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Nanoparticles for microbial control in water: mechanisms, applications, and ecological implications

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Waterborne microbial contamination poses significant threats to public health and environmental sustainability. Traditional water treatment methods, while effective to a certain extent, are often limited in their ability to completely eradicate microbial pathogens and mitigate emerging challenges such as disinfection by-products and microbial resistance. In recent years, nanoparticles have emerged as promising candidates for microbial control in water treatment due to their unique physicochemical properties and antimicrobial efficacy. This review provides a comprehensive examination of the use of nanoparticles for microbial control in water treatment, focusing on their antimicrobial mechanisms, applications, and ecological implications. The review discusses the types of nanoparticles commonly used in water treatment, including silver nanoparticles, copper nanoparticles, titanium dioxide nanoparticles, and carbon-based nanoparticles, and examines their antimicrobial mechanisms, such as cell membrane damage, reactive oxygen species generation, and interference with microbial metabolic processes. Furthermore, the review explores the applications of nanoparticles in the disinfection of drinking water, wastewater treatment, water purification in remote areas, and biofilm control. Additionally, the ecological implications of nanoparticle-based water treatment, including nanoparticle release into the environment, environmental persistence, toxicity to non-target organisms, and regulatory challenges, are critically evaluated. Finally, future perspectives and challenges in nanoparticle-based water treatment, such as enhanced nanoparticle synthesis and stability, development of sustainable treatment technologies, integration with conventional methods, and addressing knowledge gaps, are discussed. Overall, this review provides valuable insights into the potential of nanoparticles as innovative tools for addressing microbial contamination in water treatment while highlighting the need for further research and sustainable practices to ensure their safe and effective implementation.

KEYWORDS

nanoparticles, microbial control, water treatment, antimicrobial mechanisms, ecological impacts

1 Introduction

Efficient wastewater treatment, crucial for meeting both effluent and drinking water quality standards, hinges significantly on the efficacy of the disinfection stage. Traditional disinfection methods, such as chlorination and ultraviolet radiation, while widely utilized due to their effectiveness, present notable disadvantages (Rikta, 2019). Chlorination, for instance, can lead to the formation of harmful disinfection by-products (DBPs) like trihalomethanes and haloacetic acids, which are linked to an increased risk of carcinogenicity, mutagenicity, cytotoxicity, teratogenicity, and other health issues (Srivastav et al., 2020). Moreover, physical methods like ultraviolet radiation require substantial energy inputs and have limited efficacy against some resistant microbial strains, such as tetracycline-resistant *Escherichia coli* (Huang et al., 2013, Huang et al., 2016). These drawbacks underscore the need for exploring alternative disinfection technologies that can overcome these limitations while ensuring safe water.

Over the past decade, significant technological advancements have been made in water treatment processes, among which the use of nanomaterials for wastewater disinfection has emerged as a particularly notable innovation (Zhao et al., 2023). Nanoparticles are minuscule particles that exhibit unique physical and chemical properties due to their small size (<100 nm) and large surface-to-volume ratio (Salem et al., 2022). These properties include enhanced reactivity, strength, and electrical characteristics, which make them highly versatile for various applications (Khan S. A. et al., 2022). In the context of wastewater treatment, nanoparticles such as silver (nAg), fullerenes, and carbon nanotubes (CNT) have garnered attention for their potent antimicrobial properties (Epelle et al., 2022). These materials operate through diverse mechanisms, including the photocatalytic production of reactive oxygen species, disruption of microbial cell envelopes, and interference with essential biological processes like energy transduction and DNA synthesis (Li et al., 2008; Rikta, 2019). Such actions render them effective against a wide array of microbial pathogens commonly found in wastewater (Mahendra et al., 2009). The incorporation of nanoparticles into water treatment systems can significantly improve disinfection efficiency by overcoming the limitations of traditional methods, such as the formation of harmful byproducts in chlorination or the high energy requirements of ultraviolet radiation (Rikta, 2019; Epelle et al., 2022).

Nanoparticles combat microbial contaminants through a variety of sophisticated mechanisms, each tailored to the unique properties of the nanomaterial involved. For instance, titanium dioxide (TiO_2) nanoparticles leverage their photocatalytic properties under UV light to generate reactive oxygen species (ROS), such as hydroxyl radicals and peroxide, which are lethal to microorganisms (Mahendra et al., 2009). This action disrupts vital cellular components, leading to the inactivation of bacteria and viruses. Similarly, silver nanoparticles (AgNPs) exert their antimicrobial effects by releasing Ag+ ions, which interfere with the function of cellular proteins and DNA, ultimately leading to cell death (Vasiliev et al., 2023). Additionally, carbon nanotubes (CNT) employ a physical mechanism by compromising the integrity of the bacterial cell envelope through direct contact, causing structural damage that results in cell leakage and death (Mahendra et al., 2009; Asaftei et al., 2023). These diverse mechanisms highlight the versatility of nanoparticles in targeting and inactivating a wide array of pathogens, making them highly effective as disinfectants in water treatment processes.

Nanotechnology offers several compelling advantages over traditional disinfection methods in wastewater treatment. Nanoparticles like TiO_2 and silver demonstrate high efficacy against a broad spectrum of pathogens, including those resistant to conventional treatments, and do so with lower energy consumption and without the need for hazardous chemicals (Chakhtouna et al., 2021). These attributes underscore the transformative potential of nanotechnology in ensuring safer, more sustainable water treatment solutions. Given these significant advantages, this narrative review paper aims to exhaustively examine the recent advancements in nanoparticle technology and assess their feasibility for practical, large-scale applications shortly. By exploring current research and development, the paper seeks to bridge the gap between laboratory efficacy and real-world implementation, providing a comprehensive analysis of how nanotechnology can revolutionize water treatment practices and contribute to global health and sustainability goals.

2 Method

A comprehensive literature search was conducted to identify relevant studies on the use of nanoparticles for microbial control in water treatment. Data extraction was performed to gather relevant information from literature. Key information extracted from each article included nanoparticle type, synthesis method, physicochemical properties, antimicrobial mechanisms, effectiveness in water treatment, and ecological implications. Data were organized and synthesized to provide a comprehensive overview of the current state of knowledge regarding the use of nanoparticles for microbial control in water treatment. The extracted data were analyzed to identify trends, patterns, and gaps in the literature. Common themes and findings from reviewed literature were synthesized to provide insights into the efficacy, mechanisms, and challenges associated with nanoparticle-based water treatment. The implications of the findings for water treatment practice and recommendations for future research were discussed based on the analysis of the data.

3 Types of nanoparticles for microbial control

Antimicrobial resistance is emerging as a significant public health threat globally, underscoring the critical need for innovative solutions to combat this escalating challenge (Aber et al., 2023; Aijaz et al., 2023). In response, nanomaterials have been identified as effective tools for addressing these growing concerns, as shown in Table 1. Nanoparticles (NPs) are classified relative to composition, morphology, and application. Common classifications include metallic NPs, such as silver, copper, zinc, and gold, among others. They are mostly explored for antimicrobial and medical diagnostics. Nanoparticles (NPs), with their distinct

TABLE 1 Recent Advances in Nanoparticles for Microbial Control: Synthesis, Properties, and significant Characteristics.

