Emerging Technology and Future Directions in Environmental Nanotoxicology

- Chapter
- First Online: 20 March 2024
- pp 325–346
- Cite this chapter

Environmental Nanotoxicology

- Patrick Omoregie Isibor,
- Ifeoluwa Ihotu Kayode-Edwards &
- Olugbenga Samson Taiwo

Abstract

Environmental nanotoxicology constitutes a specialized scientific discipline that systematically investigates the multifaceted impact of nanomaterials on ecosystems. The rapid advancements within this field have yielded pivotal insights into the intricate behaviors exhibited by nanomaterials, elucidating their toxicity profiles and unraveling the broader ecological consequences ensuing from their introduction into various environmental compartments. Central to the research in environmental nanotoxicology is the comprehensive comprehension of nanoparticle interactions with both organisms and their surrounding environments. This encompasses an in-depth analysis of the physicochemical properties of nanomaterials, their fate and transport within ecosystems, as well as their potential uptake and bioaccumulation by living organisms at different trophic levels. In the quest for a more thorough understanding of nanoparticle impacts, cutting-edge technologies have become instrumental in pushing the boundaries of research. High-throughput screening methodologies enable the rapid assessment of a multitude of nanomaterials, expediting the identification of potential hazards. Omics techniques, encompassing genomics, transcriptomics, proteomics, and metabolomics, offer a comprehensive profiling of molecular responses to nanoparticle exposure, unraveling intricate cellular and organismal dynamics. Furthermore, computational modeling plays a pivotal role in simulating and predicting the behavior of nanomaterials in complex environmental matrices, providing valuable insights into their transport, transformation, and potential ecological risks. The trajectory of environmental nanotoxicology is now propelled toward the integration of multi-omics data, aiming for a holistic understanding of the underlying mechanisms governing nanoparticle-induced toxicity. This integrated approach holds the promise of unraveling complex biological pathways, enabling the identification of key molecular signatures associated with nanomaterial exposure. Moreover, it facilitates the development of predictive toxicology models, enhancing our capability to forecast the potential environmental impacts of various nanomaterials. Anticipated future directions in this field involve leveraging these innovations to refine risk assessment methodologies, thus contributing to the establishment of robust regulatory frameworks. The ongoing quest is not only to deepen our insights into nanoparticle behavior at the molecular and ecological levels but also to channel this knowledge towards the development of sustainable nanotechnology applications. By aligning research endeavors with the principles of sustainability, environmental nanotoxicology strives to ensure that the benefits of nanotechnology can be harnessed responsibly, mitigating potential adverse effects on ecosystems and human health.

References

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

  CAS Google Scholar

- Ahmad, F., Mahmood, A., & Muhmood, T. (2021). Machine learning-integrated omics for the risk and safety assessment of nanomaterials. *Biomaterials Science, 9*(5), 1598–1608.

  CAS Google Scholar

- Ahmad, A., Imran, M., & Sharma, N. (2022). Precision nanotoxicology in drug development: Current trends and challenges in safety and toxicity implications of customized multifunctional nanocarriers for drug-delivery applications. *Pharmaceutics, 14*(11), 2463.

  CAS Google Scholar

- Ahmed, S. F., Kumar, P. S., Kabir, M., Zuhara, F. T., Mehjabin, A., Tasannum, N., Hoang, A. T., Kabir, Z., & Mofijur, M. (2022). Threats, challenges and sustainable conservation strategies for freshwater biodiversity. *Environmental Research, 214*, 113808.

  CAS Google Scholar

- Ajayi, R. F., Barry, S., Nkuna, M., Ndou, N., Rakgotho, T., Nqunqa, S., Ngema, N., Thipe, V., & Muluadzi, T. (2022). Nanoparticles in biosensor development for the detection of pathogenic bacteria in water. In *Emerging freshwater pollutants* (pp. 331–358). Elsevier.

  Google Scholar

- Ale, A., Gutierrez, M. F., Rossi, A. S., Bacchetta, C., Desimone, M. F., & Cazenave, J. (2021). Ecotoxicity of silica nanoparticles in aquatic organisms: An updated review. *Environmental Toxicology and Pharmacology, 87*, 103689.

  CAS Google Scholar

- Alonso, D., Garcia, J., & Micó, V. (2023). Fluholoscopy—Compact and simple platform combining fluorescence and holographic microscopy. *Biosensors, 13*(2), 253.

  CAS Google Scholar

- Alsagaby, S. A., Vijayakumar, R., Premanathan, M., Mickymaray, S., Alturaiki, W., Al-Baradie, R. S., AlGhamdi, S., Aziz, M. A., Alhumaydhi, F. A., Alzahrani, F. A., & Alwashmi, A. S. (2020). Transcriptomics-based characterization of the toxicity of ZnO nanoparticles against chronic myeloid leukemia cells. *International Journal of Nanomedicine, 4*, 7901–7921.

  Google Scholar

- Anastasiadis, S. H., Chrissopoulou, K., Stratakis, E., Kavatzikidou, P., Kaklamani, G., & Ranella, A. (2022). How the physicochemical properties of manufactured nanomaterials affect their performance in dispersion and their applications in biomedicine: A review. *Nanomaterials, 12*(3), 552.

  CAS Google Scholar

- Ankley, G. T., Cureton, P., Hoke, R. A., Houde, M., Kumar, A., Kurias, J., Lanno, R., McCarthy, C., Newsted, J., Salice, C. J., & Sample, B. E. (2021). Assessing the ecological risks of per-and polyfluoroalkyl substances: Current state-of-the science and a proposed path forward. *Environmental Toxicology and Chemistry, 40*(3), 564–605.

