**NANOTECHNOLOGY FOR ENVIRONMENTAL REMEDIATION IN AQUACULTURE: MITIGATING POLLUTANTS AND PRESERVING ECOSYSTEMS**

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**ABSTRACT**

Nanotechnology has emerged as a transformative technique for addressing challenges in aquaculture, offering better solutions for water remediation, pollutant mitigation, and ecosystem preservation. Leveraging the unique physicochemical properties of nanoparticles such as zero-valent iron, zinc oxide, titanium dioxide, and silver, nanotechnology enables the efficient removal of environmental contaminants like heavy metals, pesticides, pathogens, and organic pollutants. These nanoparticles exhibit properties, like photocatalytic activity, antimicrobial effects, and enhanced adsorption capabilities, making them effective in water treatment and promoting sustainable aquaculture practices. Recent advancements underscore the potential of nanotechnology in stress management, disease treatment, and growth promotion within aquaculture systems. Selenium and zinc nanoparticles, for instance, enhance immune responses and reduce the bacterial loads of the fish, while silver and gold nanoparticles demonstrate antimicrobial activity and utility in environmental monitoring. Despite these promising applications, various challenges such as scalability, cost-effectiveness, long-term environmental impacts, and regulatory considerations remain unresolved, hindering the full integration of nanotechnology in aquaculture. To address these gaps in nanotechnology, future research should prioritize comprehensive life cycle assessments of a nanoparticle, eco-friendly synthesis methods, and robust regulatory frameworks for each and every nanoparticle. Thus, by optimizing nanoparticle applications, nanotechnology presents a sustainable pathway to revolutionize aquaculture, enhance ecosystem health, and bolster global food security through aquaculture and fisheries.

**INTRODUCTION**

Nanotechnology has revolutionized various fields by offering Novel strategies, with nanoparticles (NPs) being at the pioneering position of these advancements. Its unique optical, physical, chemical, and biological properties permit them to perform distinct functions that are not possible or difficult with conventional materials. However, these advancements come with potential implications for ecosystems and human health, making it a critical area of research (Shah and Mraz, 2020; Satishkumar et al., 2021; Akbar et al., 2021). The broad applications of NPs span across numerous domains, including drug delivery, environmental pollution control, energy production, water purification, and biological activities such as antibacterial, anticancer, and antioxidant effects (Alsheheri et al., 2021; Satishkumar et al., 2021; Vijayayaram et al., 2023; Ahmed et al., 2024). Additionally, nanostructured materials (NSMs) are gaining prominence for their properties, such as melting point, wettability, electrical and thermal conductivity, catalytic efficiency, and light interaction capabilities. These qualities highlight their importance in technical and environmentally friendly improvements by providing improved performance over conventional materials.

In the context of aquaculture and fisheries, rapid industry growth has created environmental challenges, particularly regarding wastewater disposal. This issue is critical as untreated aquaculture wastewater contains high concentrations of trophic nutrients like nitrogen and phosphorus, which stem from uneaten feed and fish excreta (Kashem et al., 2023). These effluents often include suspended solids, heavy metals, pathogens, and antibiotics, which pose a significant threat to aquatic environment (Bowley and Allan, 2012; Blandford et al., 2024). The improper disposal of the aquaculture pollutants can lead to eutrophication, biodiversity loss, and environmental degradation, necessitating the adoption of innovative strategies to mitigate these impacts (Hesni et al., 2020). Effective water treatment is thus pivotal to sustainable aquaculture, as it not only helps in environmental preservation but also addresses economic risks associated with disease outbreaks and growth retardation in aquaculture operations. Nanotechnology has emerged as a promising approach to overcoming these challenges. The application of NPs in aquaculture provides efficient and cost-effective solutions for wastewater treatment and pollutant removal. For instance, plant-based nanoparticles have shown considerable success in eliminating contaminants from wastewater, offering an eco-friendly alternative to conventional methods (Shah and Mraz, 2020; Khan et al., 2019). Nanotechnology enables the precise management of water quality parameters, addressing pollutants mainly heavy metals, hydrocarbons, and other harmful organic and inorganic compounds in both water and sediments (Sawan et al., 2020; Iravani and Varma, 2022). This approach not only reduces the harmful intermediates generated during conventional processes but also minimizes environmental impacts, making it a sustainable option for aquaculture wastewater management.

The use of nanomaterials as nano-adsorbents, nano-photocatalysts, and nano-membranes has further enhanced the efficiency of pollutant removal. These materials have demonstrated enhanced capabilities in simultaneously removing and neutralizing contaminants (Gehrke et al., 2015). Among the various NP, metals like Gold, Zinc, Silver, and Nickel (Mukhluf et al., 2005; Taylor et al., 2005; Ahmad et al., 2013; Das et al., 2020; El-Saadony et al., 2021; Mou et al., 2022) and metal oxide nanoparticles like CuO, ZnO, and TiO₂ stand out for their exceptional antibacterial, anticancer, antiviral, and antioxidant properties, making them particularly useful in aquaculture (Foster et al., 2011; Kumar et al., 2015; Shaalan et al., 2017; Das et al., 2020). Iron oxide nanoparticles, in particular, offer unique benefits such as photocatalytic properties and a wide band gap that enable effective wastewater treatment. These nanoparticles remove contaminants through mechanisms like absorption and photothermal catalytic processes, which trap and degrade pollutants, thus improving water quality (Ahmed et al., 2023; Saharan et al., 2014). Furthermore, their ability to inhibit bacterial growth enhances their utility in aquaculture by reducing the microbial load in water systems. In addition to wastewater treatment, nanotechnology also provides solutions for mitigating stress in aquaculture systems. Stress mitigation is critical for maintaining fish health and productivity in the face of abiotic and biotic challenges. Nano-nutrition, an emerging strategy, leverages the unique properties of nanoparticles to address these stress factors. Selenium nanoparticles and zinc nanoparticles, for instance, have shown great potential in enhancing aquaculture production under stressful conditions. These nanoparticles are characterized by their high bioavailability, superior efficiency, and low toxicity compared to their inorganic counterparts. Their use in aquaculture not only improves fish health but also contributes to higher productivity, making them an invaluable resource in sustainable aquaculture practices (Kumar et al., 2023).

Thus, nanotechnology emerges as a highly effective and transformative tool for tackling the various complex and multifaceted challenges of environmental remediation in aquaculture. By harnessing the advanced and unique properties of nanoparticles, it is possible to significantly enhance water treatment processes, reduce or mitigate pollution, and develop sustainable and efficient systems that help preserve and protect the aquatic ecosystems. The incorporation of nanotechnology into aquaculture operations not just facilitates the conservation and restoration of environmental health but also provides a pathway to improving the economic viability and long-term sustainability of aquaculture and fisheries industries. This innovative approach ensures a harmonious balance between optimizing fish production and maintaining ecosystem integrity, hence supporting both ecological preservation and the profitability of aquaculture. Apart from this, the versatility and effectiveness of nanotechnology offer promising solutions to the growing environmental concerns associated with wastewater disposal, pollution control, and resource management, positioning it as a critical tool for advancing sustainable aquaculture practices. As the technology continues to evolve, its applications are expected to revolutionize industries, offering new methods for improving water quality, increasing resource efficiency, and promoting environmental stewardship.

