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Toxicological effects of nanoparticles on Plankton: implications for Environmental Health

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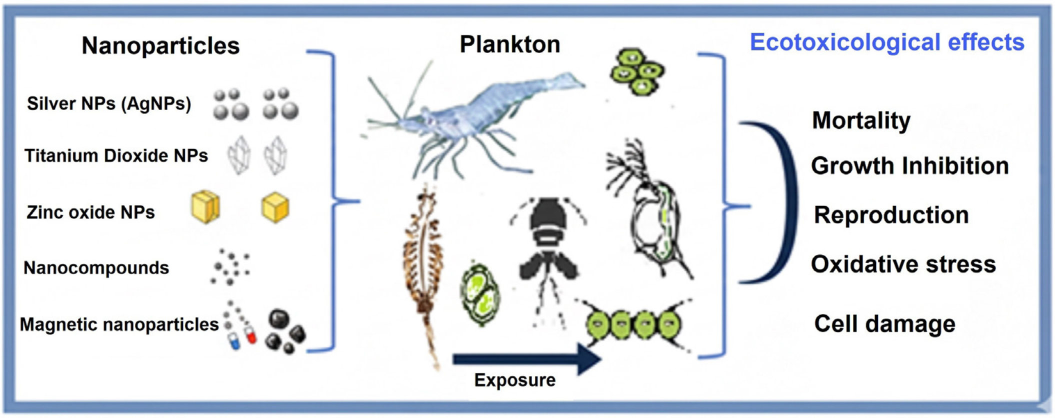
Highlights

- *Nanoparticles (NPs) impair plankton growth, reproduction, and cause stress.*
- *Ionic forms of NPs are more toxic to plankton.*
- *Chronic NP exposure has sublethal effects, harming food webs and ecosystems.*
- *Long-term ecological studies are lacking.*
- *We need to understand the toxicity of NP mixtures with other pollutants.*

Graphical Abstract



Abstract

Nanoparticles (NPs) have emerged as ubiquitous contaminants in aquatic environments due to their extensive industrial, biomedical, and agricultural applications. Their small size, high surface reactivity, and potential for toxic ion release confer upon these particles a unique capacity to interact with aquatic biota, particularly planktonic communities, which form the base of aquatic food webs. This review compiles and analyzes recent ecotoxicological findings on the effects of metallic (Ag, ZnO, TiO_2, Cu, Fe_3O_4), polymeric, and composite nanoparticles on zooplankton and phytoplankton, with emphasis on physiological, biochemical, and population-level responses. Evidence indicates that NPs can induce oxidative stress, membrane damage, growth inhibition, reproductive impairment, and metabolic disruptions in species such as *Daphnia magna*, *Ceriodaphnia silvestrii*, and *Chlorella vulgaris*. Ionic dissolution (e.g., Ag^+, Zn^{2+}) and reactive oxygen species (ROS) generation have been identified as primary toxicity pathways, although surface interactions and protein corona formation also modulate their bioavailability and toxicity. Sublethal and chronic exposures often disrupt planktonic community composition and productivity, with potential cascading effects on higher trophic levels and ecosystem stability. Despite advances, significant knowledge gaps persist regarding long-term ecological consequences, toxicity of mixtures with other pollutants, and NP behavior under environmentally realistic conditions. Future research should integrate mechanistic toxicology, nanoinformatics, and ecological modeling to predict environmental fate and impacts of NPs. The synthesis of green nanoparticles and implementation of standardized testing protocols are crucial for risk mitigation and guiding sustainable nanotechnology practices. By elucidating the complex interactions between NPs and planktonic organisms, this study contributes to a broader understanding of nanoparticle-induced perturbations in aquatic ecosystems and their implications for environmental health.

Keywords: Nanoparticles. Zooplankton. Phytoplankton. Effects. Nanotoxicology.

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INTRODUCTION

Nanomaterials are widely utilized across various industries, including agriculture, medicine, and industrial processes, owing to their unique properties. Nanoparticles (NPs), characterized by their size ranging between 1 and 100 nanometers, exhibit distinct physical and chemical attributes compared to bulk materials[1,2]. These materials play a crucial role in modern technological advancements, particularly in biological applications[3].

In the realm of aquatic ecosystems, the effects of nanoparticles on zooplankton and phytoplankton have garnered significant attention. Zooplankton and phytoplankton serve as fundamental components of aquatic food webs and play vital roles in nutrient cycling and ecosystem functioning. Understanding the interactions between nanoparticles and these key organisms is essential for assessing potential ecological risks.

Studies have demonstrated that nanoparticles can adversely affect aquatic organisms, including bacteria, algae, crustaceans, and fish[4,5,6]. The small size of nanoparticles facilitates their uptake by aquatic organisms, leading to physiological damage and cellular dysfunction. Moreover, nanoparticles, such as silver nanoparticles (AgNPs), can release toxic ions into the environment, further complicating their ecological impacts[4].

Research on nanoparticles like silver nanoparticles (AgNPs), zinc oxide (ZnONPs) and titanium dioxide (TiO_2) has also raised concerns regarding bioaccumulation and reproductive effects on key organisms such as *Daphnia*, copepods and *Chlorella vulgaris*[7,8,9,10]. Additionally, the formation of protein coronas and interactions with environmental pollutants can influence the toxicity and ecological risks associated with nanoparticles[11].

Despite the challenges in studying nanoparticle toxicity, comprehensive assessments are crucial for understanding their impacts on aquatic ecosystems. Further research is needed to develop strategies for mitigating these effects and ensuring the sustainable management of aquatic environments. By focusing on the effects of nanoparticles on zooplankton and phytoplankton, this study contributes to advancing our understanding of nanoparticle ecotoxicology and its implications for aquatic ecosystem health.

METHODOLOGY

Identification and selection of data sources

Scopus, Web of Science, DOAJ, and Scielo databases were utilized to identify relevant studies on the effects of nanoparticles on plankton.

Appropriate search terms such as "nanoparticles", "plankton", "ecotoxicology", "aquatic organisms", "effects", "zooplankton", and "phytoplankton" among others were used to ensure comprehensive search coverage.

Restriction of the search to articles published in peer-reviewed scientific journals.

Inclusion and exclusion criteria

Inclusion criteria focused on studies that investigated the impacts of NPs on zooplankton and phytoplankton, including growth suppression and community dynamics alterations.

Exclusion criteria included studies with insufficient data on environmental impact, those not peer-reviewed, and studies focusing on non-planktonic organisms.

Screening of titles and abstracts

Review of titles and abstracts of the identified articles in the initial search to determine relevance to the review objective.

Selection of articles meeting the inclusion and exclusion criteria for further detailed analysis.

Full text analysis

Comprehensive reading of the selected articles to assess their methodological quality and relevance to the review.

Extraction of relevant data such as study methods, types of nanoparticles used, tested concentrations, evaluated plankton groups, and main findings.

Data synthesis and analysis

Grouping of extracted data to identify patterns and trends in the effects of nanoparticles on plankton.

Critical evaluation of the results of included studies, considering the consistency and reliability of the presented evidence.

Identification of knowledge gaps and areas for future research.

Writing of the scientific review

Structuring the review according to the standard sections of a scientific article, including introduction, methodology, results, discussion, and conclusion.

Clear and precise description of the methods used in the review, including details on the bibliographic search, study selection criteria, and data analysis.

Presentation of the main findings of the review, highlighting the effects of nanoparticles on plankton and their implications for the aquatic environment.

Discussion of the results in the context of the existing literature and conclusions on the current state of knowledge and directions for future research.

Effects of nanoparticles on zooplankton

Effects of silver nanoparticles

The ecological focus on the synthesis of silver nanoparticles (AgNPs) is gaining significant attention due to the current challenges associated with their production. Although chemical methods for AgNP synthesis are well-established, they come with a high production cost and generate toxic residues that pose significant risks to the environment[12]. As a result, there is a growing discussion in the field of nanotechnology about finding environmentally friendly alternatives for nanoparticle synthesis[11].

Biological synthesis of AgNPs offers a promising solution to reduce environmental contamination, as it does not generate toxic residues during the process. However, before adopting this approach on a larger scale, it is crucial to thoroughly study the potential risks associated with the release of these AgNPs into the environment. Changes in environmental conditions could modify their properties and toxicity, necessitating a comprehensive assessment of their ecological impact[13]. Emphasizing ecological considerations in AgNP synthesis and environmental implications is essential for sustainable and responsible nanotechnology practices

Studies evaluating the potential impacts of synthetic silver nanoparticles (AgNPs) on aquatic systems have consistently demonstrated their toxicity to a broad range of organisms within these ecosystems, including micro and macroalgae, aquatic plants, bacteria, crustaceans, and fish[11,14]. As AgNPs can undergo alterations in their physicochemical properties in natural environments, they may become increasingly toxic, leading to detrimental effects on aquatic biota. Aquatic organisms are particularly vulnerable to nanoparticles due to their small size, which not only facilitates their uptake but also enhances their potential to cause significant physiological damage[15] and cellular dysfunction[16]. Consequently, the presence of AgNPs in aquatic environments poses a substantial risk to the health and stability of these ecosystems, necessitating further detailed research to fully understand and mitigate these impacts.

