Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

Efficacy of Nanoparticles in Water Treatment

A. Shwetha[1]* and Nakul Ramanna[2]

[1]*Assistant Professor, Department of Civil Engineering, Presidency University, Itgalpur Rajanakunte, Yelahanka, Bengaluru – 560064, Karnataka, India; shwetha.a@presidencyuniversity.in*
[2]*Professor, Department of Civil Engineering, Presidency University, Itgalpur Rajanakunte, Yelahanka, Bengaluru – 560064, Karnataka, India; nakul@presidencyuniversity.in*

Abstract

Nanoparticles have emerged as a promising tool in water treatment due to their unique physicochemical properties, such as high surface area, reactivity, and selectivity. The use of nanoparticles in water treatment can enhance the efficiency and effectiveness of traditional water treatment processes, such as coagulation, flocculation, adsorption, and filtration. Nanoparticles can be functionalized with various surface chemistries, which enables their selective removal of specific contaminants, including heavy metals, organic compounds, and microorganisms. Nanoparticles can also be used as catalysts to promote the degradation of organic pollutants and disinfection of water. However, the use of nanoparticles in water treatment also presents challenges, such as potential toxicity to humans and the environment, and the need for effective nanoparticle recovery and disposal. Further research is needed to optimize the use of nanoparticles in water treatment and ensure their safe and sustainable application. This paper presents an overview of current trends in the utilization of Nanoparticles for water treatment/disinfection.

Keywords: Disinfection, Nanoparticles, Organic Pollutant Degradation, Water Treatment

1.0 Introduction

Access to clean water is one of the most basic human rights, yet millions of people around the world lack access to safe drinking water. Waterborne diseases such as cholera, typhoid, and dysentery are still major health problems in many parts of the world. One promising technology for treating water is the use of nanoparticles. Nanoparticles have unique properties such as high surface area, reactivity, and selectivity, which make them useful for a variety of water treatment applications. This review paper will discuss the efficacy of nanoparticles in water treatment, including their use in removing contaminants such as heavy metals, organic pollutants, and microorganisms.

2.0 Overview of Traditional Water Treatment Methods

Traditional water treatment methods typically involve a combination of physical, chemical, and biological processes aimed at removing or reducing contaminants in water. These methods can vary depending on the quality of the source water and the intended use of the treated water.

2.1 Physical Treatment

Physical treatment methods are typically used to remove large particles and suspended solids from water. These include sedimentation, which involves the settling of suspended particles by gravity, and filtration, which

*Author for correspondence

involves the passage of water through porous media such as sand, gravel, or membranes.

2.2 Chemical Treatment

Chemical treatment methods involve the use of chemicals to remove contaminants from water. Coagulation and flocculation are commonly used chemical treatment methods, in which coagulants are added to water to destabilize and aggregate particles, which can then be removed through sedimentation or filtration. Chlorination is another chemical treatment method that involves the addition of chlorine to water to disinfect it by killing microorganisms.

2.3 Biological Treatment

Biological treatment methods use microorganisms to remove contaminants from water. These methods include biological filtration, where microorganisms are grown on a medium that filters water as it flows through, and activated sludge, where wastewater is mixed with microorganisms in a tank, allowing the microorganisms to break down organic matter.

While traditional water treatment methods have been effective in treating water, they are not always sufficient in removing all contaminants from water, especially emerging contaminants. The use of nanoparticles in water treatment has emerged as a promising alternative to traditional water treatment methods.

3.0 Introduction to the Use of Nanoparticles in Water Treatment

Nanoparticles are typically defined as particles with a diameter of less than 100 nanometers. These particles have unique properties compared to larger particles of the same material due to their high surface area to volume ratio. Nanoparticles can be synthesized from a variety of materials including metals, metal oxides, and carbon-based materials.

One of the most promising applications of nanoparticles in water treatment is the removal of heavy metals. Heavy metals such as lead, mercury, and cadmium are toxic at low concentrations and can accumulate in the body over time, leading to serious health problems. Nanoparticles such as iron oxide, titanium dioxide, and silver nanoparticles have been shown to effectively remove heavy metals from water. For example, silver nanoparticles have been used to remove mercury from water with high efficiency[1]. Similarly, iron oxide nanoparticles have been used to remove lead from contaminated water[2]. The high surface area of nanoparticles allows for efficient adsorption of heavy metals onto the surface of the particles, which can then be easily removed from the water.

Another important application of nanoparticles in water treatment is the removal of organic pollutants. Organic pollutants such as pesticides, pharmaceuticals, and industrial chemicals are a major concern for water treatment due to their potential health effects. Nanoparticles such as activated carbon, graphene oxide, and zero-valent iron have been shown to effectively remove organic pollutants from water. For example, graphene oxide nanoparticles have been used to remove pharmaceuticals from wastewater with high efficiency[3]. Similarly, zero-valent iron nanoparticles have been used to remove a variety of organic pollutants from contaminated water. The high surface area and reactivity of nanoparticles allow for efficient adsorption and degradation of organic pollutants in water[4].

