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Salinity and toxicity of zinc oxide nanoparticles in aquatic system: A review study

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ABSTRACT

Nanotechnology has significantly advanced in many scientific fields, particularly in nanoscale materials. Nanoparticles are distinguished by their small size and large surface area contributing to their unique functionality and reactivity. One of the most effective types of nanoparticles is zinc oxide nanoparticles (ZnO-NPs), known for their exceptional physical and chemical properties. Aquatic organisms benefit from ZnO-NPs due to their ability to promote growth and provide nutritional advantages. An aqueous solution containing ZnO-NPs has proven effective in removing lead and cadmium from water. Furthermore, incorporating zinc oxide in nanoform into fish feed enhances food palatability and increases consumption rates. However, improper handling of these nanoparticles can pose serious environmental risks. The zinc ions released by ZnO-NPs in water are considered the primary source of toxicity. The toxicity of ZnO-NPs is influenced by the presence of Zn^{2+} ions in solution and the formation of particle aggregates. Various parameters, including salinity, affect the ZnO-NP aggregates and the release of zinc ions. Salinity facilitates this complexation by providing additional chloride ions, which further reduce Zn^{2+} concentrations. While salinity increases aggregation, Zn^{2+} levels tend to decrease with rising salinity. Therefore, the salinity of water must be considered when assessing the impact of nanoparticles on aquatic life. This review, for the first time, investigated the effect of salinity on the properties and toxicity of zinc oxide nanoparticles. Additionally, it highlighted the detrimental effects of ZnO-NPs on fish. To achieve a comprehensive understanding of salinity-nanoparticle interactions, further research into the physicochemical properties and toxicity of nanoparticles, such as ZnO-NPs, is essential.

Introduction

Nanoparticles (NPs) have gained extensive applications in medical, agricultural, consumer products, and industrial processes due to their unique structural properties (Khan *et al*., 2018; Mandal *et al*., 2024). Generally, nanoparticles are defined as particles with dimensions less than 100 nanometers. Due to their small size, NPs exhibit numerous unique physicochemical properties and often outperform bulk materials for optical sensitivity, reactivity, and conductivity (Lin *et al*., 2023; Singh *et al*., 2023). Zinc oxide nanoparticles (ZnO-NPs) are among the most used (Khan *et al*., 2018). Approximately 30,000 tons of ZnO-NPs are produced globally each year, and their disposal in landfills, soils, water bodies, and the atmosphere may create habitats for various organisms (Lin *et al*., 2023). As the production of nano products increases, their release into the environment, particularly in aquatic ecosystems, also rises (Taherian *et al*., 2019). In aquaculture, nano-sized zinc oxide (Nano-ZnO) enhances zinc absorption due to its small particle size, which leads to improved feed efficiency, nutrient digestibility, and overall feed utilization in fish (Dube, 2024). Incorporating zinc oxide in its nanoform into fish feed enhances food palatability, resulting in increased consumption. This supplementation promotes DNA, RNA, and protein synthesis, which increases fish cell proliferation (Soundhariya and Rajan, 2021). Diets enriched with ZnO-NP significantly enhance the growth performance and nutritional quality of freshwater fish such as Rohu (*Labeo rohita*) (Thangapandiyan and Monika, 2020), Nile tilapia (*Oreochromis niloticus*) (Abd-Elhamed *et al*., 2021), and Asian catfish (*Clarias batrachus*) (Jewel *et al*., 2024). Additionally, ZnO NPs effectively remove toxic lead and cadmium from aqueous solutions (Rajan and Roopashree, 2022).