  CAS Google Scholar

- Aurisano, N., Albizzati, P. F., Hauschild, M., & Fantke, P. (2019). Extrapolation factors for characterizing freshwater ecotoxicity effects. *Environmental Toxicology and Chemistry, 38*(11), 2568–2582.

  CAS Google Scholar

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

  CAS Google Scholar

- Babaei, M., Tayemeh, M. B., Jo, M. S., Yu, I. J., & 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.

  CAS **Google Scholar**

- Bathi, J. R., Wright, L., & Khan, E. (2022). Critical review of engineered nanoparticles: Environmental concentrations and toxicity. *Current Pollution Reports, 8*(4), 498–518.

  CAS **Google Scholar**

- Bhat, S. A., Sher, F., Hameed, M., Bashir, O., Kumar, R., Vo, D. V. N., Ahmad, P., & Lima, E. C. (2022). Sustainable nanotechnology based wastewater treatment strategies: Achievements, challenges and future perspectives. *Chemosphere, 288*, 132606.

  CAS **Google Scholar**

- Bhomkar, P., Goss, G., & Wishart, D. S. (2014). A simple and sensitive biosensor for rapid detection of nanoparticles in water. *Journal of Nanoparticle Research, 16*, 1–17.

  Google Scholar

- Bhusal, A., Dogan, E., Nieto, D., Mousavi Shaegh, S. A., Cecen, B., & Miri, A. K. (2022). 3D bioprinted hydrogel microfluidic devices for parallel drug screening. *ACS Applied Bio Materials, 5*(9), 4480–4492.

  CAS **Google Scholar**

- Bishnoi, M., Deepika, M. N., & Jain, A. (2022). Biomedical applications of nano-biosensor. In *Nanotechnology for biomedical applications* (pp. 219–246). Singapore.

  Google Scholar

- Bollella, P., & Katz, E. (2020). Biosensors—Recent advances and future challenges. *Sensors, 20*(22), 6645.

  Google Scholar

- Boros, B. V., & Ostafe, V. (2020). Evaluation of ecotoxicology assessment methods of nanomaterials and their effects. *Nanomaterials, 10*(4), 610.

  CAS **Google Scholar**

- Casalini, T., Limongelli, V., Schmutz, M., Som, C., Jordan, O., Wick, P., Borchard, G., & Perale, G. (2019). Molecular modeling for nanomaterial–biology interactions: Opportunities, challenges, and perspectives. *Frontiers in Bioengineering and Biotechnology, 7*, 268.

  Google Scholar

- Castillo-Michel, H. A., Larue, C., Del Real, A. E. P., Cotte, M., & Sarret, G. (2017). Practical review on the use of synchrotron based micro-and nano-X-ray fluorescence mapping and X-ray absorption spectroscopy to investigate the interactions between plants and engineered nanomaterials. *Plant Physiology and Biochemistry, 110*, 13–32.

  CAS **Google Scholar**

- Choudhury, S. R., Ordaz, J., Lo, C. L., Damayanti, N. P., Zhou, F., & Irudayaraj, J. (2017). From the cover: Zinc oxide nanoparticles-induced reactive oxygen species promotes multimodal cyto- and epigenetic toxicity. *Toxicological Sciences, 156*(1), 261–274.

  Google Scholar

- Churilov, D. G., Polischuk, S. D., Churilov, G. I., Churilova, V. V., & Byshova, D. N. (2020). Investigation of the long-term toxic effect of nanoparticles of different physical-chemical characteristics. *Agronomy Research, 18*(3), 1973–1991.

  Google Scholar

- Cortez-Jugo, C., Czuba-Wojnilowicz, E., Tan, A., & Caruso, F. (2021). A focus on “bio” in bio–nanoscience: The impact of biological factors on nanomaterial interactions. *Advanced Healthcare Materials, 10*(16), 2100574.

  CAS **Google Scholar**

- Cunningham, B. E., Sharpe, E. E., Brander, S. M., Landis, W. G., & Harper, S. L. (2023). Critical gaps in nanoplastics research and their connection to risk assessment. *Frontiers in Toxicology, 5*, 1154538.

  Google Scholar

- Das, P. K., Mohanty, C., Purohit, G. K., Mishra, S., & Palo, S. (2022). Nanoparticle assisted environmental remediation: Applications, toxicological implications and recommendations for a sustainable environment. *Environmental Nanotechnology, Monitoring and Management, 18*, 100679.

  Google Scholar

- Driessen, M. D., Mues, S., Vennemann, A., Hellack, B., Bannuscher, A., Vimalakanthan, V., Riebeling, C., Ossig, R., Wiemann, M., Schnekenburger, J., & Kuhlbusch, T. A. (2015). Proteomic analysis of protein carbonylation: A useful tool to unravel nanoparticle toxicity mechanisms. *Particle and Fibre Toxicology, 12*, 1–18.

  Google Scholar

- Dusinska, M., Tulinska, J., El Yamani, N., Kuricova, M., Liskova, A., Rollerova, E., Rundén-Pran, E., & Smolkova, B. (2017). Immunotoxicity, genotoxicity and epigenetic toxicity of nanomaterials: New strategies for toxicity testing? *Food and Chemical Toxicology, 109*, 797–811.