**APPLICATIONS IN AQUATIC ENVIRONMENTS**

Heavy Metal Removal:

Heavy metal contamination in freshwater and marine ecosystems represents a critical environmental and public health challenge, with serious consequences for ecosystems and human life. This issue has been intensified by the accelerated pace of urbanization and increased industrial and anthropogenic activities (Qasem et al., 2021; Hama Aziz et al., 2023). Harmful metals, including lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr), infiltrate aquatic environments through various sources such as industrial waste, mining processes, agricultural runoff, and natural occurrences like rock weathering (Qasem et al., 2021; Olawade et al., 2024).

Nanomaterials are divided into two main categories: carbon-based and inorganic (Stone et al., 2010), and they play a significant role in environmental remediation. Among the most widely used and studied are nano zero-valent iron (NZVI) (Fu et al., 2014). Iron-based nanoparticles are applicable for both on-site and off-site remediation efforts. Zerovalent iron (ZVI or Fe⁰) can be employed in situ to treat a wide range of toxins (Ali et al., 2023). Zerovalent iron nanoparticles (ZVINPs) are widely acknowledged for their ability to effectively reduce various heavy metal ions via redox reactions. Recent studies reveal that ZVINPs effectively bind metal ions to their surfaces, enabling electron transfer those results in the formation of insoluble metal oxides or hydroxides (Olawade et al., 2024). Nano zero-valent iron (NZVI) commonly exhibits a core-shell structure developed during synthesis, with the shell comprising Fe(II), Fe(III), and zero-valent iron (Yu et al., 2021).For example, (Yang et al., 2018) utilized biochar-supported NZVI derived from corn stalks to remove heavy metal ions from water. Their findings indicated equilibrium adsorption capacities of 195.1 mg·g−1 for Pb(II), 161.9 mg·g−1 for Cu(II), and 109.7 mg·g−1 for Zn(II) within 6 hours.

Various strategies for synthesizing nanoscale zero-valent iron (nZVI) particles have been documented, with the methods generally divided into two main categories: the top-down and bottom-up approaches. The top-down approach involves breaking down bulk materials into smaller components through techniques like etching and grinding (milling), which utilize mechanical, chemical, or other energy forms. Conversely, the bottom-up approach builds materials at the atomic or molecular level, assembling atoms or molecules to create larger nanoparticle structures. This is typically achieved through methods such as self-assembly, chemical synthesis, and positional assembly. Both approaches can be conducted in environments including gas, liquid, supercritical fluids, solid states, or vacuum conditions. The specific synthesis method influences the structure of the resulting nZVI particles, leading to differences in reactivity and, consequently, varying effectiveness in remediation applications (Dan-Iya et al., 2023).

Pesticide and Fertilizer Degradation:

The overuse of chemical fertilizers has been linked to soil health deterioration, decreased food quality, and various environmental concerns. A substantial fraction of these fertilizers remains unutilized, leading to challenges like leaching, mineralization, and bio conservation. This accumulation poses wider environmental risks, impacting ecosystems such as soil microbial communities, aquatic habitats, and parasitic organisms (Gharrak et al., 2022; Goyal et al., 2023). Nanotechnology promotes the targeted delivery of fertilizers, insecticides, and other agricultural goods. Encapsulating nanoparticles allows for direct delivery to plants or pests, reducing waste and environmental effect. Nanofertilizers can transfer nutrients directly to plant roots, hence boosting nutrient uptake decreasing waste. This can lead to healthier plants and higher crop yields. Nanotech-based fertilizers deliver nutrients gradually, improving plant uptake and eliminating frequent application. This can lead to higher agricultural yields and better plant health. Nanotechnology can help promote sustainable agriculture by reducing water and pesticide usage. Nanotechnology can improve agricultural techniques, resulting in higher food production and safety (Arora et al., 2024). Nano-fertilizers, derived from innovations in nanotechnology, possess unique characteristics tailored to meet specific nutrient demands. They are broadly categorized into macro-nutrient and micro-nutrient element nano-fertilizers based on the type of nutrient they supply. For macro-nutrient elements like nitrogen, phosphorus, and potassium, reducing these elements to the nanoscale can alter their biological efficacy and influence their uptake mechanisms in crops (Chhipa, 2017). For instance, nano-nitrogen fertilizers enhance the rate at which nitrogen diffuses through the soil, increase its availability, and boost the efficiency of nitrogen absorption by plants (Upadhyay et al., 2023).

Nanoparticles are transported within plants through two primary pathways: root uptake and foliar uptake. In root uptake, nano-fertilizers enter plant cells by crossing root cell membranes via translocation or ion channels, a process influenced by factors such as soil pH, ion concentration, and temperature. On the other hand, foliar uptake occurs when nanoparticles penetrate the leaf through stomata, trichome structures, or the leaf’s cell membrane, eventually moving into tissues to support nutrient absorption. This pathway has a more immediate impact on plant growth since it is directly linked to key physiological processes such as photosynthesis. However, nanoparticles deposited on photosynthetic surfaces may cause thermal effects, block stomata, and disrupt gas exchange, leading to changes in the plant’s physiological and cellular functions (Uzu et al., 2010). Nano-fertilizers are applied through root or foliar methods. Once absorbed through the roots, they are transported to the above-ground plant parts via the endodermis and epidermis. Similarly, when absorbed through the leaves, they enter through stomatal pores and are distributed through the phloem. Because of their nanoscale size (5–20 nm), nanoparticles can bypass the cell wall and reach the plasma membrane, directly penetrating plant cells. Inside the cells, their interactions with cytoplasmic organelles can disrupt metabolic processes. Additionally, specially designed nanoparticles can enlarge existing pores or create new ones in the cell wall, thereby enhancing their uptake by plants (Tang et al., 2023).

Pathogen Removal:

