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ECOLOGICAL SIGNIFICANCE AND ROLE OF NANOPARTICLES IN BOTANY AND ZOOLOGY EMPHASIZING THE NOVEL EMERGING TECHNOLOGIES

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Abstract

Nanotechnology has emerged as a transformative field across the biological sciences, including the zoology and botany. The use of nanoparticles (NPs) in botanical and zoological research and applications has opened new avenues for diagnostics, drug delivery, toxicology, environmental monitoring, and species conservation. Their small size, large surface area, and tunable properties make them valuable tools in understanding animal physiology, detecting pathogens, and improving veterinary medicine. This review highlights the fundamental concepts, mechanisms, and applications of nanoparticles in zoological studies, summarizes the applications, mechanisms, and potential risks of nanoparticles in plants, emphasizing their role in seed germination, photosynthesis, nutrient uptake, and stress tolerance discussing their advantages, limitations, and potential environmental risks. It also explores how nanotechnology bridges molecular biology and animal science to create sustainable innovations in health, ecology, and conservation. It also highlights the challenges and research gaps that must be addressed before large-scale agricultural use becomes viable.

INTRODUCTION

Nanotechnology refers to the design and application of materials with at least one dimension in the nanometer range (1–100 nm). At this scale, materials exhibit unique physical and chemical properties distinct from their bulk counterparts. Over the past two decades, nanotechnology has moved beyond physics and chemistry to deeply influence the life sciences [1-3]. In zoology, the integration of nanoscience has provided novel insights into animal physiology, disease mechanisms, and ecological interactions. Botany, the scientific study of plants, has traditionally focused on understanding plant structure, physiology, genetics, and ecology. However, with rapid advancements in material science, nanotechnology has entered the realm of plant research, providing innovative tools for enhancing crop productivity and resilience. Nanoparticles, typically ranging from 1 to 100 nm in

size, exhibit high surface-area-to-volume ratios and reactive surfaces that can modify plant metabolic activities when applied in controlled concentrations[4-5].

Nanoparticles are synthesized through physical, chemical, or biological methods, and their composition varies from metallic oxides (e.g., ZnO, TiO_2, Fe_2O_3) to carbon-based and polymeric materials. In botany, they can function as growth promoters, nutrient carriers, stress protectants, or antimicrobial agents. Despite these benefits, their interaction with plant systems remains complex, and both positive and negative outcomes have been reported depending on the nanoparticle type, concentration, and plant species involved [6-7].

Zoology traditionally focuses on the structure, function, and behavior of animals. However, as molecular techniques and bioengineering tools evolve, discipline increasingly overlaps with materials science and biotechnology. Nanoparticles particularly metal, metal oxide, polymeric, and lipid-based types have become central to this convergence. Their applications range from drug delivery and biosensing to habitat monitoring and pollutant remediation. As animals interact continuously with their environment, nanoparticles can also influence ecological balance, making their study relevant for both applied and environmental zoology [8-10].

Table 1: summarizes the key roles, mechanisms of action, biological pathways, advantages, and disadvantages of various nanoparticles in plants and animals.

Organism	Type of Nanoparticle	Usage	Mechanism	Advantages	Disadvantages
Plants	Silver nanoparticles (AgNPs)	Promote seed germination, enhance growth, and provide antimicrobial protection.	Induce ROS generation and activate antioxidant enzymes	Improved resistance to pathogens; faster seedling growth.	Excess ROS may cause oxidative stress and damage to plant cells.
Plants	Zinc oxide nanoparticles (ZnO NPs)	Boost photosynthesis, chlorophyll content, and enzymatic activity.	Facilitate Zn2+ uptake and regulate photosynthetic pathways	Enhance nutrient use efficiency and yield.	High concentrations can inhibit root growth and cause chlorosis.
Plants	Titanium dioxide nanoparticles (TiO2 NPs)	Enhance light absorption and stress tolerance.	Activate photoreduction	Improve photosynthetic rate and drought resistance.	Possible DNA damage at high doses
Animals	Gold nanoparticles (AuNPs)	Used in diagnostics, imaging	Enter cells via endocytosis; bind to thiol	High biocompatibility and stable surface functionalization.	Potential long-term accumulation and cytotoxicity.
Animals	Silver nanoparticles (AgNPs)	Serve as antimicrobial and wound-healing agents.	Disrupt bacterial membranes and generate reactive oxygen species.	Broad-spectrum antimicrobial effect; promotes tissue regeneration.	Can damage mammalian cells and cause inflammation at high doses.
Animals	Magnetic nanoparticles (Fe3O4 NPs)	Applied in drug targeting, MRI contrast, and hyperthermia cancer therapy.	Respond to magnetic fields for guided delivery and heat induction.	Enable precise targeting and non-invasive imaging.	Potential aggregation, oxidative stress, and immune response.