Ecotoxicological studies exploring the potential toxicity of silver nanoparticles (AgNPs) have utilized a diverse array of biological models, including bacteria, algae, fungi, invertebrates, and fish[17]. These extensive investigations aim to elucidate the environmental impact of AgNPs and their potential effects on a wide range of organisms spanning different trophic levels. The toxicity of synthetic AgNPs exhibits significant variability depending on the species examined, highlighting the need for more refined studies to determine the sensitivity of various species within planktonic communities and to establish threshold concentrations for these nanomaterials[18]. Given the critical importance of aquatic ecological concerns, it is imperative to thoroughly assess the potential risks posed by AgNPs to safeguard the health and equilibrium of aquatic ecosystems.

The in vitro toxic effects of AgNPs have been extensively studied on various component organisms of plankton, encompassing bacteria[4], algae[11,19], plants[11], mollusks[20], crustaceans[21], and insects[22]. Within the aquatic environment, AgNPs exert detrimental impacts on prokaryotes, invertebrates, and fish[11]. While the precise mechanisms of toxicity for most nanoparticles, including Silver, are not fully defined, they may involve destabilization of cell membrane integrity[23], cytotoxicity[24], genotoxicity[25], and protein catabolism[26].

Due to their small size, nanoparticles (NPs) can infiltrate biological systems through multiple pathways[11]. In natural waters, NP emissions are expected to yield nanoparticles of varying sizes, which might mitigate some effects[27]. Nevertheless, even aggregated particles are likely to dissolve over time, liberating toxic Ag^+ ions[28]. Understanding the impacts of AgNPs on planktonic organisms is vital for safeguarding the delicate balance of aquatic ecosystems and the diverse life they support.

Invertebrates represent a significant portion, approximately 95%, of the Earth's species and are widely distributed with abundant populations, making them crucial subjects in ecotoxicity studies[27]. Acting as primary consumers, they play a vital role in the ecosystem by feeding on microalgae and suspended organic matter. Any disruption in the quality or quantity of the daphnid population can have cascading effects on other trophic levels, directly impacting various aquatic organisms and leading to significant environmental consequences[28,29].

Among these invertebrates, the planktonic species *Daphnia similis* holds particular importance due to its high sensitivity to pollutants and its role as a foundational species in freshwater ecosystems, serving as the base of the food chain. These characteristics make it an ideal biological model for ecotoxicology studies[29,30]. Moreover, exposure studies involving *D. magna* have been conducted with various commercial nanoparticles to assess bioaccumulation and identify the LC_{50} (lethal concentration for 50% of the population) of synthetic nanoparticles with diverse characteristics[31]. By investigating the effects of nanoparticles on these ecologically significant invertebrates, we can gain crucial insights into their potential environmental impacts and develop strategies for mitigating adverse effects on aquatic ecosystems.

Nanoparticles (NPs) also impact planktonic copepods larger than 500 µm[32] and protozoa like ostracods ranging from 5 to 15 µm[33]. The toxic effects of nanoparticles (NPs) on aquatic organisms can result in significant alterations in the community structure. Álvarez-Manzaneda *et al.*[34] conducted a study to investigate the impact of environmentally relevant concentrations of silver nanoparticles (AgNPs) on plankton communities in their natural habitat, using nominal concentrations of 4, 16, and 64 µg/L. The researchers detected alterations in the size structure of zooplanktonic communities during chronic exposure to AgNPs. Moreover, in acute treatments, there was a decrease in zooplankton abundance and biomass, indicating that short-term exposure to high concentrations of AgNPs had different effects on zooplankton communities compared to chronic exposure. Overall, this study demonstrated varying levels of AgNP toxicity across trophic levels, with more pronounced impacts on zooplankton. These observed effects on zooplankton raise concerns as they suggest that AgNP contamination has the potential to disrupt aquatic food webs[34]. The findings emphasize the importance of understanding NP effects on diverse organisms in aquatic ecosystems to safeguard their ecological balance and functioning.

The primary cause of silver nanoparticle (AgNP) toxicity in aquatic organisms is frequently attributed to the release of silver ions (Ag^+). However, the distinction between AgNPs and Ag^+ within a biological matrix remains complex, posing significant challenges to fully understanding the dissolution behavior of AgNPs in living organisms. In a comprehensive study conducted by Yan *et al.*[35], the release of Ag^+ from AgNPs of varying sizes was quantified over time using the zooplankton model *Daphnia magna*. The research demonstrated that AgNPs ingested by *D. magna* underwent dissolution into Ag^+, which was subsequently detected at elevated concentrations within the foregut. Specifically, the study revealed that approximately 8.3-9.7% of ingested AgNPs, with particle sizes of 20 and 60 nm, were released as Ag^+. Additionally, a pH sensor employed in the study indicated that the dissolution of AgNPs was partially influenced by the heterogeneous pH distribution across different sections of the zooplankton's intestine. Furthermore, Ag^+ was observed to traverse the gills, subsequently entering the daphnids, thereby indicating a potential pathway for AgNP toxicity in this zooplankton species[31,35].

This study underscores the critical need to understand the dynamics of AgNP dissolution and the consequent release of Ag^+ within aquatic organisms. Such knowledge is essential for comprehending the broader environmental impacts of AgNPs and for developing effective strategies to mitigate the risks associated with nanoparticle exposure in aquatic ecosystems. This intricate interplay between nanoparticle behavior and biological responses highlights the importance of detailed ecotoxicological assessments to safeguard the health of aquatic biota in the face of increasing nanoparticle pollution

Lekamge *et al.*[17] conducted an ecotoxicological study to evaluate the acute toxicity of tyrosine-coated silver nanoparticles (tyr-AgNPs, approximately 30 nm) on two crustacean species, *Hydra vulgaris*, *Daphnia carinata* and *Paratya australiensis*. The researchers determined the median lethal concentration (LC_{50}) of tyr-AgNPs for both species over a 24-hour exposure period, finding similar LC_{50} values of 62.04-64.24 μg/L. However, extending the exposure to 48 hours revealed differential sensitivity between the two species: *D. carinata* exhibited a significantly lower LC_{50} of 35.48 μg/L, indicating increased sensitivity compared to *P. australiensis*, which had an LC_{50} of 55.34 μg/L. The authors hypothesized that these differences in sensitivity could be attributed to the distinct feeding behaviors of the two crustaceans. *Daphnia*, as filter feeders, ingest large volumes of aqueous medium, which likely results in higher internalization of the nanoparticles. In contrast, *P. australiensis*, which primarily feeds on detritus, utilizes water mainly for respiration, potentially reducing nanoparticle uptake.

This study highlights the importance of considering species-specific behaviors and physiological traits when assessing nanoparticle toxicity in aquatic organisms. The differential sensitivity observed between the two crustacean species underscores the complexity of nanoparticle interactions within biological systems and the necessity for comprehensive evaluations across a range of species and exposure conditions[36]. Understanding these nuances is crucial for accurately assessing the environmental risks posed by nanoparticles and for developing regulatory frameworks that protect aquatic ecosystems from nanoparticle pollution

Yoo-iam *et al.*[37] conducted an in-depth study to evaluate the toxicity, bioaccumulation, and biomagnification of silver nanoparticle (AgNP) materials within a food chain context. The research focused on two forms of silver: ionic silver (Ag^+) and nanosilver (AgNPs), and their respective impacts on the species *Barbonymus gonionotus*, *Chironomus* spp., *Chlorella* sp., and *Moina macrocopa*. The findings revealed that Ag^+ exhibited greater toxicity compared to AgNPs across all four tested organisms. Specifically, the effective concentration (EC_{50}) for Ag^+ toxicity in *Chlorella* sp. was determined to be 0.39±0.32 mg/L, while the lethal concentration (LC_{50}) for *M. macrocopa* was found to be 0.026±0.43 mg/L. In contrast, *Chlorella* sp. exposed to AgNPs had an EC_{50} of 0.89±0.68 mg/L, and the LC_{50} for *M. macrocopa* exposed to AgNPs was 1.11±0.86 mg/L.

These results underscore the heightened toxicity of ionic silver over its nanoparticulate form, highlighting the need for distinct considerations in ecological risk assessments of silver-based materials. The data also provide valuable insights into the varying sensitivities of different aquatic species to silver contaminants, emphasizing the importance of tailored toxicological studies to inform environmental safety regulations and management practices aimed at protecting aquatic ecosystems from silver pollution.

In the bioaccumulation study, *Chlorella* sp. showed the highest bioaccumulation factor (BAF) of Ag^+ at 101.84 g/L, while the lowest BAF for AgNPs was found in *B. gonionotus* at 1.89 g/L[37]. The transfer of AgNPs through the food chain only occurred from *Chlorella* sp., whereas there was no evidence of biomagnification in *M. macrocopa*. These findings underscore the importance of understanding the interactions between nanoparticles and different organisms within the food chain to assess potential environmental risks and ecological impacts.