Water is a vital resource for sustaining life. However, challenges such as population growth, industrial expansion, and the looming threat of climate change have raised significant concerns regarding both the quality and availability of water. Poor water quality negatively impacts various aspects of human welfare and carries substantial social and economic consequences. Water disinfection, essential for eliminating pathogens, is traditionally performed using methods like chlorination, ultraviolet (UV) treatment, and ozonation. Despite their effectiveness, these conventional methods have notable limitations. For instance, chlorination is ineffective against certain highly resistant waterborne pathogens and can produce carcinogenic disinfection by-products (DBPs) when chlorine interacts with water. Increasing resistance of some waterborne bacteria to existing disinfectants necessitates higher doses of disinfectants, which in turn leads to a greater formation of DBPs (Motshekga et al., 2015). While ozonation generates fewer by-products, it is more expensive than chemical disinfection and can produce harmful bromate when ozone reacts with bromide ions in the water. Similarly, UV treatment, though effective, does not leave a residual disinfectant in treated water, offering no protection against recontamination in the distribution system. Given these challenges, there is a pressing need to explore innovative approaches that can improve the efficiency and reliability of water disinfection (Dimapilis et al., 2018). Nanotechnology has emerged as a transformative tool in addressing challenges related to water and wastewater treatment. With its ability to improve purification efficiency, it opens new pathways for enhancing water quality (Tiwari et al., 2008). A key feature of nanotechnology in this domain is the utilization of specialized nanomaterials with unique physicochemical properties that enable effective microbial control.Several types of nanomaterials, including silver nanoparticles (AgNP), titanium dioxide (TiO2), and zinc oxide (ZnO), are recognized for their antimicrobial capabilities. Among these, AgNP is the most extensively utilized, finding applications in the disinfection of medical devices, household appliances, and water treatment systems. The antimicrobial action of AgNP stems from the release of silver ions (Ag⁺), which generate reactive oxygen species (ROS) that induce oxidative stress in microbial cells. Similarly, TiO2, another widely studied material, has demonstrated significant potential in water photodisinfection, where its exposure to UV light triggers the release of ROS, effectively neutralizing microbial contaminants (Dimapilis et al., 2018). Table 1 summarizes the different types of NPs and their targeted pathogens (Foo et al., 2024).

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| **Nanomaterials** | **Targeted pathogens** | **Reference** |
| Silver (Ag) NPs | *Saprolegnia sp.* | (Johari et al., 2016) |
|  | *Staphylococcus aureus,*  *Aeromonas hydrophila,*  *Edwardsiella tarda,*  *Pseudomonas aeruginosa,*  *Flavobacterium*  *branchiophilum, Vibrio*  *species, Bacillus cereus,*  *and Citrobacter species* | (Swain et al., 2014) |
|  | *Ichthyophthirius multifiliis*  *Aphanomyces invadans* | (Daniel et al., 2016) |
|  | *Vibrio parahaemolyticus,*  *Vibrio harveyi* | (Sivaramasamy et al., 2016) |
|  | *Aliivibrio salmonicida* | (Dananjaya et al., 2016) |
| Titanium  Dioxide  (TiO2) NPs | *Escherichia coli,*  *Staphylococcus aureus and*  *Pseudomonas aeruginosa* | (Altaf et al., 2021) |
|  | *Escherichia coli and*  *Staphylococcus aureus* | (Sanito et al., 2021) |
|  | *Vibrio harveyi* | (Alexpandi et al., 2020) |
| Iron Oxide  (Fe2O3) NPs | *Edwardsiella tarda and*  *Aeromonas hydrophila* | (Yeh et al., 2013) |
|  | *Escherichia coli,*  *Staphylococcus saprophyticus,*  *Streptococcus pyogenes, antibiotic-resistant bacteria (S. pyogenes), and methicillin-resistant Staphylococcus aureus (MRSA)* | (Akbar et al., 2022) |
| Zinc Oxide  (ZnO) NPs | *Staphylococcus aureus,*  *Aeromonas hydrophila,*  *Edwardsiella tarda,*  *Pseudomonas aeruginosa,*  *Flavobacterium branchiophilum,*  *Vibrio species,*  *Bacillus cereus, and*  *Citrobacter species* | (Swain et al., 2014) |
| Copper Oxide  (CuO) NPs | *Staphylococcus aureus,*  *Aeromonas hydrophila,*  *Edwardsiella tarda,*  *Pseudomonas aeruginosa,*  *Flavobacterium branchiophilum,*  *Bacillus cereus, and*  *Citrobacter species* | (Swain et al., 2014) |

**VARIOUS NANOPARTICLES FOR ENVIRONMENTAL REMEDIATION**

Nanoparticles have become increasingly significant in environmental remediation due to their distinct properties, such as a high surface area, enhanced reactivity, and customizable functionality. Various types, including metal oxides, carbon-based nanoparticles, and biogenic nanoparticles, have been effectively utilized to address pollutants in water, soil, and air. These nanoparticles demonstrate remarkable adsorption capacities, photocatalytic activity, and pollutant degradation efficiency (Fajardo et al., 2022), making them highly suitable for dealing with contaminants like heavy metals, organic pollutants, and microbial pathogens. Their use in aquaculture water treatment holds great promise for improving ecosystem health through sustainable and environmentally friendly pollutant mitigation techniques. Below is an overview of the commonly used nanoparticles for environmental remediation.

1. **Titanium dioxide NPs:**

Titanium dioxide nanoparticles (TiO₂-NPs) have emerged as highly effective agents for water treatment due to their exceptional photocatalytic properties, enabling the decomposition of organic contaminants and chemicals in water (Gelover et al., 2006; McCullagh et al., 2011; Pelaez et al., 2012). These nanoparticles are integral to advanced water remediation strategies, including advanced oxidation processes (AOPs), ozonation, electrochemical methods, and photocatalytic techniques, which are widely used for the removal of organic pollutants, recalcitrant substances, and pathogens (Alsheheri, 2021). TiO₂-NPs are particularly valued for their cost-effectiveness, non-toxicity, chemical and biological stability, and efficiency as photocatalysts. Their ability to degrade contaminants and self-clean polluted environments positions them as a promising solution for wastewater treatment. Furthermore, TiO₂ nanoparticles have demonstrated significant antibacterial, antifungal, and antiviral activity, capable of eliminating a broad spectrum of Gram-positive and Gram-negative bacteria, fungi, algae, protozoa, and viruses (Foster et al., 2011).

In addition to these capabilities, TiO₂-NPs have been explored for their role in arsenic removal from drinking water (EPA, 2010) and their potential application in combating bacterial infections in aquaculture (Sherif et al., 2019). Research has also highlighted their virus-inactivating potential, with studies demonstrating effectiveness against pathogens such as MS2 bacteriophages (Cho et al., 2011), hepatitis B virus (Zan et al., 2007), and poliovirus 1 (Liga et al., 2011). The growing interest in their photocatalytic properties underscores the broad applicability of TiO₂-NPs in environmental remediation and disinfection. TiO2-NPs are also greatly used as efficient water-treatment agent in decomposition of organic contaminants and chemicals present in water through their catalytic activity (Gelover et al., 2006; McCullagh et al., 2011; Pelaez et al., 2012). The commonly used chemical strategies are advanced oxidation processes (AOP), ozonation, electrochemical methods, and photocatalytic used for water treatment. Advanced oxidation process is a water remediation technique for removal of organic pollutants, bio-recalcitrant and pathogens (alsheheri 2021). Titanium dioxide has shown tremendous ability not only as a sensor for chemical, biological, and various gases (H2, NO𝑥, CO, etc.) even at low concentrations, but also to photocatalytically degrade and self-clean the contaminated environment (Mahlambi et al., 2015). There is an increasing interest in the application of the photocatalytic properties of TiO2 for disinfection of surfaces, air and water. features such as low cost, non-toxic, efficient photo-catalyst, biologically and chemically stable, point out titanium oxide as a promising candidate for residual water treatment. Moreover, several studies have been carried out to study the photocatalytic activity of titanium dioxide, showing to be capable of killing a wide range of Gram-negative and Gram-positive bacteria, filamentous and unicellular fungi, algae, protozoa, mammalian viruses and bacteriophages (Foster et al., 2011). could be used as an additive in protocols for removal of arsenic from drinking water (EPA 2010) and can be used against bacterial infection in fish(Sherif et al., 2019). Several studies have documented the viruskilling potential of TiO2 nanoparticles.