  CAS Google Scholar

- Faghihzadeh, F., Anaya, N. M., Schifman, L. A., & Oyanedel-Craver, V. (2016). Fourier transform infrared spectroscopy to assess molecular-level changes in microorganisms exposed to nanoparticles. *Nanotechnology For Environmental Engineering, 1*, 1–16.

  Google Scholar

- Forest, V. (2021). Combined effects of nanoparticles and other environmental contaminants on human health-an issue often overlooked. *NanoImpact, 23*, 100344.

  CAS Google Scholar

- Forest, V. (2022). Experimental and computational nanotoxicology—Complementary approaches for nanomaterial hazard assessment. *Nanomaterials, 12*(8), 1346.

  CAS **Google Scholar**

- Fortouna, Y., de Vera, P., Verkhovtsev, A. V., & Solov'Yov, A. V. (2021). Molecular dynamics simulations of sodium nanoparticle deposition on magnesium oxide. *Theoretical Chemistry Accounts, 140*(7), 84.

  CAS **Google Scholar**

- Furxhi, I., Murphy, F., Poland, C. A., Sheehan, B., Mullins, M., & Mantecca, P. (2019). Application of Bayesian networks in determining nanoparticle-induced cellular outcomes using transcriptomics. *Nanotoxicology, 13*(6), 827–848.

  Google Scholar

- Gajewicz, A., Rasulev, B., Dinadayalane, T. C., Urbaszek, P., Puzyn, T., Leszczynska, D., & Leszczynski, J. (2012). Advancing risk assessment of engineered nanomaterials: Application of computational approaches. *Advanced Drug Delivery Reviews, 64*(15), 1663–1693.

  CAS **Google Scholar**

- Gaviria-Arroyave, M. I., Cano, J. B., & Peñuela, G. A. (2020). Nanomaterial-based fluorescent biosensors for monitoring environmental pollutants: A critical review. *Talanta Open, 2*, 100006.

  Google Scholar

- Giusti, A., Atluri, R., Tsekovska, R., Gajewicz, A., Apostolova, M. D., Battistelli, C. L., Bleeker, E. A., Bossa, C., Bouillard, J., Dusinska, M., & Gómez-Fernández, P. (2019). Nanomaterial grouping: Existing approaches and future recommendations. *NanoImpact, 16*, 100182.

  Google Scholar

- Goswami, L., Kim, K. H., Deep, A., Das, P., Bhattacharya, S. S., Kumar, S., & Adelodun, A. A. (2017). Engineered nano particles: Nature, behavior, and effect on the environment. *Journal of Environmental Management, 196*, 297–315.

CAS Google Scholar

- Guimaraes, P. R., Jr. (2020). The structure of ecological networks across levels of organization. *Annual Review of Ecology, Evolution, and Systematics, 51*, 433–460.

  Google Scholar

- Gupta, S., Aga, D., Pruden, A., Zhang, L., & Vikesland, P. (2021). Data analytics for environmental science and engineering research. *Environmental Science and Technology, 55*(16), 10895–10907.

  CAS Google Scholar

- Handy, R. D., van den Brink, N., Chappell, M., Mühling, M., Behra, R., Dušinská, M., Simpson, P., Ahtiainen, J., Jha, A. N., Seiter, J., & Bednar, A. (2012). Practical considerations for conducting ecotoxicity test methods with manufactured nanomaterials: What have we learnt so far? *Ecotoxicology, 21*, 933–972.

  CAS Google Scholar

- Hartmann, S., Louch, R., Zeumer, R., Steinhoff, B., Mozhayeva, D., Engelhard, C., Schönherr, H., Schlechtriem, C., & Witte, K. (2019). Comparative multi-generation study on long-term effects of pristine and wastewater-borne silver and titanium dioxide nanoparticles on key lifecycle parameters in Daphnia magna. *NanoImpact, 14*, 100163.

  Google Scholar

- Hendren, C. O., Lowry, M., Grieger, K. D., Money, E. S., Johnston, J. M., Wiesner, M. R., & Beaulieu, S. M. (2013). Modeling approaches for characterizing and evaluating environmental exposure to engineered nanomaterials in support of risk-based decision making. *Environmental Science and Technology, 47*(3), 1190–1205.

  CAS Google Scholar

- Hernandez-Viezcas, J. A., Castillo-Michel, H., Andrews, J. C., Cotte, M., Rico, C., Peralta-Videa, J. R., Ge, Y., Priester, J. H., Holden, P. A., & Gardea-Torresdey, J. L. (2013). In situ synchrotron X-ray fluorescence mapping and speciation of CeO_2 and ZnO nanoparticles in soil cultivated soybean (Glycine max). *ACS Nano, 7*(2), 1415–1423.

CAS Google Scholar

- Himič, V., Syrmos, N., Ligarotti, G. K., & Ganau, M. (2023). Latest insights on genomic and epigenomic mechanisms of nanotoxicity. In *Impact of engineered nanomaterials in genomics and epigenomics* (pp. 397–417). Wiley.

  Google Scholar

- Hobson, C. M., & Aaron, J. S. (2022). Combining multiple fluorescence imaging techniques in biology: When one microscope is not enough. *Molecular Biology of the Cell, 33*(6), tp1.

  CAS Google Scholar

- Hu, X., Li, D., Gao, Y., Mu, L., & Zhou, Q. (2016). Knowledge gaps between nanotoxicological research and nanomaterial safety. *Environment International, 94*, 8–23.

  CAS Google Scholar

- Huangfu, X., Xu, Y., Liu, C., He, Q., Ma, J., Ma, C., & Huang, R. (2019). A review on the interactions between engineered nanoparticles with extracellular and intracellular polymeric substances from wastewater treatment aggregates. *Chemosphere, 219*, 766–783.