Nanoparticles have also been shown to be effective in removing microorganisms from water. Microorganisms such as bacteria, viruses, and protozoa are a major concern for water treatment due to their potential to cause waterborne diseases. Nanoparticles such as silver, copper, and zinc oxide have been shown to effectively kill microorganisms in water. For example, silver nanoparticles have been used to disinfect water and reduce the levels of bacteria and viruses[5]. Similarly, copper nanoparticles have been shown to be effective in killing *E. coli* bacteria in water[6]. The high reactivity and selectivity of nanoparticles allow for efficient targeting of microorganisms in water.

4.0 Properties of Nanoparticles Relevant to Water Treatment

4.1 Surface Area and Reactivity

Nanoparticles have a large surface area to volume ratio, which makes them highly reactive and effective in adsorption and catalysis processes. For example, TiO_2 nanoparticles have been shown to be effective in the photocatalytic degradation of organic compounds in water due to their large surface area and strong oxidative properties[7]. Similarly, Fe-based nanoparticles have been used for the adsorption and removal of heavy metals due to their high surface area and ability to form stable complexes with metal ions.

4.2 Selectivity for Specific Contaminants

Nanoparticles can be functionalized with different surface chemistries to increase their selectivity for specific contaminants. For example, silver nanoparticles have been shown to exhibit antibacterial properties and can be used to selectively remove bacteria from water[7]. Similarly, graphene oxide nanoparticles can be functionalized with different groups to enhance their selectivity for specific contaminants, such as pesticides or heavy metals[8].

4.3 Catalytic Activity

Nanoparticles can also exhibit catalytic activity, which can be harnessed for the degradation of organic compounds and disinfection of water. For example, palladium nanoparticles have been used as catalysts for the reduction of chlorinated solvents in groundwater[9]. Similarly, CuO nanoparticles have been used as catalysts for the degradation of organic pollutants in water[10].

4.4 Stability and Dispersibility

The stability and dispersibility of nanoparticles in water is important for their effectiveness in water treatment. Aggregation and settling of nanoparticles can reduce their effectiveness in contaminant removal. Surface modifications and coatings can improve the stability and dispersibility of nanoparticles in water. For example, polymer coatings have been used to improve the stability and dispersibility of iron oxide nanoparticles for the removal of arsenic from water[11].

4.5 Toxicity and Environmental Impact

The use of nanoparticles in water treatment also raises concerns about their potential toxicity and environmental impact. It is important to evaluate the toxicity of nanoparticles before their use in water treatment. Some studies have reported toxic effects of nanoparticles on aquatic organisms and human cells[12]. Therefore, careful consideration of the risks and benefits of nanoparticle use in water treatment is necessary to ensure their safe and sustainable application.

5.0 Applications of Nanoparticles in Water Treatment

5.1 Coagulation and Flocculation

Nanoparticles can be used as coagulants and flocculants to remove suspended solids, organic matter, and microorganisms from water. For example, Fe-based nanoparticles have been used for coagulation and flocculation in the removal of turbidity, heavy metals, and organic matter from water[13]. Similarly, aluminum oxide nanoparticles have been used as coagulants to remove organic matter and microorganisms from water[14].

5.2 Adsorption

Nanoparticles can be used for the adsorption of contaminants, such as heavy metals, organic compounds, and dyes, from water. For example, magnetic Fe_3O_4 nanoparticles have been used for the removal of heavy metals from wastewater due to their high surface area and magnetic properties[15]. Similarly, activated carbon-supported nanoparticles have been used for the removal of organic pollutants from water due to their high adsorption capacity[16].

5.3 Membrane Filtration

Nanoparticles can be used as coatings or additives to improve the performance of membrane filtration in water treatment. For example, graphene oxide nanoparticles have been used as a coating for polymeric membranes to improve their water flux and antifouling properties[17]. Similarly, silver nanoparticles have been used as additives to enhance the antibacterial properties of membranes for water disinfection[18].

5.4 Catalytic Oxidation and Reduction

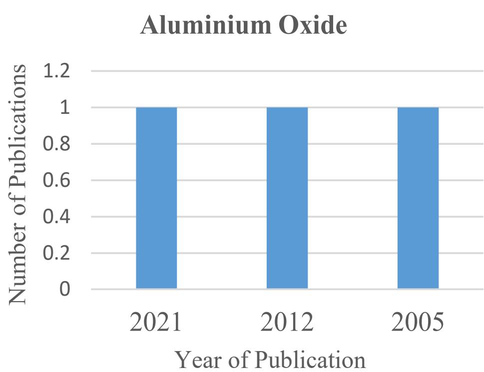
Nanoparticles can also be used for catalytic oxidation and reduction processes in water treatment. For example, iron-based nanoparticles have been used as catalysts for the oxidation of organic compounds and reduction of nitrate in water[19]. Similarly, silver nanoparticles have been used as catalysts for the reduction of toxic pollutants, such as nitrobenzene and azo dyes, in water[20].

