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रासो

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Eco-Toxicity of Nanomaterials in Aquatic Systems

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1. Introduction

Nanomaterials (NMs) are materials with at least one dimension between 1-100 nm. At this scale, materials exhibit high surface area-to-volume ratio, enhanced reactivity, quantum effects, and tunable surface chemistry. These advantages have led to their widespread application in electronics, pharmaceuticals, cosmetic products, food packaging, textiles, and environmental remediation. However, the increased production and use of nanomaterials in the past decade have resulted in the continuous release of engineered nanoparticles (ENPs) into natural water bodies. Wastewater treatment plants (WWTPs), industrial effluents, agricultural runoff, and degradation of nano-enabled products are major contributors. Research published between 2021-2025 clearly indicates that aquatic ecosystems -rivers, lakes, groundwater, and marine environments-are the most vulnerable sinks for nanomaterial accumulation.

Once released into the aquatic environment, nanomaterials interact with suspended particles, dissolved organic matter, microorganisms, invertebrates, plants, and fish, leading to physical, chemical, and biological alterations. Their eco-toxicity depends on concentration, surface coating, size, solubility, aggregation state, and environmental conditions such as pH, salinity, and ionic strength.

2. Sources of Nanomaterials in Aquatic Systems

2.1 Industrial Discharge

Nanomaterials used in paints, coatings, catalysts, dyes, and electronics often enter water through untreated or partially treated wastewater.

2.2 Wastewater Treatment Plants

Cosmetic products (sunscreens with TiO_2, ZnO; creams with AgNPs) release nanoparticles that are not completely removed by conventional treatment systems.

2.3 Agricultural Runoff

Nano-fertilizers, nano-pesticides, and nano-biosensors release particles into soil and water through irrigation channels.

2.4 Degradation of Nano-Enabled Products

Weathering of textiles, plastics, and packaging materials releases micro- and nano-scale fragments.

2.5 Accidental Spills and Leaching

Leakage from storage, transport, and disposal sites contributes to nano-pollution.

3. Types of Nanomaterials Most Commonly Detected in Aquatic Systems

Metal nanoparticles

Silver nanoparticles (AgNPs)

Gold nanoparticles (AuNPs)

Iron oxide nanoparticles (Fe_3O_4)

Metal oxides

Titanium dioxide (TiO_2 NPs)

Zinc oxide (ZnO NPs)

Cerium oxide (CeO_2 NPs)

Carbon-based nanomaterials

Carbon nanotubes (CNTs)

Graphene oxide (GO)

Fullerenes (C60)

Polymeric nanomaterials

Nano-plastics (polyethylene, polypropylene, polystyrene nano-fibers)

Quantum dots

CdSe, CdTe, PbS nanocrystals

4. Behavior of Nanomaterials in Aquatic Environments

The environmental fate of nanomaterials is governed by their physicochemical interactions with biological and non-biological components.

4.1 Aggregation and Sedimentation

Nanomaterials often aggregate due to electrostatic interactions, forming larger clusters that settle into sediments. TiO_2 and ZnO nanoparticles rapidly form aggregates in high-salt water.

4.2 Dissolution

Some nanoparticles release toxic metal ions (e.g., Zn^{2+}, Ag^{+}, Cd^{2+}), increasing chemical toxicity.

4.3 Surface Adsorption

Nanoparticles readily bind to: proteins (forming "protein corona"), humic acids, natural organic matter (NOM), microplastics. This alters their mobility and bioavailability.

4.4 Bioaccumulation and Biomagnification - Accumulation occurs in:

algae,

zooplankton,

mollusks,

crustaceans,

fish tissues (gills, liver, brain).

Through food-chain transfer, nanoparticles can reach higher trophic levels, including humans via seafood consumption.

4.5 Photocatalytic Activity

TiO_2 nanoparticles generate reactive oxygen species (ROS) when exposed to sunlight, increasing oxidative stress in aquatic organisms.

5. Mechanisms of Eco-Toxicity in Aquatic Organisms

5.1 Oxidative Stress

Nanoparticles produce excess ROS leading to:

lipid peroxidation

DNA damage

protein denaturation

enzyme inhibition

This is the most widely reported toxicity mechanism.

5.2 Physical Damage

Sharp-edged nanoparticles and nanotubes cause:

membrane rupture, blocked gill surfaces , abrasion of cell walls in algae

5.3 Ion Release

ZnO, AgNPs, and Cd-based quantum dots dissolve and release toxic metal ions.