  CAS Google Scholar

- Hughes, S., & Asmatulu, E. (2021). Nanotoxicity and nanoecotoxicity: Introduction, principles, and concepts. *Nanotoxicology and Nanoecotoxicology, 1*, 1–19.

  Google Scholar

- Hussain, M., Zahra, N., Lang, T., Zain, M., Raza, M., Shakoor, N., Adeel, M., & Zhou, H. (2023). Integrating nanotechnology with plant microbiome for next-generation crop health. *Plant Physiology and Biochemistry, 196*, 703.

  CAS Google Scholar

- Imadi, S. R., Kazi, A. G., Ahanger, M. A., Gucel, S., & Ahmad, P. (2015). Plant transcriptomics and responses to environmental stress: An overview. *Journal of Genetics, 94*, 525–537.

CAS Google Scholar

- Inkson, B. J. (2016). Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) for materials characterization. In *Materials characterization using nondestructive evaluation (NDE) methods* (pp. 17–43). Woodhead publishing.

  Google Scholar

- Jenny, J. P., Anneville, O., Arnaud, F., Baulaz, Y., Bouffard, D., Domaizon, I., Bocaniov, S. A., Chèvre, N., Dittrich, M., Dorioz, J. M., & Dunlop, E. S. (2020). Scientists' warning to humanity: Rapid degradation of the world's large lakes. *Journal of Great Lakes Research, 46*(4), 686–702.

  Google Scholar

- Jia, M., Li, S., Zang, L., Lu, X., & Zhang, H. (2018). Analysis of biomolecules based on the surface enhanced Raman spectroscopy. *Nanomaterials, 8*(9), 730.

  Google Scholar

- Ju, Y., Li, X., Ju, L., Feng, H., Tan, F., Cui, Y., Yang, Y., Wang, X., Cao, J., Qiao, P., & Xiao, L. (2022). Nanoparticles in the earth surface systems and their effects on the environment and resource. *Gondwana Research, 110*, 370–392.

  CAS Google Scholar

- Khan, A. A., Allemailem, K. S., Almatroudi, A., Almatroodi, S. A., Mahzari, A., Alsahli, M. A., & Rahmani, A. H. (2020). Endoplasmic reticulum stress provocation by different nanoparticles: An innovative approach to manage the cancer and other common diseases. *Molecules, 25*(22), 5336.

  CAS Google Scholar

- Kim, H. M., & Kang, J. S. (2021). Metabolomic studies for the evaluation of toxicity induced by environmental toxicants on model organisms. *Metabolites, 11*(8), 485.

  Google Scholar

- Kim, H. M., Long, N. P., Min, J. E., Anh, N. H., Kim, S. J., Yoon, S. J., & Kwon, S. W. (2020). Comprehensive phenotyping and multi-omic profiling in the toxicity assessment of nanopolystyrene with different surface properties. *Journal of Hazardous Materials, 399*, 123005.

  CAS Google Scholar

- Kleandrova, V. V., Luan, F., Gonzalez-Diaz, H., Ruso, J. M., Speck-Planche, A., & Cordeiro, M. N. D. (2014). Computational tool for risk assessment of nanomaterials: Novel QSTR-perturbation model for simultaneous prediction of ecotoxicity and cytotoxicity of uncoated and coated nanoparticles under multiple experimental conditions. *Environmental Science and Technology, 48*(24), 14686–14694.

  CAS Google Scholar

- Kumah, E. A., Fopa, R. D., Harati, S., Boadu, P., Zohoori, F. V., & Pak, T. (2023). Human and environmental impacts of nanoparticles: A scoping review of the current literature. *BMC Public Health, 23*(1), 1–28.

  Google Scholar

- Kumar, A., Khandelwal, M., Gupta, S. K., Kumar, V., & Rani, R. (2019). Fourier transform infrared spectroscopy: Data interpretation and applications in structure elucidation and analysis of small molecules and nanostructures. In *Data processing handbook for complex biological data sources* (pp. 77–96). Academic Press.

  Google Scholar

- Kus-Liśkiewicz, M., Fickers, P., & Ben Tahar, I. (2021). Biocompatibility and cytotoxicity of gold nanoparticles: Recent advances in methodologies and regulations. *International Journal of Molecular Sciences, 22*(20), 10952.

  Google Scholar

- Lai, A., Clark, A. M., Escher, B. I., Fernandez, M., McEwen, L. R., Tian, Z., Wang, Z., & Schymanski, E. L. (2022). The next frontier of environmental unknowns: Substances of unknown or variable composition, complex reaction products, or biological materials (UVCBs). *Environmental Science and Technology, 56*(12), 7448–7466.

CAS Google Scholar

- Li, X., Liu, W., Sun, L., Aifantis, K. E., Yu, B., Fan, Y., Feng, Q., Cui, F., & Watari, F. (2015a). Effects of physicochemical properties of nanomaterials on their toxicity. *Journal of Biomedical Materials Research Part A, 103*(7), 2499–2507.

  CAS Google Scholar

- Li, Y. F., Zhao, J., Qu, Y., Gao, Y., Guo, Z., Liu, Z., Zhao, Y., & Chen, C. (2015b). Synchrotron radiation techniques for nanotoxicology. *Nanomedicine: Nanotechnology, Biology and Medicine, 11*(6), 1531–1549.

