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REVIEW

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Nanoparticles in Aquatic Ecosystems: Origins, Destiny and Ecological Consequences

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Abstract

Aquatic ecosystems are facing an increasing amount of nanoparticles (NPs) due to their extensive use and unintentional leakage into the environment. The unique physical and chemical properties as well as the small size of NPs raise concerns about their possible effects on aquatic organisms and ecological processes. The review provides a thorough examination of the origins, destiny, and impacts of NPs in aquatic environments, utilizing a variety of scientific sources. Primary sources of NPs include consumer products, industrial procedures, and artificial NPs utilized in various applications. Subsequent to their release, NPs may undergo intricate processes such as surface modifications, aggregation, dissolution, or other transformations, intricately influencing their behavior and bioavailability. The modes of NP exposure, including ingestion, topical application, or gill absorption, can significantly impinge on the growth, reproduction, and physiological processes of aquatic species. Furthermore, the transformative capability of NPs extends to altering community structure, nutrient cycling, and primary production within ecosystems, thereby eliciting a cascading impact on higher trophic levels. A deep understanding of the complex relationships between NPs and aquatic ecosystems is crucial for accurately evaluating environmental issues and developing successful mitigation plans. Understanding the various effects of NPs on aquatic systems is crucial for promoting sustainable practices and protecting the ecological health of these important habitats.

Keywords: Aquatic ecosystems; Ecological consequences; Nanoparticle exposure; Reproductive effects; Physiological processes; Cascading impact

Introduction

Engineered nanomaterials, sometimes referred to as made nanomaterials or engineered nanoparticles (ENPs), are materials that consist of particles inside the "nanometer" size range, whether they are unbound or agglomerated. The European Union defines ENPs as materials in which over 50% of the particles have one or more exterior dimensions falling within the size range of 1–100 nm (European Commission, 2020). These materials can be precisely designed in terms of shape, size, and surface properties, giving them various and distinctive features compared to their original forms. Their ability to be adjusted in terms of physical, chemical, and biological characteristics allows them to be used in a wide range of industries such as environmental, construction, agriculture, and medicine. The increasing use of ENPs has resulted in a rise in their manufacturing, leading to a wide range of ENP-enabled devices becoming accessible in the market. The increase in nano waste has raised major concerns, leading to investigations into the fate and possible environmental impacts of this garbage (Devasena et al., 2022). Nano-sized particles (NPs) are classified into five classes according to their chemical composition: nano-metal, nano-oxide, carbon nanomaterials, quantum dots, and other NPs such as organic polymers (Junam et al., 2008).

Diverse nanoparticles are utilized in a range of industries like food packaging, textiles, optoelectronics, biomedicine, cosmetics, energy, and catalysis due to their unique properties like mechanical traits, contact reactivity, optical attributes, and electrical conductivity (Georgantzopoulou et al., 2013). Nanoecotoxicology is a specialized sub-discipline of ecotoxicology that focuses on assessing the safety of nanotechnology-based goods in the natural environment. This field aims to evaluate the environmental safety of nanotechnology applications and promote sustainable development in creative nanotechnology while addressing potential downsides (Kahru et al., 2012).

Computational modelling is a useful approach for evaluating environmental contaminant concentrations by utilizing life cycle data and production quantities. ENP content in surface waters is usually predicted to be in the lower ng^{-L} or mg^{-L} range, depending on the kind of ENP and the environmental conditions (Dumont et al., 2015). ENPs were found to have deleterious effects in aquatic environments, leading to organ failure in fish in case studies (Tayal et al., 2023; Singh and Puri, 2023; Mahajan, 2023; Bhatt et al., 2024; Goyal et al., 2023; Lopez-Barrera et al., 2021). The release of nano waste into aquatic ecosystems constitutes a two-fold threat: water scarcity in developing nations and contamination of aquatic ecosystems, which combined endanger human survival, health security, and economic progress. The appearance of ENPs in water sources is a notable difficulty, highlighting the necessity of comprehending the destiny of ENPs in the environment, encompassing chemical changes and consequent harmful effects. Understanding this information is crucial for creating policies that adhere to the principles of the circular economy, focusing on minimizing waste and maximizing the reuse and recycling of resources (Mitrano et al., 2014).

