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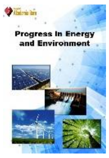

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Short Communication

Promises and Pitfalls of Metal Oxide Nanoparticles for Water Purification: A Sustainable Innovation or a Hidden Hazard?

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Abstract

Water, an indispensable resource in sustaining life, necessitates pursuing optimal purification processes amidst the rising concern of water insecurity. Technological advancements, particularly through integrating nanomaterials into separation technology, have made a significant leap in the area of water purification. This paper focuses on the application of metal oxide nanoparticles (MONPs) in separation technologies, and their incorporation into nano-infused nets (NINs), which show significant enhancement to the filtration efficiency. This can be observed in previous studies demonstrating the incorporation of MONPs in wastewater treatment can achieve 100% bacteria inactivation. While NINs hold significant promise for water solutions, concerns about potential environmental impact and health risks require further investigation and careful consideration. These concerns revolve around the risk of nanotoxicity, which may potentially occur during the employment of NINs in the event of nanoparticle detachment, resulting in MONPs entering water bodies, ecosystems, and eventually human bodies. Nanotoxicity may manifest in many forms in biosystems, such as cytotoxicity in humans, phytotoxicity in plants, and general bioaccumulation that may affect living organisms in various ways. This opinion paper explores the benefits, challenges, public concerns and ethical considerations surrounding the use of MONPs in water purification, emphasising the need for responsible implementation and international regulations that facilitate their sustainable and ethical use in water purification.

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1 Introduction

Pure water is one of the most essential resources for all living organisms, and its quality has a direct impact on safeguarding public health and well-being, environmental sustainability, and economic development. All of which makes the process of water purification more crucial in ensuring the supply of safe and clean water all around the world. Nevertheless, the rise of water pollution has triggered water security concerns; hence, there is a pressing need to design optimal, cost-effective, and sustainable water purification processes that leverage technological advancements. Numerous breakthroughs have transpired in purification technologies, particularly with the emergence of nanotechnology. Nanomaterials are widely used in water purification and have significantly enhanced the efficacy of these processes owing to their high specific surface area for pollutant sorption as well as unique properties such as photocatalytic for pollutant degradation. Currently, commercial companies such as Icon LifeSaver [1], Nanografi [2], Argonide [3], and NanoH2O Inc. by LG [4], have harnessed the potential of nanomaterials, incorporating them into water solutions.

Over the past decade, there has been a discernible surge in research papers dedicated to studying the use of nanomaterials for water purification. Based on the Boolean keyword "(Nano) AND (Water) AND (Purification)" searching through https://www.lens.org/, a total number of 134,670 patents and 15,743 scholarly works were found with a steady increment since 1980 onwards. This growing interest is reflected in the increasing number of scholarly articles exploring the diverse applications, mechanisms, and effects of utilising nanomaterials to revolutionise water purification processes.

Nanomaterials have a wide range of forms of application within the water purification and treatment processes, owing to their size and shape-dependent properties [5]. Table 1 highlights forms of nano-based applications for water purification technologies, and a comparison of the advantages and disadvantages of each form.

Table 1 Overview of Types of Nanomaterials Applied for Water and Wastewater Technologies [Adapted with permission from [5], Dove Medical Press Limited].

Nanomaterials	Properties	Applications
Nanoadsorbents	+ high specific surface, higher adsorption rates, small footprint − high production costs	Point-of-use, removal of organics, heavy metals, bacteria
Nanometals and nanometal oxides	+ short intraparticle diffusion distance compressible, abrasion-resistant, magnetic + photocatalytic (WO_3, TiO_2) − less reusable	Removal of heavy metals (arsenic) and radionuclides, media filters, slurry reactors, powders, pellets
Membranes and membrane processes	+ reliable, largely automated process − relative high energy demand	All fields of water and wastewater treatment processes

Nonetheless, the integration of nanomaterials into these technologies has brought about considerable concerns around the unforeseen risks and implications on public health and the environment. This article delves into the current applications of metal oxide nanoparticles (MONPs) in water purification, taking into account their sustainability, durability and safety aspects to answer the pivotal question: Could "MONPs" hold the key to solving our water predicaments? There is limited understanding of the long-term implications of utilising MONPs in water purification. Shi and Huang [6] emphasised the importance of thoroughly investigating the interactions of MONPs with plants to better understand the ecotoxicity concerns surrounding them [6]. Although studies conducted to assess the long-term effects of occupational exposure to MONPs have found oxidative stress across the tested workers, repeated tests suggest no evidence of potential long-term adverse effects on the health of workers under the reported exposure levels, apart from increased antioxidant enzymes activities [7,8]. There is a consensus among researchers that long-term studies are needed to assess the real-life implications of MONPs utilisation from the sustainability, environmental, and health aspects to effectively balance the benefits and risks.