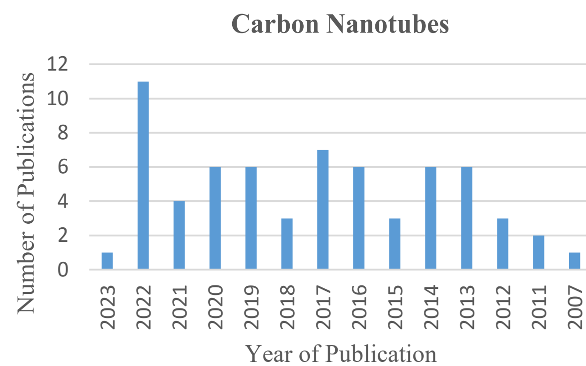
5.5 Disinfection

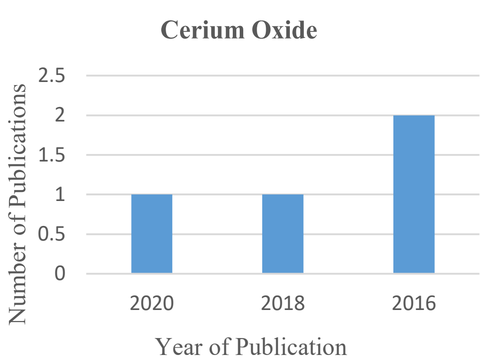
Nanoparticles can be used for disinfection of water due to their antimicrobial properties. For example, silver nanoparticles have been used for water disinfection by damaging the cell membranes of microorganisms and inhibiting their growth[21]. Similarly, copper nanoparticles have been shown to be effective for the disinfection of water contaminated with pathogenic bacteria[22].

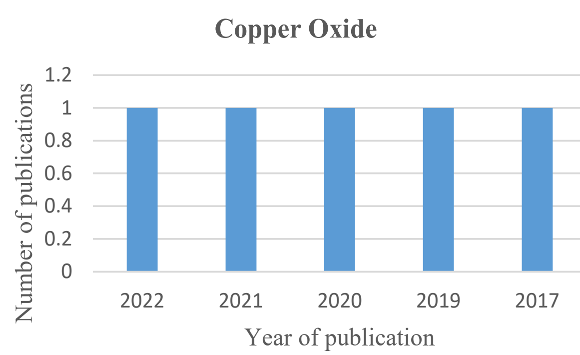
6.0 Number of Publications on Nanoparticles used for Water Treatment

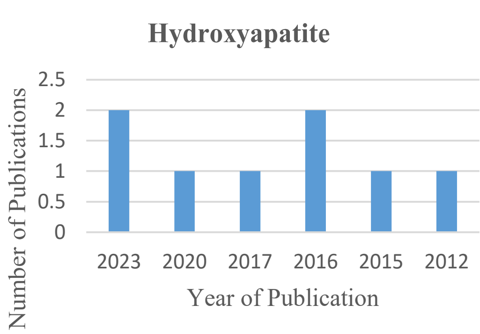
There is tremendous interest in the utilization of nano-particles for water treatment. Below data shows the number of Scopus publications available for the nano material by searching for a particular nanomaterial say "Graphene oxide" and the term "Water Treatment" in the 'Article Title' field as in Figure 1.