Water bodies close to point sources receive greater ENP loading than those located at a distance. Wastewater treatment operations focus on decreasing environmentally non-friendly pollutant (ENP) levels in wastewater before releasing it into surface waters. After being released, ENPs come into contact with many components of the environment, such as sediments and organic material. These interactions dictate their destiny, causing them to either move through water, become trapped in sediments, or experience permanent changes. ENPs undergo many changes and interactions in the environment, with their residence time in the water, known as "aging," playing a crucial role in determining their final destiny (Gottschalk & Nowack, 2011). Approximately 1% of the mass of ENPs from different goods is ultimately discharged into the environment throughout their use (Giese et al., 2018). NPs can be intentionally released for purposes such as medication manufacturing, groundwater cleanup, and medical imaging. Unintentional release can happen during operations including burning fossil fuels, automobile emissions, mining, and demolition. Approximately 60% of nanomaterials are utilized in medical/pharmaceutical and industrial sectors, increasing the probability of their discharge into wastewater.

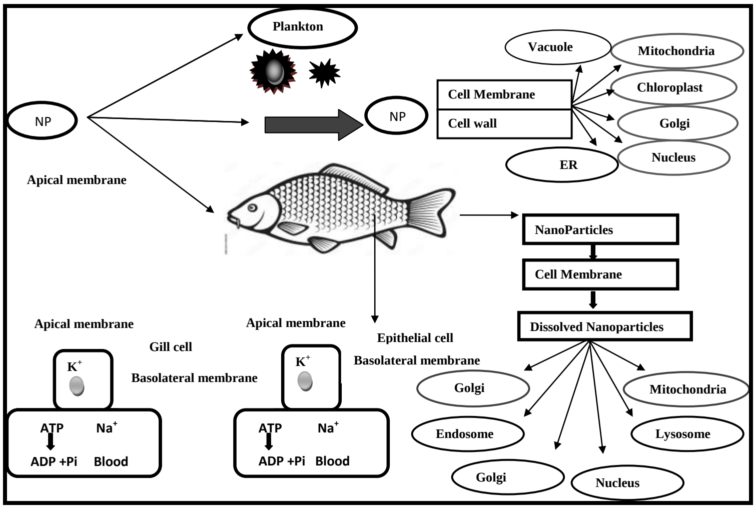

Fig. 1. Nanoparticle buildup in fish organs had harmful effects on both internal and exterior structures, as depicted in the illustration.

ENP Fate and Changes in Aquatic Ecosystems

Within complex aquatic ecosystems filled with many living forms such as fish, plants, and microorganisms that depend on freshwater, ENPs cause subtle changes to their original condition when introduced into these habitats. Three separate realms categorize the crucial processes that affect the fate and behaviour of nanomaterials in the aquatic ecosystem. Physical processes including homo/hetero aggregation, agglomeration, sedimentation, and deposition are essential. Chemical processes such as photochemical reactions, dissolution, oxidation, and sulfidation have a crucial role in determining the destiny of ENPs (Stone et al., 2010; Nowack et al., 2012; Lowry et al., 2012). Biological processes, such as microbial-mediated biodegradation and bio-modification, contribute to the complexity of the system (Lead et al., 2018). The changes are impacted by the inherent features of ENPs as well as the complex chemistry of the aquatic environment (Abbas et al., 2020). The interactions of physical, chemical, and biological processes determine how metal NPs such as Ag, ZnO, and Cu change in aquatic environments through dissolution and sulfidation, significantly affecting their toxicity (Turan et al., 2019). Biotransformation studies were conducted and demonstrated the conversion of CuO NPs into $Cu_3(PO_4)_2$ in the intestines and appendages of *Daphnids.* Various processes such as dissolution, adsorption, aggregation, sedimentation, and other reactions occur simultaneously, affecting the behaviour of ENPs in aquatic environments (Peng et al., 2017). It is important to recognize that substances attached to ENPs change their surface characteristics, affecting aggregation, dissolution, and vice versa. Algae are crucial in aquatic ecosystems since they serve as the base of food chains and help transfer NPs across the food chain, which can lead to harmful impacts on animals at higher trophic levels (Wang et al., 2014; Bundschuh et al., 2016; Kalman et al., 2015). Additionally, ENPs display adsorption characteristics on different surfaces, which greatly impact their movement and destiny in water environments. The binding of Natural organic matter (NOM) to ENP surfaces reduces their dissolution in aqueous conditions, as seen in NOM adsorption on Al_2O_3-NPs and CuO-NPs (Nanja et al., 2020). The complex changes significantly impact the movement, absorption, availability, durability, and harmful impacts of ENPs (Table. 1).