2 Metal oxide nanoparticles and their infused nets for water purification

Diverse technologies using MONPs have revolutionised water purification and remediation, each exploiting specific properties of the nano-entity to drive desired outcomes. Some of the commonly used approaches include nano-adsorption [9], photocatalytic degradation [10], and Surface-Enhanced Raman Scattering (SERS) sensing [11], all of which work through the unique feature of the selected MONPs. On the other hand, the integration of MONPs into membrane matrices to craft nano-infused nets (NIN) stands as a testament to innovation in separation technology, particularly on improving the filtration efficiency for pure water attainment. NINs present a range of advantages that can be synergistically combined with other techniques to enhance the water purification outcomes. Nanotitania-coated NINs have garnered significant interest in water purification applications, owing to titania's inherent capability to facilitate the degradation of organic contaminants and eradicate microorganisms in water upon exposure to UV light [12]. Although nanotitania has seldom been commercially employed for water purification, plenty of experiments have been conducted to prove the potential of its inherent properties in improving water purification and imparting anti-fouling properties to NINs. Nanotitania NINs find real-life applications in water purification systems, their prowess was exploited in a pilot-scale reactor achieving 100% bacteria inactivation, treating wastewater in sugar refineries, as well as photocatalytic water purification in petroleum refineries [13]. At the forefront, these innovative materials demonstrate positive impacts by efficiently removing pollutants, pathogens, and heavy metals from water sources, contributing to enhanced water filter effectiveness [14, 15].

3 Challenges and concerns

MONP-infused NINs have shown potential in water purification, with advantages such as photocatalytic efficiency and antifouling activity, specifically in ZnO and TiO_2 [16]. While the introduction of MONPs and NINs has undeniably revolutionised the field of nano-, membrane, and separation technologies, it is crucial to acknowledge that the extensive benefits they offer do not render them entirely benign concerning environmental sustainability. Similar to most nanomaterials, the interaction of MONPs with biological ecosystems raises concerns about nanotoxicity that prompt further study and investigation. Understanding these limitations is crucial to harness the sustainable benefits of NINs, ensuring that their application in the environment poses minimal to almost no harm and that advantages outweigh any drawbacks and align with responsible water resource management. In particular, the MONPs may leak out (detach) from the nets [17]; the nano-sized residues can be difficult to collect post-treatment, raising environmental and public health concerns. Careful consideration must be given to size-dependent effects, as organisms respond differently to nanomaterials based on their size. Within aquatic ecosystems, smaller nanoparticles of 12 nm have been found to interact with embryos, while particles larger than 27 nm caused reproductive effects through different mechanisms [18]. In humans, nanomaterials smaller than 20nm tend to deposit in the kidney, while larger nanoparticles accumulate in the liver [19]. Lab analysis on mammalian cells have revealed that certain MONPs, including CuO, ZnO, TiO_2, Al_2O_3, and Fe_2O_3 have been determined to cause cell damage, known as cytotoxicity [20]. The phytotoxicity and transport of MONPs through nature is influenced by several variables, such as size, charge, agglomeration rate, and stability [21,22,23]. The stability of NINs is what prevents nanomaterial's release into the environment, and it is dependent on multiple factors, from their synthesis method, material selection and surface preparation to binding strength, mechanical stress, and environmental conditions. Despite the risks involved with nanomaterials, owing to their minuscule size, it is noteworthy that no human health or environmental problem has been reported in relation to water purification through the use of nanomaterials [12]. As of now, there have been no documented real-life cases in which humans were hospitalised or treated for nanotoxicity. The current disclosure on nanotoxicity relies solely on lab experimentations and the interaction of biological cells with nanomaterials.

As the large-scale preparation and utilisation of MONPs increases, direct interactions with animals, plants, microorganisms, and humans become inevitable, posing potential threats to the environment. High concentrations of MONPs exhibit toxicity to various organisms, showcasing different mechanisms of toxicity across different species, which under complex environmental conditions are often unpredictable [24]. The cellular response to MONPs mainly manifests in the oxidative stress and hypoxia signaling pathways [25]. Mutalik et al. [26] studied the impact of various nanomaterials on Zebrafish, and found that exposure to MONPs led to various toxicities in the species, including alteration in gene expression and risk of developmental defects [26]. Fig. 1 shows the mechanism where MONPs are absorbed by fish and the ecological risks they carry to the aquatic food chain [27].