1. **Nickel and its oxide NPs:**

Nickel oxide nanoparticles exhibit outstanding photocatalytic and antibacterial properties, making them ideal for environmental remediation and energy applications due to their ability to degrade organic pollutants under ambient conditions (Mou et al., 2022). Coating these nanoparticles with graphene oxide (GO) enhances their nitrate removal efficiency, comparable to iron nanoparticles (Motamedi et al., 2014). Ni-ZnO nanoparticles have also been effectively utilized as adsorbents for selective Pb(II) removal, improving precision in ICP-OES analysis (Rahman et al., 2014). Additionally, green-synthesized Ni0/NiO nanoparticles display significant antibacterial activity, achieving near-complete inhibition of pathogens like Pseudomonas aeruginosa, Staphylococcus aureus, and E. coli at optimized doses, along with high efficiency in degrading pollutants such as crystal violet dye (Ali et al., 2022). Their versatile degradation mechanisms and ease of recovery make them promising candidates for sustainable environmental applications. Thus, Nickel oxide nanoparticles, enhanced through functionalization and green synthesis, demonstrate exceptional photocatalytic, pollutant-removal, and antibacterial capabilities, positioning them as effective tools for sustainable environmental and energy solutions.

1. **Iron nanoparticles:**

Iron nanoparticles (FeNPs) exhibit diverse applications in environmental remediation, aquaculture management, and pollutant reduction, making them highly valuable in addressing ecological challenges. They act as immunomodulators, exhibit antimicrobial properties against key fish pathogens, and enhance reproductive potential in fish, supporting aquaculture in environmentally adverse conditions (Mukherjee et al., 2022; Barik et al., 2023). Their effectiveness in remediating aquatic pollutants is notable, particularly in nitrate removal through denitrification, where FeNPs serve as efficient electron donors. This process, characterized by high reaction rates, cost-efficiency, and simplicity, makes nano zero-valent iron an ideal choice for decomposing nitrates and nitrites in water resources (Malakootian and Mobini Lotfabad, 2013; Amit and Mika, 2011; Hesni et al., 2020).

Due to their large specific surface area and superior surface reactivity compared to microscale iron, FeNPs can reduce nitrate to various products, including nitrogen, nitrite, or ammonium, depending on reaction conditions (Motamedi et al., 2014). Additionally, they are effective in degrading persistent organic pollutants, such as polychlorinated biphenyls and dioxins, into less toxic carbon compounds in groundwater (Fajardo et al., 2022). Innovations like entrapping FeNPs in calcium-alginate biopolymer beads have further enhanced their application for nitrate remediation in groundwater (Bezbaruah et al., 2016). These nanoparticles also demonstrate the ability to remove a broad spectrum of contaminants, including phenols, phosphates, inorganic anions, and nitrogenic compounds, through oxidation, reduction, precipitation, and absorption mechanisms (Lu et al., 2016). The integration of FeNPs with microalgae in bioreactors has proven highly effective in treating aquaculture effluents. Studies report significant reductions in NH₄⁺ (93.67%), NO₃⁻ (92.23%), NO₂⁻ (89.3%), and PO₄³⁻ (89.25%), highlighting their potential for wastewater purification (Hesni et al., 2020). Additionally, nano-iron biosensors enable the detection of pollutants and pathogens in trace concentrations, contributing to advanced monitoring systems in aquatic environments (Mukherjee et al., 2022).

Laboratory studies further validate the efficacy of iron oxide nanoparticles in reducing contaminants from fish farm effluents. Significant reductions in nitrate, nitrite, phosphate, ammonium, TDS, TSS, and BOD levels were observed at the reactor outlet compared to the inlet, with corresponding improvements in pH and electrical conductivity. However, system efficiency declined after extended operation due to nanoparticle sequestration and oxide layer formation, indicating the need for optimized conditions to sustain performance (Hesni et al., 2018). These findings demonstrate the immense potential of FeNPs in reducing pollutant loads and improving effluent management in aquaculture systems.

1. **Selenium NP:**

Selenium nanoparticles (SeNPs) have emerged as essential tools in aquaculture, offering a range of benefits, including antimicrobial, antioxidant, and growth-promoting properties. These nanoparticles enhance gut immunity and improve digestive efficiency in aquatic organisms, thereby supporting their overall health, growth, and resilience. By bolstering the biological systems of aquatic species, SeNPs contribute to the stability and productivity of aquaculture ecosystems, effectively addressing various challenges faced by the industry (Zhang et al., 2010; El-Batal et al., 2014; Sarkar et al., 2015). Bio-synthesized selenium nanoparticles have also been shown to reduce heavy metal accumulation and bacterial load in fish media or organs in a concentration-dependent manner (Saad et al., 2022; Kumar et al., 2023).

Beyond their biological advantages, SeNPs are highly effective in tackling environmental threats, such as heavy metal contamination and bacterial infections, which significantly impact aquaculture productivity. Their active surface properties enable them to neutralize these threats, protecting aquatic organisms and enhancing overall ecosystem health. This dual role of SeNPs in improving the health of aquatic organisms and mitigating environmental risks makes them a sustainable and innovative solution for advancing aquaculture practices (Saad et al., 2022). As an essential micronutrient, selenium plays a critical role in combating oxidative stress and exhibits potent antioxidant properties, particularly in its nanoscale form, where it also demonstrates reduced toxicity (Sarkar et al., 2015). The integration of nano selenium as a dietary supplement offers a cost-effective, non-toxic, and environmentally friendly strategy for improving aquaculture practices.

Nano-mineral supplements, particularly selenium, have shown significant potential in addressing multiple facets of aquaculture health management. Their applications support oxidative stress mitigation, improve pathogen resistance, and promote growth, making them a valuable innovation in aquaculture. The use of SeNPs represents a novel approach that aligns with sustainable and efficient aquaculture practices, offering potential long-term benefits for aquatic organisms and ecosystems (Vijayaram et al., 2024). This approach underscores the importance of exploring and adopting advanced nanotechnology-based solutions to meet the evolving challenges in aquaculture, ensuring improved productivity, health, and sustainability of aquatic farming systems.

1. **Silver NP:**

Silver nanoparticles (AgNPs) are recognized as a highly versatile and effective solution for water disinfection and microbial control due to their exceptional antimicrobial properties and adaptability. Their unique attributes, including size- and shape-dependent activity and compatibility with various support materials like zeolite and activated carbon, make them invaluable in addressing waterborne pathogens and enhancing water purification systems. In addition to their direct antimicrobial effects, the integration of AgNPs with other support systems, such as turmeric-based catalysts, further broadens their environmental and antibacterial applications, highlighting their versatility. Moving forward, optimizing the synthesis and application of AgNPs will be essential to maximize their efficacy while minimizing potential environmental impacts, contributing to the development of sustainable and efficient water purification technologies.