The fate and transport of ENPs are significantly influenced by several environmental factors in surface waters such as ionic strength, pH, electrolytes, and NOM concentrations, temperature, flow velocity, and other water chemistry parameters (Chen et al., 2010). The particle size of ENPs is the fundamental factor controlling their behaviour in surface waters, despite the presence of other physicochemical features (Goswami et al., 2017). ENPs have a small particle size which leads to bigger and more reactive surface areas, allowing for more effective interactions with microorganisms compared to larger particles (Chen & Schluesener, 2008; Auffan et al., 2009). This complex interaction reveals the various aspects of ENP behaviour in water habitats, aiding in a thorough comprehension of their ecological influence.

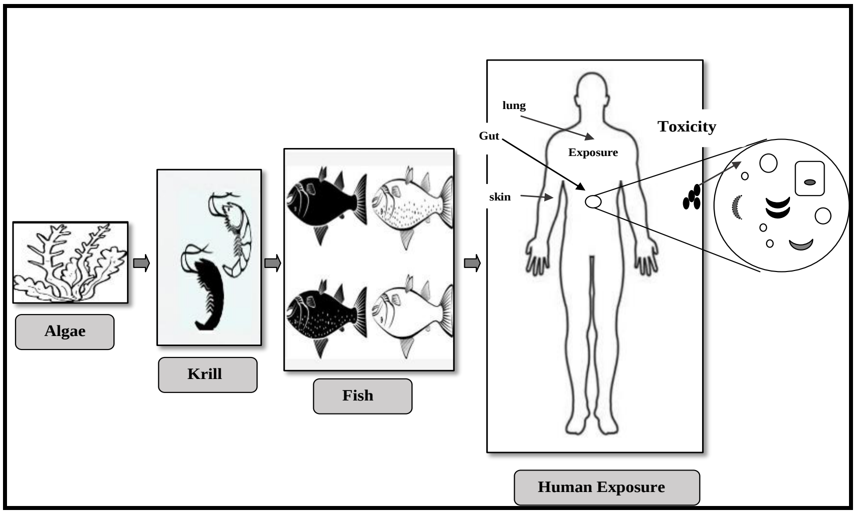

Fig. 2. Depiction of Energy Network Pathway transmission within the aquatic ecosystem's food chain.

Table. 1. Ecotoxicological effect of nanoparticles on various aquatic organisms

S. No.	Types of nanoparticles	Aquatic organisms	Ecotoxicological effect on aquatic organisms	References
1.	As-NPs	*Labeo rohita*	Liver, gills, and kidney damage	Raza et al. (2021)
2.	TiO_2	Bacterium *Bacillus thuringiensis.*	Viability, ROS a generation, enzymatic activity, Cu uptake/Increase.	Li et al. (2020)
		Zebrafish larvae	Mortality, malformation rate, No effect; Locomotion/ Decrease; Biouptake and depuration/Increase	Hu et al. (2019)
		Water fleas, Daphnia magna, Tegillarca granosa	Bioaccumulation and oxidative stress/Increased. High intestinal damage.	Liu et al. (2019)
		Mozambique tilapia (*Oreochromis mossambicus*)	TiO_2 NPs were neurotoxic to the blood clam as indicated by increased neurotransmitter concentrations, as well as the downregulated expression of Neurotransmitter-related genes.	Guan et al. (2018)
		Oreochromis mossambicus	TiO_2-NPs stimulated genotoxicity	Shahzad et al. (2022)
3.	Al_2O_3- NPs	*Nile tilapia, Oreochromis niloticus*	Altered oxidative stress parameters, stress protein, and genotoxicity parameters.	Temiz et al. (2022)
4.	ZnO	*Tetraselmis suecica*	Exposure to nano ZnO shows more toxicity in the reduction of growth	Li et al. (2017)
5.	Ag	N-related microbial community	Disturbed enzymatic activities were observed after Ag NP application.	Huang et al. (2019)
6.	ZnO	*Oreochromatis niloticus*	It might affect kidney and liver function	Chupani et al. (2018)
7.	TiO	*Prochilodus lineatus*	It accumulated in the liver, muscle, and brain and decreased muscular AchE activity	Carmo et al. (2019)
8.	TiO_2	*Tegillarca granosa*	It was a neurotoxic blood clam as indicated by increased neurotransmitter concentration as well as down regulated expression of the neurotransmitter-related gene.	Guan et al. (2018)
9.	Al_2O_3	*Oreochromis mossambicus*	It was accumulated in fish liver and caused major histological effects	Murali et al. (2017)
10.	Cu	*Rutilusrutilus caspicus*	Histological changes in kidney and liver	Aghamirkarimi et al. (2017)