Effects of titanium nanoparticles

Chronic exposure of *Daphnia magna* to titanium nanoparticles (TiO_2) commonly used in sunscreen has been found to induce low mortality but significantly reduce the growth and reproduction of the organisms. These effects may be partially attributed to the modified digestive physiology of *D. magna*[7,38,39]. Alongside *Daphnia* sp., some studies have also investigated the toxicity of silver nanoparticles (AgNPs) in zooplankton using organisms such as *Artemia salina*. The determination of EC_{50} values after 24 hours and 72 hours resulted in values of 19.63 mg/L and 10.70 mg/L, respectively[8,19,40,41]. These findings highlight the importance of understanding the potential adverse effects of nanoparticles on aquatic organisms and their ecosystems, calling for further research to assess and mitigate such impacts.

In Lucca's[10] investigation, the acute and chronic effects of nano-TiO_2 on the cladoceran *Ceriodaphnia silvestrii* were thoroughly examined, utilizing exposure through contaminated food (*Pseudokirchneriella subcapitata*). Acute toxicity tests unveiled a mean EC_{50}(48h) value of 77.57 mg/L. Transitioning to chronic toxicity assessments, notable distinctions in survival rates were discerned at a concentration as low as 0.01 mg/L. Furthermore, deleterious impacts on body length, egg production, and neonate generation manifested at concentrations starting from 1 mg/L. These findings underscore the imperative of comprehensively evaluating both acute and chronic repercussions of nano-TiO_2 on aquatic organisms. Such an approach is pivotal for a nuanced assessment of the potential risks entailed by its environmental exposure, thereby facilitating informed decision-making in regulatory and management frameworks aimed at safeguarding aquatic ecosystems[42].

Effects of zinco nanoparticles

In a study by Vijayakumar *et al.*[43], the ecotoxicological effects of zinc oxide nanoparticles (ZnONPs) were scrutinized on the freshwater planktonic crustacean *Ceriodaphnia cornuta*. The study sought to delineate the comparative impacts of biologically synthesized ZnONPs vis-à-vis zinc acetate on the mortality dynamics of this aquatic crustacean. Results unveiled a discernible contrast in toxicity profiles, with ZnONPs exhibiting relatively diminished lethality compared to zinc acetate. Specifically, within a 24-hour exposure period, ZnONPs induced a mortality rate of 42% in *Ceriodaphnia cornuta* at a concentration of 50 µg/L, while a substantially higher mortality rate of 80% was recorded under identical conditions with zinc acetate.

Further microscopic laser scanning analyses elucidated the uptake kinetics and subsequent accumulation of ZnONPs within the intestinal milieu of *C. cornuta* following exposure to a concentration of 50 µg/L for 24 hours. Concurrently, morphological aberrations were discerned in *Ceriodaphnia cornuta* subsequent to treatment with 50 µg/L of ZnONPs[43]. These observations accentuate the imperative of cultivating a nuanced comprehension regarding the potential environmental ramifications of ZnONPs, along with underscoring the exigency of probing their toxicological impacts on aquatic biota. Such endeavors are pivotal for the formulation of robust strategies aimed at management and amelioration of their deleterious effects on freshwater ecosystems.

Prato *et al.*[44] embarked on a quest to evaluate the acute toxicity of zinc oxide nanoparticles (ZnONPs) on the zooplankton *Tigriopus fulvus* (Copepoda, Harpacticoida), revealing an LC_{50}(48h) value of 1.27 (1.15–1.40) mg/L. Similarly, Wong *et al.*[38] documented an LC_{50}(96h) of 0.85 mg/L for the copepod *Tigriopus japonicus*, while for *Elasmopus rapax*, the LC_{50}(96h) stood at 1.19 mg/L upon exposure to ZnONPs. In a parallel vein, Park *et al.*[36] delved into the toxicity profile of ZnONPs in *T. japonicus*, reporting an LC_{50}(96h) value of 2.44 mg/L.

It is important to note that all these results were within the same order of magnitude. However, variations in ecotoxicological studies of nanoparticles were expected due to differences in experimental procedures, particularly regarding the preparation and suspension of NPs (such as the presence or absence of solubilization vehicles, filtration, centrifugation, and sonication), the nature of nanomaterials, and species-specific differences, which make direct comparisons challenging[44,45]. Despite these challenges, these studies offer valuable insights into the potential impact of ZnONPs on aquatic organisms, highlighting the importance of careful consideration and standardized methodologies in ecotoxicological assessments of nanomaterials.

In experiments conducted by de Souza[46], acute and chronic tests were performed using *Ceriodaphnia silvestrii* exposed to zinc nanoparticles (ZnONP). In the acute tests, after 48 hours of exposure, an EC_{50}(48h) value of 0.35 mg/L ZnONP was determined. During the 8-day chronic tests, notable effects were observed, including a significant 11.3% reduction in mean body size at a treatment concentration of 0.1 mg/L, as well as a remarkable decrease of 53.9% in the average number of accumulated eggs and neonates produced per female. Additionally, bioaccumulation and the absence of egg hatching (abortion) were observed at the highest concentrations evaluated for ZnONP. These findings indicate that both acute and chronic exposure to ZnONP can lead to toxic effects on *C. silvestrii*. Moreover, chronic exposure at a concentration as low as 0.006 mg/L affected the growth and reproduction parameters of these microcrustaceans. Understanding the potential harmful effects of ZnONP on aquatic organisms is crucial for assessing and managing their environmental impact.

In their study, Prato *et al.*[44] investigated the chronic exposure of ZnO nanoparticles (ZnONPs) and its impact on copepods. The researchers found that the developmental time from nauplii to copepodite or adult stage was not significantly affected by the nanoparticles. However, reproductive traits showed clear negative effects, including delays in phenological events such as the appearance of ovigerous females and the time required for the release of offspring, particularly at the highest concentrations of ZnONPs tested. The most significant reproductive effect was observed in fecundity, with a notable reduction in the number of nauplii produced per female during the 28-day exposure,

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even at low concentrations. These findings underscore the importance of understanding the reproductive impacts of ZnONPs on copepods, as they play a crucial role in aquatic ecosystems, and their reproductive success is vital for the stability of populations and food webs.

In their inquiry, Huang *et al.*[47] delved into the chronic exposure paradigm of ZnO nanoparticles (ZnONPs) vis-à-vis the nematode *Caenorhabditis elegans*, culminating in the discernment of pronounced impediments in growth dynamics and reproductive fecundity. Concurrently, Garbutt and Little[48] delineated a corollary narrative, whereby ZnONPs exerted deleterious ramifications on both the fecundity index and alimentary uptake kinetics of the cladoceran *Daphnia magna*. These amalgamated findings proffer cogent evidence elucidating the propensity of ZnONPs to precipitate adversative consequences across diverse aquatic taxa, thereby impinging upon their ontogenetic trajectory encompassing growth kinetics, reproductive fecundity, and trophic behavior. This confluence of empirical data underscores the pivotal exigency of undertaking a holistic appraisal delineating the putative ecological risks concomitant with the ubiquitous presence of ZnONPs within aquatic milieus.

The pivotal determinant underpinning the toxicological conundrum of ZnONPs predominantly resides in the dissolution kinetics of Zn^{+2} ions emanating from the nanoparticulate framework[48,49]. This biotic perturbation instigates a cascade of cytotoxic sequelae, encompassing perturbation of intracellular zinc homeostasis, lytic rupture of lysosomal and mitochondrial integrity, culminating in apoptotic cell demise[44,50,51]. Baun *et al.*[52] postulated an ancillary mode of toxicity, delineating a conjectural schema whereby ZnONPs intricately adhere to the integumentary exoskeleton of crustacean taxa, thereby precipitating a concomitant diminution or outright forfeiture of locomotor prowess within these aquatic denizens. These synoptic revelations collectively underscore the nuanced multifaceted labyrinth governing ZnONP-induced cytotoxicity, thereby propounding an irrefutable mandate mandating further ontological inquiry to holistically decipher its repercussions across aquatic ecosystems.

Effects of various nanocompounds of nanoparticles

In a study by Shokry *et al.*[53], the acute toxicity of various nanocompounds of nanoparticles (NC) on *Artemia salina* larvae and freshwater Ostracod (*Cypridopsis vidua*) was investigated over 48 hours. Both experimental organisms were observed to ingest the nanocompounds, with toxicity results for *C. vidua* revealing a highly toxic effect of NC at a concentration of 250 mg/L after 48 hours, yielding an EC_{50} value of 157.6 ± 6.4 mg/L. Conversely, *Artemia salina* individuals exhibited lower sensitivity compared to *C. vidua*, with an EC_{50} value of 476 ± 25.1 mg/L after 48 hours. These findings underscore the varying sensitivities of aquatic organisms to nanocompounds and underscore the need to comprehend the potential ecological implications of these materials across different species in aquatic environments.

In their investigation, Cedervall *et al.*[54] explored the molecular composition of the corona protein enveloping polystyrene nanoparticles, elucidating potential biological risks at both organismal and ecosystem levels. Like numerous other spherical nanoparticles, polystyrene can impact lipid metabolism. The researchers observed that as polystyrene nanoparticles traverse the food chain, they adversely affect the lipid metabolism of primary consumers, such as fish. These outcomes underscore the necessity of comprehending the interactions between nanoparticles and biological systems, as they can significantly influence the health and stability of aquatic ecosystems.