Silver has long been regarded as one of the most effective materials for water disinfection due to its ability to inactivate a broad spectrum of microorganisms safely. Nanocrystalline silver, in particular, stands out among antimicrobial agents for its potent antimicrobial activity and broad inhibitory spectrum, which has proven highly effective in water purification systems (Taylor et al., 2005). AgNPs exhibit their antimicrobial properties by targeting a variety of pathogens, including viruses, fungi, and bacteria. Their mechanism of action involves attaching to bacterial cell membranes, increasing membrane permeability, and causing damage to both the membrane and DNA. This results in apoptosis, effectively killing the microorganisms and ensuring thorough water disinfection (Ahmed et al., 2023). The efficacy of AgNPs in removing waterborne pathogens has been well-documented, with studies showing their success in addressing both bacterial and fungal infections. For example, nanosilver-coated zeolite filters containing 0.5% AgNPs significantly improved the survival rate of Saprolegnia-infected trout eggs, increasing it by 4.56% compared to a control group with a fungal infection rate of 6%. Furthermore, the addition of activated carbon as an absorbent medium in these filters enhanced the survival rate by up to 11.24%, demonstrating the synergistic potential of AgNPs when combined with other filtration media (Johari et al., 2016). This combination of materials highlights how AgNPs can be integrated into multi-functional systems to maximize their water purification capabilities. Nanotechnology has further expanded the applications of silver nanoparticles, with their use as photocatalysts, adsorbents, and antibacterial agents for combating waterborne diseases. The bactericidal activity of AgNPs is notably influenced by their size and shape. Smaller nanoparticles, such as those 8 nm in size, and those with truncated triangular shapes, demonstrate superior antibacterial efficiency compared to larger particles (11–23 nm) or those with spherical or rod-shaped morphologies (Mukhluf et al., 2005). These findings underline the importance of tailoring the size and morphology of AgNPs to enhance their performance in specific applications. Additionally, combining AgNPs with other functional materials has yielded promising results. For instance, turmeric-supported silver nanoparticles (Ag@TP NPs) have shown exceptional catalytic activity in degrading nitrophenols and dyes while exhibiting the highest antibacterial efficiency against E. coli compared to nickel and copper nanoparticles synthesized under similar conditions (Khan et al., 2019). This synergy highlights the potential of AgNPs to function effectively in diverse environmental and industrial contexts, further cementing their status as a critical tool for modern water treatment solutions.

Overall, AgNPs offer a multi-dimensional approach to water disinfection, combining potent antimicrobial activity, adaptability to various applications, and compatibility with complementary materials. Future research should focus on optimizing their synthesis, size, and shape, and exploring novel combinations with other functional materials to enhance their effectiveness further while addressing environmental concerns. This will ensure that AgNPs continue to play a pivotal role in advancing sustainable water purification technologies.

1. **Gold NP:**

Gold nanoparticles (AuNPs) have demonstrated remarkable potential in environmental remediation and antimicrobial applications due to their unique properties and versatility. In environmental cleanup, AuNPs have been effectively utilized to remove pesticides such as DDT, highlighting their utility in addressing persistent organic pollutants (Abd el-Aziz et al., 2018). Their application in electrochemical sensors further underscores their significance, particularly in pesticide detection, where they exhibit high sensitivity and precision. For instance, amperometric detection of the herbicide glyphosate using gold electrodes achieved a low limit of detection (LOD) of 2 µM, showcasing their efficacy in analytical applications (Noori et al., 2018). AuNPs can be deployed in colloidal form or immobilized on various supports such as graphene oxide (GO), reduced graphene oxide (rGO), and carbon nanotubes (CNTs). Both approaches have demonstrated remarkable sensitivity towards targeted analytes, as evidenced by their low LOD, making them indispensable in monitoring and detecting environmental contaminants. Additionally, biological entities such as Escherichia coli, Shewanella oneidensis, and Methylosinus trichosporium OB3b have been immobilized on screen-printed gold electrode surfaces for water pollution monitoring, further broadening their environmental applications (Abu-Ali et al., 2019). In antimicrobial applications, AuNPs have proven effective against various pathogens, including bacteria and fungi. They exhibit significant antibacterial and antibiofilm activity against Aeromonas hydrophila, a common fish pathogen, and have been shown to improve the survival rate of Oreochromis mossambicus following infection (Vijaykumar et al., 2017). The size of the nanoparticles plays a crucial role in their antimicrobial efficacy, with smaller AuNPs exhibiting stronger antifungal activity compared to their larger counterparts (Ahmad et al., 2013).

Gold nanoparticles have wide range of applications across various fields, including environmental monitoring, pesticide removal, and the treatment of microbial infections. Their unique properties, such as high surface area, stability, and ability to interact with different compounds, make them valuable tools for addressing environmental pollution, such as the removal of harmful pesticides from water sources. Also, gold nanoparticles have demonstrated remarkable efficacy in combating microbial infections by targeting harmful pathogens, making them an essential component in the development of novel antibacterial agents. This versatility emphasizes their potential as both innovative and sustainable solutions to pressing ecological and health challenges, offering a promising approach to improving environmental quality, public health, and sustainability in diverse industries.

1. **Zinc and its oxides NP:**

Zinc nanoparticles (Zn NPs) have emerged as a highly effective solution for wastewater treatment and aquaculture applications due to their multifunctional properties. Their ability to facilitate dehalogenation reactions and inhibit the growth of nitrifying bacteria has been demonstrated at a concentration of 5.0 mg/L, resulting in significant reductions in NH₄⁺-N concentrations over time (Hou et al., 2013). These superior reducing capabilities and antibacterial properties position Zn NPs as a promising alternative to iron nanoparticles (Fe NPs) for pollutant removal and water purification. The integration of Zn NPs into wastewater treatment systems has shown great potential for achieving efficient pollutant reduction and enhancing water quality (Ahmed et al., 2023). Despite their advantages, the environmental toxicity of zinc as a heavy metal remains a concern, although zero-valent iron (nZVI) has proven effective for Zn²⁺ remediation. However, nZVI efficiency diminishes in acidic conditions due to the inhibition of iron hydroxide production by H⁺ ions (Liang et al., 2014).

ZnO nanoparticles (ZnO NPs) have further extended the utility of zinc-based nanomaterials, particularly in the removal of organic pollutants such as dyes. ZnO NPs exhibit strong surface reactivity and can be synthesized through green methods using natural materials. For example, Mansour et al. (2022) utilized red seaweed (Pterocladia capillacea) to produce ZnO NPs, achieving a dye adsorption capacity of 72.24 mg/g. Under optimal conditions—0.08 g of ZnO NPs at pH 6, a temperature of 55°C, and 120 minutes of contact time—the removal efficiency of the dye Ismate Violet 2R (IV2R) reached 99%, highlighting the potential of ZnO NPs in organic pollutant remediation. In aquaculture, biogenic Zn NPs have shown remarkable antibacterial activity, reducing bacterial loads in fish and water while protecting against infections caused by pathogens such as Listeria monocytogenes, Bacillus cereus, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, and Aeromonas hydrophila (El-Saadony et al., 2021). The enhanced non-specific immunity provided by biogenic Zn NPs is attributed to their nanoscale structure, which modifies the properties of zinc and enhances its biological effectiveness (Kumar et al., 2023; Rather et al., 2011). These findings underscore the versatility and potential of Zn NPs in addressing environmental challenges and supporting sustainable aquaculture practices.