  Google Scholar

- Li, Y., Zhang, Z., Jiang, S., Xu, F., Tulum, L., Li, K., Liu, S., Li, S., Chang, L., Liddell, M., & Tu, F. (2023). Using transcriptomics, proteomics and phosphoproteomics as new approach methodology (NAM) to define biological responses for chemical safety assessment. *Chemosphere, 313*, 137359.

  CAS Google Scholar

- Lin, S., Zhang, H., Wang, C., Su, X. L., Song, Y., Wu, P., Yang, Z., Wong, M. H., Cai, Z., & Zheng, C. (2022). Metabolomics reveal nanoplastic-induced mitochondrial damage in human liver and lung cells. *Environmental Science and Technology, 56*(17), 12483–12493.

  CAS Google Scholar

- Lu, J., Wang, P., Tian, S., Qian, W., Huang, Y., Wang, Z., Zhu, X., & Cai, Z. (2021). TiO_2 nanoparticles enhanced bioaccumulation and toxic performance of PAHs via trophic transfer. *Journal of Hazardous Materials, 407*, 124834.

  CAS Google Scholar

- Lv, M., Huang, W., Chen, Z., Jiang, H., Chen, J., Tian, Y., Zhang, Z., & Xu, F. (2015). Metabolomics techniques for nanotoxicity investigations. *Bioanalysis, 7*(12), 1527–1544.

  CAS Google Scholar

- Malik, S., Dhasmana, A., Preetam, S., Mishra, Y. K., Chaudhary, V., Bera, S. P., Ranjan, A., Bora, J., Kaushik, A., Minkina, T., & Jatav, H. S. (2022). Exploring microbial-based green nanobiotechnology for wastewater remediation: A sustainable strategy. *Nanomaterials, 12*(23), 4187.

  CAS **Google Scholar**

- Mansouri, K., Grulke, C. M., Judson, R. S., & Williams, A. J. (2018). OPERA models for predicting physicochemical properties and environmental fate endpoints. *Journal of Cheminformatics, 10*(1), 1–19.

  Google Scholar

- Martins, C., Dreij, K., & Costa, P. M. (2019). The state-of-the art of environmental toxicogenomics: Challenges and perspectives of "omics" approaches directed to toxicant mixtures. *International Journal of Environmental Research and Public Health, 16*(23), 4718.

  CAS **Google Scholar**

- Mehta, C. H., Narayan, R., & Nayak, U. Y. (2019). Computational modeling for formulation design. *Drug Discovery Today, 24*(3), 781–788.

  CAS **Google Scholar**

- Mohammadinejad, R., Moosavi, M. A., Tavakol, S., Vardar, D. Ö., Hosseini, A., Rahmati, M., Dini, L., Hussain, S., Mandegary, A., & Klionsky, D. J. (2019). Necrotic, apoptotic and autophagic cell fates triggered by nanoparticles. *Autophagy, 15*(1), 4–33.

  CAS **Google Scholar**

- Mondal, S., & Palit, D. (2022). Prospects and implementation of nanotechnology in environmental remediation and clean up. In *Natural resources conservation and advances for sustainability* (pp. 271–287). Elsevier.

  Google Scholar

- Morin-Crini, N., Lichtfouse, E., Fourmentin, M., Ribeiro, A. R. L., Noutsopoulos, C., Mapelli, F., Fenyvesi, É., Vieira, M. G. A., Picos-Corrales, L. A., Moreno-Pirajána, J. C., & Giraldo, L. (2022). Removal of emerging contaminants from wastewater using advanced treatments: A review. *Environmental Chemistry Letters, 20*(2), 1333–1375.

CAS Google Scholar

- Mortimer, M., Wang, Y., & Holden, P. A. (2021). Molecular mechanisms of nanomaterial-bacterial interactions revealed by omics—The role of nanomaterial effect level. *Frontiers in Bioengineering and Biotechnology, 9*, 683520.

  Google Scholar

- Naskar, J., Boatemaa, M. A., Rumjit, N. P., Thomas, G., George, P. J., Lai, C. W., Mousavi, S. M., & Wong, Y. H. (2022). Recent advances of nanotechnology in mitigating emerging pollutants in water and wastewater: Status, challenges, and opportunities. *Water, Air, and Soil Pollution, 233*(5), 156.

  CAS Google Scholar

- National Institute of Health (NIH). (2020). Computational modeling. In *National institute of biomedical imaging and bioengineering*. U.S. Department of Health and Human Services. Available at: https://www.nibib.nih.gov/science-education/science-topics/computational-modeling. Accessed: 28 Nov, 2023

  Google Scholar

- Nel, A. E., Nasser, E., Godwin, H., Avery, D., Bahadori, T., Bergeson, L., Beryt, E., Bonner, J. C., Boverhof, D., Carter, J., & Castranova, V. (2013). A multi-stakeholder perspective on the use of alternative test strategies for nanomaterial safety assessment. *ACS Nano, 7*(8), 6422–6433.

  CAS Google Scholar

- Nizamani, M. M., Zhang, Q., Muhae-Ud-Din, G., & Wang, Y. (2023). High-throughput sequencing in plant disease management: A comprehensive review of benefits, challenges, and future perspectives. *Phytopathology Research, 5*(1), 44.

  Google Scholar

- Ogunkunle, C. O., Oyedeji, S., Okoro, H. K., & Adimula, V. (2021). Interaction of nanoparticles with soil. In *Nanomaterials for soil remediation* (pp. 101–132). Elsevier.

  Google Scholar

- Ong, T. T., Blanch, E. W., & Jones, O. A. (2020). Surface enhanced Raman spectroscopy in environmental analysis, monitoring and assessment. *Science of the Total Environment, 720*, 137601.