Furthermore, nanoparticles can also affect the behavior of zooplankton, with potential repercussions for fish and the overall functioning of the ecosystem[6]. These findings highlight the need to understand the interactions between nanoparticles and biological systems and their potential ecological consequences. Such knowledge is essential for assessing the environmental risks associated with nanoparticle exposure and for developing strategies to protect aquatic ecosystems and the organisms that inhabit them.

Effects carbon nanomaterials

Carbon nanomaterials, including oxidized carbon nanotubes, graphene oxide, and carbon dots, were subjected to evaluation against daphnids, revealing good biocompatibility and very low acute toxic effects even at higher concentrations (100 mg/L)[55,56]. Recently, research demonstrated the critical influence of protein corona formation on the toxicity of carbon nanotubes when co-exposed with metals to *Daphnia similis*. Essentially, the protein corona formation mitigated metal toxicity by reducing its bioavailability to the zooplankton[57].

Mixture toxicity studies of nanoparticles and pollutants, be they organic or inorganic, require more attention, taking into account environmentally realistic exposure scenarios to nanomaterials.

To address this, data science and nanoinformatics have emerged as promising techniques for data integration, modeling, and risk prediction of complex mixtures involving nanoparticles and environmental pollutants[57]. These approaches play a crucial role in enhancing our understanding of the potential ecological impacts of nanomaterials and their interactions with environmental pollutants, thereby supporting the development of sustainable strategies for safeguarding aquatic ecosystems.

Effects of magnetic microparticles

In recent times, magnetic microparticles (MPs) have surfaced as a propitious remedy for ameliorating eutrophic aqueous habitats[58]. Nonetheless, the environmental ramifications of these nanoparticles, especially concerning aquatic biota such as zooplankton, persistently elude comprehensive scrutiny. Endeavoring to bridge this lacuna, Álvarez-Manzaneda *et al.*[54] embarked on an investigative odyssey, unraveling the acute (immobilization) and chronic repercussions of iron (Fe) MPs on *Daphnia magna*. The chronic toxicological appraisal delved into the fecundity dynamics of offspring (both male and female) amidst the milieu of *D. magna* subjected to the vicissitudes of these nanoparticulate moieties.

In the acute toxicity assessment, it was determined that the concentration of MPs leading to 50% immobilization of *D. magna* individuals (EC_{50}) was 0.913 g/L. Conversely, chronic toxicity evaluations on *D. magna* demonstrated that the presence of dissolved Fe (dFe) significantly influenced the parthenogenetic reproduction of this *Daphnia species*. These results underscore the necessity for more extensive research into the potential ramifications of MPs in aquatic ecosystems and their impact on pivotal organisms like zooplankton. This deeper understanding is crucial for effectively informing and ensuring the safe deployment of these technologies in water restoration initiatives.

In the study conducted by Gebara[59], the effects of Fe_3O_4 nanoparticles on the *Ceriodaphnia silvestrii* were investigated through both acute and chronic toxicity tests. The results showed that there was no acute toxicity observed for nano-Fe_3O_4 during the 48-hour exposure period, as the EC(I)50-48h value was greater than 100.00 mg/L. However, in the chronic toxicity tests, at a concentration of 50.00 mg/L, significant inhibitions were observed in both growth and reproduction parameters. The maximum length of the organisms was inhibited by 12.71%, and the accumulated number of eggs decreased by 51.99%. Additionally, there was a considerable decrease of 61.37% in the number of neonates produced per female. Notably, these effects were only observed after chronic exposure to nano-Fe_3O_4 on the 14^{th} day of the experiment, indicating the importance of considering longer exposure periods in ecotoxicological assessments.

Effects of polystyrene nanoplastics

In a study conducted by Sanz Lanzas[60], *Artemia parthenogenetica* was used as a model organism to investigate the chronic toxicity of polystyrene nanoplastics functionalized with anionic carboxylic groups (NP(PS-COOH)). The researchers analyzed the effects on growth, survival, and feeding behavior, as well as subcellular enzymatic responses related to biotransformation of xenobiotics (carboxylesterase - CbE and glutathione - S-transferase - GST), nervous activity (cholinesterase - ChE), antioxidant defense (catalase - CAT), and protection against overall stress (HSP70 stress proteins). The results indicated that chronic exposure of A. parthenogenetica to NP(PS-COOH) did not alter survival, CAT activity, or HSP70 expression. However, it did lead to reduced growth and filtration rate. Furthermore, there were changes in enzymatic activities, with CbE and ChE activity decreasing and GST activity increasing[60]. These findings highlight the potential impacts of NP(PS-COOH) on the growth and physiological responses of the model organism, which may have implications for the broader aquatic ecosystem.

Table 1 - Effects of nanoparticles on zooplankton, São Paulo, Brasil (2024).

Nanoparticle Type	Organisms Affected	Main Findings	References
Silver (Ag) Nanoparticles	*Various aquatic organisms, including bacteria, algae, plants, crustaceans, and fish*	• Toxicity varies among species. • Causes physiological damage, cellular dysfunction, and destabilization of cell membranes. • Release of toxic Ag^+ ions.	Ottoni *et al*., 2019[11]; Wu *et al*., 2020[12]; Souza *et al*., 2019[13]; Tayemeh *et al*., 2020[14]; Barbieri *et al*., 2018[15]; Tortella *et al*., 2020[16]; Lekamge *et al*., 2018[17]; Turner *et al*., 2012[19]; Croteau *et al*., 2011[20]; Alves *et al*., 2022[21]; Posgai *et al*., 2011[22]; Radniecki *et al*., 2011[23]; Braydich-Stolle, 2005[24]; AshaRani *et al*., 2009[25]; Medeiros *et al*., 2019[26]; Keller *et al*., 2010[27]; Miao *et al*., 2009[28]; Shanthi *et al*., 2016[29]; Yan *et al*., 2018[31]; Álvarez-Manzaneda *et al*., 2017[34]; Yoo-iam *et al*., 2014[37]
Titanium (TiO_2) Nanoparticles	*Daphnia magna, Artemia salina*	• Reduces growth and reproduction of *Daphnia magna*. • Induces significant adverse effects on growth, egg production, and neonate production in *Ceriodaphnia silvestrii*.	Fouqueray *et al*., 2012[7]; Lacave *et al*., 2017[8]; An *et al*., 2019[9]; Lucca, 2016[10]; Rezende *et al*., 2018[39]
Zinc (ZnO) Nanoparticles	*Ceriodaphnia cornuta, Tigriopus fulvus, Tigriopus japonicus, Elasmopus rapax, Daphnia magna, Caenorhabditis elegans*	• Causes mortality, growth inhibition, and reproductive issues. • Adverse effects on offspring, feeding behavior, and enzyme activities. • Dissolution of Zn^{+2} ions leads to cytotoxic effects.	Souza, 2018[13]; Park *et al*., 2014[36]; Wong *et al*., 201038; Vijayakumar *et al*., 2017[43]; Prato *et al*., 2020[44]; Schrurs and Lison, 2012[45]; Huang *et al*., 2017[47]; Garbutt and Little, 201448; Franklin *et al*., 2007[50]; Xia *et al*., 2008[51]; Baun *et al*., 2008[52]
Various Nanocompounds	*Artemia salina, Cypridopsis vidua*	• Exhibits varying toxic effects. • High toxicity in *Cypridopsis vidua*. • Affects lipid metabolism and the food chain.	Eiras *et al*., 202[26]; Shokry *et al*., 2021[53]; Cedervall *et al*., 2012[54]
Magnetic Microparticles (MPs)	*Daphnia magna, Ceriodaphnia silvestrii*	• Inhibits growth and reproduction. • Significant reductions in body size, egg production, and neonate production.	Álvarez-Manzaneda *et al*., 2017[34]; Gebara, 2017[59]
Polystyrene Nanoplastics (NPs)	*Artemia parthenogenetica*	• Reduces growth and filtration rate. • Alters enzymatic activities and induces physiological stress responses.	Sanz Lanzas, 2017[60]

Potential research gaps in understanding the environmental implications of nanoparticle synthesis and application in aquatic environments

Exploring Environmentally Friendly Alternatives for Nanoparticle Synthesis: Investigate alternative methods for synthesizing of nanoparticles that are environmentally friendly and cost-effective, aiming to reduce the production of toxic residues and minimize environmental risks associated with NP synthesis.

Assessing Ecological Impacts of Synthetic NPs on Aquatic Systems: Conduct comprehensive studies to evaluate the ecological impacts of synthetic nanoparticles on various organisms in aquatic ecosystems, including bacteria, algae, crustaceans, and fish, considering factors such as toxicity, bioaccumulation, and trophic interactions.

Understanding Mechanisms of NP Toxicity in Aquatic Organisms: Delve into the cellular and molecular mechanisms underlying the toxicity of nanoparticles in aquatic organisms, aiming to elucidate how NPs disrupt cellular functions, induce oxidative stress, and interfere with physiological processes.

Investigating Fate and Behavior of NPs in Aquatic Environments: Explore the fate and behavior of silver nanoparticles in natural aquatic environments, including their interactions with phytoplankton cell surfaces, internal organelles, and the release of toxic Ag^+ ions, to better understand Ag-NP-phytoplankton interactions and ecological consequences.

