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Ecotoxicity of Nano-Metals and Nano-Plastics on the Aquatic Systems: A Review

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ABSTRACT

The expansion of various nanotechnology applications leads to the transfer of nanoparticles of various types, shapes, and sizes into aquatic systems, causing serious effects on humans, plants, animals, and other organisms. This prompts researchers to study the behavior, transport, and effects of these particles on biological systems, particularly to gain a deeper understanding of the hazardous effects of nanoparticles. Nanomaterials enter the food chain through multiple pathways, including industrial waste, sewage, and agricultural runoff. They are absorbed by aquatic organisms such as algae and bacteria and are then transferred to larger organisms via predation, leading to bioaccumulation at higher trophic levels such as fish, birds, and humans. Over time, this accumulation multiplies the effects of pollution. Prolonged exposure to these materials can lead to serious health problems, such as liver toxicity, lung damage, and cancer, especially when particles accumulate in tissues and organs. The main mechanisms of toxicity include free radical formation, membrane damage, and interference with cellular metabolism, leading to tissue damage and death. Therefore, there is an urgent need for extensive studies to better understand the environmental and biological effects of nanomaterials, with the aim of developing effective methods to mitigate their toxic effects on ecosystems and human health.

INTRODUCTION

With the great advances in nanotechnology, nanomaterials have become an essential part of many industries, such as food or packaged foods, textiles, optoelectronics, biomedicine, cosmetics, power, and catalysis. Nanomaterials exhibit unique properties, such as superior mechanical strength, surface interaction, optical properties, and electrical conductivity. For example, nanoparticles are used in cosmetic sunscreens to improve the effectiveness of UV protection, while nano-encapsulation materials are used in the food industry to extend shelf life and reduce contamination. These properties make nanomaterials play a crucial role in the development of many commercial products and processes **(Larguinho *et al*., 2014; Rudramurthy & Swamy, 2018)**.

Volcanic eruptions, fires, and aerosols are major natural sources of nanoparticles that disperse through the atmosphere over long distances, along with anthropogenic sources and industrial waste. The expanding use of fossil fuels has also led to a significant increase in the spread of nanoparticles, raising concerns about their potential environmental hazards. Nanomaterials are widely used in various industries and negatively impact the environment in manufacturing, transportation, consumption, and disposal processes. This leads to their deposition in water bodies and soil **(Wang *et al.*, 2019)**. Due to their nanoscale dimensions and unique properties, these materials can accumulate in ecosystems, potentially causing long-term environmental and health problems **(Faizan *et al.*, 2018; Ur Rahman, 2021)**. Previous studies have demonstrated that nanomaterials can harm living organisms through their physiological and chemical interactions **(Hou *et al*., 2019; Awashra & Piotr, 2023; Zhao *et al*., 2023)** For example, metal oxide nanoparticles, such as zinc oxide and titanium dioxide, have been shown to damage DNA, generate free radicals, and induce oxidative stress in living cells. These effects may also cause cell death or, in some cases, cancerous transformation **(Larue *et al*., 2021)**.

Nanomaterials also impact the environment in a variety of ways. In soil, they can alter chemical and physical properties, affecting the growth and activity of plants and microorganisms **(Khan *et al*., 2021; Xu *et al*., 2022)**. In aquatic environments, nanoparticles can contaminate water resources, disrupting the life cycle and distribution of aquatic organisms, changing water quality, or accumulating in surface sediments **(Zhao *et al*., 2018)**. In addition to environmental impacts, nanomaterials pose significant risks to human health. Nanoparticles can accumulate in essential organs, including the lungs, liver, and kidneys, leading to serious health problems, including infections, respiratory diseases, and cancer. Inhaling nanoparticles can also damage the respiratory system and contribute to the development of chronic diseases **(Wang *et al*., 2019)**. While nanomaterials offer promising opportunities for developing industrial production strategies and addressing environmental challenges, they also pose significant risks **(Feng *et al*., 2020; Domb *et al*., 2021; Siquan *et al*., 2024)**. The risks that arise from nanomaterials require an urgent need to understand their ecological and health effects, expand the scope of safe processing technologies, and establish effective regulatory frameworks **(Chávez-Hernández *et al*., 2024; Campalani & Monbaliu, 2025)**. Continued research on this topic is critical to balance the benefits and risks and to ensure this advanced technology's sustainable and responsible use **(Nguyen *et al*., 2023)**.

Future research in nanomaterials should focus on studying their effects on various ecosystems and developing novel technologies to detect and mitigate their harmful effects. Comprehensive studies of the interactions between nanomaterials and unique organisms, including algae, are crucial to understanding these interactions' organic and chemical mechanisms. Nanomaterials should also be manufactured and developed using new, ecofriendly technologies **(Aruoja *et al*., 2015)**. Despite the significant interest in nanomaterials, many important aspects remain unexplored. Notably, there is limited understanding of the environmental transformations these materials undergo after release and how these changes influence their toxicity. Research has focused primarily on acute effects, without adequately addressing chronic toxicity and bioaccumulation through food chains. Furthermore, realistic environmental modeling and testing under natural conditions hinder accurate risk assessment. Furthermore, the effects of environmentally transformed nanomaterials may also affect non-target organisms, especially within complex and interconnected ecosystems. Elucidating the molecular mechanisms of toxicity and how these particles interact with vital biological processes remains a pressing challenge that requires further research **(Nthunya *et al*., 2025)**.

Physicochemical properties of nanomaterials

Nanomaterials are particles ranging in diameter from 1-100 nanometers. This size range is crucial due to their unique chemical and physical properties, driven by their behavior on such small scales. For example, these materials often exhibit increased reactivity due to their high surface area-to-volume ratio, enhancing their ability to interact with other materials. The effect of nanomaterials depends on the shape, size, topography and type of the material, the NPs surface represents the binding sites for other materials, as well as its containing of functional groups and the type of surface charge (Fig. 1) **(Hossain *et al*., 2021)**. Additionally, these materials exhibit unique mechanical or optical properties and specialized or high-energy light absorption capabilities. Their nanoscale size gives them distinct physical and chemical properties that distinguish them from larger materials **(Vasyukova *et al*., 2021; El-Kalliny *et al*., 2023)**. These properties include a high specific surface area, which greatly increases their interaction with other materials. They also exhibit distinctive optical properties, such as fluorescence, which can be valuable for applications in both optics and electronics. Moreover, many nanomaterials have high thermal and electrical conductivity. For example, nanoparticles are incorporated into composite materials to improve energy transfer in solar panels, or to enhance electrical performance and reduce heat loss in electronic circuits, making them particularly suitable for use in electronics and thermal components. Their combination of energy efficiency and light weight makes them ideal for integration into composite materials and superior structural designs **(Wang *et al*., 2019; Nagaswarupa *et al*., 2024; Radhakrishnan *et al*., 2024; Salaudeen *et al*., 2024)**.

In the environment, nanomaterials interact with aquatic components, whether in the water column or sediments, including biological components, causing both beneficial and harmful effects. Their small size allows them to be easily absorbed by living organisms, which can lead to their accumulation in food chains. For example, titanium dioxide nanoparticles can interact with environmental pollutants, such as heavy metals, neutralizing them or forming more hazardous compounds **(Wang *et al.*, 2018; Emamverdian *et al*., 2022)**. Furthermore, nanomaterials can bind to environmental pollutants, producing synergistic effects that neutralize these environmental toxins or form more toxic compounds **(Wang *et al*., 2018; Emamverdian *et al*., 2022)**. Contact with nanomaterials may cause adverse effects on human health, including skin toxicity and long-term health risks, when inhaled or exposed to the skin. On the other hand, nanomaterials can bind to environmental pollutants, producing synergistic effects that neutralize these environmental toxins or form more toxic compounds **(Asghar *et al*., 2024)**. The studies have shown that inhaling carbon nanotubes can cause pneumonia and pulmonary fibrosis, which can cause respiratory damage **(Vasyukova *et al*., 2021; Mahawar *et al*., 2023)**.

Industrial, medical, and agricultural applications of nanomaterials

Nanomaterials possess exceptional chemical and physical properties that enable advanced applications in fields such as medicine, agriculture, industry, and others, as shown in Table (1) **(Hussain, 2018)**.

In industry, nanomaterials are used to improve performance and efficiency. For example, nanoparticles are added to scratch- and corrosion-resistant coatings **(Wu *et al*., 2020)**. Titanium dioxide nanoparticles are used in automotive and aircraft coatings, providing additional protection against ultraviolet radiation and extending the life of these surfaces **(Ghamarpoor *et al*., 2023)**. Some studies indicate that these coatings can extend the life of surfaces by up to 30% **(Allen *et al*., 2018; Stroea *et al*., 2021; Gao *et al*., 2024)**. Furthermore, nanotechnology has revolutionized the world of electronics, where carbon nanotubes are contributing to the development of more efficient and smaller devices, such as smartphones and high-resolution displays, while also improving battery performance. For example, carbon nanotubes have been used in the manufacture of high-performance batteries for electric motors, helping to improve energy efficiency and reduce battery weight, enhancing the overall performance of electric vehicles **(Thomas *et al*., 2019)**.

In medicine, nanomaterials have revolutionized diagnosis and treatment. Nanoparticles are used in clinical imaging to detect tumors with high accuracy, while gold nanoparticles are used as contrast materials in radiological imaging. These materials have also facilitated the introduction of smart drug delivery systems, where capsules are attached to nanoparticles that specifically target diseased cells, improving treatment efficacy and reducing side effects **(Pham *et al*., 2020; Veg *et al*., 2025)**. Furthermore, nanomaterials are used to design prosthetic limbs and advanced biosensors, expanding their clinical applications **(Akgöl *et al*., 2021)**.

