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Review Article

ENVIRONMENTAL NANOPARTICLES AND RESPIRATORY HEALTH IN VERTEBRATES: ANALYZING EMERGING HEALTH RISKS

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ABSTRACT

Environmental nanoparticles have become an area of considerable concern owing to their potential health hazards, particularly for vertebrates subjected to contaminated environments. This review explores the ramifications of these particles on respiratory health, concentrating on their origins, pathways of exposure, and the mechanisms through which they elicit detrimental effects. The primary origins of environmental nanoparticles encompass industrial operations, vehicular emissions, agricultural activities, and the degradation of plastic waste, resulting in the proliferation of nano-sized plastics and other particulates within urban locales. The review delineates inhalation exposure pathways, underscoring the deposition of nanoparticles within the respiratory tract and the challenges posed to respiratory protection. The health ramifications of nanoparticle exposure are scrutinized, accentuating lung inflammation, oxidative stress, and immune responses provoked by inhaled particulates. Furthermore, the review deliberates on the long-term health risks linked to chronic exposure, including the potential onset of chronic respiratory diseases and structural damage to lung tissue. Additionally, the article addresses the limitations of extant research, highlighting the dearth of data pertaining to chronic, low-level nanoparticle exposure in natural environments. It concludes by proposing future directions for research and policy recommendations, including advanced toxicological investigations and regulatory frameworks designed to mitigate nanoparticle pollution. By synthesizing contemporary understanding and identifying critical gaps, this review aspires to elevate awareness regarding the pressing necessity for targeted interventions to safeguard vertebrate respiratory health against the escalating threat posed by environmental nanoparticles.

Keywords: Nanoparticles, Respiratory health, Vertebrates, Environmental pollution, Lung inflammation, Toxicology.

INTRODUCTION

Nanoparticles (NPs), which measure less than 100 nanometers in diameter, are increasingly prevalent in the environment due to rapid urbanization, industrialization, and the extensive use of nanomaterials in consumer products (Najahi-Missaoui *et al*., 2021). While some nanoparticles occur naturally (e.g., volcanic ash, and sea spray), the majority are anthropogenic, originating from industrial emissions, vehicle exhaust, and the degradation of plastics(Bundschuh *et al*., 2018). Plastic pollution has led to the formation of nano-sized plastic particles, especially in urban and marine environments, creating an additional source of concern(Akash Phillip & Tushar Chauhan, 2024). These particles often enter the air through wear and tear of larger plastic pieces or breakdown under sunlight and mechanical action (Akash Phillip & Tushar Chauhan, 2024).Nanoparticles are unique due to their small size, large surface area, and potential for chemical reactivity, all of which increase their likelihood of interacting with biological systems (Martínez *et al*., 2021). This small size allows nanoparticles to penetrate deeply into biological tissues, including the respiratory system of vertebrates, where they can cross cellular barriers, deposit in lung tissues, and even translocate to other organs(Martínez *et al*., 2021).

The respiratory health of vertebrates is particularly at risk due to these particles. Aquatic and terrestrial vertebrates encounter nanoparticles directly through

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inhalation, ingestion, or skin contact, depending on their habitat(Yamini *et al*., 2023). According to (Malhotra, Ger, *et al*., 2020), fish in polluted rivers and oceans are increasingly exposed to nanoparticles present in water, while mammals in industrial regions inhale them regularly. Inhaling these particles can cause inflammation, oxidative stress, and even DNA damage in respiratory tissues(Medici *et al*., 2021). Moreover, since nanoparticles can bypass the body's natural defense mechanisms, vertebrates lack adequate means to excrete or neutralize them, leading to chronic exposure and health complications(Malhotra, Lee, *et al*., 2020).According to (Sengul & Asmatulu, 2020) study, nanoparticles' size and surface chemistry facilitate their persistence in tissues, leading to potential long-term effects, in cities with heavy traffic, concentrations of metal oxide nanoparticles, primarily from vehicle emissions, have been linked to respiratory illnesses in both humans and animals(Sengul & Asmatulu, 2020). In aquatic systems, bioaccumulation of nanoplastics is observed in fish and other organisms, showing how widespread the exposure risk has become(Malhotra, Ger, *et al*., 2020).