Although these nanoparticles offer numerous advantages, improper handling can pose significant risks to both environmental and human health (Bordin *et al*., 2024). Zinc oxide nanoparticles released from various sources can accumulate in aquatic ecosystems that may interact extensively with these ecosystems (Lin *et al*., 2023). It is estimated that between 170 and 2,985 tons of ZnO nanoparticles are released into receiving waters annually. Due to their large-scale production, and wide-ranging applications, ZnO nanoparticles are classified by the Environmental Protection Agency as one of the priority nanomaterials of environmental concern (Lai *et al*., 2023). ZnO-NPs dissolve in water, releasing zinc ions, which are recognized as the primary cause of toxicity (Tong *et al*., 2022). In this context, ZnO nanoparticles can induce toxicity in organisms through three distinct mechanisms: direct contact, the release of dissolved Zn ions, and reactive oxygen species (ROS)-mediated toxicity (Mandal *et al*., 2024). The release of Zn ions from ZnO nanoparticles increases the concentration of toxicants in the tissues and internal organs of exposed fish, leading to hazardous oxidative stress effects (Aziz *et al*., 2020). There is, however, the possibility that ZnO-NPs exhibit reduced toxicity within the pH range of 6.5 to 8.5. This is because their surface charge can decrease solubility, which in turn reduces stability and promotes aggregation. The aggregation of ZnO nanoparticles in brackish water is more pronounced than in freshwater, indicating that the characterization of ZnO nanoparticles in solution varies with salinity (Lin *et al*., 2023). Consequently, increased salinity leads to a lower toxic potency of ZnO-NPs for *Thalassiosira pseudonana*, due to diminished concentrations of dissolved Zn^{2+} released from ZnO-NPs at higher salinity levels (Yung *et al*., 2017). While previous reviews have investigated the toxicity of ZnO-NPs in aquatic ecosystems (Asghar *et al*., 2015; Hazeem, 2022; Mandal *et al*., 2024), this review underscored the detrimental impact of Zn nanoparticles on fish health and specifically investigated the effects of salinity on the properties and toxicity of zinc oxide nanoparticles for the first time. However, further research into the physicochemical properties and toxicity of nanoparticles, such as ZnO NPs, to marine organisms is essential to fully comprehend the interactions between salinity and nanoparticles.

Impact of zinc oxide nanoparticles on fish health

The aquaculture industry is rapidly integrating nanotechnology, resulting in aquatic organisms being exposed to significant quantities of nanoparticles (Luis *et al*., 2019; Tang *et al*., 2024). Zinc oxide (ZnO) is regarded as one of the most hazardous nanoparticles, posing a potential risk to fish and other aquatic animals (Aziz and Abdullah, 2023). Aquatic ecosystems are susceptible to the toxic effects of ZnO-NPs through three primary mechanisms: (1) the release of zinc ions and dissolution, particularly under oxidizing conditions; (2) the generation of reactive oxygen species (ROS) under light conditions due to the photocatalytic properties of ZnO-NPs; and (3) direct contact with cells, which may block various transport channels on the cell membrane, reducing membrane permeability and potentially resulting in cell rupture (Ng *et al*., 2017; Tang *et al*., 2024). Aquatic organisms, particularly fish, are susceptible to ecological and food chain risks due to exposure to ZnO nanoparticles, highlighting the severity of this issue (Aziz *et al*., 2020). Meanwhile, studies related to ZnO-NP toxicity in aquatic organisms have concentrated largely on fish (Amin *et al*., 2021). Kaya *et al*. (2015) demonstrated that ZnO-NPs in aquatic ecosystems are absorbed by fish and transported into tissues and organs via the bloodstream. This negatively impacts fish health and affects their physiology and biochemistry (Mandal *et al*., 2024).

Numerous studies have investigated the toxic effects of ZnO-NPs on various fish species. According to Subashkumar and Selvanayagam (2014), zinc ions contribute partially to the acute toxicity of ZnO nanoparticles in common carp, with a toxicity level of 4.897 mg/L observed in gill tissue. Banaee *et al*. (2019) revealed that a diet supplemented with ZnO-NPs at doses of 10 and 15 mg caused severe cytotoxic effects in carp (*Cyprinus carpio*), including oxidative stress and disruption of biochemical functions in fish cells. Additionally, *Cyprinus carpio* exhibited histopathological and ultrastructural changes in its gills, which are essential for respiration and osmoregulation, when exposed to 9 mg/L of ZnO nanoparticles (Carvalho *et al*., 2020; Shahbaa and Alaa, 2020). In the Indian major carp, *Catla catla*, exposure to ZnO nanoparticles at concentrations of 1, 5, and 25 mg/L altered hematological and biochemical parameters (Rangasamy *et al*., 2021). Furthermore, Rajkumar *et al*. (2022) found that ZnO nanoparticles induce toxic effects by altering antioxidant defense mechanisms, histomorphology, and genes involved in oxidative stress in *Cyprinus carpio* at concentrations of 0.382, 0.573, and 1.146 mg/L. Recently, intraperitoneal administration of ZnO-NPs to *Cyprinus carpio* at doses of 10, 15, and 20 ml/g body weight resulted in significant changes in hematological and biochemical parameters, which may adversely affect fish health and survival (Rasheed *et al*., 2023). However, Rashidian *et al*. (2021) indicated that green-synthesized ZnO-NPs at a concentration of 78.9 mg/L exhibited lower immunosuppressive effects on the skin mucus of *Cyprinus carpio*.