  CAS Google Scholar

- Oviyaa Sri, M., Ilangovan, S. S., Srisugamathi, G., Nilofar Nisha, J., Akshhayya, C., Sounder, S. S., & Srilakkshmi, K. M. (2021). Techniques, methods, procedures and protocols in nanotoxicology. In *Nanotoxicology and nanoecotoxicology* (Vol. 2, pp. 267–302). Springer International Publishing.

  Google Scholar

- Peña-Bahamonde, J., Nguyen, H. N., Fanourakis, S. K., & Rodrigues, D. F. (2018). Recent advances in graphene-based biosensor technology with applications in life sciences. *Journal of Nanobiotechnology, 16*, 1–17.

  Google Scholar

- Pikula, K., Zakharenko, A., Chaika, V., Kirichenko, K., Tsatsakis, A., & Golokhvast, K. (2020). Risk assessments in nanotoxicology: Bioinformatics and computational approaches. *Current Opinion in Toxicology, 19*, 1–6.

  Google Scholar

- Prabowo, B. A., Cabral, P. D., Freitas, P., & Fernandes, E. (2021). The challenges of developing biosensors for clinical assessment: A review. *Chem, 9*(11), 299.

  CAS Google Scholar

- Prat, O., & Degli-Esposti, D. (2019). New challenges: Omics technologies in ecotoxicology. In *Ecotoxicology* (pp. 181–208). Elsevier.

  Google Scholar

- Rajput, V., Minkina, T., Ahmed, B., Sushkova, S., Singh, R., Soldatov, M., Laratte, B., Fedorenko, A., Mandzhieva, S., Blicharska, E., & Musarrat, J. (2020). Interaction of copper-based nanoparticles to soil, terrestrial, and aquatic systems: Critical review of the state of the science and future perspectives. *Reviews of Environmental Contamination and Toxicology, 252*, 51–96.

  CAS **Google Scholar**

- Richarz, A. N. (2019). Big data in predictive toxicology: Challenges, opportunities and perspectives. In *Big data in predictive toxicology* (pp. 1–37). Royal Society of Chemistry.

  Google Scholar

- Richarz, A. N., Avramopoulos, A., Benfenati, E., Gajewicz, A., Golbamaki Bakhtyari, N., Leonis, G., Marchese Robinson, R. L., Papadopoulos, M. G., Cronin, M. T., & Puzyn, T. (2017). Compilation of data and modelling of nanoparticle interactions and toxicity in the NanoPUZZLES project. *Modelling the Toxicity of Nanoparticles, 947*, 303–324.

  CAS **Google Scholar**

- Rothen-Rutishauser, B., Bourquin, J., & Petri-Fink, A. (2019). Nanoparticle-cell interactions: Overview of uptake, intracellular fate and induction of cell responses. In *Biological responses to nanoscale particles: Molecular and cellular aspects and methodological approaches* (pp. 153–170). Springer.

  Google Scholar

- Sabharwal, R., & Miah, S. J. (2021). A new theoretical understanding of big data analytics capabilities in organizations: A thematic analysis. *Journal of Big Data, 8*(1), 1–17.

  Google Scholar

- Sahai, N., Gogoi, M., & Ahmad, N. (2021). Mathematical modeling and simulations for developing nanoparticle-based cancer drug delivery systems: A review. *Current Pathobiology Reports, 9*, 1–8.

  Google Scholar

- Savage, D. T., Hilt, J. Z., & Dziubla, T. D. (2019). In vitro methods for assessing nanoparticle toxicity. In *Nanotoxicity: Methods and protocols* (pp. 1–29). Springer.

  Google Scholar

- Schmeisser, S., Miccoli, A., von Bergen, M., Berggren, E., Braeuning, A., Busch, W., Desaintes, C., Gourmelon, A., Grafström, R., Harrill, J., & Hartung, T. (2023). New approach methodologies in human regulatory toxicology–Not if, but how and when! *Environment International, 178*, 108082.

  CAS Google Scholar

- Servin, A. D., Castillo-Michel, H., Hernandez-Viezcas, J. A., Diaz, B. C., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2012). Synchrotron micro-XRF and micro-XANES confirmation of the uptake and translocation of TiO_2 nanoparticles in cucumber (Cucumis sativus) plants. *Environmental Science and Technology, 46*(14), 7637–7643.

  CAS Google Scholar

- Shamsi, M., Mohammadi, A., Manshadi, M. K., & Sanati-Nezhad, A. (2019). Mathematical and computational modeling of nano-engineered drug delivery systems. *Journal of Controlled Release, 307*, 150–165.

  CAS Google Scholar

- Sharma, P., Pandey, V., Sharma, M. M. M., Patra, A., Singh, B., Mehta, S., & Husen, A. (2021). A review on biosensors and nanosensors application in agroecosystems. *Nanoscale Research Letters, 16*, 1–24.

  Google Scholar

- Sibiya, A., Jeyavani, J., Santhanam, P., Preetham, E., Freitas, R., & Vaseeharan, B. (2022). Comparative evaluation on the toxic effect of silver (ag) and zinc oxide (ZnO) nanoparticles on different trophic levels in aquatic ecosystems: A review. *Journal of Applied Toxicology, 42*(12), 1890–1900.

  CAS Google Scholar

- Siddhanta, S., Kuzmin, A. N., Pliss, A., Baev, A. S., Khare, S. K., Chowdhury, P. K., Ganguli, A. K., & Prasad, P. N. (2023). Advances in

Raman spectroscopy and imaging for biomedical research. *Advances in Optics and Photonics, 15*(2), 318–384.