Ergo, scientists are challenged to engineer stabilisation methods and innovate ways to harness the benefits of nanomaterials while minimising their potential biotoxicity and adverse environmental effects.

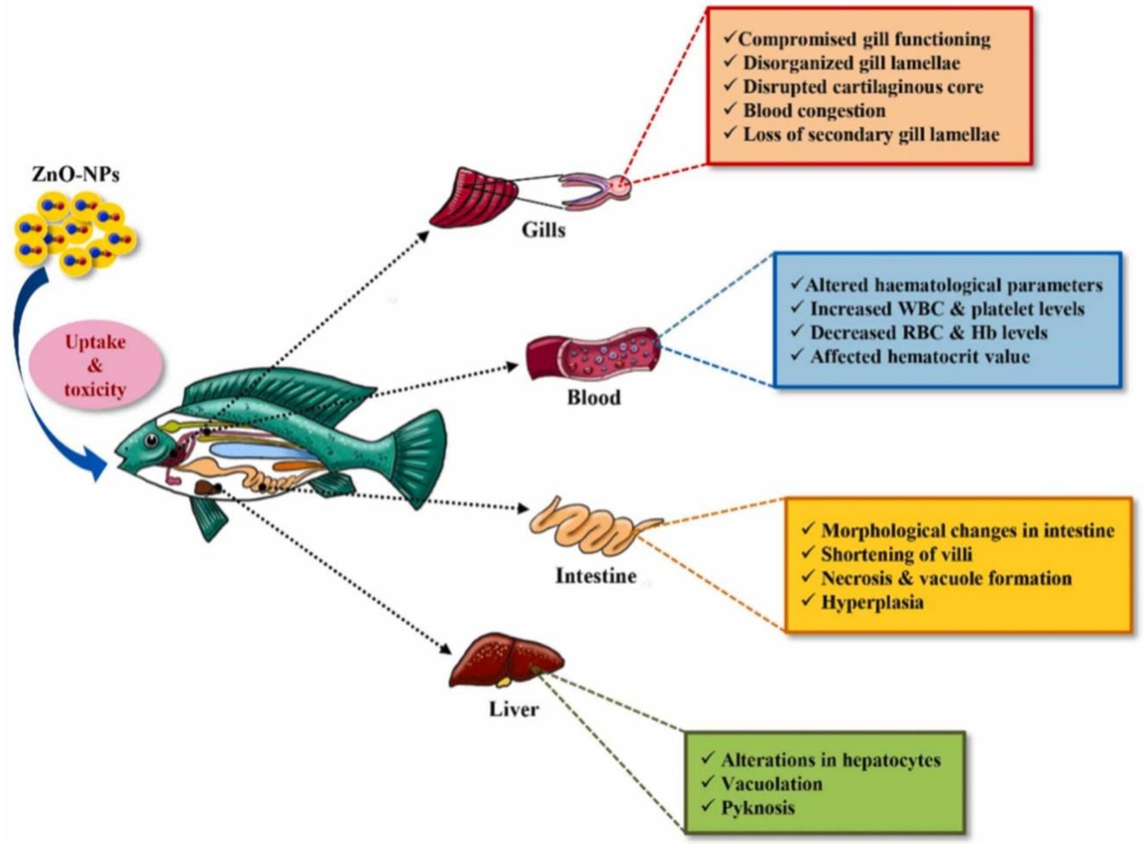

Fig. 1 ZrO2 Nanoparticles Accumulation and Transformation in Zebrafish [Adapted with permission from [**27**], Elsevier, under CC-BY license].

4 Responsible implementation and ethical considerations

Scientists shoulder a great responsibility to improve transparency in conducting and reporting research. In this regard, transparency in research opens access to research findings to the public, stimulating meaningful discussions on a wider and higher level, urging the establishment of regulations and international cooperation. This serves as a cornerstone for scientific advancements and aims to ensure the safe and sustainable use of MONPs in water purification.

With the widespread adoption of MONPs across diverse fields, a global challenge for governments has emerged for the aim of formulating regulations and international legislation addressing the repercussions of the irresponsible use of nanotechnology. Currently, there are no standardised regulations governing the use of nanomaterials in international markets [28]. However, noteworthy strides have been made with regulatory bodies such as the US Food and Drug Administration, Environmental Protection Agency, and US Department of Agriculture on Nanotechnology-based products and additives in food applications [29]. Scientists have developed advanced machine learning models (see Fig. 2) that enable them to predict the toxicity of MONPs based on their physiochemical properties. These predictive models achieved high accuracy, with an average error rate of just 1.02%, a sensitivity of true positive toxicity of 98.87%, and specificity of non-toxicity of 100% [30].