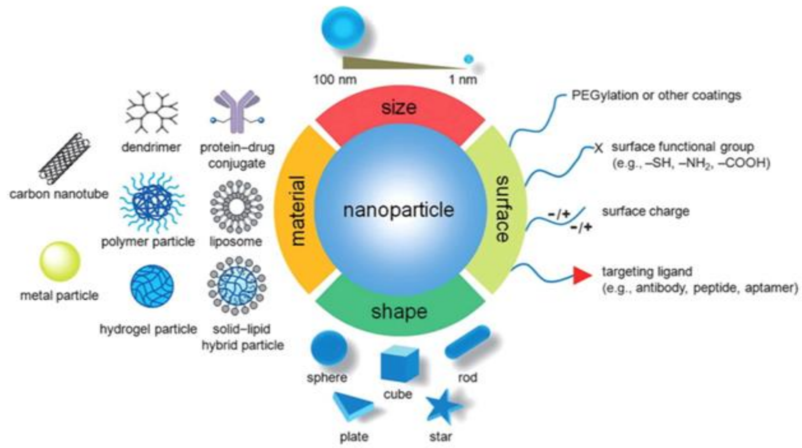

Fig. 1. Forms and applications of nanomaterials **(Hossain *et al*., 2021)**

In agriculture, nanomaterials are crucial in improving productivity and supporting environmental sustainability. They are used to manufacture nano-fertilizers and nano-pesticides, which gradually release minerals, nutrients and active ingredients, improving absorption efficiency while reducing environmental pollution. For example, zinc oxide nanoparticles promote plant growth and combat plant diseases **(Singh *et al*., 2018)**. In addition, nano-sensor systems are being used to monitor soil and water quality with high precision, enabling more informed agricultural decisions **(Santos *et al*., 2015; Mabrouk *et al*., 2021)**. These examples highlight how nanomaterials are emerging as a keystone of scientific and technological innovation. Their diverse applications in important fields not only improve quality of life and productivity but also reduce negative environmental impacts, making them an integral part of future developments **(Aruoja *et al*., 2015)**.

Table 1. Quantities and applications of nanometals and their products with potential environmental problems according to **Bhuvaneshwari *et al*. (2018)**

Nanometal Compound	Quantities (T/Y)	Applications and Uses	Environmental/Health Considerations
Titanium Dioxide (TiO_2)	3000	Cosmetics, paints and coatings, filters, consumer electronics, plastics, cleaning agents	Aquatic toxicity and possible environmental persistence; inhalation in occupational settings. concerns in occupational settings
Zinc Oxide (ZnO)	550	Cosmetics, paints and coatings, plastics/polymers	UV-blocking properties but potential for bioaccumulation and cytotoxic effects
Cerium Oxide (CeO_2)	55	Fuel catalyst	Can contribute to nanoparticle emissions in air, affecting respiratory health
Silicon Dioxide (SiO_2)	5500	Paints, coatings, fireproof glass, UV-protection, ceramics, electronics, food, plastics, sunscreen	Generally regarded as safe but inhalation may cause lung inflammation

Aluminum Oxide (Al_2O_3)	55 (AlO_x)	Batteries, grinding, fire protection, metal- and biosorption, paints	Possible lung irritation and bioaccumulation risks
Iron Oxide (Fe_2O_3)	55 (FeO_x)	Concrete additive, biomedical uses	Low toxicity, but potential for oxidative stress in cells
Manganese (III) Oxide (Mn_2O_3)	-	Catalytic applications	Environmental persistence and potential neurotoxicity concerns
Zirconium Dioxide (ZrO_2)	-	Biomedical applications as component of bioceramic implants	Generally biocompatible, but long-term stability needs further research
Magnetite (Fe_3O_4)	55 (FeOx)	Biochemical assays, removal of contaminants, biomanipulation	Can be used in remediation but may pose bioavailability risks in aquatic systems

Note: The isoelectric point (IEP) refers to the pH value at which the particles' net surface charge is zero. Changes in IEP are significant as they indicate interactions between nanomaterials and microorganisms, influencing adsorption processes and stability in different environments.

Nanotoxicity of algal cells

Algae are the primary source of oxygen and food for other organisms in aquatic ecosystems. Perhaps the most serious issue is the extent of the harmful impact of nanomaterials on algae **(Pohanka, 2019; Naz *et al*., 2020; Lau *et al*., 2022)**. Algae play a significant role in remediating certain pollutants in aquatic environments, which makes them more vulnerable to the accumulation and adverse effects of these substances **(Al-Shammari & Al-Janabi, 2022; Al-Shammari & Al-Janabi, 2023)**. The results of some studies have proven that metal oxides and nano-plastics inhibit algal growth and alter their physical functions **(Bhuvaneshwari *et al*., 2015; Wells *et al*., 2017)**. For example, copper oxide nanoparticles were found to inhibit algal growth and alter their biochemical composition; however, they ultimately reduce photosynthetic efficiency **(Bhuvaneshwari *et al*., 2015; Wells *et al*., 2017; Naz *et al*., 2020; Lau *et al*., 2022)**. CuONPs nanoparticles exhibit toxic effects on microorganisms due to the high interaction of copper with cellular components **(Naz *et al*., 2020; Mahana *et al*., 2021)**.

The toxic effects of Nano toxic metals on algae include:

1. **Release of copper ions (Cu^{2+}):** Copper oxide nanoparticles release copper ions into the aquatic environment. These are toxic to algal cells and may inhibit critical metabolic pathways **(Mahana *et al*., 2021)**. Copper ions bind to movable components, such as proteins and nucleic acids, causing damage by binding to them and thus inhibiting their growth.

$$H_2O + Cu+2 \rightarrow H_2 + O + CuO(s)$$

2. **Induction of oxidative Stress:** Copper oxide nanoparticles stimulate the generation of reactive oxygen species; hence, oxidative stress leading to damage at the cellular level.

$$2H_2O + Cu+2 \rightarrow OH- + OH. + Cu+$$

According to **Dash *et al*. (2012)**, hyperactive species such as OH; damage proteins, lipids, and nucleic acids within cells.

3. **Alteration in the biochemical Composition**: The exposure of algae to nanoparticles of copper oxide will result in changes in algal biochemical composition through a number of mechanisms.

- **Protein and lipid degradation**: Free radicals generate oxidative stress that leads to intracellular protein and lipid degradation.
- **Reduction in nucleic acid Levels:** Copper binds to nucleic acids, causes damage, and decreases a cell's ability to divide and grow.
- **Effect on photosynthetic pigments**: Inhibition by copper oxide nanoparticles of chlorophyll degradation and of other pigments necessary to photosynthesis **(Naz *et al*., 2020)**.

4. **Inhibition of photosynthesis** Copper oxide nanoparticles directly interfere with photosynthesis by disrupting the electron transport chain within chloroplasts, thus impairing conversion of light energy to chemical energy **(Pohanka, 2019)**.

- **Chlorophyll breakdown**: Oxidative stress precipitates chlorophyll degradation thereby lowering the absorption of light **(Cuong *et al*., 2022)**.
- **Photosynthetic equation impact**:

$$6CO_2 + 6H_2O + light\ energy \rightarrow C_6H_{12}O_6 + 6O_2$$

- Damage to chlorophyll or the electron transport system impedes the continuation of the process, reducing the production of oxygen and glucose needed for growth. Research also highlights the ability of nanoparticles to interact directly with algal DNA, causing DNA damage and the production of reactive oxygen species (ROS) **(Chifiriuc *et al*., 2016)**. These interactions may include the generation of gene mutations and cell death. Nanoparticles act on DNA through their physicochemical properties, which may include their size, surface charge, and ability to produce ROS, among others, leading to multiple pathways of varying genetic and cellular metabolic damage **(Gehr, 2018)**.

Transport and distribution of nanomaterials in the environment

The growing use of nanomaterials in industries, consumer products, and medical applications raises significant concerns about their fate and transport in environmental systems. Nanomaterials can enter ecosystems through direct or indirect discharges into water and soil. For example, they may reach aquatic environments via industrial effluents, treated wastewater discharge, or surface runoff from soils affected by erosion **(Lead, 2008)**. Commonly studied nanomaterials such as titanium dioxide and silver nanoparticles are frequently found in these environmental pathways, raising concerns about their potential impact **(Passarelli *et al*., 2020)**.

Once in the environment, nanomaterials undergo various transformations influenced by their intrinsic properties and the characteristics of the surrounding medium. These transformations include chemical and physical processes, such as dissolution, aggregation, and biological degradation of surface coatings designed to stabilize them (Table 2), according to **Joo and Zhao (2017)**. For instance, dissolution of nanoparticles can release toxic ions into the environment **(Abbas *et al*., 2020)**. While aggregation can affect their mobility and ability to interact with organisms **(Conway *et al*., 2015)**. Biological degradation of surface coatings may expose more reactive surfaces, potentially increasing their toxicity **(Yang *et al*., 2024)**. These processes significantly affect the environmental impact and toxicity of nanomaterials, altering their potential risks to ecosystems and human health **(Wagner *et al*., 2015)**.

In aquatic ecosystems, nanomaterials can interact with natural particles, minerals, and organic matter, affecting their distribution and mobility **(Wang *et al*., 2022)**. These interactions often lead to aggregation, altering their behavior and transport **(Lead, 2008)**. Their toxicity is influenced by interactions with living organisms, such as adsorption onto cell surfaces, disruption of cellular membranes, and interference with nutrient transport. This occurs primarily through the binding of nanomaterials to glycoproteins and lipid bilayers on cell membranes. Positively charged nanoparticles, for instance, strongly adhere to negatively charged cell membranes, compromising membrane integrity and essential functions **(Hou *et al*., 2019; Egbuna *et al*., 2021)**.

Nanomaterials also exhibit high surface-to-volume ratios and unique surface properties, enabling interactions with biomolecules that amplify their environmental impact. For example, titanium dioxide nanoparticles generate reactive oxygen species (ROS), which cause damage to cellular membranes and proteins. Similarly, silver nanoparticles disrupt ion transport by strongly binding to cell membranes, altering membrane permeability and ion channels **(Rawat *et al*., 2018)**. Nanomaterials can aggregate with other particles, modifying their mobility and toxicity **(Naasz *et al*., 2018)**. They also interact with natural organic matter, which affects their surface charge, mobility, and interactions with organisms. These interactions often result in nanomaterials accumulating in sediments, where they may persist and pose long-term environmental risks **(Misra *et al*., 2012)**.