Google Scholar

- Singh, A. V., Varma, M., Laux, P., Choudhary, S., Datusalia, A. K., Gupta, N., Luch, A., Gandhi, A., Kulkarni, P., & Nath, B. (2023). Artificial intelligence and machine learning disciplines with the potential to improve the nanotoxicology and nanomedicine fields: A comprehensive review. *Archives of Toxicology, 97*(4), 963–979.

  CAS **Google Scholar**

- Song, D., Yang, R., Long, F., & Zhu, A. (2019). Applications of magnetic nanoparticles in surface-enhanced Raman scattering (SERS) detection of environmental pollutants. *Journal of Environmental Sciences, 80*, 14–34.

  CAS **Google Scholar**

- Spedalieri, C., & Kneipp, J. (2022). Surface enhanced Raman scattering for probing cellular biochemistry. *Nanoscale, 14*(14), 5314–5328.

  CAS **Google Scholar**

- Spurgeon, D., Lahive, E., Robinson, A., Short, S., & Kille, P. (2020). Species sensitivity to toxic substances: Evolution, ecology and applications. *Frontiers in Environmental Science, 8*, 588380.

  Google Scholar

- Stan, G., & King, S. W. (2020). Atomic force microscopy for nanoscale mechanical property characterization. *Journal of Vacuum Science and Technology B, 38*(6), 21.

  Google Scholar

- Sukhanova, A., Bozrova, S., Sokolov, P., Berestovoy, M., Karaulov, A., & Nabiev, I. (2018). Dependence of nanoparticle toxicity on their physical and chemical properties. *Nanoscale Research Letters, 13*, 1–21.

  CAS **Google Scholar**

- Sun, Q., Li, T., Yu, Y., Li, Y., Sun, Z., & Duan, J. (2022). The critical role of epigenetic mechanisms involved in nanotoxicology. *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 14*(6), e1789.

  CAS Google Scholar

- Takizawa, T., & Robinson, J. M. (2012). Correlative fluorescence and transmission electron microscopy in tissues. In *Methods in cell biology* (Vol. 111, pp. 37–57). Academic Press.

  Google Scholar

- Terry, L. R., Sanders, S., Potoff, R. H., Kruel, J. W., Jain, M., & Guo, H. (2022). Applications of surface-enhanced Raman spectroscopy in environmental detection. *Analytical Science Advances, 3*(3–4), 113–145.

  CAS Google Scholar

- Thomas, S., Thomas, M. S., & Pothen, L. A. (Eds.). (2022). *Nanotechnology for environmental remediation*. Wiley.

  Google Scholar

- Tirumala, M. G., Anchi, P., Raja, S., Rachamalla, M., & Godugu, C. (2021). Novel methods and approaches for safety evaluation of nanoparticle formulations: A focus towards in vitro models and adverse outcome pathways. *Frontiers in Pharmacology, 12*, 612659.

  CAS Google Scholar

- Titus, D., Samuel, E. J. J., & Roopan, S. M. (2019). Nanoparticle characterization techniques. In *Green synthesis, characterization and applications of nanoparticles* (pp. 303–319). Elsevier.

  Google Scholar

- Tortella, G. R., Rubilar, O., Durán, N., Diez, M. C., Martínez, M., Parada, J., & Seabra, A. B. (2020). Silver nanoparticles: Toxicity in model organisms as an overview of its hazard for human health and the environment. *Journal of Hazardous Materials, 390*, 121974.

  CAS Google Scholar

- Turan, N. B., Erkan, H. S., Engin, G. O., & Bilgili, M. S. (2019). Nanoparticles in the aquatic environment: Usage, properties, transformation and toxicity—A review. *Process Safety and Environmental Protection, 130*, 238–249.

  CAS Google Scholar

- Turunen, T. A., Väänänen, M.-A., & Ylä-Herttuala, S. (2018). Epigenomics. In *Encyclopedia of cardiovascular research and medicine* (pp. 258–265). Elsevier.

  Google Scholar

- Utembe, W., Wepener, V., Yu, I. J., & Gulumian, M. (2018). An assessment of applicability of existing approaches to predicting the bioaccumulation of conventional substances in nanomaterials. *Environmental Toxicology and Chemistry, 37*(12), 2972–2988.

  CAS Google Scholar

- Vanhoof, C., Bacon, J. R., Fittschen, U. E., & Vincze, L. (2020). 2020 atomic spectrometry update–a review of advances in X-ray fluorescence spectrometry and its special applications. *Journal of Analytical Atomic Spectrometry, 35*(9), 1704–1719.

  CAS Google Scholar

- Vigneshvar, S., Sudhakumari, C. C., Senthilkumaran, B., & Prakash, H. (2016). Recent advances in biosensor technology for potential applications–an overview. *Frontiers in Bioengineering and Biotechnology, 4*, 11.

  CAS Google Scholar

- Walshe, R. (2021). The road to big data standardisation. In *The elements of big data value* (p. 333). Springer.

  Google Scholar

- Wang, B., Wang, Z., Feng, W., Wang, M., Hu, Z., Chai, Z., & Zhao, Y. (2010). New methods for nanotoxicology: Synchrotron radiation-based techniques. *Analytical and Bioanalytical Chemistry, 398*, 667–676.