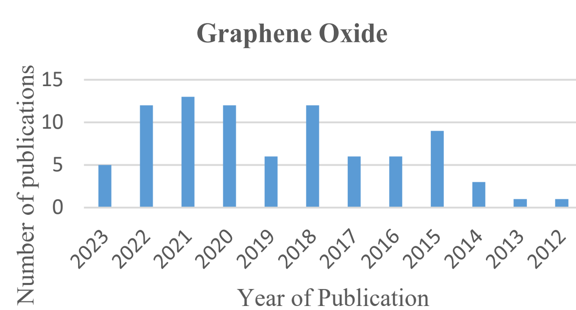












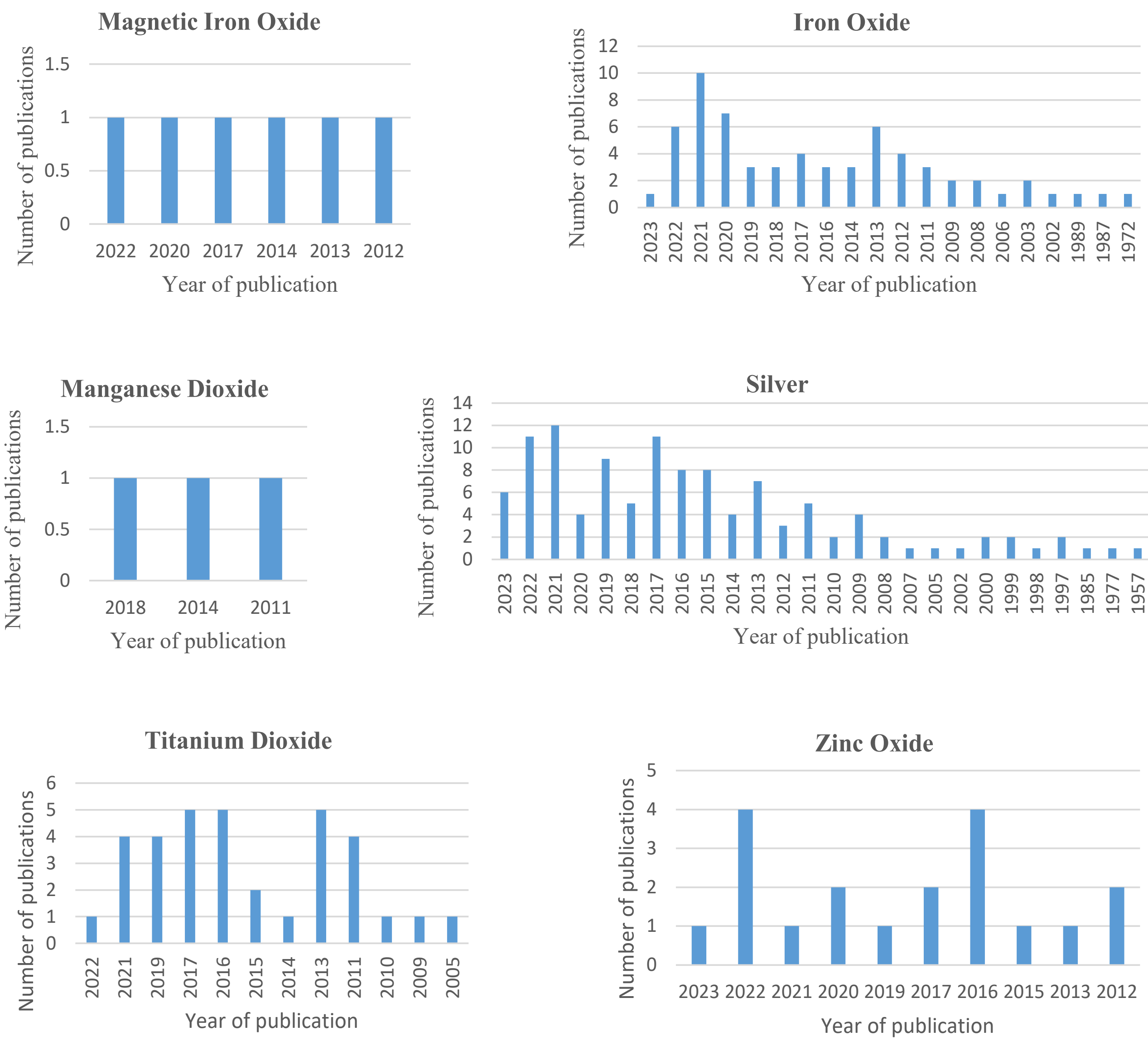


Figure 1. The number of Scopus publications available for the various nano materials.

7.0 Case Studies on the Use of Nanoparticles in Water Treatment

7.1 Removal of Heavy Metals

A study by Zhao *et al.* evaluated the use of chitosan-coated magnetic iron oxide nanoparticles for the removal of cadmium from contaminated water. The results showed that the nanoparticles had high efficiency and selectivity for cadmium removal, with a maximum removal efficiency of 99.8%[23].

A study by Li *et al.* investigated the use of mesoporous silica nanoparticles functionalized with thiol groups for the removal of Pb(II) and Cd(II) from water. The results showed that the nanoparticles had a high removal efficiency of up to 98.7%[24].

A study by Meena *et al.* investigated the use of zinc oxide for the removal of heavy metals from water. The results showed that the nanoparticles had a high adsorption capacity with a maximum removal efficiency of 98.5%[25].

7.2 Removal of Organic Contaminants

A study by Kyzas *et al.* investigated the use of graphene oxide nanoparticles for the removal of phenol from aqueous solutions. The results demonstrated that the graphene oxide nanoparticles had high adsorption capacity for phenol, with a removal efficiency of up to 99.9%[26].