Nanoparticles type	Source/Synthesis	Size (nm)	Shape	Significant characteristics
Silver (AgNPs) (Altammar, 2023)	Chemical reduction, biosynthesis using plant extracts	10–100	Spherical, rod, cube, triangular and disk shape	High surface area, broad-spectrum antimicrobial activity, biofilm inhibition, oxidative stress induction
Copper (CuNPs) (Bhagat et al., 2021)	Chemical reduction, green synthesis, thermal decomposition	90–260	Spherical, cubical, octahedral	Strong antimicrobial activity, effective against biofilms and potential environmental risks
Titanium Dioxide (TiO_2NPs) (Mhadhbi et al., 2023)	Sol-gel, hydrothermal and polyol methods, Chemical vapour deposition	30–50	Spherical, rod-like, ellipsoidal	Photocatalytic properties, ROS generation under UV light degradation of organic pollutants
Graphene Oxide (GO) (Goyat et al., 2022)	Oxidation of graphite flakes, Hummers method	<100	Sheet-like	Large surface area, oxygen functional groups, membrane disruption, photocatalytic under UV light
Carbon Nanotubes (CNTs) (Jia and Wei, 2017; Chen et al., 2023)	Chemical vapor deposition, arc discharge, laser ablation	Diameter: 0.5–3.0 (Single-walled), 2–100 (Multi-walled)	Cylindrical	High mechanical strength, physical puncturing of cell walls, effective against diverse microorganisms
Zinc Oxide (ZnONPs) (Droepenu et al., 2022)	Sol-gel, hydrothermal synthesis	30–150	Spherical, rod-like	ROS generation, broad antimicrobial activity, potential for environmental degradation
Iron Oxide (FeONPs) (Zúñiga-Miranda et al., 2023)	Co-precipitation, thermal decomposition, sol-gel	10–100	Spherical, cubic, octahedral	Induces oxidative stress, magnetic hyperthermia for microbial inactivation, environmental considerations

physicochemical properties, are gaining prominence as potent agents for antimicrobial applications. Their effectiveness in microbial control is notably attributed to their potential for non-toxic release after application (Rikta, 2019). Notable examples of nanomaterials that exhibit antimicrobial properties include silver, titanium dioxide, copper, and carbon-based nanoparticles (Mahendra et al., 2009). These nanoparticles disrupt microbial activity primarily by damaging cell membranes, thus providing a viable mechanism for inhibiting microbial growth. Furthermore, the ability to tailor the surface properties of nanoparticles enables the development of targeted strategies against specific pathogens, thus opening new avenues in the design of antimicrobial agents.

Likewise, polymer-based NPs, like dendrimers, are explored in drug delivery systems because of their biocompatibility and modified release. Another significant category is carbon-based NPs, including fullerenes and carbon nanotubes, which are notable for their excellent electrical conductivity and strength. In this paper, we extensively examine the commonly applied nanoparticles for microbial control in water.

3.1 Silver nanoparticles

Silver nanoparticles (AgNPs) have emerged as promising antimicrobial agents with broad-spectrum activity against various microorganisms, including bacteria, viruses, fungi, and protozoa (Yah and Simate, 2015). Their antimicrobial efficacy is attributed to their high surface area-to-volume ratio, which facilitates interactions with microbial cells (Sayed et al., 2022). AgNPs exert their antimicrobial effects through multiple mechanisms, including disruption of cell membrane integrity, inhibition of cellular respiration, and induction of oxidative stress. Several studies have demonstrated the effectiveness of AgNPs in water disinfection applications, showing significant reductions in microbial populations even at low concentrations (Bahcelioglu et al., 2021; Khan Y. et al., 2022). Furthermore, AgNPs have shown potential for inhibiting biofilm formation and controlling antibiotic-resistant bacteria, highlighting their versatility and promising applications in combating microbial contamination in water sources (Polinarski et al., 2021). In addition to documented AgNP antimicrobial properties, they have been the subject of recent studies, especially their mechanism of action at a molecular level. In this study, we have gathered that silver ions released from AgNPs not only disrupt the outer membrane but also precipitate vital cellular components, leading to rapid microbial death.

3.2 Copper nanoparticles

Copper nanoparticles (CuNPs) have garnered attention for their potent antimicrobial properties, particularly against bacteria (Edis et al., 2019; Nisar et al., 2019). CuNPs release copper ions that penetrate microbial cell membranes, leading to disruption of membrane integrity and interference with cellular processes. Studies have shown that CuNPs exhibit strong antimicrobial activity against a wide range of bacterial pathogens, including both Gram-positive and Gram-negative bacteria, with impressive reports of 99% microbial inhibition concentration and 100% minimum bactericidal concentration (Yadav L. et al., 2017; Sharma et al., 2022). Additionally, CuNPs have been explored for their potential to control bacterial biofilms, which are notoriously resistant to conventional disinfection methods. Despite their effectiveness, the use of CuNPs in water treatment raises concerns about potential environmental impacts, such as copper accumulation in aquatic ecosystems and the development of copper-resistant microorganisms, necessitating further research to evaluate their long-term efficacy and safety (Keller et al., 2017; Malhotra et al., 2020). Meanwhile, for minimal environmental impact, a controlled release or application of CuNPs would significantly prevent the rapid development of resistance among the microbial populations.

3.3 Titanium dioxide nanoparticles

Titanium dioxide nanoparticles (TiO_2NPs) have garnered attention for their photocatalytic properties, which enable them to generate reactive oxygen species (ROS) upon exposure to UV irradiation. These ROS, including hydroxyl radicals and superoxide ions, exhibit strong oxidizing potential, leading to damage to microbial cell membranes, proteins, and nucleic acids (Canaparo et al., 2020; Juan et al., 2021; Sargazi et al., 2022). TiO_2NPs have demonstrated effectiveness against a wide range of microorganisms, including bacteria, viruses, and algae, making them promising candidates for water disinfection and purification. Moreover, TiO_2NPs have been investigated for their potential to degrade organic pollutants and remove heavy metals from water sources (Mohammad Gheimasi et al., 2021), further highlighting their versatility and potential for sustainable water treatment applications. Additionally, ongoing research is optimizing the doping of TiO2NPs with other metals to tune their photocatalytic activity across a broader spectrum of light.

3.4 Carbon-based nanoparticles

Carbon-based nanoparticles, such as graphene oxide (GO) and carbon nanotubes (CNTs), have shown promise as antimicrobial agents due to their unique physicochemical properties (Smith and Rodrigues, 2015; Hadidi and Mohebbi, 2022). GO possesses a large surface area and numerous oxygen-containing functional groups, allowing it to interact with microbial cells and disrupt their membranes. Additionally, GO exhibits photocatalytic activity under UV irradiation, further enhancing its antimicrobial efficacy (Sun et al., 2017). Similarly, CNTs exhibit sharp edges that can physically puncture microbial cell walls, leading to cell lysis (Al-Jumaili et al., 2017). Both GO and CNTs have demonstrated effectiveness against a wide range of microorganisms, including bacteria, viruses, and fungi, making them potential candidates for water disinfection and biofilm control (Al-Jumaili et al., 2017; Mohammed et al., 2020). However, concerns about the environmental fate and toxicity of carbon-based nanoparticles necessitate further research to evaluate their long-term impacts on aquatic ecosystems and human health (Patil and Lekhak, 2020).