Nanoparticles associated characteristics in plants

When nanoparticles are applied to soil, leaves, or seeds, they can enter the plant through various pathways such as stomata, root epidermis, or wounds. Once inside, they may translocate through the xylem and phloem, accumulating in different tissues. Metal-based nanoparticles dissolve slowly, releasing ions that act as micronutrients (e.g., Zn^{2+}, Fe^{3}. Nanoparticles can induce or scavenge ROS, affecting antioxidant enzyme activity. Certain NPs alter transcriptional responses related to stress signaling and metabolism. TiO_2 and ZnO NPs improve light absorption and electron transport during photosynthesis[11-12].

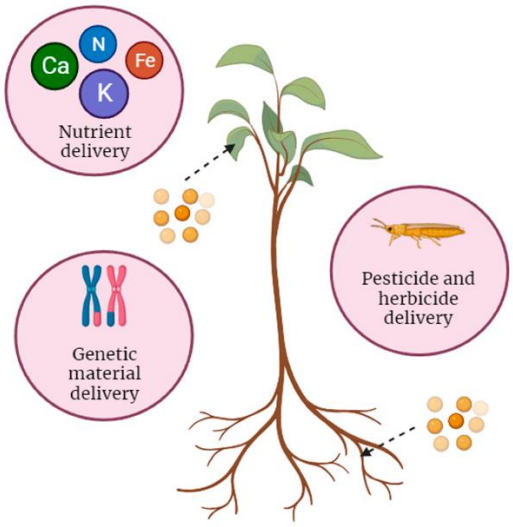

Figure 1 illustrates the emerging features of nanoparticles within plant systems

Prominent features of nanoparticles relevant to zoology

Different classes of nanoparticles are used depending on their intended biological function. Metallic nanoparticles, such as gold (Au), silver (Ag), and zinc oxide (ZnO), possess strong antimicrobial and optical properties, which make them suitable for diagnostics and disinfection. Magnetic nanoparticles, usually based on iron oxide (Fe_3O_4), are used in targeted drug delivery and bioimaging[12-13]. Polymeric and lipid nanoparticles, on the other hand, provide biodegradable and biocompatible platforms for controlled release of drugs or hormones in animals. The physicochemical characteristics of nanoparticles size, shape, surface charge, and coating strongly influence their behavior in biological systems. Smaller particles tend to penetrate tissues more efficiently, while surface functionalization can enhance biocompatibility and target specificity. In zoological research, these tunable properties allow scientists to design nanoparticles that interact precisely with animal cells, proteins, or tissues, enabling detailed studies of physiology and pathology[13-15].

Role in in plants and animal research

Nanoparticles have a wide range of applications in zoology, including diagnostics, therapeutics, nutrition, ecology, and reproduction studies. Gold and quantum dot nanoparticles label proteins, cells, and tissues for high-resolution imaging. In veterinary medicine, nanoparticle-based biosensors can detect pathogens such as Salmonella, Brucella, and Avian influenza virus. Magnetic nanoparticles allow MRI-based visualization of tissues, while fluorescent nanoparticles provide real-time imaging of biological processes in model organisms. Polymeric and lipid nanoparticles deliver drugs, hormones, or vaccines with improved efficacy and reduced toxicity. In aquaculture, chitosan nanoparticles protect fish from infections, while silver nanoparticles treat wounds due to their antimicrobial action. Nano-minerals like nano-zinc, nano-selenium, and nano-copper enhance

nutrient absorption, immune function, and fertility in livestock. However, long-term safety remains under study[16-18]. Nano-sensors detect pollutants in water and soil, while TiO_2 and Fe nanoparticles degrade toxins, aiding habitat restoration. Yet, their environmental release poses ecological concerns. Nanoparticles aid sperm and oocyte labeling, cryopreservation, and gene delivery, improving assisted reproductive technologies and conservation efforts.

