

# The role of nanotechnology in aquatic environments: perspectives on the safety and application of nanostructured materials in aquatic environments

Volume 10 Issue 1 - 2026

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## Editorial

I have been given the opportunity to feature my work in an editorial in the first volume of the International Journal of Hydrology for 2026. Global and urgent themes in the field of Hydrology include climate change and water resource management, groundwater resource sustainability, the “One Water” approach and sustainability science, and technological innovation in Hydrology. My field of expertise, nanomaterials and biomaterials, is deeply related to applied fields of Hydrology such as water quality and water treatment. From this perspective, I can consider a theme that will provide unique value to the journal.

Water is the most critical resource for life and a fundamental pillar of global sustainable development. Yet, humanity faces an unprecedented challenge in securing clean and accessible water due to rapid industrialization, population growth, and climate change. Emerging contaminants — from persistent organic pollutants and pharmaceutical residues to microplastics — are increasingly compromising the quality of both surface and groundwater. Against this backdrop, nanotechnology, particularly the utilization of engineered nanostructured materials (NMs), has emerged as a revolutionary force, offering unparalleled capabilities to monitor, purify, and manage our precious aquatic resources.<sup>1</sup>

## The promising frontier of nanomaterial applications

Nanomaterials, with their high surface-area-to-volume ratio and tuneable surface properties, provide distinct advantages over conventional water treatment technologies. Their application spans the entire water cycle, from advanced purification to novel sensing platforms.

**Advanced water purification:** NMs are highly effective for adsorption, filtration, and degradation. Nanofibers and nanocomposite membranes (such as nanofiltration membranes) offer high-flux filtration with minimal fouling, enabling efficient removal of minute particles, pathogens, and even dissolved contaminants that evade traditional systems. For instance, carbon-based nanomaterials (like graphene and carbon nanotubes) exhibit exceptional capacity for sequestering dyes and heavy metals, while metallic nanoparticles (e.g., silver and copper oxides) serve as potent disinfectants due to their antimicrobial properties. The superior process efficacy enables implementation of more compact water and wastewater treatment devices with smaller footprints.<sup>2</sup>

**Next-generation sensing and monitoring:** Nanotechnology is crucial for early detection of contaminants. Quantum dots and plasmonic nanoparticles can be integrated into highly sensitive and selective sensors, providing real-time, on-site monitoring of water quality parameters, including the presence of trace contaminants and microbial pathogens. This capability is vital for proactive water resource management and safeguarding public health.

The continuous innovation in this field promises to deliver smaller, faster, and more energy-efficient water systems, potentially bringing safe drinking water to remote or underserved communities.

## The critical imperative for safety and responsible innovation

While the transformative potential of NMs is undeniable, their widespread application necessitates a rigorous and proactive consideration of their environmental and toxicological implications. The same properties that make NMs effective purifiers — their size, reactivity, and mobility — also raise legitimate concerns about their fate and transport in natural aquatic ecosystems.

**Environmental fate and ecotoxicity:** A major challenge lies in understanding the complete lifecycle of engineered NMs, particularly their release, transformation, and accumulation in soil, water, and biological organisms. Studies must rigorously address their potential ecotoxicity to aquatic flora and fauna. Aggregation, dissolution, and surface modifications of NMs upon entering the environment can alter their toxicity, making long-term exposure assessments complex but essential.

**Regulatory and standardization gaps:** Current regulatory frameworks are often ill-equipped to handle the unique characteristics of nanomaterials. There is an urgent need for international consensus on standardized methodologies for testing and characterizing NMs in complex environmental matrices. Clear, science-based policies are essential to govern the safe development and deployment of these technologies, ensuring that innovation does not outpace environmental stewardship.<sup>3</sup>

### Outlook: charting a sustainable course

The future of water quality is inextricably linked to the responsible advancement of nanotechnology. To fully realize its benefits, the scientific community must commit to a path of interdisciplinary collaboration, integrating materials science, environmental engineering, toxicology, and regulatory expertise.

Moving forward, research must prioritize:

- I. Intrinsic safety:** Developing inherently safer or “green” nanomaterials that are biodegradable or easily recoverable from water systems after use.
- II. Lifecycle assessment:** Performing comprehensive assessments of the environmental costs and benefits of nanomaterial-based solutions.
- III. Policy bridging:** Working with policymakers to translate scientific understanding into practical, protective, and innovation-enabling regulations.

Nanotechnology holds the key to unlocking a future of greater water security. By embedding principles of sustainability and safety at the core of our research and development efforts, we can responsibly

harness this powerful technology to achieve global water quality goals.

### Acknowledgments

None.

### Conflicts of interest

The author declares there is no conflict of interest.

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