3.5 Other nanoparticles

In addition to the aforementioned nanoparticles, various other types of nanoparticles are being explored for their antimicrobial properties and potential applications in water treatment. Zinc oxide nanoparticles (ZnONPs) have shown effectiveness against bacteria, viruses, and fungi due to their ability to generate ROS and disrupt microbial cell membranes. Iron oxide nanoparticles (FeONPs) have been investigated for their potential to induce oxidative stress and magnetic hyperthermia in microbial cells, leading to microbial inactivation. Hybrid nanoparticles, composed of multiple materials, offer synergistic antimicrobial effects and enhanced stability, presenting additional options for microbial control in water treatment. Overall, nanoparticles represent a diverse and promising array of antimicrobial agents for addressing microbial contamination in water sources, offering innovative solutions for sustainable water treatment and public health protection. Table 1 provides a summary of the different nanoparticle types and their distinct characteristics, while Table 2 delves into their mechanism of action in water disinfection processes.

4 Antimicrobial mechanisms of nanoparticles

Nanoparticles have gained recognition for their potent antimicrobial properties, which arise from diverse mechanisms of action (Oluwasanu et al., 2019; Rikta, 2019; Zhao et al., 2023), as shown in Figure 1. Understanding these mechanisms is crucial for harnessing the full potential of nanoparticles in combatting microbial contamination in various settings, including water treatment, healthcare, and food preservation.

4.1 Cell membrane damage

One of the primary mechanisms through which nanoparticles exert their antimicrobial effects is by inducing damage to microbial cell membranes. Nanoparticles, particularly those with sharp edges or high surface reactivity, can physically penetrate microbial cell walls, leading to disruption of membrane integrity and leakage of cellular contents (Wu et al., 2018; Sinha et al., 2022). This disruption impairs essential cellular functions, such as nutrient uptake, waste removal, and maintenance of osmotic balance, ultimately leading to microbial death. Several studies have demonstrated the ability of nanoparticles, such as AgNPs, CNTs, and GO, to cause structural damage to microbial cell membranes, resulting in increased membrane permeability and loss of membrane integrity (Kunduru et al., 2017; Wu et al., 2018; Rikta, 2019). Additionally, nanoparticles undergo dissolution, leading to leaching out of ions, which may interact with membrane-bound proteins and lipids, further compromising membrane stability and function (Ritu et al., 2023). Overall, cell membrane damage represents a crucial antimicrobial mechanism of nanoparticles, contributing to their efficacy against a wide range of microbial pathogens.

4.2 Reactive oxygen species (ROS) generation

Another important antimicrobial mechanism of nanoparticles involves the generation of reactive oxygen species (ROS), such as hydroxyl radicals ($^{\bullet}OH$), superoxide ions ($O^{2\bullet-}$), and singlet oxygen ($^1O_2$) (Dey et al., 2018; Rikta, 2019; Franco et al., 2022; Ikram et al., 2023). Nanoparticles, particularly those composed of metal oxides (e.g., titanium dioxide nanoparticles, zinc oxide nanoparticles) or capable of photocatalysis (e.g., titanium dioxide nanoparticles), can absorb photons and transfer energy to surrounding oxygen molecules, leading to the generation of ROS through

TABLE 2 Innovative nanotechnologies for targeted water disinfection: Mechanisms, advantages, and disadvantages.

Nanotechnology type	Microbial target	Mechanism of action	Advantages	Disadvantages
Silver Nanoparticles (Salleh et al., 2020)	Bacteria, viruses, fungi	Release of silver ions leading to microbial inactivation	High antimicrobial efficacy, broad-spectrum activity, relatively low cost	Potential cytotoxicity, environmental concerns, development of resistance in microorganisms
Titanium Dioxide Nanoparticles (Rathore et al., 2023)	Bacteria, Viruses, Organic Pollutants	Similar to ZnO NPs, TiO2 NPs act as photocatalysts under UV light for disinfection and pollutant degradation	Effective disinfection, degradation of pollutants	Potential human health risks, difficulty in recovering TiO2 NPs after treatment
Carbon Nanotubes (CNTs) (Abo-Neima et al., 2020)	Bacteria, Viruses	High surface area for adsorption of microbes. Some CNTs can be functionalized for enhanced antimicrobial activity	Efficient adsorption, potential for selective targeting of microbes	Potential for CNTs to leach harmful substances, difficulty in CNT disposal
Titanium Dioxide Nanoparticles (Magaña-López et al., 2021)	Bacteria, viruses, algae	Photocatalytic generation of reactive oxygen species leading to microbial inactivation	Effective under UV light, non-toxic to humans, stable and long-lasting	Limited activity in the absence of UV light, the potential for photocatalyst leaching
Graphene-Based Nanomaterials (Omran and Baek, 2022)	Bacteria, viruses	Physical disruption of microbial membranes, generation of reactive oxygen species	High surface area, strong antimicrobial activity, potential for multifunctionality	Concerns regarding environmental impact, dispersion, and stability issues
Carbon Nanotubes (Ansari et al., 2023)	Bacteria, viruses, protozoa	Physical entrapment of microorganisms, adsorption, and inactivation of microbes	High adsorption capacity, stability, and durability, the potential for functionalization	Concerns regarding dispersion and aggregation, toxicity concerns
Nanosilver Impregnated Membranes (Rajarathinam et al., 2014)	Bacteria, Viruses	Filtration combined with the antimicrobial properties of silver nanoparticles	Effective disinfection, reusability of membranes	Membrane fouling, potential silver release
Polymeric Nanomaterials (Álvarez-Paino et al., 2017)	Bacteria and fungi	Disruption of microbial membranes, release of antimicrobial agents	Tailorable properties, biocompatibility, potential for sustained release of antimicrobials	Limited scalability, challenges in controlling release kinetics
Silver Nanoparticles (AgNPs) (Park et al., 2018)	Bacteria (e.g., *E. coli*, *S. aureus*), Viruses	Membrane disruption and reactive oxygen species generation	Effective disinfection, broad-spectrum activity	Potential human health and environmental impacts of released AgNPs
Zinc Oxide Nanoparticles (ZnO NPs) (Dimapilis et al., 2018)	Bacteria (e.g., *E. coli*), Viruses	Photocatalytic disinfection under UV light. ZnO NPs generate reactive oxygen species that kill microbes	Effective disinfection decomposes organic pollutants	Potential human health concerns, aggregation of ZnO NPs reduces efficiency

photochemical reactions (El-Sayyad et al., 2023; Younis et al., 2023). These ROS exhibit potent oxidizing properties, causing damage to microbial cell membranes, proteins, and nucleic acids. Moreover, ROS induces oxidative stress responses in microbial cells, leading to the activation of antioxidant enzymes and DNA repair mechanisms, as shown in Figure 2. However, excessive ROS production overwhelms these defense mechanisms, ultimately leading to oxidative damage and microbial death. Several studies have demonstrated the ability of nanoparticles to generate ROS and induce oxidative stress in microbial cells, highlighting the importance of this mechanism in nanoparticle-mediated antimicrobial activity (Wu et al., 2018; Shi et al., 2019; Khan M. I. et al., 2021; Dutta et al., 2023; Guerrero-Almonacid et al., 2023; Ikram et al., 2023).