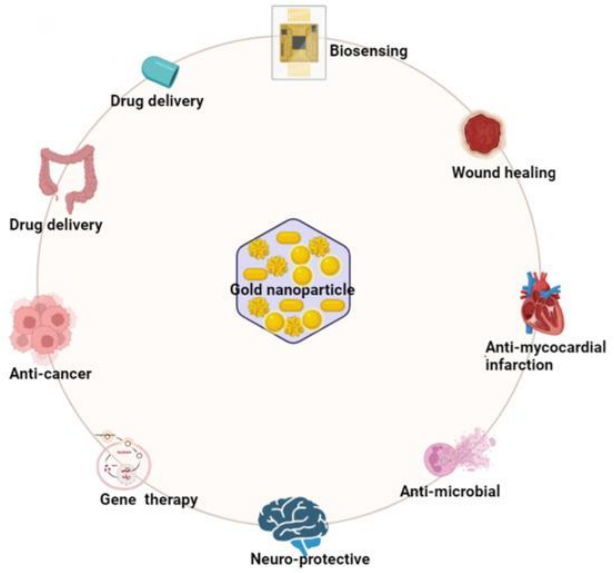

Figure 2 Shows the nanoparticles in the biological animals systems

The enhancing water uptake and enzymatic activity, show that priming seeds with silver or zinc oxide nanoparticles improves root elongation and seedling vigor. For instance, nano-ZnO enhances α-amylase activity, leading to better starch mobilization. Similarly, carbon nanotubes facilitate water absorption by creating nanopores in seed coats, resulting in faster germination. Metal oxide nanoparticles such as TiO_2 and CeO_2 have been shown to increase chlorophyll synthesis and photosynthetic efficiency. TiO_2 nanoparticles act as photocatalysts, improving light utilization by leaves and stimulating the Calvin cycle. Enhanced photosynthetic rates lead to higher accumulation and yield, particularly under low-light conditions[19-21].

Fertilizer Efficiency

Conventional fertilizers often suffer from nutrient losses due to leaching and volatilization. Nanofertilizers provide a sustainable solution by releasing nutrients gradually in response to plant demand. Chitosan-coated nanoparticles and nano-chelates (e.g., Fe, Zn, Cu) improve nutrient bioavailability and root absorption. This precision delivery system reduces environmental pollution and enhances soil health. Abiotic stresses such as drought, salinity, and heavy metals severely affect plant productivity. Nanoparticles can help plants cope with these challenges by regulating antioxidant systems and osmolyte accumulation. Silicon and selenium nanoparticles, for example, mitigate oxidative damage by increasing superoxide dismutase (SOD) and catalase (CAT) activities. Under salt stress, nano-SiO_2 enhances ion homeostasis by improving K^+/Na^+ balance[22-25].

Disease management

Silver and copper nanoparticles exhibit strong antimicrobial effects against bacterial and fungal pathogens. They disrupt microbial membranes and inhibit enzyme function. In plant pathology, AgNPs have been used to control diseases like powdery mildew and bacterial wilt. Moreover, chitosan nanoparticles act as both carriers and elicitors,

stimulating plant immune responses. Nanotechnology has enabled new methods for plant genetic modification. Nanoparticles can deliver DNA, RNA, or proteins into plant cells without using traditional gene-gun or Agrobacterium methods. This approach reduces tissue damage and enhances transformation efficiency. Gold nanoparticles are especially useful as carriers for plasmid DNA and gene-editing tools like CRISPR-Cas9. Despite their benefits, nanoparticles may generate oxidative stress, inflammation, or genotoxicity in animals. Bioaccumulation in aquatic species can disturb ecosystems. Ethical guidelines and risk assessments are essential to ensure safe application of nanotechnology in zoological research and veterinary practice[26-29]. The integration of nanotechnology into zoology continues to expand. Eco-friendly synthesis methods and smart nano-devices may soon allow real-time monitoring of animal health. Interdisciplinary research among zoologists, chemists, and engineers will be key to future advances. However, biosafety, cost, and regulatory concerns must be addressed before widespread implementation [30-31].