Table 2. Factors influencing the fate and transport of manufacture nano particles **(Joo & Zhao, 2017)**

MNPs	Factor	Mechanism	Comment
TiO_2	Contaminant (Cd)	Adsorption	Affinity of contaminant molecules affects MNPs fate.
TiO_2	Contaminant	Adsorption	Particle size is the most critical parameter, while little impact of MNP dosage.
TiO_2	Hg, second metal NPs (SiO_2)	Adsorption to SiO_2-TiO_2	Increased toxicity to microbes, compared to Hg adsorption on single MNP (TiO_2).
Iron Oxide	Contaminant (As)	Adsorption, Co-precipitation	Adsorption is proportional to surface areas.
CeO_2	Contaminant (T-N)	ROS generation from CeO_2 NPs	Removal efficiency of TN decreases as CeO_2 NP concentrations increase.
CeO_2	pH, NOM, agglomeration, dissolution	Release of Ce^{2+}	Primary factors: solution pH and amount of suspended matter; dissolution of CeO_2 NPs negligible over 7 days.
CuO	pH, NOM, agglomeration, dissolution	Release of Cu^{2+}	Extent of aggregation affects toxicity of CuO NPs.
ZnO	Temperature, Organic acid	Dissolution of ZnO and release of Zn^{2+}	Increasing temperature (reducing solubility of ZnO through the release of heat) → increased aggregation → decreased dissolution.
Fe/Al Oxides	Contaminant (*E. coli*), pH, ionic strength	Adsorption, Non-electrostatic and electrostatic forces	Electrostatic charge as the primary factor of the adsorption of *E. coli* on the two model MNPs. The adsorption of *E. coli* decreased IEP of Fe/Al oxides.

The environmental risk assessment of nanomaterials remains challenging, primarily due to difficulties in accurately measuring their concentrations in natural environments. Current estimates suggest that these concentrations are often below levels known to cause significant ecological harm. However, the potential for unexpected impacts emphasizes the need for continued research **(Lowry *et al*., 2012a)**. During wastewater treatment, nanomaterials can undergo significant transformations, such as the conversion of silver nanoparticles into less toxic silver sulfide particles in sulfur-rich conditions. These materials may also interact with metallic and organic components, leading to sedimentation and aggregation into sludge, which can be reused as activated sludge **(Lowry *et al*., 2012b; Zhang *et al*., 2012)**.

Behavior of nanomaterials in the environment

The environmental behavior of nanomaterials is determined and influenced by their physical and chemical properties, including size, shape, surface composition, and charge. In aquatic environments, these materials impact their mobility, stability, and interactions with organic matter, including organic molecules, metals, and pollutants **(Zheng *et al*., 2019)**. Small-sized nanomaterials harmoniously interact with surrounding molecules, enhancing their dispersibility and reactivity toward soils and biological membranes. Carbon nanotubes, for example, have aspect ratios that are very high in length compared to their diameter, thus they can easily adhere to organic particles, thereby increasing aggregation or adsorption onto surfaces **(Albanese *et al*., 2012)**. Surface composition is also essential. Water-dispersible functional groups, like hydroxyl or carboxyl, can stabilize nanomaterials in water or alter the nature of their interaction with pollutants. Bare particles are more likely to aggregate and lose mobility **(Demir, 2021)**. Surface charge is the most critical parameter governing the behavior of nanomaterials; positively or negatively charged particles strongly interact with oppositely charged pollutants or biological membranes. For example, positively charged nanomaterials will readily adsorb on the negatively charged cell membrane, offering a potential pathway for direct toxic effects. Besides these, further solubility introduces them to the dispersion and increases the likelihood of interaction with organisms or transfer through food chains **(Griffitt *et al*., 2008)**. Nanomaterials are pollutant carriers, effectively transporting pollutants across environmental media or leading to the localized accumulation of pollutants. For example, titanium dioxide nanoparticles remain stable in polluted water as the heavy metals adsorb on the nanoparticles. Silver nanoparticles can also bind to dissolved organic molecules, which would enhance their toxicity to microorganisms **(Lead, 2008)**. Sometimes, nano-plastics have been found to aggregate with natural particles such as clay and organic matter, affecting their toxic mobility. In freshwater, they tend to form larger aggregates with particulate organic matter, while in saltwater, salinity alters their surface charge, promoting aggregation. Another important property is their ability to enable long-range transport across ecosystems, as they can easily bind with pollutants such as PCBs, heavy metals, and others **(Sakka *et al.*, 2016; Xiao *et al.*, 2018)**.

The biological approach supports the fact that nano-plastics are capable of binding to cellular membranes, hence perturbing lipid bilayers and compromising membrane permeability. This interaction primarily impairs cell barrier function, as previously mentioned, while simultaneously disabling ion channels that stimulate the production of reactive oxygen species (ROS), leading to cell dysfunction or death **(Xu *et al*., 2019; Egbuna *et al*., 2021)**. All of these factors pose significant environmental risks, accumulating in aquatic sediments and entering food chains, disrupting aquatic ecosystems **(Cunningham *et al*., 2013; Larue *et al*., 2014)**. This will play an integral role in the safety of risk assessment and the responsible use of nanoparticles. Their interactions-aggregation, sedimentation, binding to natural and biological surfaces differ vastly from the interactions that take place with larger particles. Improved knowledge of behavior will support sustainable development and safe application of nanotechnology in environmental management and public health **(Cunningham *et al*., 2013; Ang *et al*., 2019)**.

Toxicity of nanomaterials

Nanomaterials, both metallic and plastic, exhibit multiple toxic effects on living organisms in various ecosystems **(Jahan *et al*., 2017)**. Zinc oxide nanoparticles (ZnO NPs) are among the most extensively studied nanomaterials in terms of their toxic effects on living organisms **(Salieri *et al*., 2015)**. Studies indicate that exposure to ZnO nanoparticles induces the production of reactive oxygen species (ROS) and increases lipid peroxidation, adversely affecting various living organisms. In animals, the effect is primarily observed in aquatic organisms, such as fish and invertebrates, where it results in damage to cell membranes in the liver and nervous system, and disrupts ionic balance and metabolic functions **(Geitner *et al*., 2016; Eker *et al*., 2024)**. In plants, the effect occurs in root and leaf cells, leading to oxidative stress that inhibits growth and nutrient absorption processes **(Hadi & Alwan, 2025)**.

1. Toxic effects of zinc oxide nanoparticles

These effects disrupt vital cellular functions, such as in green algae, reflecting high toxicity that depends on concentration and exposure duration **(Brun *et al*., 2014)**. Copper oxide nanoparticles (CuO NPs) exhibit similar toxic effects, where exposure to these nanoparticles causes disruption in algae growth and an increase in ROS production. CuO nanoparticles interact with cellular components, leading to damage to the cell membrane and disruption of enzymatic activity essential for cellular function. These nanoparticles exhibit greater toxicity compared to traditional copper ions at the same concentration, indicating that their nanoscale size is associated with the toxic effects **(Ho *et al.*, 2018)**. Regarding plastic nanoparticles, studies show that these particles pose a significant threat to aquatic organisms. Plastic nanoparticles can aggregate with other organic materials and pollutants, further complicating their toxicity **(Kalčíková *et al*., 2017)**.

When algae are exposed to these nanoparticles, ROS production is precipitated, together with a growth within the interest of enzymes responsible for protecting in opposition to oxidative pressure **(Janova *et al*., 2021)**. This leads to the damage of cell membranes, disrupting cellular transport mechanisms. The effect occurs through changes in membrane permeability caused by oxidative stress, hindering the movement of ions, essential molecules, nutrients, and waste **(Huang *et al.*, 2021)**. As a result, the ability of algae to maintain internal stability is compromised, which disrupts growth and reproductive processes in aquatic organisms **(Kokalj *et al.*, 2019)**.

2. Complex toxicity of plastic nanoparticles

Plastic nanoparticles exhibit more complex toxic effects when present alongside other environmental pollutants such as heavy metals. For instance, the interaction of these nanoparticles with cadmium results in an increased accumulation of cadmium in living cells, significantly enhancing the toxic effects. These nanoparticles act as carriers for pollutants, resulting in synergistic interactions that amplify toxicity and pose greater risks to aquatic organisms **(van Weert *et al*., 2019)**. Scientific evidence indicates that nanomaterials, whether metal oxides or plastic nanoparticles, possess toxic properties that significantly impact the environment and living organisms. The degree of toxicity depends on several factors, including the source of exposure, duration of exposure and interaction of nanomaterials with various environmental factors **(El-Kady *et al*., 2023)**. This requires further research to fully understand their effects and develop techniques to mitigate their harmful effects **(Sundbæk *et al*., 2018)**.

Absorption of nanomaterial by aquatic organisms

Nanomaterials enter aquatic environments through various pathways, including industrial discharges, treated wastewater, and surface runoff from contaminated soils. These particles seep into rivers, lakes, and oceans, where they can interact with aquatic organisms such as algae. After entering the aquatic environment, nanomaterials begin processes of absorption and entry into the cells of aquatic organisms **(Lead, 2008)**.