4.3 Interference with microbial metabolic processes

Nanoparticles can also exert antimicrobial effects by interfering with microbial metabolic processes essential for cell survival and proliferation (Mtavangu et al., 2022). For example, nanoparticles may disrupt enzymatic reactions involved in energy production, biosynthesis, and nutrient metabolism, leading to metabolic dysfunction and cellular toxicity (Ritu et al., 2023). Additionally, nanoparticles may interfere with microbial DNA replication, transcription, and translation processes, impairing cellular proliferation and growth (Crisan et al., 2021; Rosli et al., 2021), as shown in Figure 2. Furthermore, nanoparticles may disrupt microbial quorum sensing mechanisms, which regulate gene expression and coordinate population-wide behaviours, such as biofilm formation and virulence factor production (Franci et al., 2015). By targeting multiple metabolic pathways and cellular processes, nanoparticles can effectively inhibit microbial growth and survival (He et al., 2022). Several studies have demonstrated the ability of nanoparticles, such as silver nanoparticles and copper nanoparticles, to disrupt microbial metabolic processes and inhibit the growth of bacterial and fungal pathogens (Rajabi et al., 2017; Oquendo-Cruz and Perales-Pérez, 2018; Saha et al., 2018; Shi et al., 2019; Adeyemi et al., 2020; Noohpisheh et al., 2020; Xiao et al., 2021; Sinha et al., 2022). Overall, interference with microbial metabolic processes represents a multifaceted antimicrobial mechanism of

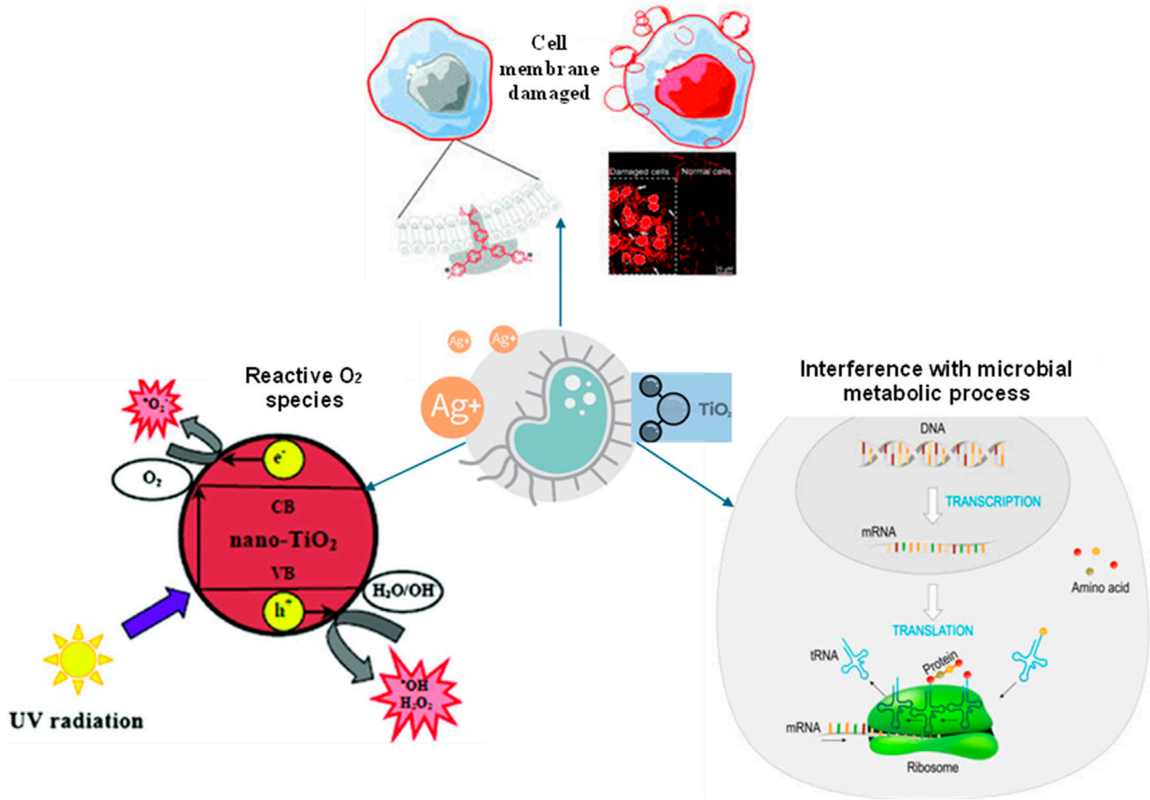

FIGURE 1
Illustration of the diverse mechanisms through which nanoparticles exert antimicrobial effects, including cell membrane damage, reactive oxygen species (ROS) generation, and interference with microbial metabolic processes.

nanoparticles, contributing to their broad-spectrum activity against diverse microbial pathogens.

4.4 Combination therapy

Combination therapy, involving the simultaneous or sequential administration of multiple antimicrobial agents, represents a promising strategy for enhancing the efficacy of nanoparticle-based antimicrobial treatments (Ahmed et al., 2019; Singh et al., 2022). Combining nanoparticles with different mechanisms of action or synergistic antimicrobial agents, such as antibiotics, antimicrobial peptides, or natural antimicrobial compounds, can achieve enhanced antimicrobial activity, overcome microbial resistance, and reduce the risk of treatment failure. Several studies have demonstrated the effectiveness of combination therapy using nanoparticles and conventional antimicrobial agents against multidrug-resistant bacterial and fungal pathogens (Ahmed et al., 2019; Yang et al., 2019; Singh et al., 2022; Markowicz, 2023). Moreover, combination therapy allows for lower doses of individual agents, minimizing potential adverse effects and toxicity. However, optimal combination regimens, dosage formulations, and treatment protocols need to be carefully evaluated to maximize therapeutic efficacy while minimizing the risk of adverse effects and antimicrobial resistance development. Overall, combination therapy represents a promising approach for enhancing the antimicrobial efficacy of nanoparticles and combating microbial contamination in various settings. Figure 1 summarises the different mechanisms employed by NPs for antimicrobial activities.

