

Silver Nanoparticles in Aquatic Ecosystems: From Molecular Responses to Community-Level Effects

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Nanotechnology, recognized as the sixth truly revolutionary technology of the modern era, has led to widespread use of engineered nanomaterials (ENMs) and their increasing release into aquatic environments, raising key questions for their environmental implications. Predicting the environmental impacts of ENMs requires understanding how their physicochemical properties and transformations together with their biological responses [1]. In this study, by comparing citrate-coated AgNPs and dissolved silver (Ag^+), we investigate toxicity pathways in aquatic microorganisms, from single-species to artificial and natural phytoplankton assemblages, thereby linking molecular responses to community-level outcomes.

At the cellular level, exposure to AgNPs and Ag^+ induced significant perturbations in central metabolic pathways, including amino acid, nucleotide, fatty acid, antioxidant metabolism, and the tricarboxylic acid (TCA) cycle. While dissolved Ag released from AgNPs emerged as a major toxicity driver, AgNPs exerted nano-specific effects, particularly on TCA cycle activity, glutathione metabolism, and polyamine synthesis. These metabolic alterations correlated with intracellular silver accumulation, impaired photosynthetic performance, and altered carbonic anhydrase activity, with ROS induction observed exclusively following AgNP exposure.

Species-specific and interactive responses were further examined using artificial phytoplankton assemblages composed of *Chlamydomonas reinhardtii*, *C. meneghiniana* and *Synechocystis* sp. across a broad range of AgNP and Ag^+ concentrations. Spectral flow cytometry enabled single-cell analysis of growth and photosynthetic performance within mixed assemblages. Results revealed pronounced species-specific sensitivity, with *Synechocystis* sp. being most affected by AgNPs, while *C. meneghiniana* showed greater tolerance. Ag^+ caused rapid toxicity, whereas AgNPs induced delayed but persistent effects. Interspecies interactions mitigated AgNP toxicity, resulting in higher EC50 values and sustained photosynthetic performance in co-occurring eukaryotic species. Finally, experiments with natural phytoplankton assemblages from lakes with contrasting trophic status showed higher sensitivity of eutrophic communities to AgNP exposure, with cyanobacteria and smaller phytoplankton consistently more affected.

Overall, this work demonstrates that integrating nanomaterial chemistry, bioassays and single-cell analytical tools is essential for linking ENM physicochemical properties with biological responses and for improving ecological risk assessment of AgNPs in aquatic ecosystems.

[1] A. A. Keller; V. I. Slaveykova Advances and challenges in the ecological risk assessment of engineered nanomaterials in aquatic ecosystems: A review *Science of The Total Environment*, 1003, 180739, 2025.