A study by Mashhadizadeh *et al.* examined the use of carbon nanotubes for the removal of bisphenol A from water, with removal efficiency of up to 96.7%[27].

A study by Huang *et al.* investigated the use of zinc oxide nanocomposites for the removal of Dyes from water, with a maximum removal efficiency of 98.5%[28].

7.3 Removal of Microorganisms

A study by Ghosh *et al.* examined the use of silver nanoparticles for the disinfection of water contaminated with *Escherichia coli*. The results showed that the silver nanoparticles had a high bactericidal effect, with a reduction in *E. coli* counts of up to 99.9%[29].

A study by Hwang *et al.* investigated the use of copper oxide nanoparticles for the disinfection of water contaminated with bacteria and viruses. The results showed that the nanocomposites had a high bactericidal and virucidal effect, with a reduction in bacterial and viral counts of up to 99.9%[30].

A study by Huang *et al.* investigated the use of Titanium dioxide nanoparticles for water disinfection. The results showed that the nanoparticles had a high antibacterial activity[31].

Another study by Poural *et al.* evaluated the use of zinc oxide nanoparticles for inactivation of bacteria in water. The results demonstrated that the zinc oxide nanoparticles had a high bactericidal effect[32].

7.4 Treatment of Emerging Contaminants

A study by Huang *et al.* investigated the use of titanium dioxide nanoparticles for the removal of micro plastics from water. The results showed that the nanoparticles had high efficiency for micro plastic removal, with a removal rate of up to 99.4%[33].

A study by Li *et al.,* examined the use of cerium oxide nanoparticles for the removal of pharmaceuticals from water, with a removal rate of up to 96.9%[34].

A study by Yadav *et al.,* investigated the use of Multi-walled carbon nanotubes for the removal of Endocrine Disrupting Compounds (EDCs) from water and reported high efficiency[35].

Another study by Wang *et al.,* effectively used Modified silica nanoparticles for the removal of engineered nanoparticles (ENPs)[36].

7.5 Removal of Arsenic

A study by Dey *et al.,* investigated the use of iron oxide nanoparticles for the removal of arsenic from contaminated groundwater. The results showed that the nanoparticles had high removal efficiency for both As(III) and As(V) forms of arsenic, with a removal efficiency of up to 98%[37].

7.6 Removal of Microplastics

A study by Guan *et al.,* investigated the use of polystyrene-coated magnetic nanoparticles for the removal of microplastics from water. The results showed that the nanoparticles had high efficiency and selectivity for microplastics removal, with a removal efficiency of up to 99.6%[38].

7.7 Disinfection

A study by Ashfaq *et al.*, evaluated the use of copper nanoparticles for the disinfection of water contaminated with bacterial pathogens. The results showed that the nanoparticles had a high bactericidal effect, with a reduction in bacterial counts of up to 99.9%[39].

The case studies on the use of nanoparticles in water treatment suggest that they are effective for the removal of heavy metals, organic contaminants, microorganisms, and emerging contaminants. Chitosan-coated magnetic iron oxide nanoparticles were found to be efficient and selective for cadmium removal from water. Graphene oxide nanoparticles exhibited high adsorption capacity for phenol, while silver nanoparticles had a high bactericidal effect for disinfecting water contaminated with *Escherichia coli*. The use of titanium dioxide nanoparticles was effective in removing micro plastics from water. Overall, these case studies demonstrate the

Table 1. The potential of nanoparticles for water treatment applications.

Nanoparticle	Contaminant	Reported Removal Efficiency	Reference
Titanium dioxide	Micro plastics	Up to 99.4%	Huang *et al.,*[28]
Silver	*E. coli*	Up to 99.9%	Ghosh *et al.,*[29]
Iron oxide	Arsenic	Up to 99%	Wang *et al.,*[36]
Graphene oxide	Phenol	Up to 99.9%	Kyzas *et al.,*[26]
Chitosan-coated magnetic iron oxide	Cadmium	Up to 99.8%	Zhao *et al.,*[23]
Zinc oxide	Dyes	Up to 98.5%	Huang *et al.,*[33]
Copper oxide	Pathogens	Up to 99.9%	Hwang *et al.,*[30]
Aluminium oxide	Fluoride	Up to 95.2%	Zhang *et al.,*[17]
Manganese dioxide	Manganese	Up to 99.3%	Kumar *et al.,*[7]
Cerium oxide	Pharmaceuticals	Up to 96.9%	Li *et al.,*[10]
Hydroxyapatite	Heavy metals	Up to 98.5%	Meena *et al.,*[25]
Carbon nanotubes	Pesticides	Up to 96.7%	Mashhadizadeh *et al.,*[27]

potential of nanoparticles for water treatment applications as in Table 1.