4.5 Influence of environmental parameters

The antibacterial efficacy of nanoparticles, such as silver nanoparticles (AgNPs), copper nanoparticles (CuNPs), titanium dioxide nanoparticles (TiO_2NPs), and zinc oxide nanoparticles (ZnONPs), is significantly influenced by various environmental parameters, including pH, temperature, ionic strength, and the presence of organic matter (Dobrescu et al., 2023; Adetuyi et al., 2024). For instance, the pH of the environment can alter the surface charge and solubility of these nanoparticles, affecting their interaction with microbial cells (Badawy et al., 2010). Studies have shown that AgNPs exhibit optimal antibacterial activity at neutral to slightly alkaline pH levels, where their stability and reactivity are enhanced (Bélteky et al., 2019; Gibała et al., 2021). Similarly, CuNPs and ZnONPs also display varying degrees of antimicrobial effectiveness depending on the pH conditions (Wang et al., 2015; Ribut et al., 2018). Temperature is another crucial factor that affects the antibacterial activity of nanoparticles. Higher and lower temperatures were reported to affect the antibacterial activity of nanoparticles (Qu et al., 2010; Pourali et al., 2013). Ionic strength, determined by the concentration of

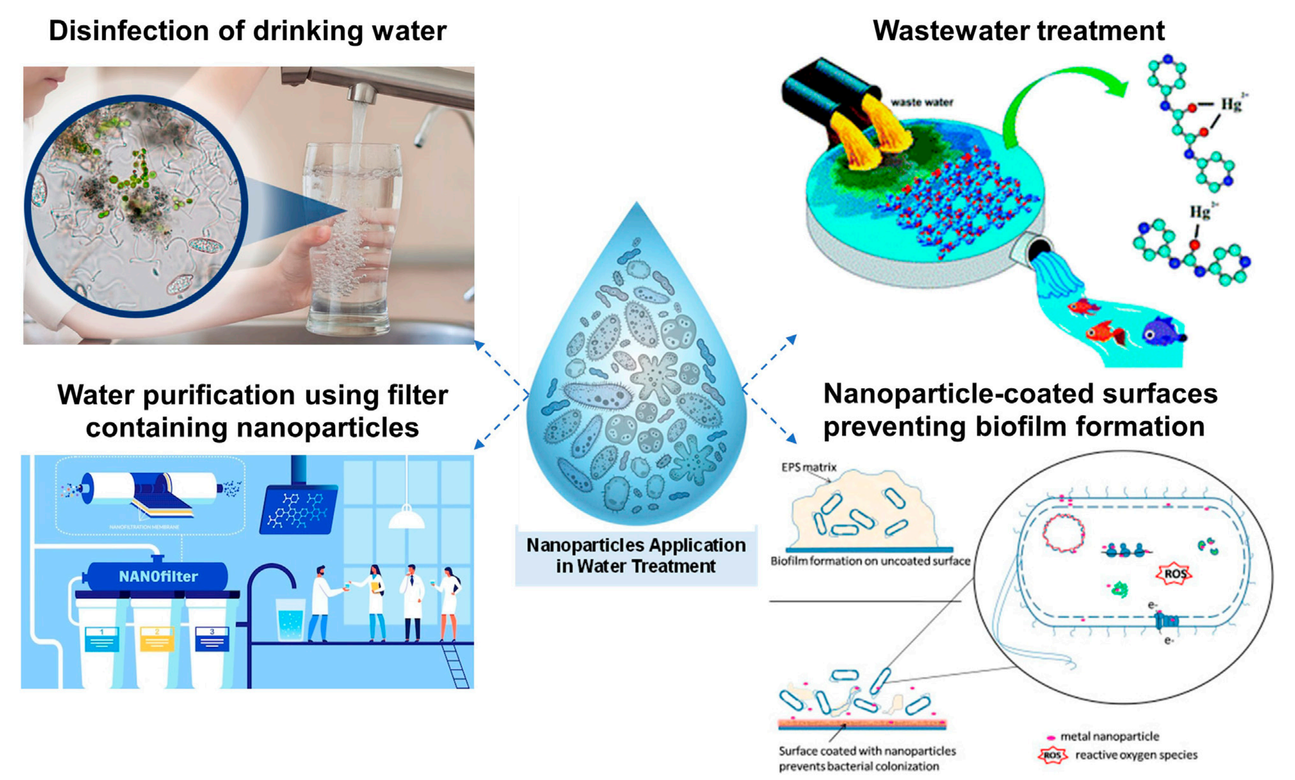

FIGURE 2
A visual overview of multifaceted applications of nanoparticles in water treatment.

salts in the water, can affect the aggregation state of nanoparticles. High ionic strength environments can induce nanoparticle aggregation, reducing their surface area and subsequent antimicrobial activity (Chambers et al., 2014; Wang et al., 2020). Additionally, the presence of organic matter, such as humic substances, can interact with nanoparticles, forming a corona that may either enhance or hinder their antibacterial properties (Fabrega et al., 2009; Wang et al., 2015). For example, organic matter can increase the stability and dispersion of nanoparticles in water, but it can also reduce their availability to interact with bacterial cells by acting as a physical barrier. Therefore, understanding and optimizing these environmental parameters is essential for maximizing the antibacterial activity of nanoparticles like AgNPs, CuNPs, TiO_2NPs, and ZnONPs in various water treatment applications.

5 Applications of nanoparticles in water treatment

Nanoparticles are rapidly evolving in the field of water treatment, offering innovative approaches to combat water pollution and scarcity, as shown in Figure 2. Their unique physicochemical characteristics, coupled with a remarkably high surface area-to-volume ratio, enable a diverse range of applications that contribute to purifying, remediating, and disinfecting water sources. From eliminating contaminants to improving filtration processes, nanoparticles play a crucial role in enhancing water quality and ensuring access to clean drinking water. Their versatile applications span various techniques and technologies, including adsorption, catalysis, membrane filtration, and advanced oxidation processes. These multifaceted uses highlight the potential of nanoparticles to transform water treatment methods, providing sustainable and effective solutions to environmental challenges and public health concerns. Figure 2 provides a summary of NPs' utilization in water treatment.

5.1 Disinfection of drinking water

In the realm of drinking water treatment, nanoparticles offer novel approaches to disinfection, aiming to improve water quality and safeguard public health (Eloffy et al., 2021). AgNPs have been extensively studied for their efficacy in disinfecting drinking water due to their potent antimicrobial properties (Rus et al., 2017; Deshmukh, et al., 2019; Bhardwaj et al., 2021). Silver nanoparticle-infused ceramic filters outperformed those lacking nanoparticles and exhibited superior bacteria removal in both laboratory and field trials in Guatemala. Deployed to 62 households, these filters achieved an average 90% reduction in total coliforms and *E. coli* while maintaining an effluent concentration of ionic silver 0.02 mg/L below the U.S. EPA standard of 0.1 mg/L (Kallman et al., 2011). AgNPs can effectively target a wide range of microorganisms, including bacteria, viruses, and protozoa, by disrupting cellular functions and inhibiting microbial growth (Kowalczyk et al., 2021). Studies have demonstrated that AgNPs can achieve rapid and effective disinfection of water, even at low concentrations, making them promising candidates for replacing or supplementing traditional disinfection methods such as chlorination (Yang, 2016) The antiviral effects of AgNPs within a continuous system were investigated, alongside their antibacterial properties, utilizing a "phase inversion" technique to synthesize membranes impregnated with AgNPs, which exhibited potent inactivation against MS2 coliphage, *E. coli* K12, and *Pseudomonas mendocina* KR1(Zodrow et al., 2009). A Belgian team explored viral inactivation using biogenic nanosilver immobilized in polyvinylidene fluoride (PVDF) membranes. Employing a continuous flow system with these membranes, they achieved approximately 4-log removal of UZ1 bacteriophage after 2 h at a flow rate of 0.375 L/h and a hydraulic retention time (HRT) of 1 h while maintaining a low Ag+ concentration of 27 ± 8 μg/L in the treated water (De Gusseme et al., 2010).

