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Environmental Nanotoxicology

Combatting the Minute Contaminants

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The book is dedicated to God Almighty, the giver of life and inspirations. It is also dedicated to Iwinosa Davina Isibor—the daughter of Dr. Patrick Omoregie Isibor—for being a source of inspiration that envisioned the book.

Preface

In today's age of remarkable technological advancement, the burgeoning field of nanotechnology holds incredible promise across numerous industries, offering groundbreaking solutions to complex challenges. However, this burgeoning promise is accompanied by a profound responsibility—to meticulously examine and comprehend the toxicity potential of nanomaterials on our environment and living organisms.

Environmental Nanotoxicology: Combatting the Minute Contaminants stands at the forefront of this critical discourse, delving deep into the intricate interaction of nanomaterials with the delicate balance of our ecosystems and the well-being of microscopic and macroscopic life forms. As the science and technology advances in harnessing the benefits of nanomaterials for various cutting-edge applications, cutting cross medicine, agriculture, electronics, and environmental remediation, there arises a crucial need to comprehend their potential ecological impact. Comprehending the toxicodynamics and toxicokinetics of nanomaterials requires rigorous scientific inquiries and compendium of perspectives from leading experts in the fields of nanoscience, toxicology, environmental studies, and ecology. The book thus transcends mere exploration; it serves as a guiding light through the complexities surrounding nanotoxicity in our environment. The prelude to this meticulous exposition encompasses an in-depth analysis of the diverse facets of environmental nanotoxicology. From the physicochemical properties of nanoparticles to their interactions with biological systems, their fate in various ecosystems, their potential bioaccumulation and biomagnification through food chains.

Furthermore, the book navigates the intricate landscapes of regulatory policies, offering a critical assessment of existing frameworks while proposing visionary strategies aimed at ensuring the safe and sustainable utilization of nanomaterials. It aims not just to enlighten but to empower policymakers, researchers, and stakeholders with the actionable knowledge necessary to make informed decisions shaping the future of nanotechnology. It serves as an indispensable guide, shedding light on the nuanced interactions between nanomaterials and the environment, propelling us toward a future where innovation coexists harmoniously with ecological stewardship.

The profound commitment to safeguarding our planet's delicate ecosystems thus requires knowledge provided in *Environmental Nanotoxicology: Combatting the Minute Contaminants*, to explore, engage, and contribute to shaping a future where nanotechnology thrives in harmony with nature.

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About the Book

Environmental Nanotoxicology: Combatting the Minute Contaminants stands as a pivotal compendium poised to provide cutting-edge scientific knowledge that meets the critical challenge of safeguarding our environment from the inconspicuous nanoparticles shaping our technological world. This comprehensive material encapsulates a profound exploration into the application of nanomaterials and their impacts on our ecosystems and their lifeforms, from a standpoint of nanotoxicity. This work represents an interdisciplinary collaboration, bringing together the collective knowledge of leading experts from diverse fields—nanoscience, toxicology, environmental studies, ecology, biochemistry and microbiology. It serves as a guide to students, researchers, experts, stake holders, policy makers, and enthusiastic individuals.

The book is rooted in a thorough examination of nanomaterials, dissecting their physicochemical properties, biological interactions, fate in ecosystems, and potential impacts on diverse organisms. From elucidating mechanisms of bioaccumulation and biomagnification to investigating the intricate pathways of nanoparticle-induced toxicity, each chapter offers a scholarly exploration of the complexities surrounding nanotoxicology. It presents the critical aspects of the discourse in sequential chapters in a schematic fashion occasioned by visionary insights and characterized by the pragmatic perspectives. It navigates regulatory frameworks, providing a critical assessment of existing policies while charting visionary strategies aimed at ensuring the safe and sustainable integration of nanomaterial safety in our world. The book's narrative goes beyond academic discourse; it extends an invitation to policymakers, researchers, industry professionals, and stakeholders alike. At the end of this book, the audience is expected to emerge equipped with a profound understanding and practical tools to navigate the landscapes of environmental nanotoxicity.

Contents

About the Editors

Patrick Omoregie Isibor, PhD is a specialist in Pollution Studies and Ecotoxicology and a Lecturer/Researcher in the Department of Biological Sciences at Covenant University. He received his PhD and MSc in Environmental Quality Management from the University of Benin and a BSc in Zoology from Ambrose Alli University. Dr. Isibor's research interests include ecotoxicology, hydrobiology, bioaccumulation, biosequestration, biodiversity conservation, and aquatic ecology. He is a member of the Association for Environmental Impact Assessment of Nigeria (AEIAN), the International Association of Risk and Compliance Professionals (IARCP), and the African Society for Toxicological Sciences (ASTS). Dr. Isibor is co-editor of the book *Biotechnological Approaches to Sustainable Development Goals* (Springer, 2023), an Editor for the *African Journal of Health, Safety, and Environment*, and a reviewer for several reputable international journals.