Ecotoxicological Studies on NP Effects Across Trophic Levels: Conduct ecotoxicological studies to assess the impacts of silver nanoparticles on different trophic levels in aquatic ecosystems, focusing on key organisms such as zooplankton and fish, to evaluate the cascading effects of NPs induced alterations on ecosystem stability.

Understanding Interactions Between NPs and Biological Systems: Investigate the interactions between nanoparticles and biological systems, including the formation of protein coronas, to understand their potential biological risks and implications for organismal health and ecosystem functioning.

Assessing Long-Term Effects of NP Exposure on Aquatic Organisms: Explore the chronic effects of nanoparticle exposure on aquatic organisms, including growth, reproduction, and feeding behavior, to better understand the long-term ecological impacts of NPs on freshwater ecosystems.

Mixture Toxicity Studies of NPs and Environmental Pollutants: Investigate the mixture toxicity of nanoparticles and environmental pollutants in aquatic ecosystems, utilizing data science and nanoinformatics approaches to predict the ecological risks associated with complex mixtures involving NPs.

Examining Effects of NPs on Planktonic Organisms: Study the effects of nanoparticles on planktonic organisms, including copepods, protozoa, and ostracods, to assess potential alterations in community structure and ecosystem dynamics in response to NP contamination.

Developing Strategies for Mitigating NP-Associated Risks in Aquatic Environments: Develop strategies for mitigating the environmental risks associated with nanoparticles in aquatic ecosystems, focusing on sustainable practices and policies to safeguard ecosystem health and biodiversity.

Effects of nanoparticles on phytoplankton

Nanoparticles (NPs) have garnered significant attention due to their potential impacts on aquatic ecosystems, particularly on phytoplankton populations (Figure 1). Several studies have investigated the effects of nanoparticles, such as silver nanoparticles (AgNPs), on phytoplankton communities. Miller *et al.*[61] and Bielmyer-Fraser *et al.*[62] demonstrated suppressive effects of NPs on phytoplankton growth and population. However, the complexities of NP interactions with environmental factors and biological systems warrant further exploration.

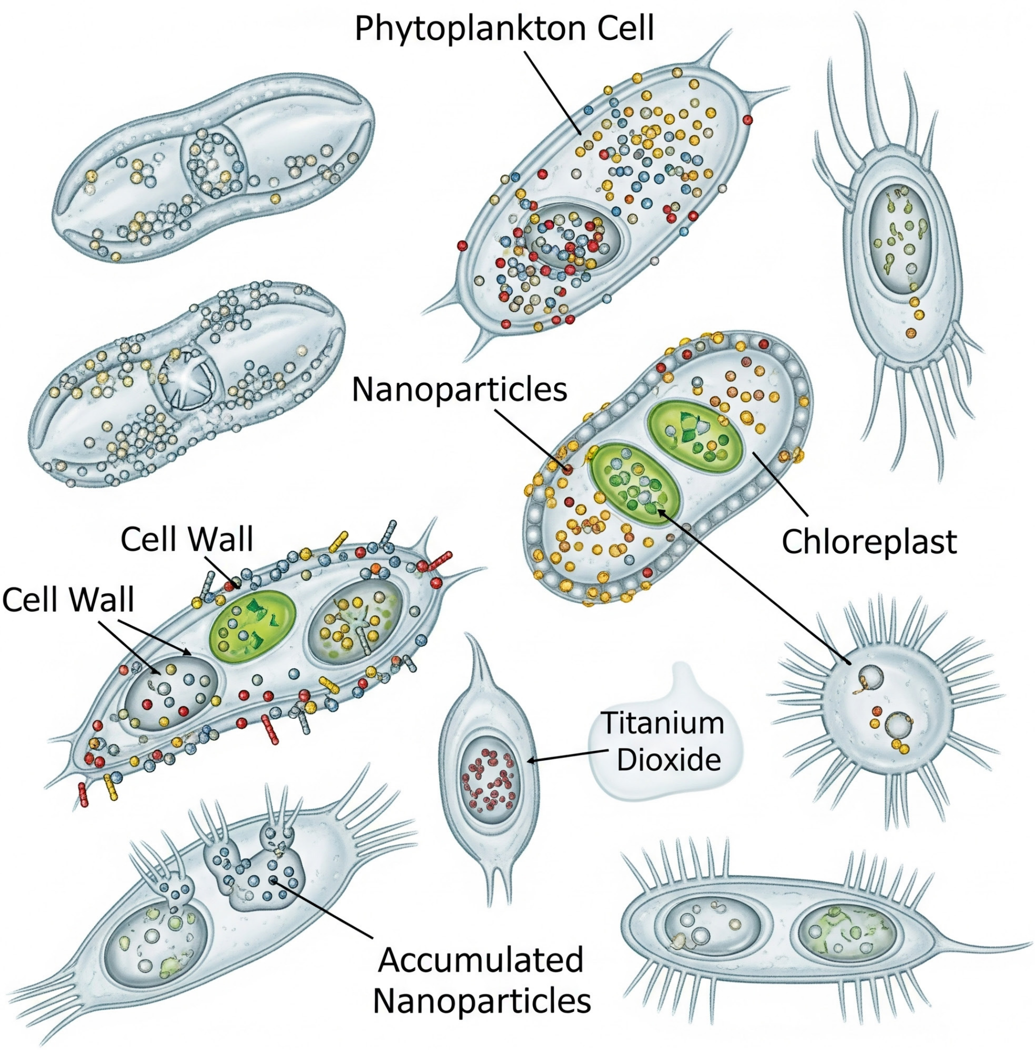

Figure 1 - Potential effects on phytoplankton populations.

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Effects of silver nanoparticles

Conine *et al.*[63] examined the impact of AgNPs on phytoplankton communities in lakes and surprisingly found no significant effects on taxonomy, pigment concentration, or biomass. They attributed this lack of toxicity to natural environmental processes, suggesting that factors like temperature and dissolved nutrients may have a more substantial influence on community dynamics than NP exposure alone.

On the contrary, other studies, such as Baptista *et al.*[64] and Romero *et al.*[65], have reported significant toxic effects of AgNPs on phytoplankton, indicating a potential ecological significance. Moreover, investigations by Navarro *et al.*[66] and Oukarroum *et al.*[67] shed light on the mechanisms underlying NP toxicity, revealing the intricate interplay between nanoparticles and biological systems.

These findings underscore the importance of considering the variability of natural environmental factors when assessing the effects of contaminants on aquatic ecosystems. Furthermore, the potential ecological implications of NP toxicity on phytoplankton highlight the need for comprehensive evaluations of nanomaterials' environmental safety and risks in aquatic environments. Understanding the interactions between nanoparticles and key components of the aquatic food web, such as phytoplankton, is crucial for safeguarding the health and stability of aquatic ecosystems.

Nanoparticles (NPs) have been shown to have suppressive effects on the population and growth rate of various phytoplankton populations[61,68]. A study by Conine *et al.*[63] investigated the impact of adding AgNPs to lakes to assess their effects on phytoplankton. Surprisingly, they found that exposure to relevant concentrations of AgNPs did not significantly affect phytoplankton communities in terms of taxonomy, pigment concentration, and biomass. The lack of negative toxicological results was attributed to natural environmental processes such as temperature and dissolved nutrients, which appeared to influence the community more significantly. Conine *et al.*[63] concluded that the 2 year exposure to environmentally relevant concentrations of AgNPs did not substantially alter phytoplankton communities in boreal lakes. This highlights the importance of considering the variability of natural environmental factors, such as temperature, pH, salinity, etc., in analyses attempting to determine the effects of contaminants on aquatic ecosystems.

Silver nanoparticles (AgNPs) have demonstrated substantial impacts on phytoplankton and bacterioplankton communities, chiefly through their influence on zooplankton grazing behaviors[64]. Exposure to AgNPs at concentrations ≥ 500 μg/L elicited a marked reduction in the growth rates of both phytoplankton and bacterioplankton populations[44]. Moreover, grazing rates within these populations exhibited a propensity to diminish upon AgNP exposure, thereby perturbing a specific trophic stratum. Additionally, phytoplankton photosynthetic efficiency underwent a notable downturn at AgNP concentrations ≥ 500 μg/L[64].

Intriguingly, these effects did not manifest at relatively lower Ag concentrations known to be toxic to certain bacterial species and other organisms. This observation intimates that at environmentally relevant concentrations, compensatory mechanisms at the community level might assuage the impacts of AgNP exposure, as elucidated by Baptista *et al.*[64].

Building upon these observations, Romero *et al.*[65] similarly documented significant toxic effects of AgNPs on *Chlorella vulgaris*. Through an array of morphological, physiological, and metabolic analyses, they unveiled a pronounced impairment in the health status of the microalgae, highlighting the acute nature of the nanoparticle-induced stress. These findings emphasize the potential ecological ramifications of AgNPs within aquatic ecosystems and stress the necessity of comprehensively evaluating community-level responses to nanoparticle exposure.