CAS Google Scholar

- Wang, C., Lv, B., Hou, J., Wang, P., Miao, L., & Ci, H. (2019). Quantitative measurement of aggregation kinetics process of nanoparticles using nanoparticle tracking analysis and dynamic light scattering. *Journal of Nanoparticle Research, 21*, 1–15.

  Google Scholar

- Wang, S., Alenius, H., El-Nezami, H., & Karisola, P. (2022a). A new look at the effects of engineered ZnO and TiO_2 nanoparticles: Evidence from transcriptomics studies. *Nanomaterials, 12*(8), 1247.

  Google Scholar

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

  Google Scholar

- Wei, C. C., Yen, P. L., Chaikritsadakarn, A., Huang, C. W., Chang, C. H., & Liao, V. H. C. (2020). Parental CuO nanoparticles exposure results in transgenerational toxicity in Caenorhabditis elegans associated with possible epigenetic regulation. *Ecotoxicology and Environmental Safety, 203*, 111001.

  CAS Google Scholar

- Wright, J.S. (2020). *Colloidal characterisations for environmental exposure assessment in support of the risk assessment of nano-biomaterials for biomedical applications*. pp 79. http://dspace.unive.it/bitstream/handle/10579/16325/865297-1223485.pdf?sequence=2

- Wu, X., Zhou, Q., Mu, L., & Hu, X. (2022). Machine learning in the identification, prediction and exploration of environmental toxicology: Challenges and perspectives. *Journal of Hazardous Materials, 438*, 129487.

  CAS Google Scholar

- Xuan, L., Ju, Z., Skonieczna, M., Zhou, P. K., & Huang, R. (2023). Nanoparticles-induced potential toxicity on human health: Applications, toxicity mechanisms, and evaluation models. *MedComm, 4*(4), e327.

  CAS **Google Scholar**

- Yan, X., Yue, T., Winkler, D. A., Yin, Y., Zhu, H., Jiang, G., & Yan, B. (2023). Converting nanotoxicity data to information using artificial intelligence and simulation. *Chemical Reviews, 123*, 8575.

  CAS **Google Scholar**

- Yu, C., Zeng, H., Wang, Q., Chen, W., Chen, W., Yu, W., Lou, H., & Wu, J. (2022). Multi-omics analysis reveals the molecular responses of Torreya grandis shoots to nanoplastic pollutant. *Journal of Hazardous Materials, 436*, 129181.

  CAS **Google Scholar**

- Zhang, S., & Wang, C. (2023). Precise analysis of nanoparticle size distribution in TEM image. *Methods and Protocols, 6*(4), 63.

  Google Scholar

- Zhang, M., Yang, J., Cai, Z., Feng, Y., Wang, Y., Zhang, D., & Pan, X. (2019). Detection of engineered nanoparticles in aquatic environments: Current status and challenges in enrichment, separation, and analysis. *Environmental Science: Nano, 6*(3), 709–735.

  CAS **Google Scholar**

- Zhang, Y., Yang, H., Yu, Y., & Zhang, Y. (2022). Application of nanomaterials in proteomics-driven precision medicine. *Theranostics, 12*(6), 2674.

  Google Scholar

- Zhang, G., LiBretto, N., Purdy, S., Cesar, L., & Miller, J. (2023). X-ray absorption spectroscopy (XAS): Surface structural determination of alloy nanoparticles. In *Springer handbook of advanced catalyst characterization* (pp. 659–669). Springer International Publishing.

  Google Scholar

- Zhu, Y., Wu, X., Liu, Y., Zhang, J., & Lin, D. (2020). Integration of transcriptomics and metabolomics reveals the responses of earthworms to the long-term exposure of TiO_2 nanoparticles in soil. *Science of the Total Environment, 719*, 137492.

  CAS Google Scholar

Author information

Authors and Affiliations

1. **Department of Biological Sciences, Covenant University, Ota, Ogun State, Nigeria**
   Patrick Omoregie Isibor, Ifeoluwa Ihotu Kayode-Edwards & Olugbenga Samson Taiwo

Corresponding author

Correspondence to Patrick Omoregie Isibor .

Editor information

Editors and Affiliations

1. **Biological Sciences, Covenant University, Ota, Nigeria**
   Patrick Omoregie Isibor
2. **Mechanical and Industrial Engineering, National University of Science and Technology, Sultanate of Oman, Oman**
   Geetha Devi
3. **Environmental Management and Toxicology, University of Benin, Benin City, Nigeria**
   Alex Ajeh Enuneku

Rights and permissions

Copyright information

About this chapter

Cite this chapter

Isibor, P.O., Kayode-Edwards, I.I., Taiwo, O.S. (2024). Emerging Technology and Future Directions in Environmental Nanotoxicology. In: Isibor, P.O., Devi, G., Enuneku, A.A. (eds) Environmental Nanotoxicology. Springer, Cham. https://doi.org/10.1007/978-3-031-54154-4_16

Download citation

- .RIS
- .ENW
- .BIB

- DOIhttps://doi.org/10.1007/978-3-031-54154-4_16
- Published20 March 2024
- Publisher NameSpringer, Cham
- Print ISBN978-3-031-54153-7
- Online ISBN978-3-031-54154-4
- eBook PackagesEarth and Environmental ScienceEarth and Environmental Science (R0)

Buy Chapter

eBook **EUR 139.09**

Hardcover Book **EUR 169.99**

Tax calculation will be finalised at checkout

Purchases are for personal use only

Institutional subscriptions

- Sections
- References

- Abstract
- References
- Author information
- Editor information
- Rights and permissions
- Copyright information
- About this chapter
- Publish with us