This review provides a comprehensive assessment of the health risks that environmental nanoparticles pose to vertebrate respiratory health, with a focus on the sources and types of nanoparticles that contribute to respiratory issues. This review will explore the mechanisms by which these particles impact respiratory systems, including inducing lung inflammation, triggering immune responses, and posing long-term health risks associated with prolonged exposure. Recent case studies and research findings across various vertebrate species will be examined to illustrate the scope and effects of nanoparticle exposure. Additionally, this review will address the significant challenges in current research, such as limited data on chronic exposure and ecosystem-level impacts, which highlight the need for further studies in these areas. Finally, this review will outline future research directions and discuss potential policy recommendations aimed at reducing environmental nanoparticle pollution, ultimately underscoring the need for increased awareness and focused action to protect vertebrate respiratory health from this escalating environmental threat.

Sources of environmental nanoparticles

Environmental nanoparticles originate from various anthropogenic and natural processes. Understanding these sources is crucial in assessing the risk they pose to vertebrate health.

Nanoparticles generated through industrial activities

Industrial processes contribute significantly to the generation of nanoparticles. Manufacturing industries, particularly those involved in metal processing, electronics, and textiles, release nanoparticles as by-products(Khan *et al*., 2022). According to (Rashid *et al*., 2021), factories producing titanium dioxide (TiO_2) nanoparticles can emit substantial quantities into the atmosphere, leading to local pollution. Similarly (Musial *et al*., 2020), found that emissions from industries in urban areas can exceed 10 mg/m³ of nanoparticles during peak operational periods.

Nanoparticles generated from automotive emissions

Vehicles are major contributors to nanoparticle pollution, particularly through the combustion of fossil fuels. Diesel engines, in particular, emit a higher concentration of ultrafine particles (UFPs), which are less than 100 nm in diameter(Vojtíšek-Lom *et al*., 2021). According to (Samaras *et al*., 2020), road transport is responsible for approximately 40% of particulate matter emissions in urban environments, which includes a significant proportion of nanoparticles. In metropolitan areas, the average concentration of traffic-related UFPs can reach 100,000 particles/cm³, especially near highways(Le *et al*., 2023).

Nanoparticles generated from agricultural practices

The application of nanomaterials in agriculture, such as pesticides and fertilizers, can lead to nanoparticle runoff into water bodies and the atmosphere(Al-khattaf, 2021). Nanoparticles such as silver (Ag) are commonly used for their antimicrobial properties(Cruz-Luna *et al*., 2021). According to (Al-khattaf, 2021), the application of nano-silver can lead to detectable levels of these particles in agricultural runoff, which may contribute to aquatic pollution. According to (Sun *et al*., 2021)study, it was found that approximately 15% of applied nanomaterials in agricultural settings can enter water systems.

Nanoparticles generated through the degradation of plastic waste

The degradation of conventional plastics is a significant source of nano-plastics, which are formed as larger plastic debris breaks down due to environmental factors such as UV radiation and physical abrasion(Abdelbasir *et al*., 2020). Estimates suggest that up to 5 trillion pieces of plastic are in the oceans, and a significant portion of this degrades into nano-sized particles(Wojnowska-Baryła *et al*., 2022). According to (Dimassi *et al*., 2022), microplastics can generate nano-plastics during weathering processes, with studies reporting that an average of 1.3 million plastic particles per square kilometer are found in oceanic regions. Table 1 provides a clear overview of the sources of environmental nanoparticles, detailing their origins and relevant data that highlight their impact on the environment and vertebrate health.

Types and characteristics of environmental nanoparticles

Environmental nanoparticles can be classified based on their composition and characteristics, which influence their toxicity and interaction with biological systems.

Nano-Plastics

These particles, typically ranging from 1 to 100 nm in size, are generated from the degradation of larger plastic items(Cai *et al*., 2021). Their small size allows them to easily enter biological tissues, potentially causing cellular damage(Shi *et al*., 2024). (Mitrano *et al*., 2021) study demonstrated that nano-plastics can be absorbed by marine organisms, with concentrations reaching up to 10^6 particles/g in some sediment samples.

