis of TiO2 nanoparticles and their photocatalytic activity in dye degradation. *Materials Research Bulletin, 126*, 110842.
73. Schoonjans, R., Castenmiller, J., Chaudhry, Q., Cubadda, F., Daskaleros, T., Franz, R., . . . Oomen, A. G. (2023). Regulatory safety assessment of nanoparticles for the food chain in Europe. *Trends in Food Science & Technology, 134*, 98-111.
74. Singh, S., Pavithra, N., Naik, T., Uppara, B., Thamaraiselvan, C., Behera, S., . . . Khan, N. A. (2023). Removal of Pb ions using green Co3O4 nanoparticles: Simulation, modeling, adsorption, and biological studies. *Environmental research, 222*, 115335.
75. Singh, V., Singh, N., Verma, M., Kamal, R., Tiwari, R., Sanjay Chivate, M., . . . Singh, M. P. (2022). Hexavalent-chromium-induced oxidative stress and the protective role of antioxidants against cellular toxicity. *Antioxidants, 11*(12), 2375.
76. Sosa Lissarrague, M. H., Alshehri, S., Alsalhi, A., Lassalle, V. L., & López Corral, I. (2023). Heavy metal removal from aqueous effluents by TiO2 and ZnO nanomaterials. *Adsorption Science & Technology, 2023*, 2728305.
77. Sun, P., Wang, Z., An, S., Zhao, J., Yan, Y., Zhang, D., . . . Lyu, H. (2022). Biochar-supported nZVI for the removal of Cr (VI) from soil and water: Advances in experimental research and engineering applications. *Journal of environmental management, 316*, 115211.

 © Copyright 2024 GSAR Publishers All Rights Reserved

78. Thakur, A., & Kumar, A. (2023). *Ecotoxicity analysis and risk assessment of nanomaterials for the environmental remediation.* Paper presented at the Macromolecular Symposia.
79. Ullah, Q., Qasim, M., Abaidullah, A., Afzal, R., Mahmood, A., Fatima, A., & Haidri, I. (2024a). EXPLORING THE INFLUENCE OF NANOPARTICLES AND PGPRS ON THE PHYSICO-CHEMICAL CHARACTERISTICS OF WHEAT PLANTS: A REVIEW. *EPH-International Journal of Agriculture and Environmental Research, 10*(1), 1-9.
80. Ullah, Q., Qasim, M., Ghaffar, A., Haidri, I., Munir, T., Chawla, M., . . . Ismail, M. (2024b). Harnessing Plant Growth-Promoting Rhizobacteria (PGPRs) for Sustainable Management of Rice Blast Disease Caused by Magnaporthe Oryzae: Strategies and Remediation Techniques in Indonesia. *Indonesian Journal of Agriculture and Environmental Analytics, 3*(2), 65-76.
81. Umar, W., ur Rehman, M. Z., Umair, M., Ayub, M. A., Naeem, A., Rizwan, M., . . . Karri, R. R. (2022). Use of nanotechnology for wastewater treatment: potential applications, advantages, and limitations *Sustainable nanotechnology for environmental remediation* (pp. 223-272): Elsevier.
82. Ummer, K., Khan, W., Iqbal, M. A., Abbas, M. Q., Batool, R., Afzal, R., . . . Haidri, I. (2023). THE INTRICACIES OF PHOTOCHEMICAL SMOG: FROM MOLECULAR INTERACTIONS TO ENVIRONMENTAL IMPACT. *EPH-International Journal of Applied Science, 9*(2), 23-33.
83. Upadhyay, K., Tamrakar, R. K., Thomas, S., & Kumar, M. (2023). Surface functionalized nanoparticles: a boon to biomedical science. *Chemico-Biological Interactions, 380*, 110537.
84. Upadhyay, R. (2022). Heavy metals in our ecosystem *Heavy Metals in Plants* (pp. 1-15): CRC Press.
85. Utami, M., Wang, S., Musawwa, M. M., Purbaningtias, T. E., Fitri, M., Yuspita, I., . . . Bang, D. (2023). Simultaneous photocatalytic removal of organic dye and heavy metal from textile wastewater over N-doped TiO2 on reduced graphene oxide. *Chemosphere, 332*, 138882.
86. Waseem, M., Abbas, M. Q., Ummer, K., Fatima, R., Khan, W., Gulzar, F., . . . Haidri, I. (2023). PHYTO-REMEDIES FOR SOIL RESTORATION: A DEEP DIVE INTO BRASSICA'S PLANT CAPABILITIES IN CADMIUM REMOVAL. *EPH-International Journal of Biological & Pharmaceutical Science, 9*(1), 23-44.
87. Wu, Y.-S., Osman, A. I., Hosny, M., Elgarahy, A. M., Eltaweil, A. S., Rooney, D. W., . . . Gopinath, S. C. (2024). The toxicity of mercury and its chemical compounds: molecular mechanisms and environmental and human health implications: a comprehensive review. *ACS omega, 9*(5), 5100-5126.
88. Yadav, K. K., Cabral-Pinto, M. M., Gacem, A., Fallatah, A. M., Ravindran, B., Rezania, S., . . . Al-shareef, T. H. (2024). Recent advances in the application of nanoparticle-based strategies for water remediation as a novel clean technology–A comprehensive review. *Materials Today Chemistry, 40*, 102226.
89. Yamini, V., Shanmugam, V., Rameshpathy, M., Venkatraman, G., Ramanathan, G., Garalleh, H. A., . . . Rajeswari, V. D. (2023). Environmental effects and interaction of nanoparticles on beneficial soil and aquatic microorganisms. *Environmental research, 236*, 116776.
90. Younis, A. B., Haddad, Y., Kosaristanova, L., & Smerkova, K. (2023). Titanium dioxide nanoparticles: Recent progress in antimicrobial applications. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 15*(3), e1860.
91. Yuan, L., Wang, K., Zhao, Q., Yang, L., Wang, G., Jiang, M., & Li, L. (2024). An overview of in situ remediation for groundwater co-contaminated with heavy metals and petroleum hydrocarbons. *Journal of environmental management, 349*, 119342.
92. Zafar, A., Javed, S., Akram, N., & Naqvi, S. A. R. (2024). Health Risks of Mercury *Mercury Toxicity Mitigation: Sustainable Nexus Approach* (pp. 67-92): Springer.
93. Zhang, X., Xu, H., Xi, M., & Jiang, Z. (2023). Removal/adsorption mechanisms of Cr (VI) and natural organic matter by nanoscale zero-valent iron-loaded biochar in their coexisting system. *Journal of Environmental Chemical Engineering, 11*(3), 109860.

*Corresponding Author: **Arslan Younas** © Copyright 2024 GSAR Publishers All Rights Reserved