Impact of NPs on Fish in Water Environments

Aquatic species, particularly fish, are sensitive indicators of aquatoxicity and are significantly affected by ENPs in aquatic systems. The particles negatively affect different levels of the food chain, such as bacteria, algae, plants, invertebrates, and vertebrates, as shown by Falfushynska et al. (2022), Rana and Kumar (2022), Vali et al. (2020), and Handy et al. (2008). NPs have adverse effects on the reproductive system and the development of embryos in bony fishes like zebrafish and mammals such as mice, as shown by Sun et al. (2013) and Blum et al. (2012). The rapid expansion of nanotechnology heightens the potential risks for microorganisms. Ag-NPs are potentially detrimental to microorganisms due to their release of silver ions and production of reactive oxygen species (Zhang et al., 2016). Bacteria, ubiquitous throughout ecosystems, are essential in the food chain and contribute to environmental activities. They are in aquatic habitats and have lower susceptibility to NP toxicity than other organisms due to their ability to adapt to stress and strengthen their defense systems (Freixa et al., 2018).

The routes by which fish come into contact with ENPs impact their absorption and the magnitude of their potential impacts on fish. Fish absorb environmental NPs via consuming animals such as algae, weeds, insects, worms, and *Tilapia mossambica* that may contain ENPs. Demersal species are exposed to or eat ENPs that have accumulated in sedimented aggregates. Uptake can also happen by drinking water consumption. Various studies have demonstrated that NPs can cause different physiological issues in fish, such as reproductive toxicity, developmental toxicity, and respiratory problems. Several studies have demonstrated that NPs can cause histological alterations and affect the genetic material of fish (Khan et al., 2017; Bacchetta et al., 2017; Qualhato et al., 2017; Kumar et al., 2020; Abdel-Khalek et al., 2020; Khan et al., 2018). Fish species like *Labeo rohita*, *Tilapia mossambica*, and *Oncorhynchus mykiss* saw changes in their blood composition due to NP poisoning. ENPs, when introduced into natural water systems, attach to fish gills or skin due to their distinctive surface features and high surface free energy through absorption or adsorption. Atlantic salmon gills exhibited elevated silver concentrations in comparison to the gastrointestinal system after being exposed to silver NPs in water. Food intake led to increased silver concentrations in the gastrointestinal system (Kleiven et al., 2018). CuO-NPs and ZnO-NPs were shown to accumulate in the intestines of *Carassius auratus* at concentrations 10 times higher when exposed to water compared to food intake (Ates et al., 2015). Once attached to the fish, ENPs are moved through diffusion or endocytosis into the intracellular environment or across the epithelium (Oprsal et al., 2021; Geppert et al., 2021). The chemicals attach to specific receptor locations on the cell membrane and are subsequently taken into the cell through internalization. ENPs have been detected in multiple organs such as the kidney, gills, muscles, brain, gonad, hepatopancreas, and liver (Figure 1).

The presence of TiO_2-NP in the organs/tissues, cytoplasm, and nucleus of *Centropomus parallelus* confirms the uptake of ENPs. The internalization and movement of ENPs are affected by the particle size. Ag-NPs of 20 nm were transported to the basolateral membrane, while those of 110 nm were stuck on the apical membrane (Osborne et al., 2015). Upon entering the cell, ENPs engage with many intracellular components, impacting cellular functions. Differences in uptake, internalization, and translocation among species can result in different levels of toxicity. ENPs are used in several sectors due to their outstanding characteristics. ENPs affect the ability to kill bacteria and viruses in healthcare settings by interfering with cell membranes, producing reactive oxygen species, inducing oxidation, destabilizing proteins, damaging DNA, and releasing toxic substances. Other organisms in the biosphere, including fish, may potentially be affected by the same outcomes. The negative impact of ENPs in natural water habitats varies from the toxicity shown in fish laboratories where ENPs are deliberately added. Concentration levels in laboratories are usually far greater than those observed in natural aquatic systems. Recreating natural aquatic systems is difficult because of the differences in non-living and living factors, as well as ecological-geological conditions. ENPs can alter their toxicity when interacting with different components in natural aquatic environments. Lee et al. (2022) discovered that Ag-NPs and ZnO-NPs caused no harm to developing zebrafish embryos in their natural aquatic environment, but exhibited significant toxicity when the embryos were exposed to water containing Ag-NPs or ZnO-NPs. While ENPs in natural aquatic systems may now be present in low concentrations, there is a possibility for buildup and harm to the aquatic environment. The toxicity of ENPs can fluctuate depending on the aquatic setting and the behavior of ENPs post-absorption by fish. Particle characteristics including size, shape, surface charge, surface coatings, and qualities of exposure media impact fish toxicity as stated by Monikh et al. (2022). Factors such as ENP content, stability in fish after uptake, interaction time, and accumulation in tissues and organs affect fish toxicity.