Carbon-based nanoparticles

Carbon-based nanoparticles, such as fullerenes and carbon nanotubes, are known for their unique properties and are used in various applications, including electronics and nanocomposites(Fallah *et al*., 2021). Their size and structure can significantly influence their toxicity. According to (Peng *et al*., 2020), carbon nanotubes can cause inflammation and cellular damage in lung tissues when inhaled. In vitro studies indicate that exposure to carbon nanotubes can lead to reactive oxygen species (ROS) generation and cytotoxicity(Joze-Majidi *et al*., 2023).

Table 1. **A** clear overview of the sources of environmental nanoparticles.

Source	Description	Key Data	References
Industrial Activities	Nanoparticles are generated as by-products from manufacturing processes, particularly in metal processing and electronics.	Titanium dioxide (TiO_2) emissions can exceed 10 mg/m³ during peak operations in urban areas.	(Khan *et al*., 2022; Musial *et al*., 2020; Rashid *et al*., 2021)
Automotive Emissions	Vehicles, especially diesel engines, contribute to nanoparticle pollution through fossil fuel combustion, releasing ultrafine particles (UFPs).	Road transport accounts for 40% of particulate matter emissions in urban areas. Average UFP concentration can reach 100,000 particles/cm³ near highways.	(Le *et al*., 2023; Samaras *et al*., 2020; Vojtíšek-Lom *et al*., 2021)
Agricultural Practices	The use of nanomaterials (e.g., nano-silver) in pesticides and fertilizers leads to nanoparticle runoff into waterways.	About 15% of applied nanomaterials can enter water systems as runoff. Silver nanoparticles (Ag) are commonly used for antimicrobial properties.	(Al-khattaf, 2021; Cruz-Luna *et al*., 2021; Sun *et al*., 2021)
Degradation of Plastic Waste	Conventional plastics break down into nano-sized particles due to UV radiation and abrasion, significantly contributing to nano-plastics.	An estimated 5 trillion pieces of plastic are in the oceans, with a significant portion degrading into nano-sized particles. An average of 1.3 million plastic particles/sq kmare found in ocean regions.	(Abdelbasir *et al*., 2020; Dimassi *et al*., 2022; Wojnowska-Baryła *et al*., 2022)

Metal oxides nanoparticles

Metal oxide nanoparticles, including titanium dioxide (TiO_2) and zinc oxide (ZnO), are prevalent in various industrial applications and consumer products, including sunscreens and coatings. Their photocatalytic properties make them useful, but they also raise concerns regarding their environmental impact (Ünal *et al*., 2021). For instance, (Liang *et al*., 2022) study has shown that TiO_2 nanoparticles can induce oxidative stress in vertebrate respiratory systems, contributing to chronic respiratory diseases. The toxicity of these nanoparticles often depends on their size, shape, and surface modifications. According to (Herrera-Rodríguez *et al*., 2023)study found that smaller TiO_2 nanoparticles (less than 25 nm) showed significantly higher cytotoxicity compared to larger counterparts.

Organic nanoparticles

Organic nanoparticles, such as those derived from combustion processes or biological sources (e.g., plant debris), can also be significant. These particles can carry toxic organic compounds, leading to cumulative effects in exposed vertebrates (Ettlinger *et al*., 2022). According to (Xin *et al*., 2021) these nanoparticles can penetrate biological barriers and accumulate in tissues, leading to potential long-term health risks. Table 2 provides a comprehensive overview and comparison of the different types of environmental nanoparticles, their characteristics, toxicity mechanisms, and relevant data that highlight their environmental and health implications.

Exposure routes and deposition of nanoparticles in the respiratory tract of vertebrates

The respiratory system is one of the primary routes for nanoparticle exposure, especially in environments with high levels of pollution or particulate matter. Understanding how nanoparticles enter and interact with respiratory pathways is critical to assessing the potential health risks for vertebrates, particularly those living in areas with significant environmental pollution.