AgNPs have shown capabilities in enhancing water disinfection processes. Unlike conventional methods, they minimize the risk of creating disinfection by-products, often associated with carcinogenic risks. This property, alongside their efficient performance and lower energy requirements, makes AgNPs a favorable alternative in water treatment technologies (Bahcelioglu et al., 2021). Additionally, TiO_2NPs have gained attention for their photocatalytic activity, which enables them to generate ROS under UV irradiation, causing them to act as bacterial disinfectants (Liao et al., 2020). TiO_2NPs have shown effectiveness against bacteria, viruses, and protozoa, making them suitable for disinfection applications in drinking water treatment plants (Michael-Kordatou et al., 2018). Despite their stability during the degradation of contaminants and microorganisms, TiO_2 nanoparticles require UV lamps for activation due to their large bandgap energy. A molecularly imprinted TiO_2 photocatalyst was developed *via* the sol-gel method, demonstrating its efficacy in selectively degrading the herbicide- 2,4-dichlorophenoxyacetic acid and the insecticide-imidacloprid (Fiorenza et al., 2019). Overall, nanoparticles offer promising solutions for enhancing the disinfection of drinking water, providing safer and healthier water sources for communities worldwide.

5.2 Wastewater treatment

Nanoparticles also hold significant potential for wastewater treatment, offering opportunities to remove contaminants and pollutants from wastewater streams effectively. In wastewater treatment plants, nanoparticles can be employed in various processes, including coagulation, flocculation, adsorption, and photocatalysis, to improve the removal efficiency of organic and inorganic pollutants (Khan S. et al., 2021; Jabbar et al., 2022). For example, iron-based nanoparticles, such as iron oxide nanoparticles (FeONPs), have been utilized as adsorbents for the removal of heavy metals and organic pollutants from wastewater because they can selectively adsorb contaminants onto their surfaces, facilitating their removal through sedimentation or filtration processes (Ajith et al., 2021). Efficacy of FeNPs and FeONPs in removing Cd^{2+} (Ebrahim et al., 2015), Cu^{2+} (Poguberović et al., 2016), Co^{2+} and Ni^{2+} (Hooshyar et al., 2013) and chlorinated organic contaminants ((Guo et al., 2017) has been extensively studied and reported.

Similarly, carbon-based nanoparticles, such as GO and CNTs, have shown promise for adsorbing organic compounds and pharmaceuticals from wastewater streams owing to their high surface area and affinity for hydrophobic molecules (Thakur et al., 2024). Furthermore, photocatalytic nanoparticles, such as TiO_2NPs and zinc oxide nanoparticles (ZnONPs), can be employed to degrade organic pollutants and disinfect wastewater under UV irradiation (Yashni et al., 2021). These nanoparticles generate ROS, which reacts with organic molecules, leading to their degradation and mineralization (Sultana et al., 2020). Overall, nanoparticles offer versatile and effective solutions for wastewater treatment, enabling the removal of contaminants and the production of clean water for either reuse or discharge into the environment (Hlongwane et al., 2019).

5.3 Water purification in remote areas

Nanoparticles also hold promise for water purification in remote or resource-limited areas where access to clean and safe drinking water is limited. Portable and low-cost nanoparticle-based water purification technologies have been developed to provide sustainable solutions for addressing waterborne diseases and improving public health outcomes in underserved communities (Kumar, 2023). For example, AgNPs can be incorporated into point-of-use water treatment devices, such as ceramic filters or membrane cartridges, to disinfect water and remove microbial contaminants (Kannan et al., 2023; Rowles, et al., 2023). These devices utilize the antimicrobial properties of AgNPs to inactivate pathogens and provide safe drinking water to households without access to centralized water treatment infrastructure. Similarly, GO-based membranes have been developed for desalination and water purification applications, offering high water permeability and selectivity for removing salts and organic compounds from water sources (Song et al., 2018). These nanoparticle-based technologies have the potential to significantly improve access to clean water in remote areas, contributing to poverty alleviation, health promotion, and sustainable development.

5.4 Biofilm control

Biofilms, complex microbial communities embedded in a matrix of extracellular polymeric substances, pose significant challenges in water treatment systems, leading to fouling, corrosion, and contamination (Shukla et al., 2021). Nanoparticles offer innovative strategies for controlling biofilm formation and mitigating its adverse effects on water quality and system performance (Mohanta et al., 2023). Metal-based nanoparticles, such as AgNPs and CuNPs, have shown efficacy in inhibiting biofilm formation and disrupting established biofilms through their antimicrobial properties (Mammari et al., 2022).

Using mixed metal oxides in precise ratios was reported to have a more significant impact than utilizing a free metal oxide, such as ZnO:MgO NPs, which at low concentrations prevent *Bacillus subtilis* and *P. mirabilis* from forming biofilms (Mohanta et al., 2023) and the zinc-doped copper oxide (Zn:CuO NPs) coated teeth improved the killing of *S. mutans* and lowered biofilm development by 88% as

TABLE 3 Comparative analysis of antibacterial activity, applications and implications of nanoparticles in water treatment.