Toxicity Mechanisms: Oxidative Stress

Oxidative stress, stemming from an imbalance between oxidants and antioxidants in the body, is a major toxicity mechanism induced by ENPs. Antioxidant enzymes such glutathione peroxidase (GPx), catalase (CAT), glutathione-S-transferase (GST), glutathione reductase (GR), and superoxide dismutase (SOD) play a crucial role in controlling levels of oxidants (Correia et al., 2019; Abdel et al., 2021; Khan et al., 2022; Temiz et al., 2022). Alterations in the activity of these enzymes are widely recognized as signs of toxicity in other organisms, such as fish when they come into contact with ENPs. Al_2O_3-NPs treatment decreased the activity of antioxidant enzymes (SOD, CAT, and GPx) in *Oreochromis niloticus*, indicating oxidative stress (Temiz et al., 2022). Oxidants, such as reactive oxygen species (ROS), can be produced during normal cellular activities or induced by external stimuli such as pollution, leading to an accumulation of ROS and causing cell damage through oxidative stress (Chowdhury et al., 2020).

Genetic harm

ENPs cause genetic harm in fish by inducing DNA damage. It can bind to DNA, induce oxidative stress, and trigger inflammatory responses, resulting in genomic changes such as DNA strand breakage, lesions, deletions, missegregation, or non-disjunction. Studies have demonstrated genetic damage, including cytoplasmic, nuclear, and DNA damages, in *Oreochromis mossambicus* when exposed to SiO_2-NPs, Al_2O_3-NPs, TiO_2-NPs, and Fe_3O_4-NPs at concentrations lower than those causing death. *Cyprinus carpio* treated with copper oxide NPs exhibited micronuclei formation and DNA damage (Vidya et al., 2018).

Disruptions to Reproductive and Developmental Processes

Research indicates that ENPs can disrupt the growth and reproduction of aquatic organisms, impacting many levels of the food web. *Daphnia magna* exposed to Titanium Dioxide NPs experienced decreased body length and reproductive capacity, which varied according to the concentration, indicating chronic toxicity. Metal oxide NPs originating from marine microalgae were found to cause reduced survival rates and abnormal growth in sea urchin larvae, according to studies conducted by Zhao et al. (2010), and Chen et al. (2015). Zebrafish that ate *Daphnia magna* containing TiO_2 NPs had higher levels of TiO_2 NPs than those that were just exposed to a TiO_2 NP solution, showing the transfer of NPs through ingestion (Cedervall et al., 2012). Nano-polystyrene in the aquatic food chain has significant effects on the behavior and lipid metabolism of fish, as demonstrated by Bai et al. (2010). Studies show that enhancing the food chain is crucial for the accumulation of toxins at higher trophic levels, which can later move from aquatic to terrestrial ecosystems, posing a potential threat to humans (Bundschuh et al., 2016).

Accumulation and transmission of ENPs across the food chain

Fish and other aquatic organisms play a vital role in nutrient cycles, and the buildup of ENPs poses a significant threat to human survival (Figure 2). Thoroughly studying the intricate relationships of these NPs in water settings is necessary to understand their effects on the transfer via the food chain and the resulting concentration increase. Persistent environmental contaminants can disrupt fish development, reproductive, and nutritional systems. Furthermore, these manipulated nanomaterials infiltrate the human diet by being consumed by fish after becoming part of the aquatic food chain. Phytoplankton and algae are essential nutritional sources for small fish and zooplankton, establishing the foundation of this food chain. An important study demonstrated the accumulation of Ag-NPs at higher concentrations in organisms as they progress up the food chain, offering valuable information about trophic toxicity. The investigation revealed bioconcentration factor (BCF) values of 826 for *Dunaliella salina*, 131 for *Artemia salina*, and around 1000 for *Poecilia reticulate* within the food chain. The BMF values exceeding 1 in fish exposed to prawns with Ag-NPs suggest the potential for biomagnification of Ag-NPs across trophic levels (Babaei et al., 2022). Zinc oxide NPs, cobalt NPs, and titanium dioxide NPs have biomagnification factors more than 1, demonstrating the complexities of trophic transfers (Skjolding et al., 2014; Li et al., 2022; Mei et al., 2021).