Inhalation exposure to nanoparticles

Inhalation is the most common exposure route for environmental nanoparticles, particularly for vertebrates in urban and industrialized areas. Due to their tiny size, nanoparticles remain airborne for extended periods and can travel over large distances (Praphawatvet *et al*., 2020). This characteristic allows them to be readily inhaled into respiratory systems. According to (Sonwani *et al*., 2021) study has shown that nanoparticles smaller than 100 nanometers (nm) can evade the natural filtration mechanisms in the nose and mouth, making it easier for them to reach deeper regions of the lungs. For instance, according to (Malamatari *et al*., 2020)ultrafine particles from vehicular emissions in urban areas could easily penetrate the lower respiratory tract in both humans and animals. Similarly, recent data by (De Berardis *et al*., 2021), also highlights the high prevalence of nanoparticle inhalation in polluted regions. For example, according to (Ivaneev *et al*., 2024), in major cities like Los Angeles and Beijing, where high levels of particulate matter are present, people are exposed to thousands of nanoparticles per cubic centimeter of air. This is also a concern for animals that live close to urban or industrial environments, as they share these airspaces and are vulnerable to similar respiratory effects (Larsen *et al*., 2020). In marine environments, nanoparticles generated from sources like shipping activities and port emissions create respiratory hazards for marine vertebrates such as sea lions and seabirds, which may come in close contact with polluted coastal air (Vimercati *et al*., 2020).

Table 2. A comprehensive overview and comparison of the different types of environmental nanoparticles.

Type of Nanoparticle	Size Range	Sources/ Formation	Toxicity Mechanisms	Key Data	References
Nano-plastics	1 to 100 nm	Degradation of larger plastic items	Can enter biological tissues, potentially causing cellular damage	Concentrations in marine organisms can reach up to 10^6 particles/g in sediment samples.	(Cai *et al*., 2021; Mitrano *et al*., 2021; Shi *et al*., 2024)
Carbon-based nanoparticles	Typically <100 nm	Used in electronics and nanocomposites; produced from combustion	Causes inflammation and cellular damage; generates reactive oxygen species (ROS)	In vitro studies show cytotoxicity and ROS generation in lung tissues after exposure to carbon nanotubes.	(Fallah *et al*., 2021; Joze-Majidi *et al*., 2023; Peng *et al*., 2020)
Metal oxides nanoparticles	Variable (often <100 nm)	Industrial applications (e.g., TiO_2 in sunscreens)	Induces oxidative stress; toxicity influenced by size, shape, surface modifications	Smaller TiO_2 nanoparticles (<25 nm) exhibit significantly higher cytotoxicity compared to larger ones.	(Herrera-Rodríguez *et al*., 2023; Liang *et al*., 2022; Ünal *et al*., 2021)
Organic nanoparticles	Variable	Combustion processes; biological sources (e.g., plant debris)	Carry toxic organic compounds; can penetrate biological barriers	Research indicates accumulation in tissues can lead to long-term health risks for exposed vertebrates.	(Ettlinger *et al*., 2022; Xin *et al*., 2021)

Mechanisms for nanoparticle deposition in vertebrate respiratory tract

Once inhaled, nanoparticles deposit at various points within the respiratory tract depending on their size, shape, and composition. The process of particle deposition is influenced by mechanisms such as impaction, sedimentation, and diffusion.

Impaction and sedimentation of nanoparticles in the respiratory tract of vertebrates

Larger nanoparticles, typically over 100 nm, tend to deposit in the upper respiratory tract (e.g., the nasal passages and trachea) through impaction, where particles hit and stick to the walls of the airways(Kuga *et al*., 2023). Sedimentation also plays a role in depositing slightly smaller particles in the bronchi, where gravity assists in the settling of particles onto the airway surfaces(Islam *et al*., 2020). According to (Rahman *et al*., 2022) larger particles, such as those emitted from diesel exhausts, often accumulate in the nasal and throat regions, which can lead to chronic inflammation and irritation.

Diffusion of nanoparticles into the respiratory tract of vertebrates

For ultrafine particles under 100 nm, diffusion is the dominant mechanism, allowing these particles to travel to the deeper parts of the lungs, including the alveoli, where gas exchange occurs(Nho, 2020). In the alveoli, nanoparticles can cross the air-blood barrier and enter systemic circulation, thereby affecting other organs(Portugal *et al*., 2024). According to (Bessa *et al*., 2021) animal models, like mice and rats, have demonstrated that nanoparticles can translocate from the lungs to the liver, kidneys, and even the brain, highlighting the far-reaching effects of respiratory nanoparticle exposure. In mammals, prolonged exposure to fine particles in the alveoli has been associated with inflammation, oxidative stress, and potential carcinogenic effects(Nho, 2020).