One of the main ways nanomaterials enter aquatic organisms is through adsorption onto the cell surface. Nanoparticles tend to bind to cell surfaces due to their small size and high surface-to-volume ratio, which increases their interaction with cell membranes **(Chen *et al*., 2016)**. During adsorption, nanomaterials bind to sugars and proteins present on the cell surface, enhancing their accumulation on the cell membranes **(Dutta *et al*., 2007)**. For example, electron microscopy examination shows that copper nanoparticles interact with extracellular polymeric substances (EPS) secreted by algae, indicating the presence of a protective mechanism that limits the toxic effects of the nanomaterials **(Zhao *et al*., 2016)**. After adsorption onto the cell surface, nanomaterials can penetrate the cell wall through several mechanisms. One of these mechanisms is active transport, in which cells utilize specialized transport proteins to move nanoparticles across the cell membrane. Additionally, nanomaterials can enter the cell through passive delivery, utilizing gaps within the cellular wall to skip via. Research suggests that metal oxide nanoparticles, such as ZnO and CuO, can penetrate and combination with components of the cell wall, inflicting harm to the plasma membrane and leading to changes within the inner cell shape **(Xia *et al*., 2015)**. Once inside the cell, the nanoparticles can reach internal organelles such as mitochondria and the nucleus **(England *et al*., 2015)**. This transition typically occurs through a process known as bioaccumulation, where nanoparticles accumulate within the cell vacuoles. Studies have shown that copper oxide nanoparticles can cause significant damage to DNA, proteins, and lipids, leading to disruption of fundamental cellular processes and death of algal cells **(Kalman *et al*., 2015)**.

Nanomaterials in the food chain

Nanomaterials inclusive of metal oxides and nano-plastic can input the food chain via numerous pathways. This process often begins with nanomaterials entering the aquatic environment via industrial waste, sewage, and contaminated soil runoff. Once in aquatic structures, they may be taken up by organisms, such as algae and bacteria, by adsorption to cell surfaces or direct penetration of cell membranes. When small organisms, such as algae, uptake these residues, they are passed on to larger organisms via predation, thus entering the food chain **(Kalman *et al.*, 2015; Bundschuh *et al*., 2016)**.

Nanomaterials transfer through food chains by the consumption of organisms containing these materials by other organisms at higher trophic levels as **Wang *et al*. (2019)** explained in Fig. (2). For example, small fish may consume algae contaminated with nanomaterials, and then larger fish and predatory birds consume the small fish. This process results in the accumulation of nanomaterials in the bodies of organisms at each trophic level, enhancing their toxic effects as they move through the food chain **(Dalai *et al.*, 2013)**. An example of this is the accumulation of silver nanoparticles (Ag NPs). In fish. Studies have shown that chronic exposure to these residues can damage cellular tissue and accelerate the production of reactive oxygen species (ROS), resulting in damage to DNA and proteins within cells. Similarly, titanium dioxide nanoparticles (TiO_2 NPs) can cause similar effects, leading to cell damage and inhibiting metabolic processes in fish, affecting their growth and overall health **(Geitner *et al.*, 2016)**. The effects of nanomaterials on the food chain are expected to lead to reduced biodiversity and changes in the structure of food webs. The accumulation of nanomaterials in organisms can lead to dysfunctional organ functions and inhibited growth, reducing the ability of these organisms to survive and reproduce. In the long term, these effects could lead to changes in the shape of the food chain and the balance of the environment, affecting species abundance and overall ecological balance **(Gambardella *et al.*, 2014)**. In the long term, nanomaterials are expected to have significant impacts on many ecosystems. The accumulation of these materials can disrupt the stability of aquatic ecosystems, leading to biodiversity loss and a reduction in the abundance of sensitive species. Furthermore, nanomaterials may also alter ecological interactions between unusual species, reshaping food webs and having severe consequences for predatory species **(Wang *et al.*, 2019)**.

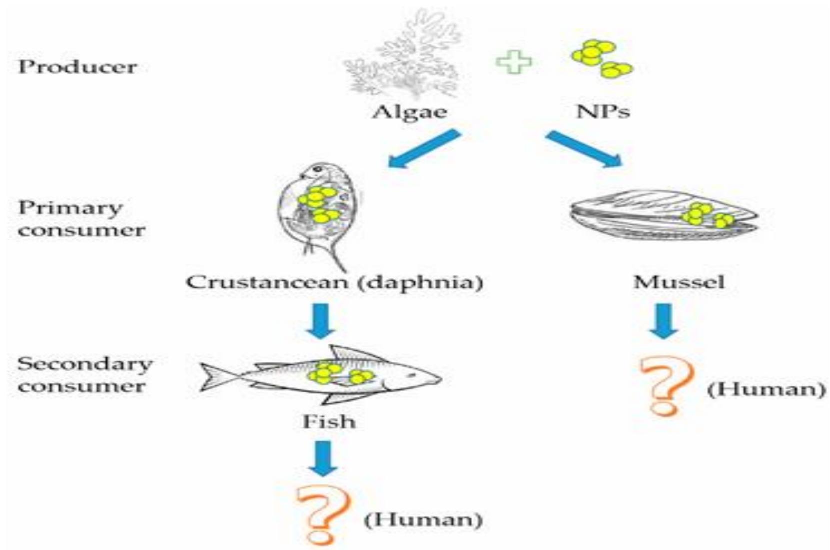

Fig. 2. Fate of NPs in the aquatic food chain **(Wang *et al.,* 2019)**

Nanomaterials can accumulate in living organisms through the food chain, resulting in severe health effects. For humans, persistent exposure to nanomaterials through the consumption of contaminated foods or consumer products can lead to health problems, including pulmonary toxicity, liver toxicity, and chronic diseases such as cancer. Studies have demonstrated that nanomaterials can penetrate natural barriers and reach vital organs, including the liver, kidneys, and brain, resulting in toxic reactions in these organs **(Wu *et al*., 2017)**. The toxic impacts of nanomaterials are not limited to individual organisms but extend to entire ecosystems. The accumulation of these materials in food chains can lead to widespread effects, threatening ecosystem stability. For example, nanomaterials can transfer from algae to microcrustaceans and then to fish, causing bioaccumulation that disrupts energy flow within the ecosystem **(Barreto & Lombardi 2016)**. A distinguish example of this is the impact of nanoplastic waste in the oceans. These wastes have been found to accumulate in the bodies of marine organisms, including fish and shellfish, resulting in toxic effects, such as increased inhibition and tissue damage. This not only affects the health of marine organisms but also extends to those who consume them as part of their diet, increasing the risk of exposure to contamination **(Yang *et al*., 2014)**.

Bioaccumulation of nanomaterials

There are exceptions to the general low toxic effects noted earlier for carbon-based nanomaterials. Biodegradation by liver and other body systems converts base forms of carbon nanotubes to other harmless degradation by-products, affording a certain degree of protection against hazards such as fibrosis. Similarly, liver degradation capabilities provide protection through one of the pathways, as the body is designed to eliminate these particles; otherwise, without a metabolic pathway, they accumulate **(Xiao *et al*.,**

2022). The bioaccumulation of nanomaterials in aquatic systems forms a dynamic and engaging environmental problem **(Bhuvaneshwari *et al*., 2018)**. Such materials combine outstanding physical and chemical aspects with a pronounced capability toward biological influence **(Zhu *et al*., 2010)**. Nanomaterials possess a large surface area and high chemical reactivity, allowing for easy interaction with biological constituents, such as proteins and cellular membranes **(Yan & Wang, 2021)**. This arrangement opens the feasibility of easy entrance of nanomaterials into aquatic organisms, their accumulation in the tissues, and their further transfer through the food chains with certain ecological effects which can reach to higher trophic levels **(Wang *et al*., 2016)**. In the aquatic environment, it is taken up by the primary producers (algae and phytoplankton) due to their active surface properties. While higher organisms consume these primary producers, nanomaterials eventually move to higher trophic levels, like zooplankton then to fish and larger marine organisms, initiating upward bioaccumulation along the food chain **(Bhuvaneshwari *et al*., 2017; Khoshnamvand *et al*., 2020)**. The transfer of nanomaterials through trophic interactions is selective by nature influenced by several factors that can sometimes change typical trophic feeding patterns in an ecosystem. Organisms at intermediate or high trophic levels often exhibit an altered feeding behavior in response to the nanomaterials **(Sendra *et al*., 2017; Hossain *et al*., 2021)**. For example, zooplankton and small fish would select not to feed on algae or some other plankton when they have a choice, and in turn, the ingestion of contaminated food decreases. This change in behavior has an impact on growth as well as reproduction rates of these organisms and consequently would create an ecological net imbalance in the aquatic system **(Babaei *et al*., 2022).**

The effects of nanomaterials on environmental factors are not limited to altering the feeding patterns of aquatic organisms; on a broader scale, they primarily result from direct impacts on the most crucial biological processes occurring within these organisms. Their accumulation in the tissues of these organisms may cause modification of biochemical interplays taking place within the cells. Such chemical substances will further cause damage to cellular components; proteins, lipids, and even DNA leading to cellular dysfunction and increased mortality rates for the contaminated organisms **(Poynton *et al*., 2019)**. Another major way through which nanomaterials can inflict harm is the disruption of major metabolic pathways. For instance, it has been demonstrated that nanomaterials interfere with the glutathione pathway, which is the most important aspect of the primary defense mechanism against oxidative stress. They also act on other pathways, such as amino acids and protein production, which are essential for growth and reproduction **(Chen *et al*., 2019)**, respectively. The manifestations are a lower nutritional value by the organisms involved, with fish being impaired and exhibited low protein content plus high lipid levels, which bear down on their nutritional value as higher consumers in the food chain **(Li *et al*., 2022)**.

Several environmental factors influence the processes of bioaccumulation and trophic transfer of nanomaterials. These include the basic properties of the nanomaterials, such as size, shape, and solubility in water. Smaller nanomaterials have a higher ability to penetrate cellular membranes and accumulate within cells. Similarly, the geometric shape of the material can affect its interaction with proteins and biological molecules **(Zhang *et al.*, 2024)**. Environmental conditions such as temperature, pH, and the presence of other organic compounds also play significant roles. For example, higher temperatures may enhance the interactions between nanomaterials and living organisms, potentially increasing their bioavailability and toxicity, whereas organic compounds in water can mitigate toxicity through interactions that reduce nanoparticle reactivity **(Silva *et al*., 2022; Dang *et al*., 2023)**.

