Beyond the Microscopic: Advancing NanoToxicology through Cutting-Edge *In Vitro, In Vivo,* and *In Silico* Models

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Abstract

Nanotechnology has revolutionized numerous industries, but concerns surrounding the potential adverse effects of nanomaterials on human health and the environment necessitate the development of comprehensive NanoToxicology approaches. Recent advancements in the field have led to the integration of advanced *in vitro* and *in vivo* models, with an emerging emphasis on incorporating *in silico* methods to enhance our understanding of nanomaterial toxicity. Amphibian erythrocyte, as an *in vitro* cell model, enables more accurate evaluation of nanoparticles toxicity and their effects on cellular responses. Erythrocyte morphological alternations provide a fingerprint for NPs-induced cito and genotoxicity assessment. Limited systemic complexity of in vitro cell models necessitates the use of *in vivo* models to understand nanomaterial toxicity in the context of whole organisms. Amphibians and zebrafish provide a good in vivo model to study nanoparticle biodistribution, metabolism and molecular mechanisms of their long-term effects. Nowadays, *in silico* methods, which involve computer simulations and modeling, have emerged as powerful tools to complement *in vitro* and *in vivo* approaches. By leveraging molecular dynamics simulations, molecular docking modeling, and systems biology approaches, in silico methods facilitate the prediction of nanomaterial properties, toxicity, and potential interactions with biological systems. These computational models aid in the prioritization of nanomaterials for further experimental investigation, reducing the time and cost associated with traditional trial-and-error approaches. By combining these multidisciplinary approaches, we can enhance our understanding of nanomaterial toxicity and accelerate the responsible development and safe utilization of nanotechnology.

Keywords: *nanotoxicology, erythrocyte, molecular docking, zebrafish, toxicity fingerprint*