In a complementary investigation focusing on *Chlamydomonas reinhardtii*, Navarro *et al.*[66] delved into the toxicity of silver nanoparticles (AgNPs) and ionic silver (Ag^+) utilizing photosynthesis as the primary endpoint, assessed via fluorometry. Their study revealed that, concerning the overall silver concentration, the toxicity of $AgNO_3$ (ionic silver) surpassed that of AgNP by 18-fold, as indicated by EC_{50} values. However, when evaluating toxicity in terms of Ag^+ concentration, AgNP exhibited significantly greater adverse effects compared to $AgNO_3$. Intriguingly, the measured levels of ionic Ag^+ in the AgNP suspensions failed to fully account for the observed toxicity, suggesting the involvement of additional mechanisms or interactions contributing to the detrimental outcomes.

To understand this phenomenon, the researchers investigated the role of cysteine, a strong Ag^+ binder. They found that cysteine abolished the inhibitory effects of both AgNP and Ag^+ on photosynthesis. This indicated that the toxicity of AgNP is mediated by Ag^+ ions, and the interaction of AgNP with algae plays a crucial role in influencing its toxicity[67].

This study revealed that AgNP acts as a source of Ag^+ ions, which form in the presence of algae, contributing to the toxicity observed in *Chlamydomonas reinhardti*[68,69]. The findings highlight the complex nature of AgNP toxicity and emphasize the importance of considering the interactions between nanoparticles and biological systems in understanding their environmental impact[62].

In their study, Oukarroum *et al.*[67] investigated the toxic effects of 50 nm silver nanoparticles (AgNPs) on two phytoplanktonic microalgae: *Chlorella vulgaris* and *Dunaliella tertiolecta*. The algae were exposed to concentrations of 0 to 10 mg/L of AgNPs over a 24-hour period. The results showed that AgNPs had a direct interaction with the surface of *Chlorella vulgaris* cells, leading to the formation of large aggregates. The exposure to AgNPs had a negative impact on both *Chlorella vulgaris* and *Dunaliella tertiolecta*. This was evidenced by a considerable decrease in chlorophyll content and viable algal cells, along with an increase in the formation of reactive oxygen species (ROS) and lipid peroxidation.

Nikokherad *et al.*[70] assessed the impact of exposure to commercial AgNPs (30 nm) at concentrations ranging from 0.5 mg/L on the growth of *C. vulgaris* and *Spirulina platensis*. Their findings indicated that following 96 hours of exposure to concentrations equal to or exceeding 0.05 mg/L, both organisms experienced nearly complete growth inhibition.

A recent investigation by Abo-Elmagd *et al.*[71] delved into the exposure of the microalgae *Chlorella vulgaris* and *Chlorella minutissima* to silver nanoparticles (AgNPs) biosynthesized using the cyanobacterium Oscillatoria limnetica and coated with gelatin. The AgNPs, characterized by average sizes of 8.47 nm and 17.66 nm for *C. vulgaris* and *C. minutissima*, respectively, exhibited both negative and positive charges. Following four days of exposure, a concentration of 100 µg/L of AgNPs resulted in a pronounced inhibition of cell growth, reducing it by 91.2% and 88.85% in *C. vulgaris* and *C. minutissima*, respectively.

However, prior investigations by Romero *et al.*[65] and Zhang *et al.*[72] underscore the multifaceted nature of AgNP toxicity, influenced by various factors such as preparation method, aggregation state, size, morphology, medium composition, exposure duration, and electrical charge. Zhang *et al.*[72] particularly emphasize the substantial impact of AgNPs' surface charge on their accumulation kinetics within algal cells. Aguiar *et al.*[4] observed a notable difference in the absorption rates between positively and negatively charged AgNPs, with the former exhibiting approximately 20 times higher absorption. Conversely, Silva *et al.*[73] reported a reduction in the cell density of the microalgae *Chlorella vulgaris* by 40% following 96 hours of exposure to AgNPs, especially at the highest concentration examined (100 µg/L). These findings underscore the intricate interplay of various factors influencing the toxicological response of microalgae to AgNPs and highlight the necessity for comprehensive investigations to elucidate their impacts on aquatic ecosystems.

Interestingly, the sensitivity to AgNPs varied between the two algae species, indicating differences in their response to nanoparticle exposure. These adverse effects on phytoplanktonic algae can have significant consequences on the structure and functioning of phytoplanktonic communities[74].

The findings highlight the potential ecological implications of AgNP toxicity on important primary producers like phytoplankton, which play a vital role in aquatic ecosystems. Understanding the impacts of nanoparticles on these key organisms is crucial for assessing the overall health and stability of aquatic environments.

The toxic effects of nanoparticles on phytoplankton can lead to significant alterations in the structure of the community. Álvarez-Manzaneda *et al.*[34] conducted a study to investigate the impacts of environmentally relevant concentrations of AgNPs on plankton communities in natural environments, using nominal concentrations of 4, 16, and 64 µg/L. They observed that the AgNPs accumulated in phytoplankton, resulting in changes to the biomass of the phytoplankton community[34].

Pithophora oedongia and *Chara vulgaris*, two significant members of photosynthetic eukaryotic algae in the phytoplankton community, play vital roles in the global aquatic ecosystem. Dash *et al.*[75] conducted a study to assess the impact of silver nanoparticles (AgNPs) on the growth and morphology of these algae. Their findings revealed that increasing concentrations of AgNPs led to a progressive reduction in chlorophyll content, chromosomal instability, and mitotic disorders in the exposed algal stalks, resulting in morphological malformations in the filaments of *Chara vulgaris*. Microscopic images highlighted significant changes in the cell walls, such as breakdown and degradation, in the algae treated with nanoparticles. While these results indicate serious harmful effects of silver nanoparticles on aquatic organisms, they also present an opportunity for a bioengineering approach to manage the growth of harmful algae that can obstruct municipal water supplies, water channels, and cause fouling in water bodies. Understanding the impact of nanoparticles on algae can pave the way for innovative strategies in algae control, ultimately helping mitigate their detrimental effects on the environment.

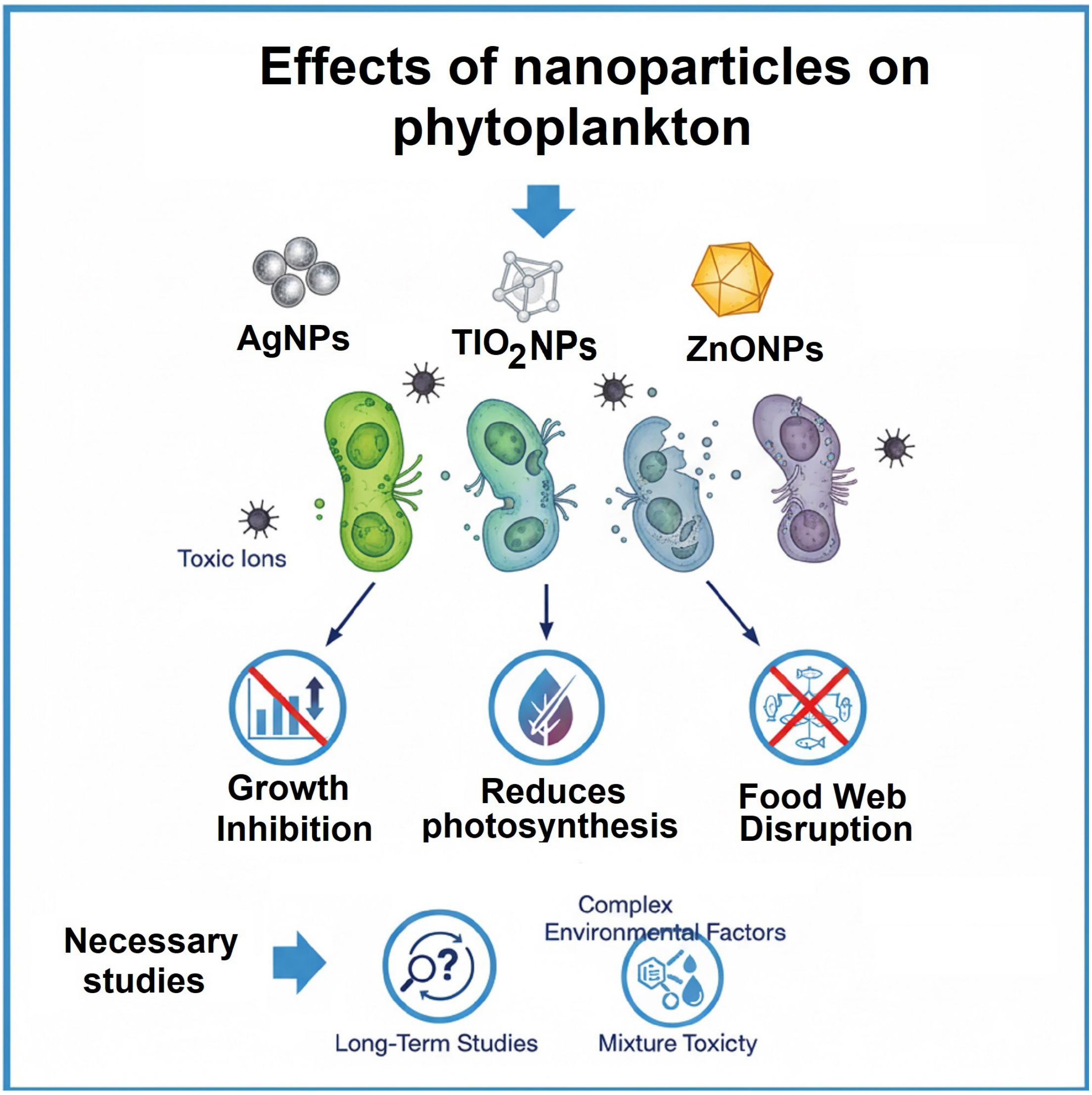

Figure 2 - Effects of NPs on Phytoplancton.