On the other hand, certain factors can mitigate the adverse effects of nanomaterials. Organisms such as algae may reduce the concentration of free nanomaterials in the water by absorbing them into their cells, thus lowering the risks to other organisms **(Connolly *et al*., 2023)**. Furthermore, studies suggest that exposure length plays a critical role in determining the severity of nanomaterial consequences. Long-term exposure will increase the chance of bioaccumulation in dwelling organisms, even as brief-time period publicity may also have less pronounced however nonetheless significant ecological risks **(Galúcio *et al*., 2022)**. The impact of nanomaterials on aquatic structures extends beyond living organisms to the entire ecosystem. Changes at lower trophic levels have cascading effects that reach higher levels, ultimately disrupting the distribution of energy and vitamins in the food web. These disruptions can cause permanent changes in the shape and nature of aquatic ecosystems **(Gaur & Jagadeesan, 2021)**.

Toxic concentrations of nanomaterials

Monitoring the concentrations and toxicity of nanomaterials in the environment is a vital area of scientific research. With the increasing use of nanomaterials in various commercial, scientific, and technological applications, they pose significant environmental challenges, necessitating focused efforts to understand their impacts on ecosystems and biodiversity **(Bäuerlein *et al*., 2017)**. Scientists use specific terms to describe scenarios that mimic realistic conditions in which organisms are exposed to nanomaterials. Rather than focusing solely on acute toxicity assessments using unrealistically high concentrations, actual concentrations found in the environment are taken into consideration. Recent studies indicate that nanomaterial concentrations in aquatic systems typically range between 1 ng/l and 1 μg/l, with the exception of titanium-based nanomaterials, which can reach 1 mg/l in some cases **(Azimzada *et al*., 2021; Hauser & Nowak, 2021; Rand *et al*., 2021)**. The toxic effects of nanomaterials vary depending on the type of material, the content, and the target organism **(Miranda *et al*., 2016)**. For example, titanium oxide nanoparticles showed high toxicity when organisms were exposed to concentrations up to 2.4mg/ L, while silver nanoparticles showed higher toxicity at much lower concentrations, up to 1ng/ L **(Bacchetta *et al*., 2017)**.

Research indicates that nanomaterials can cause serious effects on organisms even at relatively low concentrations. For example, algae such as *Scenedesmus* spp. and *Chlorella* spp. They exhibit high sensitivity to titanium dioxide nanoparticles (TiO_2NPs), resulting in reduced growth rates and increased oxidative stress, especially at concentrations of up to 50µg/ L **(Syafiuddin *et al*., 2018)**. For microcrustaceans such as *Daphnia magna*, studies have shown that exposure to silver nanoparticles (AgNPs) at concentrations between 10 and 100ng/ L resulted in multiple effects, including DNA damage, behavioral disturbances, and long-term effects that may persist across generations **(Black *et al*., 2017)**. Fish are also exposed to low levels of these substances. Zebrafish (*Danio rerio*), one of the most extensively studied species, showed adverse effects when exposed to low concentrations of TiO_2NPs or AgNPs, ranging from 1µg/ L to 2.4mg/ L. Observed outcomes included oxidative stress, genetic alterations, and inhibition of nervous system enzymes. Additionally, the accumulation of nanomaterials in fish tissues, including the liver and brain, has raised significant questions about their long-term effects **(Dedman *et al*., 2021)**.

CONCLUSION

Nanomaterials, particularly metal oxides and nano-plastics, have been shown to exhibit high toxicity to aquatic life, impairing growth and essential biological functions. For example, titanium dioxide nanoparticles and silver nano-plastics interfere with the metabolic pathways of aquatic organisms. This toxicity depends on factors such as nanoparticle concentration, shape, and size, all of which must be carefully considered in environmental risk assessments. Toxicity mechanisms include free radical formation, disruption of cell membranes, and interference with metabolic processes, ultimately leading to cell death and tissue damage. For instance, silver nanoparticles are known to generate free radicals that cause oxidative stress in fish, resulting in tissue damage and stunted growth. These nanomaterials also pose risks to the food chain due to their bioaccumulation in organisms such as fish and birds, which further impacts higher trophic levels, including humans. This accumulation leads to uptake by top predators like birds **(Kakakhel *et al.*, 2021)**. The long-term effects of these particles typically include liver toxicity, lung damage, and cancer, as they accumulate in biological tissues.

These findings highlight the urgent need for broader research on the environmental and health impacts of various nanomaterials, along with the development of effective strategies to mitigate their harmful effects on ecosystems and human health. However, current studies on long-term impacts and the full extent of bioaccumulation remain limited, leaving significant knowledge gaps regarding the overall risks of nanomaterials. This emphasizes the importance of sustained research efforts and the development of practical mitigation measures to address these uncertainties.

Future research should focus on evaluating the long-term effects of nanomaterials on aquatic organisms, investigating the mechanisms of their bioaccumulation and transport through the food chain, and analyzing their impacts on gene expression and metabolic pathways. Furthermore, accurate predictive models must be developed to assess environmental risks and to design more environmentally friendly nanomaterials with reduced toxicity potential.

REFERENCES

Abbas, Q.; Yousaf, B.; Ali, M.U.; Munir, M.A.M.; El-Naggar, A.; Rinklebe, J. and Naushad, M. (2020). Transformation pathways and fate of engineered nanoparticles (ENPs) in distinct interactive environmental compartments: A review. Environment International, **138**: 105646.

Akgöl, S.; Ulucan-Karnak, F.; Kuru, C. I. and Kuşat, K. (2021). The usage of composite nanomaterials in biomedical engineering applications. Biotechnology and Bioengineering, 118(8), 2906-2922.

Albanese, A.; Tang, P. S. and Chan, W. C. (2012). The effect of nanoparticle size, shape, and surface chemistry on biological systems. Annual review of biomedical engineering, 14(1), 1-16.

Allen, N. S.; McIntyre, R.; Kerrod, J. M.; Hill, C. and Edge, M. (2018). Photo-stabilization and UV blocking efficacy of coated macro and nano-rutile titanium dioxide particles in paints and coatings. Journal of Polymers and the Environment, 26(11), 4243-4257.

Al-Shammari, A. H. R. and Al-Janabi, A. I. H. (2022). Treatment of Municipal Wastewater Contaminated with Heavy Metals and Hydrocarbons by *Chlorella vulgaris*. Int. J. of Aquatic Science, 13(1), 400-411.

Al-Shammari, A. H. and Al-Janabi, A. H. (2023). *Chlorella vulgaris* has been used in the biological treatment of some pollutants and heavy metals in municipal wastewater. Revista Bionatura, 8(2), 63.

Ang, M. B. M. Y.; Pereira, J. M.; Trilles, C. A.; Aquino, R. R.; Huang, S. H.; Lee, K. R. and Lai, J. Y. (2019). Performance and antifouling behavior of thin-film nanocomposite nanofiltration membranes with embedded silica spheres. Separation and Purification Technology, 210, 521-529.

Aruoja, V.; Pokhrel, S.; Sihtmäe, M.; Mortimer, M.; Mädler, L. and Kahru, A. (2015). Toxicity of 12 metal-based nanoparticles to algae, bacteria and protozoa. Environmental Science: Nano, 2(6), 630-644.

Asghar, N.; Hussain, A.; Nguyen, D. A.; Ali, S.; Hussain, I.; Junejo, A. and Ali, A. (2024). Advancement in nanomaterials for environmental pollutants remediation: a systematic review on bibliometrics analysis, material types, synthesis pathways, and related mechanisms. Journal of Nanobiotechnology, 22(1), 26.

Awashra, M. and Młynarz, P. (2023). The toxicity of nanoparticles and their interaction with cells: an in vitro metabolomic perspective. Nanoscale Advances, 5(10), 2674-2723.

Azimzada, A.; Jreije, I.; Hadioui, M.; Shaw, P.; Farner, J. M. and Wilkinson, K. J. (2021). Quantification and characterization of Ti-, Ce-, and Ag-nanoparticles in global surface waters and precipitation. Environmental Science & Technology, 55(14), 9836-9844.

Babaei, M.; Tayemeh, M. B.; Jo, M. S.; Yu, I. J. and Johari, S. A. (2022). Trophic transfer and toxicity of silver nanoparticles along a phytoplankton-zooplankton-fish food chain. Science of the Total Environment, 842, 156807.

Bacchetta, C.; Ale, A.; Simoniello, M. F.; Gervasio, S.; Davico, C.; Rossi, A. S. and Cazenave, J. (2017). Genotoxicity and oxidative stress in fish after a short-term exposure to silver nanoparticles. Ecological indicators, 76, 230-239.

Barreto, D. M. and Lombardi, A. T. (2016). Environmentally relevant concentrations of TiO_2 nanoparticles affected cell viability and photosynthetic yield in the Chlorophyceae *Scenedesmus bijugus*. Water, Air, & Soil Pollution, 227(12), 450.

Bäuerlein, P. S.; Emke, E.; Tromp, P.; Hofman, J. A.; Carboni, A.; Schooneman, F.; and van Wezel, A. P. (2017). Is there evidence for man-made nanoparticles in the Dutch environment? Science of the Total Environment, 576, 273-283.

Bhuvaneshwari, M.; Iswarya, V.; Archanaa, S.; Madhu, G. M.; Kumar, G. S.; Nagarajan, R.; and Mukherjee, A. (2015). Cytotoxicity of ZnO NPs towards fresh water algae *Scenedesmus obliquus* at low exposure concentrations in UV-C, visible and dark conditions. Aquatic Toxicology, 162, 29-38.

Bhuvaneshwari, M.; Kumar, D.; Roy, R.; Chakraborty, S.; Parashar, A.; Mukherjee, A.; and Mukherjee, A. (2017). Toxicity, accumulation, and trophic transfer of chemically and biologically synthesized nano zero valent iron in a two species freshwater food chain. Aquatic toxicology, 183, 63-75.