**MECHANISM OF ACTION**

**Reactive oxygen species mechanism**

Ravikumar et al. (2011) proposed that the antimicrobial properties of metal oxide nanoparticles are primarily due to their ability to generate reactive oxygen species (ROS). This mechanism is further supported by Wu et al. (2014), who recognized ROS-induced oxidative stress as a well-established pathway of toxicity. The generation of ROS from nanoparticles primarily results from complex interactions between the NPs and cellular systems. These interactions can induce oxidative stress, which occurs when there is an imbalance between ROS production and the cell's ability to counteract or detoxify these reactive species. In the case of nickel nanoparticles, antibacterial activity is exhibited through the release of nickel ions that penetrate bacterial cells and adhere to their membranes. This interaction disrupts essential cellular organelles involved in metabolism, ribosomes, and mitochondria, leading to chromatin condensation and margination, both of which are indicators of apoptotic cell death as observed by Ali et al. (2021). The mechanism behind this process is mainly driven by electrostatic interactions between the negatively charged surfaces of bacteria, fungi, and viruses, and the positively charged nickel ions.

The mechanism as described by Wu et al. (2014) starts with the unique physicochemical properties of NPs, including their size, shape, surface area, and chemical composition. These properties allow nanoparticles to interact directly with cellular components such as membranes, mitochondria, or even DNA. For instance, metal-based NPs like zinc oxide (ZnO) or titanium dioxide (TiO2) can release metal ions, which may catalyze reactions like the Fenton reaction, leading to the production of ROS such as superoxide anions, hydroxyl radicals, and hydrogen peroxide. Another mechanism involves the disruption of mitochondrial function. Nanoparticles may enter cells and interact with mitochondria, causing electron transport chain disruptions, which inadvertently leads to an overproduction of ROS. Furthermore, nanoparticles can interact with cellular enzymes, affecting antioxidant systems like superoxide dismutase or catalase, reducing the cell’s ability to neutralize ROS effectively. Prolonged ROS production due to nanoparticles can cause oxidative damage to proteins, lipids, and DNA, potentially leading to inflammation, apoptosis, or necrosis. These pathways emphasize the dual nature of nanoparticles, being both promising in biomedical applications and hazardous due to their potential to induce oxidative stress. Figure 1 further illustrate the process in a schematic representation showing various potential mechanisms of antimicrobial action for nanoparticles (Ali et al., 2022).

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| Figure 1: Representation of antimicrobial action for nanoparticles |

**Factors Influencing ROS Generation:**

The generation of ROS due to nanoparticles depends on several key factors (Wu et al., 2014):

1. Particle Size: Smaller particles tend to have a higher surface-to-volume ratio, increasing their reactivity and ROS production.
2. Surface Chemistry: Modifications in the surface coating or charge of NPs can significantly impact their interaction with cells and their ability to generate ROS.
3. Chemical Composition: The material of the nanoparticles (e.g., metals, metal oxides, carbon-based materials) determines their oxidative potential.
4. Dissolution Rate: Nanoparticles that dissolve rapidly release ions, which may catalyze ROS generation.
5. Aggregation State: The degree to which nanoparticles aggregate affects their surface area and reactivity.
6. Biological Environment: The presence of biomolecules, pH levels, and oxidative enzymes in the surrounding environment influences ROS dynamics.
7. Cellular Uptake and Localization: The internalization of NPs and their distribution within cellular compartments like mitochondria or lysosomes can amplify their oxidative impact.

**Mechanism of photocatalysis**

The first step in photocatalysis involves the generation of electron-hole pairs in the titania semiconductor upon exposure to sufficiently energetic light. Light excitation promotes electrons to the conduction band, leaving holes in the valence band. These electron-hole pairs can either recombine within the semiconductor’s volume or surface, dissipating energy as heat, or they can migrate to the surface to participate in redox reactions. Electrons reaching the surface act as strong oxidants, while holes serve as effective reductants. However, electron-hole recombination significantly hinders charge transfer, reducing the photocatalytic efficiency. This limitation can be mitigated by adsorbing suitable electron donor and acceptor species onto the semiconductor surface, which helps suppress recombination and enhance catalytic activity (Alsheheri et al., 2021).

The steps involved in electron-hole formation for photocatalysis are given in Figure 2 (Alsheheri et al., 2021).

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| Figure 2: Electron-hole formation for photocatalysis |

**Factors Affecting Photocatalytic Efficiency**

1. **Particle Size**:
   1. Smaller catalyst particles increase the number of active sites.
   2. Excessively small particles may lead to dominant electron-hole recombination, reducing efficiency.
   3. An optimal particle size is crucial to balance active site availability and recombination suppression.
2. **Electron-Hole Pair Dynamics**:
   1. Electron-hole pairs are generated within 100 femtoseconds (fs).
   2. Surface attachment of these pairs occurs within 100 picoseconds (ps) to 10 nanoseconds (ns).
   3. Hydroxyl radical formation on titania surfaces requires about 10 ns, whereas electron-hole recombination occurs in 10–100 ns.
   4. Efficient trapping and minimal recombination are necessary to improve quantum efficiency.
3. **Charge Carrier Trapping**:
   1. Defects in the catalyst surface improve charge carrier trapping, extending the lifespan of electrons and holes.
   2. Conduction band electrons are typically trapped within nanoseconds, while valence band holes require ~250 ns.
   3. Electron trapping creates Ti³⁺ sites, as observed in ESR studies, while shallowly trapped holes remain reactive.
4. **Competition Between Reactions**:

Quantum efficiency in photocatalysis depends on minimizing charge carrier recombination (10–100 ns) while maximizing trapping (100 ps–10 ns) and ensuring efficient interfacial charge transfer to sustain reactive species.

1. **Surface Defects and Doping**:
   1. Doping with transition metals introduces defect sites, enhancing charge carrier trapping in the valence and conduction bands.
   2. Defects in the band gap improve visible light absorption.
   3. Dual transition metal doping enhances charge separation through synergistic effects.
2. **Suppression of Recombination**:
   1. Incorporating transition metals into titania reduces electron-hole recombination.
   2. Transition metals facilitate charge transfer between the semiconductor and the solution interface, increasing efficiency.
3. **Charge Transfer Timescale**:

The timescale for charge transfer to oxygen molecules ranges from 100 microseconds (µs) to milliseconds (ms), which influences overall quantum efficiency.