NP type	MIC (μg/mL)	Target microorganisms	Synthesis method	Surface area (m2/g)	Applications	Ecological implications
Ag NPs (Singh et al., 2020)	3.12 (*E. coli*), 1.56 (*P. aeruginosa*)	*Escherichia coli, Pseudomonas aeruginosa*	Green synthesis using Solibacillus isronensis	High	Biofilm inhibition, Antibacterial coatings	Potential for biocompatibility, Sustainability
Cu NPs (Alao et al., 2022)	Inhibition Zones: 17.0 ± 4.24 mm (*P. aeruginosa*)	*Pseudomonas aeruginosa, Shigella* sp., *Staphylococcus aureus, Salmonella typhi, Escherichia coli*	Green synthesis using Kigelia africana fruit extract	Moderate	Antibacterial and antifungal applications	Potential for green synthesis and sustainable use
TiO_2 NPs (Salem et al., 2021)	—	*Salmonella typhi, Enterobacter ludwigii, Morganella morganii, Klebsiella pneumoniae, Enterococcus faecium*	Green synthesis using ethyl acetate extracts from marine algae (Caulerpa racemosa, Codium fragile, Cystoseira myrica)	High	Water treatment, Antibacterial coatings, Biofilm control	Green synthesis, Non-toxic, Environmentally friendly
Graphene Oxide NPs (Khalil et al., 2020)	—	*Escherichia coli, Staphylococcus aureus, Candida albicans*	Hybrid synthesis using chitosan (CS) or ethylene diamine tetraacetic acid (EDTA) with GO	High	Oxidative and membrane stress, Wrapping isolation	Cost-effective, Eco-friendly, High stability
Multi-Walled Carbon Nanotubes (MWCNTs) (El-Newehy et al., 2023)	—	*Escherichia coli O157, Salmonella enterica, Staphylococcus aureus, Enterococcus faecalis, Rhizopus oryzae*	Characterization: TEM, SEM, XRD, FTIR, DLS, Zeta Potential. FTIR spectra: 11,029 cm^{-1}; Particle size: 425 nm; Zeta potential: 28.89 m	Ultra High	Wastewater disinfection, Pathogen inactivation, Antimicrobial agents	Potential toxicity to aquatic life; Requires careful dosage

opposed to 70% with free CuO NPs (Eshed et al., 2014). These nanoparticles can penetrate the biofilm matrix and target microbial cells, leading to cell membrane damage and microbial death (Li et al., 2021). Additionally, nanoparticles can be incorporated into coatings, membranes, or surfaces to prevent biofilm formation and promote the self-cleaning properties of water treatment equipment (Zhang et al., 2016; Mi et al., 2018). For example, GO coatings have been shown to inhibit biofilm formation on surfaces by preventing microbial adhesion and growth, with biofilm inhibition percentage reaching 90%–100% at GO contents of 180 and 200 μg (Yadav N. et al., 2017). Furthermore, nanoparticles can be employed in combination with conventional biocides or antimicrobial agents to enhance biofilm control efficacy and minimize the risk of microbial resistance development (Liu et al., 2017). Therefore, nanoparticles offer promising solutions for biofilm control in water treatment systems, improving system efficiency, longevity, and water quality.

Table 3 provides a comparative analysis of the antimicrobial activity of NPs, their applications, and ecological implications.

6 Ecological implications of nanoparticle-based water treatment

The integration of engineered nanomaterials in water treatment processes represents a groundbreaking advancement in environmental management. Nanoparticles have shown immense promise in water treatment, but their use raises concerns regarding potential ecological implications. The potential ecological impacts of nanoparticle residues in treated water are multifaceted. There is a risk that nanoparticles could exhibit toxicity to aquatic organisms, affecting their health and biodiversity. Likewise, studies have shown the possibilities of nanoparticle bioaccumulation in living tissue (Lasagna-Reeves et al., 2010; Lin et al., 2015), leading to physiological and reproductive toxicity (Liu et al., 2016; Brohi et al., 2017). There is also concern about the half-life of these nanoparticles and their potential to catalyze unintended chemical reactions in the environment, leading to secondary pollution. Hence, understanding these implications is crucial for ensuring the sustainable and safe implementation of nanoparticle-based water treatment technologies. Moreover, the complexity of ecosystems necessitates a careful examination of the long-term ecological impacts of nanoparticle-based water treatment technologies. As these technologies become more widespread, it is imperative to develop frameworks for continuous environmental monitoring to detect and mitigate any unforeseen effects of nanoparticles on non-target organisms. Also, the knowledge of nanoparticle half-life before its usage will be vital in ensuring that environmental benefits outweigh the potential risks associated with their use.

6.1 Nanoparticle release into the environment

One of the primary ecological concerns associated with nanoparticle-based water treatment is the release of nanoparticles into the environment. During water treatment processes, nanoparticles may be released into receiving water bodies through effluent discharge or residual nanoparticle accumulation in sludge. Once released, nanoparticles can undergo transformations, such as aggregation, dissolution, and surface modification, which may alter their behaviour, fate, and toxicity in the environment (Levard et al., 2012; Turan et al., 2019). Moreover, nanoparticles may adsorb onto natural particles and colloids, facilitating their transport and dispersal in aquatic ecosystems. Studies have shown that nanoparticles, such as AgNPs and TiO_2NPs, can persist in the environment for extended periods and accumulate in sediments, soils, and biota, raising concerns about their potential ecological impacts (Schaumann et al., 2015; Sinouvassane et al., 2016).

6.2 Environmental persistence

Another ecological implication of nanoparticle-based water treatment is the environmental persistence of nanoparticles. Nanoparticles can resist degradation and persist in the environment for long periods (Bundschuh et al., 2018; Abbas et al., 2020), leading to their accumulation and bioaccumulation in environmental compartments. The long-term environmental fate and behaviour of nanoparticles depend on various factors, including their physicochemical properties, interactions with environmental matrices, and exposure conditions. For example, metal-based nanoparticles, such as silver nanoparticles and copper nanoparticles, may undergo transformation processes, such as oxidation and sulfidation, which can influence their stability, mobility, and toxicity in aquatic environments. Additionally, carbon-based nanoparticles, such as GO and CNTs, may exhibit varying degrees of stability and persistence in natural waters, depending on their surface chemistry, aggregation state, and interactions with dissolved organic matter (Burduşel et al., 2018; Lead et al., 2018; Yu et al., 2018; Turan et al., 2019). Furthermore, nanoparticles can aggregate or disaggregate depending on the ionic strength and pH of their environment, which affects their distribution and persistence (Baalousha, 2009; Badawy et al., 2010). Understanding the environmental persistence of nanoparticles is essential for assessing their potential risks and designing effective mitigation strategies to minimize their environmental impacts.

6.3 Toxicity to non-target organisms

Nanoparticle-based water treatment also raises concerns about the potential toxicity of nanoparticles to non-target organisms in aquatic ecosystems (Bellanthudawa et al., 2023). While nanoparticles are designed to target microbial pathogens, they may inadvertently affect non-target organisms, including aquatic plants, invertebrates, and fish. The toxicity of nanoparticles to non-target organisms depends on various factors, including nanoparticle properties (e.g., size, shape, surface chemistry), exposure duration and concentration, and organism sensitivity. Studies have shown that nanoparticles, such as AgNPs and TiO_2NPs, can induce adverse effects in aquatic organisms, including oxidative stress, DNA damage, and alterations in gene expression (Zou et al., 2014; Zeumer et al., 2020). Additionally, nanoparticles may bioaccumulate in aquatic organisms through dietary uptake or direct exposure, leading to potential biomagnification in food webs (Powell et al., 2010; Zhao and Wang, 2010). Therefore, assessing the ecotoxicity of nanoparticles to non-target organisms is essential for evaluating their environmental risks and establishing regulatory guidelines for their safe use in water treatment.