Zhao *et al*. (2013) found that nano-ZnO at concentrations of 50 and 100 mg/L negatively affects hatching and alters gene expression in zebrafish embryos due to oxidative stress. Furthermore, zinc oxide nanoparticles cause adverse physiological outcomes in embryonic and larval zebrafish, resulting from impaired signal transduction when exposed to concentrations of 0.01, 0.1, 1, and 10 mg/L for 96 hours post-fertilization (Choi *et al*., 2016). In tilapia (*Oreochromis mossambicus*) treated with 1 and 10 mg/L ZnO NPs for 14 days exhibited increased levels of oxidative stress and toxic effects in the liver, gills, intestine, kidney, brain, and muscles (Kaya *et al*., 2015). Additionally, zinc oxide nanoparticles at doses of 250 mg, 500 mg, 1000 mg, 1500 mg, and 2000 mg are administered over 14 days to assess their toxicity on tilapia fish. These findings suggest that ZnO nanoparticles adversely affect tilapia behavior, hematological parameters, and biochemical parameters (Rajan *et al*., 2016). Khan *et al*. (2022) demonstrated that tilapia exposed to 20 ppb of ZnO-NPs for 96 hours exhibited significant alterations in hematological parameters and histological structures, resulting in a decline in their populations in natural water sources.

The gills, muscles, liver, and heart of rohu (*Labeo rohita*) exhibited toxicity following chronic exposure to zinc oxide nanopowder at concentrations of 31.15 mg/L and 57.84 mg/L for 80 days (Aziz *et al*., 2020). Furthermore, the toxic effects of ZnO-NPs at a concentration of 20 mg/L on the obscure puffer (*Takifugu obscurus*), an economically important fish in China, resulted in a significant decrease in hatching rates and larval survival rates. This decline is correlated with increasing ZnO-NP concentrations, primarily due to the toxic effects of the nanoparticles, with Zn^{2+} playing a secondary role (Tang *et al*., 2024). In rainbow trout, high concentrations of ZnO-NPs at non-lethal levels (500 μg/L) resulted in significant gill damage due to impaired essential functions, including respiration and ion regulation, after 14 days of waterborne exposure (Mansouri *et al*., 2018). In comparison to chemical synthesis, rainbow trout (*Oncorhynchus mykiss*) exposed to a concentration of 25.50 mg/L of green-synthesized ZnO nanoparticles exhibited low toxicity (Taherian *et al*., 2019). The nanoparticles appear to be non-toxic to the rainbow trout, suggesting that green-synthesized ZnO nanoparticles may serve as a viable and safe alternative for various applications.

Salinity effects on properties and toxicity of zinc oxide nanoparticles

Zinc oxide nanoparticles are highly soluble in water, and this solubility contributes to their toxicity in aquatic ecosystems (Kandeil *et al*., 2024; Mandal *et al*., 2024). The concentrations of ZnO-NPs in the environment range from 0.001 to 0.058 μg/L in surface waters, from 0.24 to 0.661 μg/kg in soil, and from 0.22 to 1.42 μg/L in sewage treatment plant effluent, with concentrations expected to continue rising (Wu *et al*., 2019). The toxicity mechanism of ZnO-NP in aquatic ecosystems involves the generation of reactive oxygen species (ROS), which can induce oxidative damage, suppress antioxidant enzyme activity, and disrupt cellular homeostasis (Abdel-Daim *et al*., 2019). The toxicity of ZnO-NPs is influenced by the presence of dissolved Zn^{2+} ions and particle aggregates (Bordin *et al*., 2024). Although Zn^{2+} is an essential trace metal for living organisms, excessive concentrations can be toxic, even to aquatic life (Pérez-López *et al*., 2020). Soluble Zn^{2+} can enter cell membranes and interact with mitochondria, promoting ROS production and initiating autophagy in response to oxidative stress (Bacchetta *et al*., 2016). Furthermore, the formation of ZnO-NP aggregates is influenced by various parameters, including the suspension medium, pH, dispersion methods, ionic strength, particle surface area, and salinity (Mehta *et al*., 2016; Lai *et al*., 2020; Amin *et al*., 2021).