Bhuvaneshwari, M.; Thiagarajan, V.; Nemade, P.; Chandrasekaran, N.; and Mukherjee, A. (2018). Toxicity and trophic transfer of P25 TiO_2 NPs from *Dunaliella salina* to *Artemia salina*: effect of dietary and waterborne exposure. Environmental research, 160, 39-46.

Black, M. N.; Henry, E. F.; Adams, O. A.; Bennett, J. C. F.; and MacCormack, T. J. (2017). Environmentally relevant concentrations of amine-functionalized copper nanoparticles exhibit different mechanisms of bioactivity in *Fundulus Heteroclitus* in fresh and brackish water. Nanotoxicology, 11(8), 1070-1085.

Bundschuh, M.; Seitz, F.; Rosenfeldt, R. R.; and Schulz, R. (2016). Effects of nanoparticles in fresh waters: risks, mechanisms and interactions. Freshwater Biology, 61(12), 2185-2196.

Campalani, C. and Monbaliu, J. C. M. (2025). Towards sustainable quantum dots: Regulatory framework, toxicity and emerging strategies. Materials Science and Engineering: R: Reports, 163, 100940.

Chávez-Hernández, J. A.; Velarde-Salcedo, A. J.; Navarro-Tovar, G.; and Gonzalez, C. (2024). Safe nanomaterials: from their use, application, and disposal to regulations. Nanoscale Advances, 6(6), 1583–1610.

Chen, Q.; Hu, X.; Yin, D.; and Wang, R. (2016). Effect of subcellular distribution on nC60 uptake and transfer efficiency from *Scenedesmus obliquus* to *Daphnia magna*. Ecotoxicology and Environmental Safety, 128, 213-221.

Chen, X.; Zhu, Y.; Yang, K.; Zhu, L.; and Lin, D. (2019). Nanoparticle TiO_2 size and rutile content impact bioconcentration and biomagnification from algae to daphnia. Environmental Pollution, 247, 421-430.

Chifiriuc, M. C.; Ratiu, A. C.; Popa, M.; and Ecovoiu, A. A. (2016). Drosophotoxicology: an emerging research area for assessing nanoparticles interaction with living organisms. International Journal of Molecular Sciences, 17(2), 36.

Connolly, M.; Salomé, M. M.; Judit, K.; José-María, N.; Eric, B.; and María-Luisa, F. C. (2023). Considerations for bioaccumulation studies in fish with nanomaterials. Chemosphere, 312, 137299.

Conway, J. R.; Adeleye, A. S.; Gardea-Torresdey, J.; and Keller, A. A. (2015). Aggregation, dissolution, and transformation of copper nanoparticles in natural waters. Environmental Science & Technology, 49(5), 2749–2756.

Cunningham, S.; Brennan-Fournet, M. E.; Ledwith, D.; Byrnes, L.; and Joshi, L. (2013). Effect of nanoparticle stabilization and physicochemical properties on exposure outcome: acute toxicity of silver nanoparticle preparations in zebrafish (*Danio rerio*). Environmental science & technology, 47(8), 3883-3892.

Cuong, H. N.; Pansambal, S.; Ghotekar, S.; Oza, R.; Hai, N. T. T.; Viet, N. M.; and Nguyen, V. H. (2022). New frontiers in the plant extract mediated biosynthesis of copper oxide (CuO) nanoparticles and their potential applications: A review. Environmental Research, 203, 111858.

Dalai, S.; Pakrashi, S.; Nirmala, M. J.; Chaudhri, A.; Chandrasekaran, N.; Mandal, A. B.; and Mukherjee, A. (2013). Cytotoxicity of TiO_2 nanoparticles and their detoxification in a freshwater system. Aquatic Toxicology, 138, 1-11.

Dang, F.; Yuan, Y.; Huang, Y.; Wang, Y.; and Xing, B. (2023). Trophic transfer of nanomaterials and their effects on high-trophic-level predators. NanoImpact, 32, 100489.

Dash, A.; Singh, A. P.; Chaudhary, B. R.; Singh, S. K.; and Dash, D. (2012). Effect of silver nanoparticles on growth of eukaryotic green algae. Nano-micro letters, 4(3), 158-165.

Dedman, C. J.; King, A. M.; Christie-Oleza, J. A.; and Davies, G. L. (2021). Environmentally relevant concentrations of titanium dioxide nanoparticles pose negligible risk to marine microbes. Environmental Science: Nano, 8(5), 1236-1255.

Demir, E. (2021). A review on nanotoxicity and nanogenotoxicity of different shapes of nanomaterials. Journal of Applied Toxicology, 41(1), 118-147.

Domb, A. J.; Sharifzadeh, G.; Nahum, V.; and Hosseinkhani, H. (2021). Safety evaluation of nanotechnology products. Pharmaceutics, 13(10), 1615.

Dutta, D., Sundaram, S. K., Teeguarden, J. G., Riley, B. J., Fifield, L. S., Jacobs, J. M., ... and Weber, T. J. (2007). Adsorbed proteins influence the biological activity and molecular targeting of nanomaterials. *Toxicological Sciences*, *100*(1), 303-315.

Egbuna, C.; Parmar, V. K.; Jeevanandam, J.; Ezzat, S. M.; Patrick-Iwuanyanwu, K. C.; Adetunji, C. O.; and Ibeabuchi, C. G. (2021). Toxicity of nanoparticles in biomedical application: nanotoxicology. Journal of toxicology, 2021(1), 9954443.

Eker, F.; Duman, H.; Akdaşçi, E.; Bolat, E.; Sarıtaş, S.; Karav, S.; and Witkowska, A. M. (2024). A comprehensive review of nanoparticles: from classification to application and toxicity. Molecules, 29(15), 3482.

El-Kady, M. M.; Ansari, I.; Arora, C.; Rai, N.; Soni, S.; Verma, D. K.; Singh, P.; and Mahmoud, A. E. D. (2023). Nanomaterials: A comprehensive review of applications, toxicity, impact, and fate to environment. Journal of Molecular Liquids, 370, 121046.

El-Kalliny, A. S.; Abdel-Wahed, M. S.; El-Zahhar, A. A.; Hamza, I. A.; and Gad-Allah, T. A. (2023). Nanomaterials: a review of emerging contaminants with potential health or environmental impact. Discover Nano, 18(1), 68.

Emamverdian, A.; Ding, Y.; Barker, J.; Liu, G.; Hasanuzzaman, M.; Li, Y.; and Mokhberdoran, F. (2022). Co-application of 24-epibrassinolide and titanium oxide nanoparticles promotes *pleioblastus pygmaeus* plant tolerance to Cu and Cd toxicity by increasing antioxidant activity and photosynthetic capacity and reducing heavy metal accumulation and translocation. Antioxidants, 11(3), 451.

England, C. G.; Gobin, A. M.; and Frieboes, H. B. (2015). Evaluation of uptake and distribution of gold nanoparticles in solid tumors. The European Physical Journal Plus, 130(11), 231.

Faizan, M.; Faraz, A.; Yusuf, M.; Khan, S. T.; and Hayat, S. (2018). Zinc oxide nanoparticle-mediated changes in photosynthetic efficiency and antioxidant system of tomato plants. Photosynthetica, 56(2), 678-686.

Feng, X.; Zhang, Y.; Zhang, C.; Lai, X.; Zhang, Y.; Wu, J.; Hu, C.; and Shao, L. (2020). Nanomaterial-mediated autophagy: Coexisting hazard and health benefits in biomedicine. Particle and Fiber Toxicology, 17(1), 53.

Galúcio, J. M.; de Souza, S. G. B.; Vasconcelos, A. A.; Lima, A. K. O.; da Costa, K. S.; de Campos Braga, H.; and Taube, P. S. (2022). Synthesis, characterization, applications, and toxicity of green synthesized nanoparticles. Current pharmaceutical biotechnology, 23(3), 420-443.

Gambardella, C.; Gallus, L.; Gatti, A. M.; Faimali, M.; Carbone, S.; Antisari, L. V.; and Ferrando, S. (2014). Toxicity and transfer of metal oxide nanoparticles from microalgae to sea urchin larvae. Chemistry and Ecology, 30(4), 308-316.

Gao, X.; Li, X.; Chen, J.; Huo, D.; Yin, Y.; and Nan, D. (2024). TiO_2-Modified Graphene Oxide Fillers Strengthen Acrylic Coated Samples Corrosion and Weathering Resistance on Q235 Steel. Langmuir, 41(2), 1418–1428.

Gaur, S. S. and Jagadeesan, H. (2021). Titanium Dioxide (TiO_2) based photocatalysis for textile wastewater treatment–its applications and biosafety–A Review. Int. J. Mech. Eng, 6, 974-5823.

Gehr, P. (2018). Interaction of nanoparticles with biological systems. Colloids and Surfaces B: Biointerfaces, 172, 395-399.

Geitner, N. K.; Marinakos, S. M.; Guo, C.; O'Brien, N.; and Wiesner, M. R. (2016). Nanoparticle surface affinity as a predictor of trophic transfer. Environmental science & technology, 50(13), 6663-6669.

Ghamarpoor, R.; Fallah, A.; and Jamshidi, M. (2023). Investigating the use of titanium dioxide (TiO_2) nanoparticles on the amount of protection against UV irradiation. Scientific Reports, 13(1), 9793.

Griffitt, R. J.; Luo, J.; Gao, J.; Bonzongo, J. C.; and Barber, D. S. (2008). Effects of particle composition and species on toxicity of metallic nanomaterials in aquatic organisms. Environmental toxicology and chemistry, 27(9), 1972-1978.

Hadi, O. J. and Alwan, S. W. (2025). Cytotoxicity of Some Nano-Pollutants on *Allium Cepa* Plant. International Journal of Environmental Sciences, 11(7s), 845-858.

Hauser, M. and Nowack, B. (2021). Probabilistic modelling of nanobiomaterial release from medical applications into the environment. Environment international, 146, 106184.