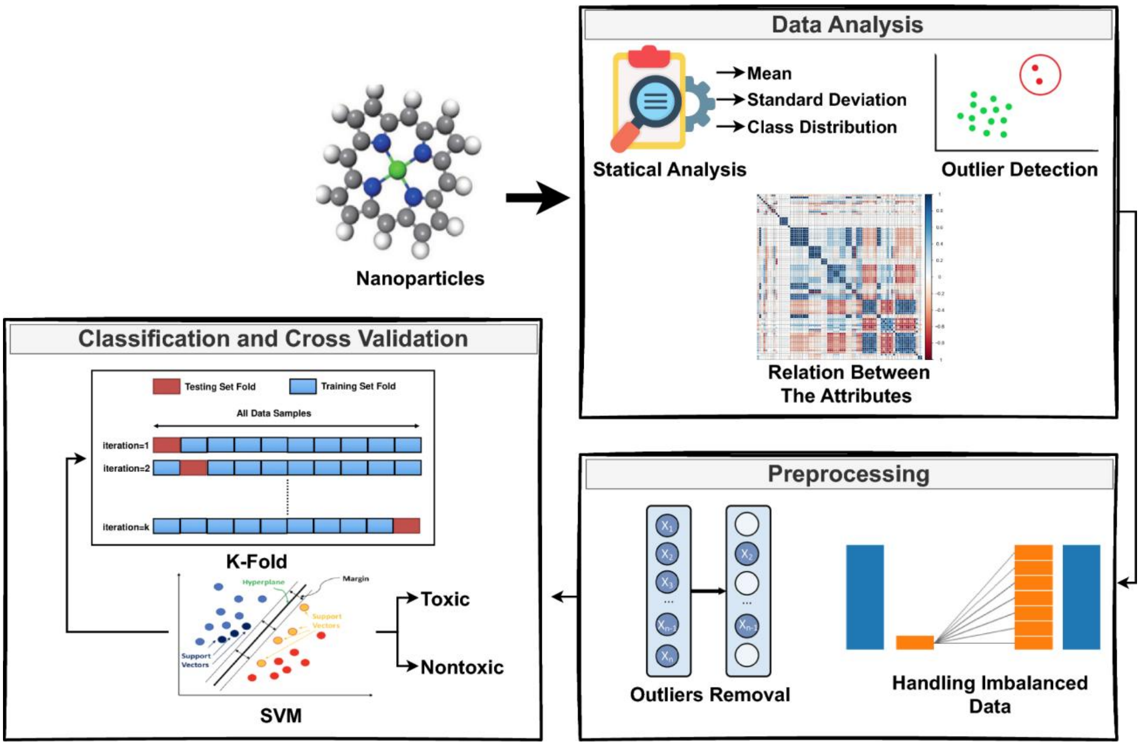

Fig. 2 A Suggested Machine Learning-based Nanotoxicity Detection Model Block Diagram [Adapted with permission from [30], Springer Nature, under CC-BY 4.0 license]. (Note SVM: support vector machine)

The need for comprehensive and globally applicable regulations remains paramount to mitigate the potential risks associated with the expanding use of MONPs. Evidently, solutions that leverage technological innovations such as predictive modeling shall be included to advance the research in nanotoxicity in a sustainable, environmentally conscious manner. From an ethical standpoint, consumers have the right to be informed about water purification systems containing nanomaterials that they use through device labeling.

5 Conclusion and future outlook

As we navigate the matter of integrating MONPs and NINs into water purification technologies, the larger question looms: are they a sustainable marvel or an obscured menace? Science speaks loudly as it backs the tremendous potential of nanomaterials, demonstrating how innovative solutions that employ MONPs and NINs could hold the key to solving global water challenges. Yet, beneath the promising efficacy of this technology lie concerns about the environmental risks centering on nanotoxicity. To determine the environment's stance, a balance needs to be struck in conducting a meticulous risk-benefit analysis. The remedy is to allow research to take its course in developing safer ways of harnessing the prowess of MONPs, while addressing concerns and acknowledging the limitations of this technology. The future role of research is crucial in forming comprehensive guidelines that ensure responsible implementation and are driven by ethical considerations. Ultimately, the sustainable impact of MONPs and NINs in water purification hinges on the cooperative efforts of scientists, practitioners, policymakers, and the public.

Declaration of Conflict of Interest

The authors declared that there is no conflict of interest with any other party on the publication of the current work.

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