Conclusion

Nanoparticles have become vital tools in modern zoology, contributing to diagnostics, therapeutics, nutrition, and ecology. Their nanoscale interactions with biological systems provide unprecedented insights into animal physiology and environmental health. Responsible and ethical use of nanotechnology can help enhance animal welfare and ecosystem stability, ensuring that its benefits outweigh potential risks. Magnetic nanoparticles allow MRI-based visualization of tissues, while fluorescent nanoparticles provide real-time imaging of biological processes in model organisms.

REFERENCES

1. Ahmed, T., Noman, M., & Almatroudi, A. (2022). *Applications of nanotechnology in veterinary and animal sciences: A review.* Journal of Animal Science and Biotechnology, 13(1), 1–18.
2. Singh, A., Sharma, P., & Chauhan, R. S. (2021). *Nanotechnology in animal health and production: A new frontier in veterinary sciences.* Veterinary World, 14(9), 2455–2464.
3. Al-Attar, A. M., & Alshammari, G. M. (2023). *Toxicological impact of nanoparticles on aquatic and terrestrial animals: Mechanisms and ecological implications.* Environmental Research, 233, 116–131
4. Youssef, M. E., & Abdelrahman, M. (2020). *Nano-minerals in animal nutrition: A review on benefits and risks.* Animal Feed Science and Technology, 265, 114–182.
5. Khan, F. A., & Rehman, S. (2021). *Nanoparticles in aquaculture: Mechanistic insights, benefits, and concerns.* Aquaculture Reports, 19, 100642.
6. Sharma, S., & Ghosh, S. (2024). *Advances in nano-based diagnostics and therapeutics for animal diseases.* Frontiers in Veterinary Science, 11, 1302564.
7. Prasad, R., & Pandey, R. (2022). *Green synthesis of nanoparticles and their applications in biosensing and animal health.* Journal of Cleaner Production, 367, 132945.
8. Nguyen, D. T., & Park, S. (2023). *Nanomaterials in environmental zoology: Tools for monitoring and remediation.* Environmental Nanotechnology, Monitoring & Management, 20, 100780.
9. Alavi, M., & Rai, M. (2021). *Role of metallic nanoparticles in veterinary drug delivery and immunomodulation.* Drug Delivery and Translational Research, 11(6), 2364–2381.
10. Gupta, S., & Singh, J. (2025). *Emerging trends of nanotechnology in zoological and wildlife conservation research.* Trends in Biotechnology, 43(2), 112–126.
11. Rai, M., & Ingle, A. (2012). Role of nanotechnology in agriculture with special reference to nanofertilizers and nanopesticides. *Nanotechnology Reviews, 1*(1), 45–56.