Hossain, M.; Pati, N. C.; Pal, S.; Rana, S.; Pal, N.; and Layek, G. C. (2021). Bifurcations and multistability in a food chain model with nanoparticles. Mathematics and Computers in Simulation, 190, 808-825.

Hou, J.; Wang, L.; Wang, C.; Zhang, S.; Liu, H.; Li, S.; and Wang, X. (2019). Toxicity and mechanisms of action of titanium dioxide nanoparticles in living organisms.

Hussain, C. M. (Ed.). (2018). Handbook of nanomaterials for industrial applications, Elsevier.

Jahan, S.; Yusoff, I. B.; Alias, Y. B.; and Bakar, A. F. B. A. (2017). Reviews of the toxicity behavior of five potential engineered nanomaterials (ENMs) into the aquatic ecosystem. Toxicology Reports, 4, 211-220.

Joo, S. H. and Zhao, D. (2017). Environmental dynamics of metal oxide nanoparticles in heterogeneous systems: A review. Journal of Hazardous Materials, 322, 29-47.

Kakakhel, M. A.; Wu, F.; Sajjad, W.; Zhang, Q.; Khan, I.; Ullah, K.; and Wang, W. (2021). Long-term exposure to high-concentration silver nanoparticles induced toxicity, fatality, bioaccumulation, and histological alteration in fish (*Cyprinus carpio*). Environmental Sciences Europe, 33(1), 14.

Kalman, J.; Paul, K. B.; Khan, F. R.; Stone, V.; and Fernandes, T. F. (2015). Characterization of bioaccumulation dynamics of three differently coated silver nanoparticles and aqueous silver in a simple freshwater food chain. Environmental Chemistry, 12(6), 662-672.

Khan, S. T.; Adil, S. F.; Shaik, M. R.; Alkhathlan, H. Z.; Khan, M.; and Khan, M. (2021). Engineered nanomaterials in soil: their impact on soil microbiome and plant health. Plants, 11(1), 109.

Khoshnamvand, M.; Hao, Z.; Fadare, O. O.; Hanachi, P.; Chen, Y.; and Liu, J. (2020). Toxicity of biosynthesized silver nanoparticles to aquatic organisms of different trophic levels. Chemosphere, 258, 127346.

Larguinho, M.; Correia, D.; Diniz, M. S.; and Baptista, P. V. (2014). Evidence of one-way flow bioaccumulation of gold nanoparticles across two trophic levels. Journal of nanoparticle research, 16(8), 2549.

Larue, C.; Castillo-Michel, H.; Sobanska, S.; Cécillon, L.; Bureau, S.; Barthès, V.; and Sarret, G. (2014). Foliar exposure of the crop *Lactuca sativa* to silver nanoparticles: evidence for internalization and changes in Ag speciation. Journal of hazardous materials, 264, 98-106.

Larue, C.; Sarret, G.; Castillo-Michel, H.; and Pradas del Real, A. E. (2021). A critical review on the impacts of nanoplastics and microplastics on aquatic and terrestrial photosynthetic organisms. Small, 17(20), 2005834.

Lau, Z. L.; Low, S. S.; Ezeigwe, E. R.; Chew, K. W.; Chai, W. S.; Bhatnagar, A.; and Show, P. L. (2022). A review on the diverse interactions between microalgae and nanomaterials: Growth variation, photosynthetic performance and toxicity. Bioresource technology, 351, 127048.

Lead, J. R. (2008). Nanomaterials in the environment: Behavior, fate, bioavailability. Environmental Toxicology and Chemistry/SETAC, 27(9), 1825-1851.

Li, M.; Zhang, Y.; Feng, S.; Zhang, X.; Xi, Y.; and Xiang, X. (2022). Bioaccumulation and biomagnification effects of nano-TiO*2* in the aquatic food chain. Ecotoxicology, 31(6), 1023-1034.

Lowry, G. V.; Espinasse, B. P.; Badireddy, A. R.; Richardson, C. J.; Reinsch, B. C.; Bryant, L. D.; and Wiesner, M. R. (2012b). Long-term transformation and fate of manufactured Ag nanoparticles in a simulated large scale freshwater emergent wetland. Environmental science & technology, 46(13), 7027-7036.

Lowry, G. V.; Gregory, K. B.; Apte, S. C.; and Lead, J. R. (2012a). Transformations of nanomaterials in the environment. 6893-6899.

Mabrouk, M.; Das, D. B.; Salem, Z. A.; and Beherei, H. H. (2021). Nanomaterials for biomedical applications: production, characterizations, recent trends and difficulties. Molecules, 26(4), 1077.

Mahana, A.; Guliy, O. I.; and Mehta, S. K. (2021). Accumulation and cellular toxicity of engineered metallic nanoparticle in freshwater microalgae: Current status and future challenges. Ecotoxicology and environmental safety, 208, 111662.

Mahawar, L.; Ramasamy, K. P.; Suhel, M.; Prasad, S. M.; Živčák, M.; Brestic, M.; and Skalický, M. (2023). Silicon nanoparticles: Comprehensive review on biogenic synthesis and applications in agriculture. Environmental Research, 232, 116292.

Miranda, R. R.; Damaso da Silveira, A. L. R.; De Jesus, I. P.; Grötzner, S. R.; Voigt, C. L.; Campos, S. X.; and Filipak Neto, F. (2016). Effects of realistic concentrations of TiO_2 and ZnO nanoparticles in *Prochilodus lineatus* juvenile fish. Environmental Science and Pollution Research, 23(6), 5179-5188.

Misra, S. K.; Dybowska, A.; Berhanu, D.; Luoma, S. N.; and Valsami-Jones, E. (2012). The complexity of nanoparticle dissolution and its importance in nanotoxicological studies. Science of the total environment, 438, 225-232.

Naasz, S.; Altenburger, R.; and Kühnel, D. (2018). Environmental mixtures of nanomaterials and chemicals: The Trojan-horse phenomenon and its relevance for ecotoxicity. Science of the Total Environment, 635, 1170-1181.

Nagaswarupa, H. P.; Sillanpää, M. E.; Murthy, H. A.; and Naik, R. (Eds.). (2024). Multifunctional inorganic nanomaterials for energy applications. CRC Press.

Naz, S.; Gul, A.; and Zia, M. (2020). Toxicity of copper oxide nanoparticles: a review study. IET nanobiotechnology, 14(1), 1-13.

Nguyen, M. K.; Lin, C.; Nguyen, H. L.; Le, V. G.; Haddout, S.; Um, M. J.; and Nguyen, D. D. (2023). Ecotoxicity of micro-and nanoplastics on aquatic algae: facts, challenges, and future opportunities. Journal of Environmental Management, 346, 118982.

Nthunya, L. N., Mosai, A. K., López-Maldonado, E. A., Bopape, M., Dhibar, S., Nuapia, Y., ... & Mamba, B. B. (2025). Unseen threats in aquatic and terrestrial ecosystems: Nanoparticle persistence, transport and toxicity in natural environments. Chemosphere, 382, 144470.

Passarelli, C., Cui, X., Valsami-Jones, E., and Underwood, G. J. (2020). Environmental context determines the impact of titanium oxide and silver nanoparticles on the functioning of intertidal microalgal biofilms. *Environmental Science: Nano*, *7*(10), 3020-3035.

Pham, S. H.; Choi, Y.; and Choi, J. (2020). Stimuli-responsive nanomaterials for application in antitumor therapy and drug delivery. Pharmaceutics, 12(7), 630.

Pohanka, M. J. B. L. L. (2019). Copper and copper nanoparticles toxicity and their impact on basic functions in the body. Bratisl. Lek. Listy, 120(6), 397-409.

Poynton, H. C.; Chen, C.; Alexander, S. L.; Major, K. M.; Blalock, B. J.; and Unrine, J. M. (2019). Enhanced toxicity of environmentally transformed ZnO nanoparticles relative to Zn ions in the epibenthic amphipod *Hyalella azteca*. Environmental Science: Nano, 6(1), 325-340.

Radhakrishnan, S.; Das, P. P.; Alam, A.; Dwivedi, S. P.; and Chaudhary, V. (2024). Mechanical, thermal, and electrical properties of 2D nanomaterials for advanced applications. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 238(17), 8739-8755.

Rand, L. N.; Flores, K.; Sharma, N.; Gardea-Torresdey, J.; and Westerhoff, P. (2021). Quantifying nanoparticle associated Ti, Ce, Au, and Pd occurrence in 35 US surface waters. ACS ES&T Water, 1(10), 2242-2250.

Rawat, S.; Pullagurala, V. L.; Adisa, I. O.; Wang, Y.; Peralta-Videa, J. R.; and Gardea-Torresdey, J. L. (2018). Factors affecting fate and transport of engineered nanomaterials in terrestrial environments. Current Opinion in Environmental Science & Health, 6, 47-53.

Rudramurthy, G. R. and Swamy, M. K. (2018). Potential applications of engineered nanoparticles in medicine and biology: an update. JBIC Journal of Biological Inorganic Chemistry, 23, 1185–1204.

Sakka, Y.; Skjolding, L. M.; Mackevica, A.; Filser, J.; and Baun, A. (2016). Behavior and chronic toxicity of two differently stabilized silver nanoparticles to *Daphnia magna*. Aquatic toxicology, 177, 526-535.

Salaudeen, H. D.; Akinniranye, R. D.; Kolawole, M. I.; and Yahaya, S. (2024). Nanomaterials in electronics: Advancements and challenges in high-performance devices. World Journal of Advanced Research and Reviews, 24(1), 830–845.

Salieri, B.; Righi, S.; Pasteris, A.; and Olsen, S. I. (2015). Freshwater ecotoxicity characterization factor for metal oxide nanoparticles: A case study on titanium dioxide nanoparticle. Science of the Total Environment, 505, 494-502.

Santos, C. S.; Gabriel, B.; Blanchy, M.; Menes, O.; García, D.; Blanco, M.; and Neto, V. (2015). Industrial applications of nanoparticles–a prospective overview. Materials Today: Proceedings, 2(1), 456-465.