Barriers to respiratory protection

The respiratory system has natural barriers that typically protect against large particles, such as the nasal mucosa and the ciliated cells in the trachea and bronchi, which trap particles and move them back out of the body (Campione *et al*., 2020). However, due to their small size, nanoparticles can evade these defense mechanisms. Nanoparticles under 10 nm, for instance, can bypass mucociliary clearance systems, and studies suggest that around 30-50% of inhaled nanoparticles can reach the alveoli (Leikauf *et al*., 2020). Moreover, many nanoparticles have chemical properties that enable them to evade immune detection, reducing the body's ability to identify and clear these particles from the respiratory system (Hadrup *et al*., 2020).

Effects of nanoparticle exposure and deposition on vertebrate respiratory health

Environmental nanoparticles have significant implications for respiratory health in vertebrates. Due to their minute size and unique surface properties, nanoparticles are capable of penetrating deeply into the lungs, where they can trigger a cascade of physiological responses. The primary health impacts include lung inflammation, oxidative stress, immune response activation, and, in cases of prolonged exposure, chronic respiratory conditions.

Lung inflammation and oxidative stress due to nanoparticle exposure and depositionin vertebrate respiratory systems

One of the immediate effects of inhaling nanoparticles is lung inflammation(Yang *et al*., 2021). Due to their high surface area and reactivity, many nanoparticles catalyze the formation of reactive oxygen species (ROS) once they enter lung tissues(Sies *et al*., 2022). ROS are unstable molecules that can damage cells and tissues by oxidizing cellular components like lipids, proteins, and DNA. This oxidative stress initiates an inflammatory response as the body attempts to counteract the damage (Kumah *et al*., 2023).According to (Baranowska-Wójcik *et al*., 2020) study showed that mice exposed to titanium dioxide (TiO_2) nanoparticles experienced a sharp increase in lung inflammation markers, including elevated levels of interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), both key mediators of inflammation. TiO_2 nanoparticles, commonly found in industrial emissions and consumer products, are highly reactive and easily generate ROS, exacerbating cellular damage in the lungs (Dar *et al*., 2020).

Additionally, oxidative stress can impair cellular repair mechanisms, making lung tissue more susceptible to long-term damage. For example, according to (Simpson & Oliver, 2020) study on rats exposed to diesel exhaust nanoparticles demonstrated increased levels of lipid peroxidation in lung tissues, indicating oxidative damage to cellular membranes. Diesel exhaust is a prevalent source of nanoparticles in urban settings, and these findings highlight the impact that such particles can have on lung health in both humans and animals living in polluted areas(Weitekamp *et al*., 2020).

Response of the immune system to exposure and deposition of nanoparticlesin vertebrate respiratory systems

The immune response to inhaled nanoparticles is another key factor in respiratory health impacts. Upon entry into the lung, nanoparticles are recognized by immune cells such as macrophages, which attempt to engulf and eliminate these foreign particles through a process known as phagocytosis (Mostovenko *et al*., 2022). However, due to their small size and potentially harmful surface properties, nanoparticles can evade or overwhelm macrophages, leading to a prolonged immune response. Macrophages release cytokines, signaling molecules that mediate inflammation and recruit other immune cells to the site of exposure(Shabbir *et al*., 2021). According to (Dong *et al*., 2020) study it was found that rats exposed to silica nanoparticles exhibited significantly higher levels of cytokines like IL-1β and TNF-α. These cytokines triggered a cycle of inflammation, as the constant presence of nanoparticles required continued immune activity. Over time, this chronic inflammation can damage lung tissues and lead to scar formation(Dong *et al*., 2020).

Moreover, nanoparticles may impair the function of alveolar macrophages, the immune cells responsible for clearing debris and pathogens from the alveoli (air sacs). This impairment leaves the respiratory system more vulnerable to infections and other environmental toxins(Osman *et al*., 2020). For instance, a study on urban pigeons, which are frequently exposed to high levels of particulate matter, showed compromised macrophage function, making these birds more susceptible to respiratory infections(Morsy *et al*., 2021).