Yoo-iam *et al.*[37] undertook a comprehensive investigation to evaluate the toxicity and bioaccumulation potential of materials incorporating silver nanoparticles within the food chain. This study scrutinized two distinct forms of silver, namely Ag^+ particles and nano Ag° (AgNPs), and their impact on *Chlorella* sp. The findings elucidated that Ag^+ exhibited greater toxicity compared to AgNPs across all four organisms assessed. Specifically, the EC_{50} value for Ag^+ toxicity in *Chlorella* sp. was determined to be 0.39±0.32 mg/L

These findings emphasize the potential disruption nanoparticles can cause to the delicate balance of aquatic ecosystems. As phytoplankton play a crucial role in the food web and are essential for sustaining marine life, any disturbances to their populations can have far-reaching consequences on the entire ecosystem. Therefore, understanding the interactions between nanoparticles and phytoplankton is crucial for assessing the ecological implications of nanomaterials in aquatic environments.

Effects of titanium nanoparticles

In chronic toxicity tests assessing the impact of titanium nanoparticles on the chlorophyte microalgae *Pseudokirchneriella subcapitata*, a notable inhibition of algal growth was observed at a concentration of 64 mg/L of nano-TiO_2. Additionally, the 96-hour exposure to nano-TiO_2 resulted in a 50% inhibition concentration of algal cells (LC_{50} - 96h) at 201.22 mg/L[42].

These findings underscore the potential adverse effects of titanium nanoparticles on aquatic microorganisms. As microalgae play a fundamental role in freshwater ecosystems by contributing to primary productivity and serving as a food source for higher trophic levels, their disruption can have cascading impacts on the entire ecological balance. It is essential to comprehensively assess the toxicity of nanoparticles on various aquatic organisms to better understand their potential risks and develop effective strategies for environmental protection.

Effects of titanium and zinc nanoparticles

In their research, Takasu *et al.*[74] delved into the repercussions of TiO_2 and ZnO nanoparticles on natural phytoplankton communities in coastal waters. They observed a notable decline in the growth rates of these communities upon exposure to 10 mg/L of TiO_2 and ZnO nanoparticles. Furthermore, the introduction of nanoparticles induced a shift in the size distribution of phytoplankton communities, with cyanobacteria displaying heightened susceptibility. Given that the dietary preferences of herbivores hinge heavily on algal cell size, nanoparticle pollution may disrupt higher trophic levels. It's worth highlighting that cyanobacteria play a pivotal role in the microbial loop, rendering this energy transfer mechanism potentially more vulnerable to nanoparticle contamination (Figure 2).

Effects of magnetic nanoparticles

In the investigation of the effects of iron magnetic nanoparticles (Fe_3O_4, Cu-Fe_2O_4, and $CoFe_2O_4$) on the freshwater phytoplankton species *Raphidocelis subcapitata*, Melo[76] observed that significant alterations in the physiological response of the microalgae occurred only at high nanoparticle concentrations exceeding 50 mg/L. At these elevated concentrations, the magnetic nanoparticles induced an increase in lipid and protein concentrations within the microalgae. Furthermore, the study demonstrated that chlorophyll fluorescence parameters and oxidative stress, induced by the generation of reactive oxygen species (ROS), were particularly sensitive to the presence of nanoparticles, especially at higher concentrations. These findings highlight the potential impact of magnetic nanoparticles on microalgae and their physiological processes, warranting further investigation to assess their implications in aquatic ecosystems. Understanding the effects of nanoparticles on key components of the aquatic food web, such as phytoplankton, is crucial for a comprehensive evaluation of their environmental safety and potential risks.

Effects of si nanoparticles

In their comprehensive investigation, Wang *et al.*[77] thoroughly examined the toxic mechanism of $nSiO_2$ nanoparticles on the microalgae *Nitzschia closterium f. minutissima* through a series of growth inhibition experiments. Spanning a duration of 96 hours, the study meticulously tracked the growth patterns and biological responses of the algae under exposure to diverse concentrations of $nSiO_2$, ranging from 0.5 to 30 mg/L, within f/2 media. The results unveiled a clear-cut inhibition of *N. closterium* f. *minutissima* growth, showcasing a concentration- and time-dependent trend influenced by the presence of the nanoparticles.

Effects of cuper nanoparticles

Vignardi *et al.*[78] conducted an extensive exploration into the ramifications of rapidly agglomerated Nano-Cu within seawater, elucidating subsequent reductions in particle size owing to Cu dissolution dynamics. Their meticulous investigation spanned several weeks, meticulously tracking dissolution rates that initially tapered from weeks 1 to 4, maintaining subdued levels until the 15th week, when larger agglomerates underwent rapid dissolution once more. Phytoplankton communities underwent sequential 5-day exposures to nano-Cu over aging periods spanning 1 to 15 weeks, across concentrations ranging from 0.01 to 20 ppm. Notably, toxicity to phytoplankton, as manifested by alterations in population growth rates, exhibited a discernible decline during the early stages of particle aging, from 0 to 4 weeks. However, a pronounced escalation in toxicity emerged in the 15-week treatment phase, likely attributable to the intensified Cu dissolution from reagglomerated particles. These insightful findings underscore the intricate interplay of physicochemical aging processes, significantly shaping the fate, transformation, and toxicity profiles of nano-Cu within marine ecosystems.

Effects of iron-based nanoparticles

The research led by D'ors *et al.*[79] undertook a comprehensive analysis to assess the impact of nZVI nanoparticles (nanoscale zero-valent iron) on the growth rate, photosynthetic activity, and reactive oxygen species (ROS) production in the freshwater green alga *Scenedesmus armatus* and the cyanobacterium *Microcystis aeruginosa*. Additionally, the study evaluated microcystin production in these organisms. This extensive examination involved subjecting both algal species to individual exposures to nZVI at effective concentrations for 72 hours, aiming for a maximum response of 10% over a duration of 28 days. The findings unveiled significant alterations in the cell growth rate of *S. armatus* initially, with subsequent normalization to control levels after 28 days of exposure, while *M. aeruginosa* exhibited consistent responses comparable to control values throughout the study period. Furthermore, the analysis revealed an increase in dark respiration (R) in both algal strains, contrasting with net photosynthesis (Pn), which remained relatively stable. Interestingly, gross photosynthesis (Pg) showed a modest increase at the 7-day mark, subsequently aligning with control levels by the 28th day of exposure. Notably, the progressive generation of ROS by nZVI nanoparticles over the 28-day period was more pronounced in the green algae than in the cyanobacteria. These insightful findings from D'ors *et al.*[79] contribute valuable insights into the potential risks associated with nZVI exposure, thereby facilitating informed decision-making processes concerning the utilization of nZVI for environmental remediation purposes.

Table 2 - Effects of nanoparticles on phytoplankton.

Study	Nanoparticles	Organism	Effects/Findings
Conine *et al.* (2018)[63]	Silver nanoparticles (AgNPs)	*Phytoplankton communities*	No significant effects on taxonomy, pigment concentration, or biomass observed in lakes after 2-year exposure to environmentally relevant concentrations of AgNPs.
Baptista *et al.*(2015)[64]	Silver nanoparticles (AgNPs)	*Phytoplankton populations*	Significant reduction in growth rates of phytoplankton and bacterioplankton populations observed at concentrations ≥ 500 µg/L of AgNPs.
Romero *et al.*(2020)[65]	Silver nanoparticles (AgNPs)	*Chlorella vulgaris*	Pronounced impairment in health status of *Chlorella vulgaris*, indicating acute nanoparticle-induced stress.
Navarro *et al.*(2008)[66]	Silver nanoparticles (AgNPs)	*Chlamydomonas reinhardtii*	Toxicity of AgNPs mediated by Ag^{+} ions, indicating the role of AgNP-algae interaction in influencing toxicity.
Oukarroum *et al.*(2012)[67]	Silver nanoparticles (AgNPs)	*Chlorella vulgaris, Dunaliella tertiolecta*	Direct interaction of AgNPs with algal cell surface, leading to a decrease in chlorophyll content, viable algal cells, and an increase in ROS and lipid peroxidation.
Nikokherad *et al.* (2022)[68]	Silver nanoparticles (AgNPs)	*Chlorella vulgaris, Spirulina platensis*	Growth inhibition observed in both organisms following 96-hour exposure to concentrations ≥ 0.05 mg/L of commercial AgNPs.
Abo-Elmagd *et al.* (2022)[71]	Silver nanoparticles (AgNPs)	*Chlorella vulgaris, Chlorella minutissima*	Pronounced inhibition of cell growth in both organisms following exposure to 100 µg/L of biosynthesized AgNPs.
Takasu *et al.* (2023)[74]	Titanium dioxide (TiO_2), Zinc oxide (ZnO)	*Phytoplankton communities*	Decline in growth rates of phytoplankton communities upon exposure to 10 mg/L of TiO2 and ZnO nanoparticles, inducing a shift in size distribution, with heightened susceptibility of cyanobacteria.
Melo (2016)[76]	Iron magnetic nanoparticles (Fe_3O_4, Cu-Fe_2O_4, $CoFe_2O_4$)	*Raphidocelis subcapitata*	Significant alterations in physiological response of microalgae, increased lipid and protein concentrations, changes in chlorophyll fluorescence parameters and oxidative stress.
Wang *et al.* (2024)[77]	Silicon dioxide ($nSiO_2$) nanoparticles	*Nitzschia Closterium f. minutissima*	Inhibition of growth patterns in *N. closterium f. minutissima* in a concentration- and time-dependent manner influenced by nSiO2 nanoparticles.
Vignardi *et al.* (2023)[78]	Copper nanoparticles (Cu)	*Phytoplankton communities*	Sequential exposures to nano-Cu over aging periods induced toxicity in phytoplankton communities, with toxicity escalating at longer particle aging times.
D'ors *et al.* (2023)[79]	Nanoscale zero-valent iron (nZVI)	*Scenedesmus armatus, Microcystis aeruginosa*	Significant alterations in cell growth rate, photosynthetic activity, ROS production, and microcystin production observed in algae following nZVI exposure.