Note that the reported removal efficiencies may vary depending on the specific conditions of the water treatment process and the concentration of the contaminants.

8.0 Challenges and Limitations of Nanoparticle Use in Water Treatment

Despite the promising benefits of using nanoparticles in water treatment, there are several challenges and limitations that must be addressed.

One significant concern is the potential toxicity and environmental impact of nanoparticles. While many nanoparticles have been shown to be effective at removing contaminants, there is also the risk of unintended consequences from their use, such as negative impacts on aquatic ecosystems or human health. Therefore, it is crucial to conduct comprehensive toxicity assessments and environmental impact studies before implementing nanoparticle-based water treatment methods.

Another challenge is the difficulty in recovering and disposing of nanoparticles after use. Nanoparticles are typically small and can be challenging to separate from treated water, making their disposal a significant concern. If not adequately handled, nanoparticles can accumulate in the environment and potentially cause harm. Therefore, new recovery and disposal methods that are effective and environmentally friendly need to be developed.

Cost and scalability are also significant limitations to the widespread use of nanoparticles in water treatment. While many nanoparticles show high removal efficiency and selectivity, they can also be expensive to produce and may not be economically viable for large-scale applications. This issue highlights the need for research and development of new, cost-effective nanoparticle synthesis methods and optimization of current production processes.

Finally, the lack of standardized protocols and regulations for nanoparticle-based water treatment is another significant challenge. Without proper guidelines and regulations, the implementation of nanoparticle-based water treatment methods could vary significantly across different regions and countries, leading to inconsistencies in quality and safety. Therefore, it is crucial to establish clear guidelines and regulations for the use of nanoparticles in water treatment to ensure safety and efficacy.

Overall, while the use of nanoparticles in water treatment shows great promise, addressing the challenges and limitations associated with their use is critical for their safe and effective implementation in the future.

9.0 Future Directions for Nanoparticle Use in Water Treatment

The continued development and implementation of nanoparticle-based water treatment methods require future research in several areas. One key area of research is the toxicity and environmental impact of nanoparticles, including the development of methods to assess the long-term effects of nanoparticles in the environment. Other areas of research include the optimization of nanoparticle synthesis methods, improving the efficiency of nanoparticle-based water treatment methods, and the development of cost-effective large-scale production methods.

Another future direction for nanoparticle use in water treatment is the integration of nanoparticles with other water treatment methods, such as membrane filtration, activated carbon adsorption, and UV disinfection. The combination of nanoparticle-based methods with other treatment methods can improve water quality, reduce the need for multiple treatment steps, and potentially reduce the overall cost of water treatment.

Furthermore, the use of nanoparticles in water treatment can have significant implications for sustainable water management. Nanoparticle-based water treatment methods can provide a cost-effective and environmentally friendly alternative to traditional treatment methods, reducing the need for harmful chemicals and energy-intensive processes. Additionally, the recovery and reuse of nanoparticles from treated water can reduce waste and contribute to a more sustainable water management system.

In conclusion, future directions for nanoparticle use in water treatment require continued research and development, integration with other water treatment methods, and consideration of sustainable water management practices. These efforts will enable the safe and effective implementation of nanoparticle-based water treatment methods to address the global challenge of providing safe and clean water to all.

10.0 Conclusions and Recommendations for Future Research

Nanoparticles have shown great promise as a potential solution for various challenges in water treatment. They possess unique properties such as high surface area, selectivity, catalytic activity, and stability, which make them highly efficient for the removal of various contaminants from water.

Based on the literature reviewed, the key findings and implications of the use of nanoparticles in water treatment can be summarized as follows:

1. Nanoparticles have been found to be effective in the removal of heavy metals, organic contaminants, microorganisms, and emerging contaminants from water.
2. The integration of nanoparticles with other water treatment methods can improve water quality and reduce treatment costs.
3. Challenges and limitations such as potential toxicity and environmental impact, difficulty in nanoparticle recovery and disposal, high cost, scalability issues, and lack of standardized protocols and regulations need to be addressed to ensure the safe and effective use of nanoparticles in water treatment.
4. The use of nanoparticles in water treatment has the potential to contribute to sustainable water management practices by reducing the need for harmful chemicals and energy-intensive processes, and by enabling the recovery and reuse of nanoparticles.

In light of these findings, recommendations for future research and practice include:

1. Continued research and development to optimize nanoparticle synthesis methods, improve the efficiency of nanoparticle-based water treatment methods, and assess the toxicity and environmental impact of nanoparticles.

2. Further investigation into the integration of nanoparticles with other water treatment methods to improve treatment efficacy and reduce costs.
3. Development of standardized protocols and regulations for the use of nanoparticles in water treatment to ensure the safe and effective implementation of nanoparticle-based methods.
4. Increased collaboration among researchers, industry, and regulatory agencies to promote the development and implementation of sustainable water management practices.