12. Kah, M., & Hofmann, T. (2014). Nanopesticide research: current trends and future priorities. *Environment International, 63*, 224–235.
13. Siddiqui, M. H., Al-Whaibi, M. H., & Faisal, M. (2015). Role of nanoparticles in plants: a review. *Saudi Journal of Biological Sciences, 22*(2), 146–151.
14. Tripathi, D. K., et al. (2017). An overview on manufactured nanoparticles in plants: uptake, translocation, accumulation and phytotoxicity. *Plant Physiology and Biochemistry, 110*, 2–12.
15. Wang, P., Lombi, E., Zhao, F. J., & Kopittke, P. M. (2016). Nanotechnology: a new opportunity in plant sciences. *Trends in Plant Science, 21*(8), 699–712.
16. Rico, C. M., et al. (2011). Physiological and biochemical responses of plants to engineered nanoparticles. *Plant Physiology and Biochemistry, 49*(8), 1009–1023.
17. Singh, J., & Lee, B. K. (2016). Influence of nano-TiO_2 particles on the stress physiology and growth of plants: a review. *Environmental Toxicology and Pharmacology, 48*, 241–253.
18. Mukherjee, A., et al. (2016). A review on the use of nanoparticles in agriculture and their potential impacts on the environment. *Environmental Nanotechnology, Monitoring & Management, 6*, 93–102.
19. Jangid, H.; Singh, S.; Kashyap, P.; Singh, A.; Kumar, G. Advancing biomedical applications: An in-depth analysis of silver nanoparticles in antimicrobial, anticancer, and wound healing roles. *Front. Pharmacol.* 2024, *15*, 1438227.
20. Farinha, P.; Coelho, J.M.P.; Reis, C.P.; Gaspar, M.M. A Comprehensive Updated Review on Magnetic Nanoparticles in Diagnostics. *Nanomaterials* 2021, *11*, 3432.
21. Libin, K.V.; Sisodiya, S.; Debnath, M. Biosynthesis and antimicrobial activities of Tinospora cordifolia zinc nanoparticles. *Mater. Today Proc.* 2023, *79*, 367–374.
22. Mozafari, M.R.; Torkaman, S.; Karamouzian, F.M.; Rasti, B.; Baral, B. Antimicrobial applications of nanoliposome encapsulated silver nanoparticles: A potential strategy to overcome bacterial resistance. *Curr. Nanosci.* 2021, *17*, 26–40.
23. Xu, L.; Wang, Y.-Y.; Huang, J.; Chen, C.-Y.; Wang, Z.-X.; Xie, H. Silver nanoparticles: Synthesis, medical applications and biosafety. *Theranostics*
24. Liu, Q.; Shen, J.; Yu, X.; Yang, X.; Liu, W.; Yang, J.; Tang, H.; Xu, H.; Li, H.; Li, Y.; et al. Unveiling the origin of boosted photocatalytic hydrogen evolution in simultaneously (S, P, O)-Codoped and exfoliated ultrathin g-C_3N_4 nanosheets. *Appl. Catal. B Environ.* 2019, *248*, 84–94
25. Pang, J.; Bachmatiuk, A.; Yin, Y.; Trzebicka, B.; Zhao, L.; Fu, L.; Mendes, R.G.; Gemming, T.; Liu, Z.; Rummeli, M.H. Applications of Phosphorene and Black Phosphorus in Energy Conversion and Storage Devices. *Adv. Energy Mater.* 2018, *8*, 1702093.
26. Tang, S.; Zhao, M.; Yuan, D.; Li, X.; Wang, Z.; Zhang, X.; Jiao, T.; Ke, J. Fe_3O_4 nanoparticles three-dimensional electro-peroxydisulfate for improving tetracycline degradation. *Chemosphere* 2021, *268*, 129315.
27. Sebastian Cabeza, V. *Chapter High and Efficient Production of Nanomaterials by Microfluidic Reactor Approaches*; InTechOpen: London, UK, 2016.
28. Samrot, A.V.; Sahithya, C.S.; Selvarani, J.; Purayil, S.K.; Ponnaiah, P. A review on synthesis, characterization and potential biological applications of superparamagnetic iron oxide nanoparticles. *Curr. Res. Green Sustain. Chem.* 2021, *4*, 100042
29. Cho, E.J.; Holback, H.; Liu, K.C.; Abouelmagd, S.A.; Park, J.; Yeo, Y. Nanoparticle Characterization: State of the Art, Challenges, and Emerging Technologies. *Mol. Pharm.* 2013, *10*, 2093–2110.

30. Kalidasan, B.; Pandey, A.K.; Shahabuddin, S.; George, M.; Sharma, K.; Samykano, M.; Tyagi, V.V.; Saidur, R. Synthesis and characterization of conducting Polyaniline@ cobalt-Paraffin wax nanocomposite as nano-phase change material: Enhanced thermophysical properties. *Renew. Energy* 2021, *173*, 1057–1069.
31. Waiskopf, N.; Ben-Shahar, Y.; Banin, U. Photocatalytic hybrid semiconductor–metal nanoparticles; from synergistic properties to emerging applications. *Adv. Mater.* 2018, *30*, 1706697.