Sendra, M.; Yeste, P. M.; Moreno-Garrido, I.; Gatica, J. M.; and Blasco, J. (2017). CeO_2 NPs, toxic or protective to phytoplankton? Charge of nanoparticles and cell wall as factors which cause changes in cell complexity. Science of The Total Environment, 590, 304-315.

Silva, P. V.; Pinheiro, C.; Morgado, R. G.; Verweij, R. A.; van Gestel, C. A.; and Loureiro, S. (2022). Bioaccumulation but no biomagnification of silver sulfide nanoparticles in freshwater snails and planarians. Science of the Total Environment, 808, 151956.

Singh, A.; Singh, N. Á.; Afzal, S.; Singh, T.; and Hussain, I. (2018). Zinc oxide nanoparticles: a review of their biological synthesis, antimicrobial activity, uptake, translocation and biotransformation in plants. Journal of materials science, 53(1), 185-201.

Siquan, L.; Weilin, C.; Xiuwen, C.; Meiyan, Z.; Weihong, G.; and Xiaoli, F. (2024). Evaluating the safety and efficiency of nanomaterials: A focus on mitochondrial health. Biomedicine and Pharmacotherapy, 180, 117484.

Stroea, L.; Chibac-Scutaru, A. L.; and Melinte, V. (2021). Aliphatic polyurethane elastomers quaternized with silane-functionalized TiO_2 nanoparticles with UV-shielding features. Polymers, 13(8), 1318.

Sundbæk, K. B.; Koch, I. D. W.; Villaro, C. G.; Rasmussen, N. S.; Holdt, S. L.; and Hartmann, N. B. (2018). Sorption of fluorescent polystyrene microplastic particles to edible seaweed *Fucus vesiculosus*. Journal of Applied Phycology, 30(5), 2923-2927.

Syafiuddin, A.; Salmiati, S.; Hadibarata, T.; Kueh, A. B. H.; Salim, M. R.; and Zaini, M. A. A. (2018). Silver nanoparticles in the water environment in Malaysia: inspection, characterization, removal, modeling, and future perspective. Scientific reports, 8(1), 986.

Thomas, S.; Grohens, Y.; and Pottathara, Y. B. (Eds.). (2019). Industrial applications of nanomaterials. Elsevier.

ur Rahman, M. (2021). Sources of nanomaterials. In Nanomaterials: Synthesis, Characterization, Hazards and Safety (pp. 15-29). Elsevier.

van Weert, S.; Redondo-Hasselerharm, P. E.; Diepens, N. J.; and Koelmans, A. A. (2019). Effects of nanoplastics and microplastics on the growth of sediment-rooted macrophytes. Science of the Total Environment, 654, 1040-1047.

Vasyukova, I. A.; Zakharova, O. V.; Chaika, V. V.; Pikula, K. S.; Golokhvast, K. S.; and Gusev, A. A. (2021). Toxic Effect of metal-based nanomaterials on representatives of marine ecosystems: A review. Nanobiotechnology Reports, 16(2), 138-154.

Veg, E.; Hashmi, K.; Raza, S.; Joshi, S.; Rahman Khan, A.; and Khan, T. (2025). The role of nanomaterials in diagnosis and targeted drug delivery. Chemistry & Biodiversity, 22(1), e202401581.

Wagner, S.; Legros, S.; Löschner, K.; Liu, J.; Navratilova, J.; Grombe, R.; and Hofmann, T. (2015). First steps towards a generic sample preparation scheme for inorganic engineered nanoparticles in a complex matrix for detection, characterization, and quantification by asymmetric flow-field flow fractionation coupled to multi-angle light scattering and ICP-MS. Journal of Analytical Atomic Spectrometry, 30(6), 1286-1296.

Wang, F.; Guan, W.; Xu, L.; Ding, Z.; Ma, H.; Ma, A.; and Terry, N. (2019). Effects of nanoparticles on algae: Adsorption, distribution, ecotoxicity and fate. Applied Sciences, 9(8), 1534.

Wang, F.; Guan, W.; Xu, L.; Ding, Z.; Ma, H.; Ma, A.; and Terry, N. (2019). Effects of nanoparticles on algae: Adsorption, distribution, ecotoxicity and fate. Applied Sciences, 9(8), 1534.

Wang, J.; Dai, H.; Nie, Y.; Wang, M.; Yang, Z.; Cheng, L.; Liu, Y.; Chen, S.; Zhao, G.; and Wu, L. (2018). TiO_2 nanoparticles enhance bioaccumulation and toxicity of heavy metals in Caenorhabditis elegans via modification of local concentrations during the sedimentation process. Ecotoxicology and Environmental Safety, 162, 160–169.

Wang, X.; Liang, D.; Wang, Y.; Peijnenburg, W. J. G. M.; Monikh, F. A.; Zhao, X.; Dong, Z.; and Fan, W. (2022). A critical review on the biological impact of natural organic matter on nanomaterials in the aquatic environment. Carbon Research, 1(1), 13.

Wang, Z.; Yin, L.; Zhao, J.; and Xing, B. (2016). Trophic transfer and accumulation of TiO2 nanoparticles from clamworm (*Perinereis aibuhitensis*) to juvenile turbot (*Scophthalmus maximus*) along a marine benthic food chain. Water research, 95, 250-259.

Wells, M. L.; Potin, P., Craigie, J. S.; Raven, J. A.; Merchant, S. S.; Helliwell, K. E.; and Brawley, S. H. (2017). Algae as nutritional and functional food sources: revisiting our understanding. Journal of applied phycology, 29(2), 949-982.

Wu, F.; Bortvedt, A.; Harper, B. J.; Crandon, L. E.; and Harper, S. L. (2017). Uptake and toxicity of CuO nanoparticles to *Daphnia magna* varies between indirect dietary and direct waterborne exposures. Aquatic toxicology, 190, 78-86.

Wu, Q.; Miao, W.; Zhang, Y.; Gao, H.; and Hui, D. (2020). Mechanical properties of nanomaterials: A review. Nanotechnology Reviews, 9(1), 259–273.

Xia, B.; Chen, B.; Sun, X.; Qu, K.; Ma, F.; and Du, M. (2015). Interaction of TiO_2 nanoparticles with the marine microalga *Nitzschia closterium*: growth inhibition, oxidative stress and internalization. Science of the total Environment, 508, 525-533.

Xiao, B.; Yang, R.; Chen, P.; Yang, J.; Sun, B.; Wang, K.; and Zhu, L. (2022). Insights into the lower trophic transfer of silver ions than silver containing nanoparticles along an aquatic food chain. Science of The Total Environment, 804, 150228.

Xiao, Y.; Vijver, M. G.; and Peijnenburg, W. J. (2018). Impact of water chemistry on the behavior and fate of copper nanoparticles. Environmental pollution, 234, 684-691.

Xu, Y.; Wang, C.; Hou, J.; Wang, P.; You, G. and Miao, L. (2019). Effects of cerium oxide nanoparticles on bacterial growth and behaviors: induction of biofilm formation and stress response. Environmental Science and Pollution Research, 26(9), 9293-9304.

Xu, Z.; Long, X.; Jia, Y.; Zhao, D. and Pan, X. (2022). Occurrence, transport, and toxicity of nanomaterials in soil ecosystems: A review. Environmental Chemistry Letters, 20(6), 3943–3969.

Yan, N. and Wang, W. X. (2021). Novel imaging of silver nanoparticle uptake by a unicellular alga and trophic transfer to *Daphnia magna*. Environmental Science & Technology, 55(8), 5143-5151.

Yang, S.; Ye, R.; Han, B.; Wei, C. and Yang, X. (2014). Ecotoxicological effect of nano-silicon dioxide particles on *Daphnia magna*. Integrated Ferroelectrics, 154(1), 64-72.

Yang, Z.; Wu, S.; Gao, Y.; Kou, D.; Lu, K.; Chen, C.; Zhou, Y.; Zhou, D.; Chen, L. and Ge, J. (2024). Unveiling the Biologically Dynamic Degradation of Iron Oxide Nanoparticles via a Continuous Flow System. Small Methods, 8(3), 2301479.

Zhang, L.; Cui, Y.; Xu, J.; Qian, J.; Yang, X.; Chen, X.; and Gao, P. (2024). Ecotoxicity and trophic transfer of metallic nanomaterials in aquatic ecosystems. Science of The Total Environment, 924, 171660.

Zhang, P.; Ma, Y.; Zhang, Z.; He, X.; Zhang, J.; Guo, Z.; and Chai, Z. (2012). Biotransformation of ceria nanoparticles in cucumber plants. ACS nano, 6(11), 9943-9950.

Zhao, J., Cao, X., Liu, X., Wang, Z., Zhang, C., White, J. C. and Xing, B. (2016). Interactions of CuO nanoparticles with the algae Chlorella pyrenoidosa: adhesion, uptake, and toxicity. *Nanotoxicology*, *10*(9), 1297-1305.

Zhao, Y.; Tao, S.; Liu, S.; Hu, T.; Zheng, K.; Shen, M. and Meng, G. (2023). Research advances on impacts micro/nanoplastics and their carried pollutants on algae in aquatic ecosystems: A review. Aquatic Toxicology, 264, 106725.

Zhao, Y.; Ye, L. and Zhang, X. X. (2018). Emerging pollutants–part I: occurrence, fate and transport. Water Environment Research, 90(10), 1301-1322.

Zheng, S.; Zhou, Q.; Chen, C.; Yang, F.; Cai, Z.; Li, D. and Wang, H. (2019). Role of extracellular polymeric substances on the behavior and toxicity of silver nanoparticles and ions to green algae *Chlorella vulgaris*. Science of the Total Environment, 660, 1182-1190.

Zhu, X.; Wang, J.; Zhang, X.; Chang, Y. and Chen, Y. (2010). Trophic transfer of TiO2 nanoparticles from daphnia to zebrafish in a simplified freshwater food chain. Chemosphere, 79(9), 928-933.