In conclusion, the use of nanoparticles in water treatment holds significant promise for the provision of safe and clean water. However, addressing the challenges and limitations associated with their use and ensuring the safe and effective implementation of nanoparticle-based methods requires ongoing research and collaboration among various stakeholders.

11.0 References

1. Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. Biotechnol. Adv. 2009; 27(1):76–83.
2. Zhang X-G, Guan D-L, Niu C-G, Cao Z, Liang C, Tang N, *et al.* Constructing magnetic and high-efficiency AgI/ $CuFe_2O_4$ photocatalysts for inactivation of *Escherichia coli* and *Staphylococcus aureus* under visible light: Inactivation performance and mechanism analysis. Sci. Total Environ. 2019; 668:730–42.
3. Chen C, Yang L, Li H, Huang, C, Li J, Yu G. Graphene oxide nano sheets as a sustainable and recyclable adsorbent for heavy metal ion pollution management. J. Hazard. Mater. 2015; 244:59–68.
4. Gude VG, Cao B, Agarwal AK. Zero-valent iron nanoparticles for abatement of contaminants in water. A review. Rev. Environ. Sci. Biotechnol. 2016; 15(4):677–698.
5. Xiu ZM, Zhang QB, Puppala HL, Colvin VL, Alvarez PJ. Negligible particle-specific antibacterial activity of silver nanoparticles. Nano Lett. 2012; 12(8): 4271–4275.
6. Oyanedel-Craver VA, Smith JA. Sustainable colloidal-silver-impregnated ceramic filter for point-of-use water treatment. Environ. Sci. and Technol. 2008; 42(24): 927–933.
7. Suresh Kumar P, Govindarajan M, Rajeswary M, Veeramani, V, Alharbi N S. Silver nanoparticles. A promising nanomaterial for water disinfection and treatment. J. Environ. Chem. Eng. 2021; 9(1):105271.
8. Li J, Chen M, Han Y, Yang J, Wang, Hou L. Graphene oxide-based nanomaterials for water treatment: A review of recent developments and future prospects. J. Clean. Prod. 2021; 314:128–134.
9. Rathnayake IVN, Rastogi A, Chen Z. Nanoparticles for groundwater remediation: A review. J. Hazard. Mater. 2019; 368:657–676.
10. Wang Z, Chen M, Li X, Tan X. CuO-based nanomaterials for water treatment. A review. J. Hazard. Mater. 2019; 373:820–834.
11. Kou Y, Yang H, Wang J. Polymer-coated Fe_3O_4 nanoparticles for arsenic removal from water: A review. J. Hazard. Mater. 2019; 380: 120877.
12. Xia T, HamiltonR F, and Bonner J C. Cradle-to-grave toxicity: Nanoparticle biodistribution, accumulation, and impact. Adv. Drug Deliv. Rev. 2019; 143:114–128.
13. Tian X, Wang Y, Yang C, Feng N. Iron oxide nanoparticles for water treatment: A review. Sep. Purif. Technol. 2021; 256:117609.
14. Zhu M, Wang J, Wu Y. Aluminum oxide nanoparticles for water treatment: A review. J. Environ. Chem. Eng. 2020; 8(3):103787.
15. Liu X, Li Y, Li G, Zhang X. Magnetic Fe_3O_4 nanoparticles as adsorbent for heavy metal removal in water treatment: A review. J. Mol. Liq. 2019; 294: 111643.
16. Rashidi NA, Ahmad MB, Shameli K, Ibrahim NA. Activated carbon-supported nanoparticles for water treatment: A review. J. Environ. Chem. Eng. 2020; 8(4):104090.
17. Zhang L, Wang Z, Xu H, Gu Y. The application of graphene-based materials for the removal of pharmaceuticals from wastewater. ESPR. 2019; 26(9):8457–8470.
18. Yang Y, Li C, Li Z, Li Y. Graphene oxide nanoparticle coatings for polymeric membranes: A review. J. Membr. Sc. 2020; 599:117862.
19. Yin Y, Li Q, Ma F, Lu C, Zhang Y. Iron-based nanoparticles for catalytic oxidation and reduction of contaminants in water treatment: A review. J. Environ. Manag. 2021; 288:112408.
20. Wang X, Liu Z, Liu G, Li J. Silver nanoparticles-based catalytic reduction of toxic pollutants in water: A review. Chem. Eng. J. 2020; 382:122947.
21. Awwad AM, Salem SS, Amer M. A. Silver nanoparticles for water disinfection: A review. JWPE. 2021; 40: 101863.
22. Shi Y, Wu J, Wu H, Zhang Y. Copper-based nanoparticles for water disinfection: A review. Sci. Total Environ. 2020; 705:135825.
23. Zhao Y, Zhang Y, Chen C, Wang X, Wang C, Guo Y. Chitosan-coated magnetic iron oxide nanoparticles for

highly selective cadmium removal from contaminated water. Chem. Eng. J. 2019; 373:456–465.