Advancing understanding of nanoparticle toxicity on phytoplankton and aquatic ecosystems: future directions and research opportunities

Future study could explore the ecological ramifications of nanoparticles (NPs) on phytoplankton populations, delving into the intricate interactions between NPs and environmental factors. For instance, investigations could focus on elucidating the mechanisms underlying the suppressive effects of NPs on phytoplankton growth and population dynamics. Additionally, studies could further examine the variability in phytoplankton responses to NPs, considering factors such as particle size, concentration, and exposure duration.

Furthermore, research could aim to unravel the complexities of NP toxicity on phytoplankton communities in natural environments. By conducting comprehensive evaluations, researchers can better understand how NP exposure influences taxonomy, pigment concentration, biomass, and other ecological parameters within phytoplankton communities. Such studies could shed light on the adaptive mechanisms of phytoplankton to NP exposure and their implications for ecosystem functioning.

Exploring the potential ecological significance of NP toxicity on phytoplankton, particularly in the context of trophic interactions and community dynamics, would be valuable. Future investigations could assess the cascading effects of NP-induced alterations in phytoplankton populations on higher trophic levels and overall ecosystem stability. Moreover, studies focusing on the interactions between NPs and key components of the aquatic food web, such as zooplankton and fish, could provide insights into the broader ecological implications of NP exposure in aquatic ecosystems.

Additionally, future research could delve into the underlying mechanisms of NP toxicity on phytoplankton at the cellular and molecular levels. By elucidating how NPs disrupt cellular functions, induce oxidative stress, and interfere with physiological processes in phytoplankton, researchers can gain a deeper understanding of the mechanisms driving NP-induced toxicity. Furthermore, investigations into the fate and behavior of NPs in aquatic environments, including their interactions with phytoplankton cell surfaces and internal organelles, would contribute to our knowledge of NP-phytoplankton interactions and their ecological consequences.

Overall, future articles should strive to advance our understanding of the ecological implications of NP exposure on phytoplankton populations and aquatic ecosystems. By addressing key knowledge gaps and exploring novel research avenues, researchers can contribute to the development of informed policies and management strategies aimed at safeguarding aquatic environments from the potential risks associated with NP contamination.

CONCLUSION

In conclusion, the ecological focus on the effects of nanoparticles on zooplankton and phytoplankton and other aquatic organisms is of paramount importance for understanding and mitigating potential environmental risks. The synthesis of nanoparticles using environmentally friendly approaches is being explored as an alternative to conventional chemical methods, which can generate toxic residues. However, before widespread adoption, thorough investigations of the ecological impact of biologically synthesized nanoparticles are necessary.

Studies have shown that nanoparticles can be toxic to various aquatic organisms, including zooplankton, algae, plants, crustaceans, and fish. The toxicity of nanoparticles is influenced by factors such as particle size, concentration, and exposure duration. Exemple, the release of toxic silver ions (Ag^{+}) from AgNPs can further exacerbate their adverse effects on aquatic biota. Due to the small size of nanoparticles, they can easily enter biological systems and disrupt cellular functions, leading to physiological damage and altered behavior.

Various aquatic species, such as *Daphnia*, copepods, and cladocerans, have been used as model organisms in ecotoxicological studies to assess the impacts of nanoparticles. Chronic exposure to nanoparticles has been shown to negatively affect growth, reproduction, and feeding behavior of these organisms, indicating potential disruptions in the aquatic food web and overall ecosystem functioning.

Understanding the dynamics of nanoparticle dissolution and the formation of protein coronas around nanoparticles is crucial for comprehending their behavior within living organisms and the environment. Additionally, mixture toxicity studies involving nanoparticles and environmental pollutants require further attention, as realistic exposure scenarios may differ from controlled laboratory conditions.

It is evident from the research that nanoparticles can have diverse and complex effects on aquatic organisms, depending on their properties and interactions with the environment. Therefore, standardized methodologies and interdisciplinary approaches, including data science and nanoinformatics, are crucial for assessing and predicting the ecological implications of nanoparticles in aquatic ecosystems.

Overall, the findings from these studies underscore the significance of ecological considerations in nanoparticle synthesis, as well as the necessity of comprehensive ecotoxicological assessments to safeguard the health and balance of aquatic ecosystems. Implementing sustainable and responsible nanotechnology practices requires a deeper understanding of nanoparticle behavior and their potential impacts on aquatic biota, which will aid in the development of effective strategies for mitigating adverse effects and preserving the ecological integrity of aquatic environments.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the workreported in this paper.

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Supplementary Material

Summary - Number of Studies per Nanoparticle Type and Organism Group.

Organism Group / Nanoparticle Type	AgNPs	TiO_2	ZnO	CNTs Carbon Nanotubes	Fe_3O_4, CuO, Polymers	Total per Group
Fish *D. rerio*, *O. niloticus*	5, 8, 16, 37, 54	6, 39	6	3, 15, 21, 40, 42, 55	6 (CuO), 26 (GO + Elements), 41 (GO)	**18**
Crustaceans *Daphnia*, *Ceriodaphnia*, Shrimp	4, 5, 8, 9, 17, 29, 31, 37, 53, 73	7, 10, 39, 61	10, 32, 36, 38, 43, 44, 46, 48, 49	21, 41, 57, 58	34 (Magnetic), 46 ($ZnSO_4$), 59 (Fe_3O_4), 60 (Nanopla	**39**
Algae *Chlorella*, *Pseudokirchneriella*	14, 28, 37, 63, 65, 66, 67, 68, 69, 70, 71, 75	10, 50, 61, 74	36, 49, 50, 51, 74		74 (CuO), 76 (Magnetic), 77 ($nSiO_2$, mPS), 78 (CuO), 79 (Fe)	**29**
Other Invertebrates *Caenorhabdi-tis*, *Hydra*, *Chironomus*	17, 20, 23, 33, 37, 47		47		22 (TiO_2 on *Drosophila*), 23 (Nitrosomonas), 33 (CdSe), 34 (Magnetic), 37 (*Chironomus*), 47 (ZnO)	**13**

to be continued...

continuation...

Organism Group / Nanoparticle Type	AgNPs	TiO_2	ZnO	CNTs Carbon Nanotubes	Fe_3O_4, CuO, Polymers	Total per Group
Communities/Assays with Multiple Organisms	63, 64, 69, 70	61, 74	74	30 (GO), 58	74 (CuO), 78 (CuO)	**12**
Human Cells/ *in vitro* Assays	24, 25, 35				24 (Fe_3O_4, MoO_3), 25 (Ag, TiO_2), 35 (Ag)	**6**
Reviews / Modeling / Other	1, 2, 13, 16, 18, 45, 52	1, 45, 52	12, 45, 49, 52	1, 2, 45, 52, 56	1, 2, 12, 45, 52, 72	**19**
Total per Nanoparticle	**30**	**13**	**15**	**12**	**22**	**92**

Legend and Explanatory Notes:

AgNPs: Silver Nanoparticles.

TiO_2: Titanium Dioxide.

ZnO: Zinc Oxide.

CNTs: Carbon Nanotubes (including multi-walled carbon nanotubes).

Other: Includes a variety of nanoparticles such as copper oxide (CuO), iron oxide (Fe_3O_4, Fe), cerium oxide, quantum dots (CdSe), nanoplastics, graphene oxide (GO), among others.

Counting: The numbers in the cells refer to the IDs of the references listed in your query. The total count (92) is higher than the total number of references (79) because many studies investigated more than one type of nanoparticle or organism.

Grouping:

Crustaceans: Includes cladocerans (*Daphnia*, *Ceriodaphnia*), copepods, shrimp, and *Artemia*.

Algae: Includes microalgae and cyanobacteria.

Reviews: This category groups review articles, modeling studies, synthesis, and characterization papers that did not perform specific ecotoxicological assays with organisms.