6.4 Risk assessment and regulation

Addressing the ecological implications of nanoparticle-based water treatment requires comprehensive risk assessment and regulation to ensure the protection of environmental health and ecosystem integrity. Risk assessment involves evaluating the hazards, exposure pathways, and potential risks associated with nanoparticle release and exposure in aquatic environments. This includes assessing the environmental fate and behaviour of nanoparticles, predicting their ecological impacts, and identifying sensitive receptors and ecosystems. Furthermore, regulatory frameworks and guidelines are needed to govern the safe use, disposal, and monitoring of nanoparticles in water treatment processes. Regulatory agencies, such as the Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA), play a crucial role in developing and implementing regulations for nanoparticle-based water treatment technologies (Hegde et al., 2016). These regulations may include restrictions on nanoparticle use, labelling requirements, monitoring and reporting obligations, and risk management measures to minimize environmental risks and ensure the sustainable use of nanoparticles in water treatment. Additionally, research efforts should focus on developing eco-friendly nanoparticle formulations, designing effective nanoparticle recovery and recycling technologies, and exploring alternative water treatment approaches that minimize environmental impacts while ensuring water quality and public health protection. Overall, addressing the ecological implications of nanoparticle-based water treatment requires a multidisciplinary approach involving collaboration between scientists, policymakers, industry stakeholders, and regulatory agencies to balance technological innovation with environmental sustainability.

7 Future perspectives and challenges

Nanoparticle-based water treatment technologies hold immense promise for addressing microbial contamination and improving water quality. However, several key challenges must be overcome to realize their full potential and ensure their sustainable implementation. Future research and development efforts should focus on addressing these challenges and advancing nanoparticle-based water treatment toward widespread adoption.

7.1 Enhanced nanoparticle synthesis and stability

One of the key challenges in nanoparticle-based water treatment is the synthesis of nanoparticles with enhanced stability, efficacy, and environmental compatibility (Nehra and Chauhan, 2019; Zhao et al., 2023). Current synthesis methods often involve complex chemical processes and may result in nanoparticles with variable properties and stability (Yang et al., 2016; Saha et al., 2018). Future research should focus on developing novel synthesis techniques that allow precise control over nanoparticle size, shape, surface chemistry, and stability. Additionally, efforts should be made to improve nanoparticle scalability and reproducibility to facilitate large-scale production and commercialization (Xiao et al., 2015). Moreover, strategies for enhancing nanoparticle stability in diverse water matrices and environmental conditions should be explored to ensure their long-term efficacy and safety in water treatment applications (Xiao et al., 2021).

7.2 Development of sustainable nanoparticle-based water treatment technologies

Another challenge in nanoparticle-based water treatment is the development of sustainable and environmentally friendly technologies that minimize energy consumption, chemical usage, and waste generation (Rosli et al., 2021). Current nanoparticle-based water treatment methods may involve high energy inputs, use of toxic chemicals, or produce secondary pollutants, raising concerns about their environmental impact (Rajabi et al., 2017; Yu et al., 2022; Zikalala et al., 2022). Future research should focus on developing sustainable nanoparticle synthesis methods using green chemistry principles and renewable resources (Rajabi et al., 2017; Saha et al., 2018; Noohpisheh et al., 2020; Ritu et al., 2023; Sachin et al., 2023). Additionally, efforts should be made to design nanoparticle-based water treatment systems that operate efficiently, consume minimal resources, and generate minimal waste. Integration of renewable energy sources, such as solar or hydroelectric power, into nanoparticle-based water treatment processes, can further enhance their sustainability and reduce their carbon footprint.

7.3 Integration of nanoparticles with conventional water treatment methods

To overcome the limitations of nanoparticle-based water treatment and maximize their effectiveness, nanoparticles must be integrated with conventional water treatment methods (Rikta, 2019). Combining nanoparticles with techniques such as filtration, coagulation, and membrane separation can enhance water treatment efficiency, improve pathogen removal, and reduce treatment costs. For example, nanoparticles can be immobilized onto filtration membranes to enhance their antimicrobial properties and prevent biofouling (Yu et al., 2022; Chakachaka et al., 2023; Zhan et al., 2023). Similarly, nanoparticles can be incorporated into coagulants or disinfectants to improve their efficacy and reduce chemical dosage requirements. Future research should focus on optimizing the integration of nanoparticles with conventional water treatment processes to achieve synergistic effects and overcome the limitations of individual techniques.

7.4 Addressing knowledge gaps and research needs

Despite significant advancements in nanoparticle-based water treatment, there remain several knowledge gaps and research needs that must be addressed to facilitate further progress in this field. One critical area for future research is the assessment of nanoparticle environmental fate, transport, and ecotoxicity in aquatic ecosystems. Understanding how nanoparticles interact with environmental matrices, undergo transformations, and affect non-target organisms is essential for evaluating their environmental risks and designing effective mitigation strategies (Parmar et al., 2022; Qi et al., 2022). Additionally, research efforts should focus on developing standardized methods for nanoparticle characterization, toxicity testing, and risk assessment to ensure consistency and comparability across studies. Moreover, further research is needed to explore the long-term impacts of nanoparticle-based water treatment on ecosystem health, biodiversity, and ecosystem services to inform sustainable water management practices (Mohammed, 2021).

8 Conclusion

This review has systematically explored the significant strides made in the application of nanoparticles for water disinfection, illuminating their potential to revolutionize water treatment methodologies. Across various sections, we delved into the antimicrobial mechanisms of nanoparticles such as silver, titanium dioxide, and copper, which include the generation of reactive oxygen species, disruption of microbial cell membranes, and interference with microbial metabolic processes. These mechanisms underline the capacity of nanoparticles to address pathogens resistant to conventional treatment methods while minimizing the adverse effects associated with traditional disinfectants such as chlorination.

Despite their promising antimicrobial efficacy, the application of nanoparticles in water disinfection is not devoid of challenges. Among these, the potential ecological impacts stand out, including the toxicity to non-target organisms and the environmental persistence of nanoparticles, which could lead to unforeseen ecological imbalances. The review also highlighted the technological advancements in the synthesis and stability of nanoparticles, which are critical for their practical application in large-scale water treatment systems.

Looking forward, it is essential to bridge the existing knowledge gaps in the long-term environmental and health impacts of nanoparticles. Future research should focus on developing safer nanoparticle formulations, enhancing their biodegradability, and understanding their interactions within complex environmental matrices. Moreover, integrating nanoparticles with existing water treatment technologies could provide a synergistic approach to enhance water quality and safety effectively. Ensuring regulatory compliance and conducting comprehensive risk assessments will be vital in advancing the sustainable use of nanoparticle technologies in water disinfection. Overall, this review underscores the necessity for continued research and development to optimize the benefits of nanotechnology in water treatment while mitigating its risks.

Author contributions

DBO: Conceptualization, Methodology, Project administration, Resources, Writing–original draft, Writing–review and editing. OZW: Conceptualization, Formal Analysis, Validation, Writing–original draft, Writing–review and editing. OF: Methodology, Validation, Writing–original draft, Writing–review and editing. BE: Data curation, Writing–original draft, Writing–review and editing. OA: Data curation, Writing–original draft, Writing–review and editing. AOI: Software, Writing–original draft, Writing–review and editing.

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Conflict of interest

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