The study of metallic nanoparticles (MNPs) in aquatic ecosystems remains largely unexplored despite the current knowledge acquired. Renault et al. (2008) observed the buildup of Au-NPs in the digestive system of *Corbicula fluminea*, and Lammel et al. (2019) detailed the movement of CuO NPs from sediment to oligochaete worm and subsequently to three-spined stickleback. Additional comprehensive research is needed to investigate the intricate differences in absorption, bioaccumulation, and trophic transmission between MNPs and their non-nanoparticle equivalents. Comprehensive studies and in-depth analyses of complex trophic food chains are essential for comprehending the detailed processes of MNP trophic transfer in aquatic ecosystems (Renault et al., 2008; Lammel et al., 2019; Zhao et al., 2017).

Challenges persist in fully grasping the fate and transport of NPs in aquatic ecosystems. Short-term studies utilizing basic two-step food chains for 7-10 days may lack the required intricacy for a thorough evaluation. Utilizing algae as producers and crustaceans, bivalves, or snails as consumers provide little comprehension. Thorough research is essential to comprehend the chemical and physical transformations of MNPs at various trophic levels to better understand their intricate benefits and potential hazards (Zhao et al., 2017).

Understanding the intricacies of nanoparticle absorption in aquatic organisms

Understanding the complicated interplay between NPs and aquatic animals is vital for evaluating the broader consequences on ecosystem structure and function. Bioavailability and uptake investigations serve as crucial bridges between the ambient chemistry of NPs and their biological impacts (Dai et al., 2015; Ramskov et al., 2015; Pang et al., 2013; Cozzari et al., 2015). Central issues in this domain comprise the subtle first contact of NPs with external organism surfaces, wherein the features and behaviors of NPs greatly impact bioaccumulation. Particle size, content, shape, and synthesis process emerge as critical elements determining bioaccumulation dynamics. Notably, studies reveal that nano-sized particles demonstrate heightened bioavailability to invertebrates compared to their bulk or micron-sized counterparts (Pang et al., 2013; Cozzari et al., 2015).

In the context of fish, NPs play the role of alien chemicals, interrupting normal physiological functions during both embryonic development and growth stages (Kim et al., 2013). The primary mechanisms of nanoparticle toxicity in animals involve oxidative stress, genotoxicity leading to DNA breakage, and eventual cell apoptosis (Kim et al., 2013). NPs may potentially produce abnormalities in embryonic tissues, becoming deadly (Ahmad et al., 2015). Size plays a vital role, as the minuscule dimensions of NPs permit penetration into cells, altering cell membrane structure and function, consequently affecting ion transport systems and signal transduction.

The positive electric charges of NPs and their precisely designed surface coatings further contribute to the disintegration of membrane lipid bilayers and impair cellular structures (Hondroulis et al., 2014). Once ensconced within the cell, NPs infiltrate organelles like mitochondria, interrupting basic metabolic activity and potentially leading to cell death (Suganya et al., 2019). The ramifications extend to microbes, which play a critical role in nutrient cycling across ecosystems, and their absence could limit essential bio-accessible elements (Isobe et al., 2014). In addition, the toxicity of NPs can potentially be altered by the interaction of other toxicants or organic materials present in water bodies (Yan et al., 2014). NPs entering algal cells display a diverse impact on cellular structures, including the careful breakdown of cell walls and membranes (Wang et al., 2016; Hu et al., 2014). Deposition in the periplasmic space, and contact with organelles like chloroplasts, vacuoles, endoplasmic reticulum, Golgi apparatus, and mitochondria lead to structural and functional modifications (Bhuvaneshwari et al., 2015; Zhao et al., 2016). NPs can harm chloroplast membranes, disturb thylakoid grana lamellae, and impair mitochondrial activity, impacting metabolic processes (Zhao et al., 2016). Penetrating the nucleus causes aberrant nuclear effects, chromatin clumping, and DNA damage, which impede the cell division process (Hu et al., 2014; Karen et al., 2008).