5.4 Genotoxicity and Mutagenicity

Studies show:

chromosomal abnormalities

DNA fragmentation

disrupted cell cycle

5.5 Reproductive Toxicity

In fish and crustaceans: reduced fecundity, abnormal embryonic development , delayed hatching

5.6 Neurotoxicity

Nanoparticles can cross the blood-brain barrier in fish, causing:

altered neurotransmitter levels ,behavioral changes (stress, reduced mobility)

5.7 Immunotoxicity

Immune suppression makes organisms more vulnerable to disease.

6. Toxicity Effects on Aquatic Species

6.1 Phytoplankton and Algae

Nanomaterials reduce:, photosynthetic efficiency chlorophyll levels , cell division, TiO_2 and AgNPs inhibit algae growth at extremly low concentrations.

6.2 Zooplankton

Daphnia magna shows: ,reduced feeding, swimming impairment, mortality at high exposure , gut blockage by nano-plastics

6.3 Aquatic Plants

Carbon nanotubes can penetrate plant roots, affecting:

water uptake ,nutrient transport, gene expression

6.4 Mollusks

Filter feeders accumulate large quantities of nanoparticles, causing:

oxidative damage , gene suppression ,shell formation defects

6.5 Crustaceans

Shrimps and crabs exposed to nanoparticles exhibit:

hepatopancreas damage, stress protein expression changes

6.6 Fish

Fish absorb nanoparticles via: gills, gut, skin

Effects include: ,gill inflammation, liver injury

Neurotoxicity, reproductive dysfunction

7. Eco-Toxicity of Specific Nanomaterials

7.1 Silver Nanoparticles (AgNPs)

Highly antimicrobial, Causes oxidative stress and DNA damage in fish, Bioaccumulates in liver and brain, Toxic even at $\mu g/L$ levels

7.2 Titanium Dioxide (TiO_2 NPs)

Photocatalytic toxicity under UV light

Damages algae and fish gills

Causes developmental abnormalities in embryos

7.3 Zinc Oxide (ZnO NPs)

Rapid dissolution into Zn^{2+} ions, Extremely toxic to phytoplankton

7.4 Carbon Nanotubes (CNTs)

Induce inflammation and physical blockage

Persistent and non-biodegradable , Accumulate in sediments

7.5 Quantum Dots

Release heavy metals (Cd, Pb), Highly toxic to algae, zebrafish embryos and invertebrates

7.6 Nano-plastics

Ubiquitous in marine systems, Absorb hydrophobic pollutants, Enter food chains

Affect development in fish and crustaceans

8. Environmental Risk Assessment Challenges

8.1 Lack of Standardized Testing Methods

Current toxicity tests designed for chemicals are not suitable for nanomaterials.

8.2 Complex Behavior in Natural Water

Nanomaterials constantly change form, making prediction difficult.

8.3 Low Environmental Concentrations

Despite low concentrations, their high reactivity makes them dangerous.

9 Strategies to Reduce Nanomaterial Eco-Toxicity

9.1 Green Synthesis of Nanoparticles

Using biological methods (plants, microbes) reduces toxicity.

9.2 Surface Coating and Functionalization

Coatings such as PEG, citrate, or polymer layers minimize ion release

9.3 Improved Wastewater Treatment

Membrane filtration

Nano-adsorbents

Advanced oxidation processes

9.4 Biodegradable Nanomaterials

Developing eco-friendly and self-degrading nanomaterials.

9.5 Environmental Monitoring

Real-time sensors for nanoparticle detection in water bodies.

10 Future Research Directions (2025-2030)

Long-term chronic toxicity studies

Development of biodegradable nano-plastics

AI-based predictive models for nano-behavior

Safer nano-enabled agriculture

Ethical and sustainable nanotechnology regulations

11 Conclusion

Nanomaterials provide tremendous benefits, but their increasing release into aquatic ecosystems poses significant ecological risks. Their small size, high reactivity, and ability to accumulate and biomagnify result in toxicity across all levels of aquatic life-from phytoplankton to fish. With rising global nanotechnology applications (projected $500 billion by 2030), eco-toxicological research is essential to maintain environmental balance. A combination of scientific innovation, strict regulations, and sustainable design is urgently needed to protect aquatic biodiversity and human health.

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