Long-term health risks associated with nanoparticle exposure and deposition in vertebrate respiratory systems

Chronic exposure to environmental nanoparticles can lead to several long-term respiratory issues, including fibrosis, reduced lung function, and structural damage to lung tissues. Fibrosis, a condition characterized by the thickening and scarring of lung tissue, is particularly concerning (Henderson *et al*., 2020). When nanoparticles continuously stimulate an inflammatory response, fibroblasts (cells that generate connective tissue) are recruited to the site of inflammation, leading to the formation of fibrotic tissue (Kakakhel *et al*., 2021). Over time, fibrosis reduces lung elasticity and impairs oxygen exchange. According to (Florek *et al*., 2023) rats exposed to carbon nanotubes, observed extensive fibrotic changes in lung tissues after just six months of exposure. Carbon nanotubes are widely used in industrial applications, and this study highlights their potential to induce lasting damage in vertebrate respiratory systems. Fibrosis is a serious health risk because it is irreversible, and the loss of lung function can lead to chronic respiratory diseases(Henderson *et al*., 2020). In addition to fibrosis, nanoparticles are associated with structural lung damage that increases the risk of chronic obstructive pulmonary disease (COPD) and other long-term respiratory illnesses(Duan *et al*., 2020). According to (Bi *et al*., 2023) study on factory workers in South Korea, revealed that individuals with prolonged exposure to metal oxide nanoparticles exhibited higher rates of reduced lung function and early markers of COPD. While this study focused on humans, similar risks are posed to vertebrates in nanoparticle-polluted environments, where prolonged exposure may compromise respiratory function.

Current challenges and knowledge gaps in understanding nanoparticle impacts on respiratory health

The investigation of the health impacts of environmental nanoparticles, particularly concerning respiratory health in vertebrates, faces significant challenges and knowledge gaps that hinder the development of effective mitigation strategies and regulatory frameworks.

Research limitations

Current research methodologies often fall short of providing a comprehensive understanding of the long-term effects of nanoparticle exposure. Many studies tend to focus on acute exposure scenarios, overlooking the complex interactions and cumulative effects that arise from chronic exposure in natural environments. For instance, a meta-analysis conducted by (Mohammadpour *et al*., 2020) revealed that only 15% of studies on nanoparticle toxicity involved chronic exposure assessments, while the majority were limited to short-term laboratory experiments. This narrow focus results in a limited understanding of how nanoparticles behave over time in biological systems, particularly in the context of environmental and ecological interactions.

Additionally, many existing studies utilize simplified models that do not accurately represent the multifaceted nature of real-world ecosystems. For instance, according to (Spurgeon *et al*., 2020), animal studies often rely on controlled laboratory conditions, which may fail to account for variables such as pollutant mixtures, environmental stressors, and variations in individual susceptibility across different vertebrate species. According to (Zhang *et al*., 2022) study, it was highlighted how laboratory conditions can underestimate the toxicity of nanoparticles by up to 50% compared to natural environments where multiple stressors interact.

Data on chronic exposure to nanoparticles

The scarcity of data on chronic, low-level nanoparticle exposure in natural habitats represents a critical knowledge gap in the field. Most research has concentrated on high concentrations of nanoparticles, which do not reflect the exposure levels that vertebrates experience in polluted environments over time. For instance, (Boyes & van Thriel, 2020) emphasized the need for more nuanced studies that investigate the effects of long-term exposure to lower concentrations of nanoparticles, which are more relevant to real-world scenarios. According to (Xu *et al*., 2024) study on urban birds found that those living in areas with high levels of airborne nanoparticles exhibited significant declines in respiratory health metrics over a year-long observation period. This study reported a 25% increase in respiratory distress symptoms in exposed populations compared to control groups, demonstrating that even low levels of chronic exposure can lead to serious health outcomes (Xu *et al*., 2024). However, the lack of robust longitudinal studies across various vertebrate species remains a significant barrier to understanding the full spectrum of nanoparticle effects.

Moreover, existing databases on environmental pollutants often lack specific data on nanoparticles, making it challenging for researchers to correlate exposure levels with health outcomes effectively. According to (Chen *et al*., 2023) the public health impact of nanoparticles indicated that over 70% of existing datasets did not include information on chronic exposure, limiting the ability to draw comprehensive conclusions about long-term health risks.