An increase in salinity compresses the electric double layers surrounding the particles, resulting in an attractive van der Waals force that promotes particle aggregation (Yung *et al*., 2017). At higher salinities, ZnO-NPs can form larger aggregates and produce lower concentrations of Zn^{2+}, thereby reducing their toxicity (Lin *et al*., 2023). Zinc ions may be complex with other anions present in salt water, leading to decreased bioavailable zinc (Yung *et al*., 2017; Lin *et al*., 2023). The presence of salt can provide additional chloride ions to facilitate this complexation, further reducing Zn^{2+} concentrations. Consequently, as salinity increases, the extent of aggregation rises while Zn^{2+} levels decrease (Dong *et al*., 2019). Higher salinity has been associated with reduced toxicity of ZnO-NPs to the marine diatom *Thalassiosira pseudonana* and the anadromous fish *Takifugu obscurus* in brackish water, likely due to lower concentrations of dissolved Zn^{2+} being released from ZnO-NPs at elevated salinities (Yung *et al*., 2017; Lin *et al*., 2023). The concentration of dissolved Zn^{2+} in brackish water may be lower than in freshwater, which could mitigate the toxic effects of ZnO-NPs (Lin *et al*., 2023). In freshwater environments, ZnO-NPs tend to dissolve quickly, increasing the risk of acute toxicity in aquatic organisms (Shaalan *et al*., 2017). Therefore, increased salinity generally correlates with decreased trace metal uptake by fish and invertebrates, suggesting that high salinity may offer protection against metal toxicity (Park *et al*., 2014). According to the available literature, there has been limited research on the salinity and toxicity of nanoparticles in aquatic environments. In this context, zinc oxide nanoparticles present significant research potential for examining the effects of salinity on their physical and chemical properties. Salinity should be a critical factor when assessing the impact of nanoparticles on aquatic life. Figure 1 describes the effects of salinity on the properties and toxicity of zinc oxide nanoparticles.

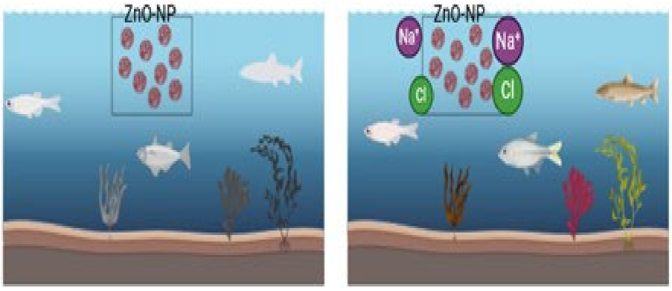

Figure 1 illustrates the effects of salinity on the properties and toxicity of zinc oxide nanoparticles in aquatic ecosystems.

Conclusion

The field of nanotechnology is regarded as a crucial element of advanced technologies, with a wide range of applications in agriculture, industry, and medicine. Despite the advancements in nanotechnology, certain environmental risks are associated with its use. The release of nanomaterials into aquatic ecosystems can adversely affect aquatic organisms, particularly fish. To mitigate potential harm, it is advisable to limit the discharge of nanoparticles into water bodies and to develop innovative strategies to address these concerns. This review indicates that salinity induces particle aggregation by compressing the electric double layers surrounding the particles, which creates an attractive van der Waals force. As salinity increases, ZnO-NPs can form larger aggregates, resulting in a reduced release of Zn^{2+} ions and consequently lowering the toxicity of these particles. A complex interaction between zinc ions and other anions in saline water may lead to a decrease in the bioavailability of zinc. However, further research is necessary to determine the optimal concentrations of nanoparticles, the best application timings, and the methods for synthesizing ZnO-NPs through green synthesis to minimize their toxicity. Additionally, it is essential to explore the combination of green synthesis and salinity to further mitigate nanoparticle toxicity.

Conflict of interest

The authors declare that they have no conflict of interest.

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