**Mechanism of de-halogenation**

Dehalogenation, a crucial process for mitigating the toxicity of halogenated organic compounds, leverages the catalytic properties of advanced materials such as nanoparticles to effectively remove halogen atoms. Among these, zero-valent iron nanoparticles (Fe⁰-NPs) and noble metal nanoparticles like gold and silver are extensively studied for their high efficiency in breaking carbon-halogen bonds. Fe⁰-NPs are particularly effective in reductive dehalogenation processes, where they act as electron donors. These nanoparticles facilitate their cleavage by transferring electrons to the carbon-halogen bonds, converting harmful halides into less harmful and more biodegradable hydrocarbons. Similarly, noble metal nanoparticles, such as gold and silver, enable dehalogenation through hydrogen atom transfer mechanisms. This approach is especially effective for degrading pollutants like haloacetic acids (HAAs), which are resistant to conventional remediation techniques (Adhikary et al., 2018).

The underlying mechanism of nanoparticle-mediated dehalogenation typically begins with an oxidative addition step, wherein the halogenated organic compound interacts with the nanoparticle surface. This interaction promotes the transfer of electrons from the nanoparticles to the carbon-halogen bond, initiating its cleavage. The subsequent reductive elimination releases the halogen atom, often assisted by the availability of protons or hydride donors, resulting in the production of hydrocarbons as the final product. This process is further enhanced by composite materials like polyaniline/zero-valent iron (PANI/Fe⁰) nanofibers, which provide a larger surface area for reactions and help stabilize reactive intermediates, improving efficiency and catalyst recyclability.

Additionally, the inclusion of transition metals like nickel or noble metals such as palladium further enhances the process by enabling efficient electron transfer and reducing the activation energy required for bond cleavage. This enhancement significantly improves reaction kinetics, making the dehalogenation process more effective under diverse conditions (Giri et al., 2016). Nanoparticles are recognized for their versatility, high reactivity, and ability to function under ambient conditions, making them indispensable tools for environmental remediation. Their application extends to the detoxification of various halogenated pollutants in water and soil systems, addressing critical environmental challenges. The ability of these nanoparticles to operate efficiently across different matrices underscores their importance in developing sustainable and scalable solutions for pollution control and ecosystem protection. Figure 3 illustrates the key steps in the mechanism of dehalogenation (Giri et al., 2016).

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| Figure 3: Steps of dehalogenation |

**NANOTECHNOLOGY IN AQUACULTURE**

Role of nanoparticles in maintaining water quality in aquaculture systems:

Water treatment is a critical component of sustainable aquaculture, especially in addressing the escalating global issue of water pollution caused by culture practices, as well as the overuse of antibiotics and chemicals in fish farming. This pollution not only reduces the availability of clean water but also poses significant risks to human health as well as aquatic ecosystems as consuming contaminated fish and seafood can lead to food-borne illnesses and disturb the ecosystem (Shah and Mraz., 2020). To tackle these challenges, nanoparticles have emerged as highly effective tools for monitoring and improving water quality. These advanced materials can be tailored to detect specific pollutants, including microorganisms, heavy metals, and organic compounds, with remarkable precision. Research demonstrates the potential of nanotechnology in detecting and mitigating surface water pollution, thereby promoting environmental sustainability (Khan et al., 2024).

In aquaculture, nanotechnology offers innovative solutions for water purification by leveraging the photocatalytic and adsorptive properties of nanomaterials, enabling efficient and cost-effective treatment methodology (Fajardo et al., 2022). Current nano-enabled technologies utilize materials like activated carbon and alumina, enriched with additives such as zeolite and iron-based compounds, to support aerobic and anaerobic biofilms for removing ammonia, nitrites, and nitrates. Additionally, ultrafine nanoscale iron powders have proven effective in breaking down hazardous pollutants like trichloroethane, carbon tetrachloride, dioxins, and polychlorinated biphenyls into less toxic carbon-based compounds, paving the way for advancements in nano-aquaculture (Rather et al., 2011). Nanoparticle-based sensors can be effectively incorporated into remote monitoring systems, enabling real-time and continuous data collection from a variety of water sources. This approach is especially useful in remote or hard-to-reach locations where regular on-site monitoring is impractical. Additionally, remote monitoring allows for the early identification of water quality issues, ensuring prompt corrective measures. While the upfront costs for research and implementation may be higher, nanoparticle-based water quality monitoring can prove economically viable over time, as these sensors generally demand lower maintenance costs and fewer consumables compared to conventional methods (Khan et al., 2024). Nanoparticles (NPs) are gaining widespread attention for their ability to eliminate microbes, organic and inorganic contaminants, halogenated substances such as pesticides, and heavy metals, while also preventing biofouling in water systems, especially in inland aquaculture. Their effectiveness is attributed to key properties of nanostructures, including their nanoscale size, remarkable stability, and ease of handling. Among the most extensively researched nanomaterials for improving aquaculture water quality are zinc oxide (ZnO) nanoparticles, iron oxide (Fe₃O₄) nanoparticles, tin oxide (TiO₂) nanoparticles, silver (Ag) nanoparticles, and carbon nanotubes (CNTs). Additionally, their performance is significantly enhanced when combined with biopolymers like algae, leveraging the natural surface hydrology and photosynthetic capabilities of these materials (Ogunfowora et al., 2021).

Prevention of biofouling and pathogen control:

Biofouling is the unwanted accumulation of microorganisms, macroalgae, and invertebrates on man-made surfaces, leading to their progressive biodeterioration. In marine environments, this process impacts structures such as pipes, water intake systems, desalination equipment, probes, sensors, ship hulls, construction materials, and filters (Hellio and Yebra, 2009). Marine biofoulers are typically categorized into three groups: primary, secondary, and tertiary colonizers. Primary colonizers, which include microorganisms like bacteria and microalgae, are the first to adhere to surfaces. These pioneering organisms can colonize unprotected surfaces within just a few hours of exposure. Their activity has been associated with biocorrosion, a process driven by the synergistic interactions between the metal surface, abiotic corrosion products, and microbial cells along with their metabolic by-products (Beech and Sunner, 2004). Secondary macrofoulers consist of protozoa and macroalgae spores, contributing to up to a 10% increase in the frictional drag of ships. Algal fouling, in particular, is associated with significant technical and environmental harm to man-made structures. For instance, the accumulation of algae on structures like aquaculture nets, buoys, and marine markers can lead to substantial weight increases, potentially causing these structures to sink. Algal fouling on ship hulls is especially prevalent, as ships traverse regions with diverse biological, physical, and chemical characteristics while remaining in the photic zone (Archana & Sundaramoorthy, 2019).

Tertiary colonizers, also known as hard macrofoulers, settle on unprotected surfaces after 2–3 weeks of immersion. These organisms include mussels, tubeworms, and bryozoans, which significantly increase frictional drag—up to a 40% rise in some cases—and can even cause structural damage to ship hulls (Gollasch, 2006). Nanotechnology offers significant promise in boosting aquaculture production and shrimp farming by improving approaches to disease control, feed optimization, and biofouling management. Biofouling, which arises from the accumulation of biofilms formed by harmful bacteria, along with invertebrates such as barnacles and mussels, and algae like diatoms and seaweeds, can be addressed through the use of nanostructured coatings or paints (Handy et al., 2012). These coatings, incorporating nanoparticles of metal oxides such as ZnO, CuO, and SiO2, create highly effective antifouling surfaces. This technology enhances antifouling methods, providing valuable applications in fishing and aquaculture equipment, antibacterial agents for aquaculture systems, and advanced packaging solutions for marine products (Nasr-Eldahan et al., 2021).