In summary, NPs' entry into algal cells wreaks havoc on cellular structures, drastically affecting metabolism and reproductive activities. These intricately engineered interactions shed light on the profound impacts of NPs on aquatic biota, underscoring the need for comprehensive studies to decipher the broader consequences on ecosystem structure and function (Kim et al., 2013; Pang et al., 2013; Hondroulis et al., 2014; Hu et al., 2014; Ramskov et al., 2015; Bhuvaneshwari et al., 2015; Dai et al., 2015; Cozzari et al., 2015; Ahmad et al., 2015; Zhao et al., 2016; Wang et al., 2016; Suganya et al., 2019; Isobe et al., 2021).

Analytical Techniques and Detection: Navigating the Vast Aquatic Realm of ENPs

In the modern scientific adventure across aquatic habitats, analytical techniques serve as our guiding stars. Spectroscopy, functioning as our compass, deciphers the spectral signatures of ENPs, while electron microscopy works as our magnifying glass, unveiling the minute intricacies of ENP morphology and structure. Chromatography, comparable to a divining rod, extracts ENPs from the sea of natural particles. Yet, this technological journey is not without hurdles, from identifying ENPs amidst natural particles to detecting low concentrations and navigating the dynamic transformations of ENPs in complicated environmental matrices. Only through the relentless application of rigorous procedures can we overcome these hurdles and effectively monitor and estimate the risks.

Regulatory Framework: Navigating ENP Oversight in the Regulatory Seascape

In the wide ocean of regulatory frameworks, the supervision currents of ENPs ebb and flow under the effect of international collaboration. However, rocky shoals and perilous waters develop in the form of gaps in standardized testing techniques and procedures, casting shadows on our navigational maps. International initiatives, like lighthouses on faraway shores, guide us toward safer harbors where regulations are harmonized, and knowledge gaps are closed. Together, let us navigate these waters, forging a road toward transparent and accountable ENP management to conserve our aquatic habitats.

Mitigation and Remediation Strategies: Weaving Threads of Innovation and Sustainability

In the enormous tapestry of environmental stewardship, we intertwine threads of innovation and sustainability to develop mitigation and remedial techniques against ENP contamination. Like alchemists of old, we create ecologically beneficial NPs, changing the base materials of pollution into solutions for environmental restoration. With the accuracy of master artisans, we create wastewater treatment technologies that sculpt systems to purify waters from ENP pollutants. Through sustainable nanomaterial design, we construct a landscape of resilience where pollution encounters eco-friendly solutions. Embark on this transformative journey, constructing a narrative of hope and restoration for our aquatic ecosystems.

Conclusion

In recent years, progress in nanotechnology has made it possible to include newly engineered nanoparticles in nearly all commercial products to achieve economic advantages. The growing use of nano-enabled products is leading to the release of significant amounts of ENPs into various environmental compartments throughout the product lifecycle. Exposure of ENPs to many species results in harmful impacts on their growth and survival. When exposed to light, photoactive ENPs such as ZnO and TiO2 are harmful to organisms even at concentrations lower than 1mg per liter. The main cause of nanotoxicity in microorganisms and multicellular organisms, including mammals (humans), is oxidative stress resulting from the overproduction of reactive oxygen species (ROS). Generally, interactions between ENPs and plants tend to have stimulatory effects at low concentrations and inhibitory effects at high concentrations. ENPs induce phytotoxicity by altering metabolic pathways, affecting both physiological and morphological aspects. Plants react to ENP particles by changing the expression of various genes relevant to distinct biological processes. The toxicity of ENPs to different species is determined by parameters such as exposure concentration, type of exposure, organism growth stage, habitat, and environmental circumstances. Managing nano-waste is critical since roughly 90% of ENPs in nano-products are disposed of in landfills or sewage sludge worldwide. In many countries, particularly in poorer ones, the disposal of nano waste at open landfill sites or its use on agricultural fields exacerbates the situation. It is necessary to employ sustainable ways of generating nano-enabled items and managing nano-waste in an eco-friendly manner. Phytoremediation of locations contaminated with nanowaste, together with transforming plant biomass into renewable energy sources and green synthesis materials, is a good strategy.

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