Future directions in research and policy for addressing nanoparticle pollution

As the understanding of the health impacts of environmental nanoparticles continues to evolve, it is imperative to adopt a multi-faceted approach that includes advanced research methodologies and robust policy frameworks to mitigate risks to vertebrate health.

Advances in toxicological studies

Future research should prioritize advanced toxicological studies that delve deeper into the mechanisms of nanoparticle toxicity. This involves identifying and validating specific biomarkers that can serve as early indicators of adverse health effects in vertebrates exposed to nanoparticles. According to (Abdelkader *et al*., 2023), the use of omics technologies, including genomics, proteomics, and metabolomics, can provide comprehensive insights into how nanoparticles alter biological pathways at the molecular level. Similarly, according to (Marana *et al*., 2022) study, showcased the utility of metabolomics in detecting metabolic alterations in fish exposed to nano-sized plastic particles, revealing pathways associated with oxidative stress and immune response that warrant further investigation.

Moreover, the incorporation of in vivo and in vitro models that mimic natural exposure scenarios is essential. Integrative approaches that combine laboratory experiments with field studies can yield more relevant data on the chronic effects of nanoparticle exposure in real-world conditions. For instance, utilizing wildlife species as bioindicators can facilitate the assessment of health impacts in natural habitats, as demonstrated in (Gomes *et al*., 2023) study, which explored the effects of environmental nanoparticles on amphibians in polluted wetlands. Additionally, collaborative efforts between ecotoxicologists, epidemiologists, and environmental scientists will enhance the quality and applicability of research findings. By establishing interdisciplinary research networks, scientists can share data, methodologies, and insights, fostering innovation and improving the understanding of nanoparticle interactions in complex ecosystems.

Policies for managing nanoparticle contamination

To effectively mitigate nanoparticle pollution and protect vertebrate health, policymakers must develop and implement comprehensive regulatory strategies that address the sources and impacts of these pollutants. Current regulations often do not account for the unique properties and risks associated with nanoparticles. According to (Mech *et al*., 2022) report from the European Commission emphasized the need for updated frameworks that specifically address nanomaterials, proposing a tiered approach that categorizes nanoparticles based on their toxicity and environmental persistence. One key recommendation is the establishment of strict emission standards for industries that produce or utilize nanoparticles. For example, implementing emission controls similar to those applied to conventional pollutants could significantly reduce the release of harmful nanoparticles into the environment. According to (Nazarenko *et al*., 2020) case study in California demonstrated that stringent regulations on particulate matter emissions led to a 30% reduction in airborne nanoparticles over five years, highlighting the effectiveness of proactive policy measures.

Furthermore, raising public awareness about the potential dangers of nanoparticles and promoting sustainable practices among industries can also contribute to pollution reduction(Calderón-Garcidueñas & Ayala, 2022). Educational campaigns that inform the public and stakeholders about the sources and impacts of nanoparticle pollution will enhance community engagement and drive demand for cleaner alternatives(Cowan *et al*., 2021). For instance, initiatives that encourage industries to adopt green chemistry principles can minimize the generation of nanoparticles at the source, ultimately benefiting both public health and the environment (Soltys *et al*., 2021). Additionally, global partnerships can facilitate data sharing, best practices, and coordinated responses to environmental challenges (Allan *et al*., 2021).

CONCLUSION

The increasing prevalence of environmental nanoparticles poses significant health risks to vertebrates, particularly in terms of respiratory health. This review highlights several critical findings, including the mechanisms by which nanoparticles induce lung inflammation and oxidative stress, the immune system's response to these particles, and the potential long-term consequences such as chronic respiratory diseases and structural lung damage. The evidence underscores the urgent need to understand the complex interactions between nanoparticles and vertebrate health, emphasizing that prolonged exposure can lead to serious and lasting health issues. In light of these findings, there is an imperative call for action from the scientific community, policymakers, and conservationists. Continued research is essential to fill knowledge gaps regarding chronic exposure, the full spectrum of health effects, and effective mitigation strategies. Additionally, conservation strategies that protect habitats from nanoparticle pollution, alongside the development of comprehensive policy measures, are crucial to safeguard vertebrate populations. It is vital to foster collaboration among researchers, government agencies, and industries to develop innovative solutions that address this emerging environmental concern, ensuring the health of both wildlife and ecosystems in the face of growing nanoparticle pollution.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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