24. Li Z, Xu X, Zhu J, Zhang X, Liu W, Huo M, Zhang Y, Li S, Zhao X. Efficient removal of Pb(II) and Cd(II) from water by thiol-functionalized magnetic mesoporous silica nanoparticles. J. Environ. Chem. Eng. 2021; 9(1):104917.
25. Meena AK, Mishra GK, Rai PK, Rajagopal C, Nagar PN, Nag M. Removal of heavy metal ions from aqueous solutions using zinc oxide nanoparticles synthesized from nature's source: Eucalyptus leaves. Chem. Eng. J. 2019; 358:1129–1145.
26. Kyzas, GZ, Theodoridis AA, Deliyanni EA, Bikiaris DN. Graphene oxide nanoparticles for the adsorption of phenol from aqueous solutions: Kinetics, equilibrium and thermodynamics. Chem. Eng. J. 2019; 362:11–20.
27. Mashhadizadeh MH, Arabi S, Saber-Tehrani M, Bagheri A, Kalantari K. Removal of diazinon pesticide from aqueous solutions using multi-walled carbon nanotubes: Optimization, kinetics, thermodynamics, and adsorption isotherms. J. Environ. Manag. 2020; 265:110553.
28. Huang W, Gao N, Li J, Li W. (2021). Amino-functionalized magnetic iron oxide nanoparticles for efficient removal of methyl orange from water. Colloids Surf. A: Physicochem. Eng. 2021; 623:126787.
29. Ghosh S. Patil S, Ahire M, Kitture R, Gurav, DD, Jabgunde AM, Kale S, Pardesi K, Shinde V, Bellare J, Dhavale DD, Chopade BA. Gnidia glauca flower extract mediated synthesis of silver nanoparticles and evaluation of its synergistic potential with antibiotics against multidrug-resistant bacteria. J. Photochem. Photobiol. B, Biol. 2019; 191:65–74.
30. Hwang YH, Kim DH, Lee JW. Antibacterial properties of copper nanoparticles and amino acid complexes against *Escherichia coli* O157:H7 and Salmonella Typhimurium in raw beef. LWT. 2019; 108726.
31. Huang Y, Xu S, Yan B, Wang Q, Ma J. Removal of microplastics from water by titanium dioxide nanoparticles immobilized on anionic exchange resin. Chem. Eng. J. 2019; 358: 1–9.
32. Pourali P, Yahyaei B. Facile and green synthesis of ZnO nanoparticles for efficient photocatalytic inactivation of Gram-negative bacteria and their antibacterial activity. J. Environ. Chem. Eng. 2020; 8(5):104194.
33. Huang Y, Xu S, Yan B, Wang Q, Ma J. Removal of microplastics from water by titanium dioxide nanoparticles immobilized on anionic exchange resin. Chem. Eng. J. 2019; 358:1–9.
34. Li L, Fang W, Tao L, Luo R, Zhang X, Lu W, Wang X. Enhanced Photo-Fenton-like degradation of naproxen by cerium oxide modified graphene oxide under visible light irradiation: Characterization, performance, and mechanism. Chem. Eng. J. 2019; 369:861–871.
35. Yadav GD, Bhagat AS, Gupta SK. Emerging trends in the removal of endocrine disrupting compounds (EDCs) from water: A review. J. Environ. Chem. Eng. 2019; 7(2):102992.
36. Wang Y, Li H, Chen Z, Li Y, Wu M, Zhou L. Enhanced removal of engineered nanoparticles from water using silica nanoparticles with a quaternary ammonium groups modification. J. Hazard. Mater. 2019; 366:431–438.
37. Dey U, Bera A, Majumder CB, Mondal NK, Das SK. Arsenic removal from groundwater using iron oxide nanoparticles: A study on the effect of particle size and pH. Environ. Nanotechnol. Monit. Manag. 2018; 9:25–34.
38. Guan Y, Chen Z, Li X, Li X, Li J, Li Q, Qian Y, Gao S. Efficient removal of microplastics from water by polystyrene-coated magnetic nanoparticles. J. Hazard. Mater. 2020; 385:121537.
39. Ashfaq M, Verma N, Rizwan-ul-Haq M, Khan, ZM, Shahid-ul-Islam S, Majeed S, Afzal M, Qayyum MA, Nazir J, Rehman IU. Synthesis, characterization and disinfection potential of copper nanoparticles against bacterial pathogens. J. Photochem. Photobiol. B, Biol. 2018; 180:46–52.