**LIMITATIONS**

Concerns over NPs' possible release into aquatic environments have grown as a result of their expanding use in a variety of industries, including semiconductors, electronics, biomedicine, food additives, and the chemical industry (Zhang and Elliott, 2006). Among these, iron nanoparticles have been extensively studied for environmental remediation purposes due to their ability to remove contaminants like heavy metals and organic pollutants from water. However, the application of Fe NPs is not without challenges. One significant issue is their rapid oxidation, which leads to the formation of a metal oxide layer on their surface. This oxide layer significantly reduces the nanoparticles' reactivity, limiting their effectiveness in environmental cleanup applications. Additionally, Fe NPs tend to aggregate under certain environmental conditions, driven by magnetic and Van der Waals forces. In high concentrations, this aggregation leads to the formation of larger particles that rapidly settle, reducing the overall efficiency of the system and limiting their practical application in remediation processes (Motamedi et al., 2014; Hesni et al., 2018). Also, the use of colloidal silver nanoparticles (AgNPs) for water disinfection has raised environmental and ecological concerns, as their direct addition to water systems poses potential risks to both aquatic organisms and the surrounding environment (Foo et al., 2024).

In contrast, titanium dioxide nanoparticles (TiO₂ NPs) have shown considerable promise in aquaculture, particularly due to their potent antibacterial properties. These nanoparticles have been demonstrated to effectively inhibit the growth of harmful bacteria such as *Aeromonas hydrophila*, a pathogen commonly found in fish, with a minimum inhibitory concentration (MIC) of 20 µg/g body weight. This concentration was found to be effective in combating the bacteria without negatively affecting the health of *Oreochromis niloticus* (Sherif et al., 2019). One of the advantages of TiO₂ NPs is their ability to be administered via fish feed, which has proven to be the most suitable method for ensuring targeted action with minimal systemic effects. This delivery method allows for controlled exposure, reducing the likelihood of adverse impacts on the fish and the surrounding ecosystem. However, while TiO₂ NPs offer substantial benefits, their application in aquaculture requires careful consideration of dosage. At higher concentrations, TiO₂ NPs can induce immunosuppression in fish, impairing their immune system and making them more susceptible to diseases. Additionally, excessive doses of TiO₂ NPs can lead to the generation of reactive oxygen species (ROS), which can cause oxidative stress, damage to cellular structures, and long-term health issues in aquatic organisms. This raises concerns about the potential for ecological destabilization if nanoparticles are not properly regulated. Therefore, it is crucial to optimize the concentration and delivery method of TiO₂ NPs to balance their disease-fighting properties with the need to maintain fish health and ecosystem stability.

These challenges underline the importance of a well-strategized approach to incorporating nanotechnology into aquaculture. To maximize the benefits of nanoparticles while minimizing potential risks, several factors need to be carefully considered. These include nanoparticle stability, to prevent unwanted aggregation or loss of reactivity; targeted delivery, to ensure that the nanoparticles reach the intended site of action; and proper dose regulation, to avoid toxicity or adverse ecological effects. By addressing these concerns, nanoparticles such as Fe NPs and TiO₂ NPs can be used effectively for environmental remediation and disease control in aquaculture, ensuring that they contribute to sustainable practices while preserving ecosystem health.

**FUTURE PROSPECTS**

In the field of fish therapeutics, nanotechnology holds great promise, yet several research gaps remain that must be addressed for its widespread adoption. Specifically, the antiviral and antifungal properties of NPs in the treatment of fish diseases need further exploration (Foster et al., 2011; Ahmed et al., 2013). Additionally, for nanotechnologies to be integrated into aquaculture on a larger scale, further research into vaccine development and the optimization of fish diet compositions is necessary. Despite the proven high efficacy of NPs in water disinfection, monitoring, regulation, and remediation, key factors such as cost, scalability, energy consumption during synthesis, toxicity, and waste management in aquaculture applications have not been sufficiently studied. These factors pose significant challenges to the commercialization of NPs in aquaculture and must be addressed in future research.

Materials functionalized with nanoparticles, or those incorporating NPs onto their surface, present potential environmental risks, as nanoparticles may leach or be emitted into the environment, where they could accumulate over extended periods (Gehrke et al., 2015). While the cost of producing nanotechnologies has historically been a major barrier, current methods for NP production have been identified as relatively inexpensive, as they can be produced under milder conditions. Furthermore, studies have demonstrated low-cost, eco-friendly synthesis methods, such as scalable, water-based synthesis using flow reactors. To ensure the responsible use of NPs, it is crucial to perform a comprehensive life cycle assessment (LCA) for each type of NP. This will provide valuable insights into the full environmental impact, from production through to disposal, helping to evaluate their long-term consequences and fate in the environment. As we move toward incorporating NPs into aquaculture, it is essential to consider the potential environmental impact and long-term effects on the surrounding ecosystem. Further research is required to assess the risks associated with bioaccumulation and toxicity of NPs in both fish and the aquatic ecosystem. NPs could adversely affect fish health by causing oxidative stress, cellular damage, and impairing physiological functions. To better understand these effects, additional work is needed to characterize the redox activity of nanostructures under various bio-microenvironmental conditions, examining how the intrinsic physicochemical properties of NPs influence their reactivity in aquatic environments.

To address these challenges, future research should focus on improving the scalability of NP production while reducing costs and environmental risks. Studies exploring alternative, eco-friendly synthesis routes should continue, along with an increased focus on developing methods to minimize nanoparticle release into the environment. Furthermore, developing standard guidelines for the life cycle analysis of nanomaterials used in aquaculture will be essential for ensuring that their benefits outweigh any potential environmental or health risks. This will support the responsible, sustainable integration of nanotechnology into aquaculture, ensuring that it contributes positively to water remediation efforts while safeguarding ecosystem health.

**CONCLUSION**

Nanotechnology offers solutions for aquaculture, addressing several Significant challenges of water treatment, pollutant removal, and ecosystem preservation. With its unique properties such as high reactivity, antimicrobial efficiency, and photocatalytic capabilities, nanoparticles effectively mitigate pollutants from culture system and enhance water quality while promoting fish health and growth. However, barriers such as cost, scalability, environmental risks, and regulatory challenges limit widespread adoption. Addressing these issues through lifecycle assessments, eco-friendly synthesis methods, and robust regulations is essential for sustainable integration. By overcoming these challenges, nanotechnology holds immense potential to revolutionize aquaculture, ensuring ecological balance, resource efficiency, and enhanced global food security through fisheries and aquaculture in the long term.

**KEYWORDS**

* Antimicrobial property
* Environmental remediation
* Heavy metal removal
* Nanoparticles
* Photocatalysis
* Wastewater purification

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