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Chapter 10
Nanoparticles in Air and Their Impact on Air Quality

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10.1 Introduction

Nanoparticles range in size from 1 to 100 nanometers and can be made of a variety of materials, including metals, organic compounds, metal oxides, and carbon. In comparison to particles of larger dimensions, nanoparticles have prominent biological, chemical, and physical properties (Awasthi et al., 2023). Many aspects, such as a significantly greater surface area-to-volume ratio, improved mechanical strength, improved chemical reactivity or stability, and other pertinent considerations, can be linked to this occurrence. Different dimensions, forms, sizes, and compositions are displayed by nanoparticles (Khan & Hossain, 2022). A wide range of synthesis techniques are being created or modified in an effort to improve properties and lower production costs. Different methods are used to improve specific nanoparticles' chemical, physical, mechanical, and optical properties (Yaqoob et al., 2020).

The nanoparticles that are most commonly found in fabrics, paints, cosmetics, water disinfectants, and food packaging are those that come in powder, suspension, or spray form, and they provide a significant danger of inadvertent inhalation (Geiser et al., 2017). The uptake of particles varies depending on their size. Smaller particles (diameters between 0.1 and 1 μm) tend to concentrate in the tracheobronchial region, whereas bigger particles (diameters between 5 and 30 μm) generally remain in the nasopharyngeal region. On the other hand, particles smaller than 0.5 μm can penetrate the blood vessels' thin epithelium (De Matteis, 2017). Furthermore, there are two ways that nanoparticles in the nasal cavity could absorb:

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either they would cross the respiratory epithelium and reach the underlying blood vessels, or they would enter the brain through the olfactory epithelium (Fröhlich & Salar-Behzadi, 2014). But most studies on the toxicity of inhaled nanoparticles concentrate on nontherapeutic versions, which often show morbidity and mortality. Therapeutic nanoparticles are distinguished from these forms by their much smaller sizes, inorganic composition, water insolubility, and ability to be administered at different doses and frequencies. As such, the toxicological research is not transferable to biological nanoparticles (Zhang et al., 2011).

Technological advancement has made it easier to characterize nanoparticles more effectively and harness them afterward. Currently, numerous sectors use nanoparticles, including renewable energy sources, food utensils, electronics, and the aerospace sector. The integration of nanotechnology is critical to realizing a sustainable and ecologically mindful future. Grounded on a 2007 report by the Intergovernmental Panel on Climate Change (IPCC), nanoparticles influence the universal urban visibility and climate by acting as predecessors of rougher particles through their accumulation all the way through the atmosphere's aging process. They also impact the universal climate and atmospheric chemistry owing to their unique chemical constitution and reactive ability (Sonwani et al., 2021a). Particles with diameters between 0.1 and 10 μm have a residence length of about 1 week. Lesser particles can be eliminated by coagulation and diffusion only, but coarser particulate matter can be eliminated by settling (Cescon & Jiang, 2020). Furthermore, the primary causes of the challenges in removing nanoparticles (NPs) from the atmosphere and the resulting health risks to humans are their fine size and longer atmospheric retention duration. In addition to being created in the bodies of insects, plants, and people, nanoparticles are also released via combustion processes, forest fires, automobile exhaust, and industrial emissions (Khan et al., 2022). As stated by Vera-Reyes et al. (2018), nanoparticles are also important in plants because they enter through the apoplastic and symplastic pathways. From there, they interact primarily with the environment and cells through stearic, electrostatic, and van der Waals interactions. One of the agents that plants are harmed by is metal oxides attached to NPs (Giorgetti, 2019). In addition to tropospheric ozone, NPs are another phytotoxic agent for plant species that compromises the world food security system. As NPs can enter the body through a variety of routes, including the skin, the respiratory system, and the digestive system, it is speculated that they may adversely affect human health (Sonwani et al., 2021a).

In Asian countries, there is a high concentration of nanoparticles in the atmosphere because of factors like rapid urbanization, industrialization, vehicle emissions, life-threatening events (like storms, volcanic eruptions, dust, and forest fires), and sporadic events (like fireworks and burning crop residue) (Sonwani et al., 2021b). Metal, carbon, or silicon oxides make up the bulk of anthropogenic nanoparticles. Excess of 110,000 tons of particulate matter, 1.2 million tons of NOx, and 4.3 million tons of SO_2 is released annually by coal-fired power stations in India.

The development of atmospheric brown clouds (ABCs) is another notable occurrence (Bundschuh et al., 2018).

Increases in mortality and visitations to emergency rooms are linked with exposure to particulate matter (PM). When inhaled, these particles penetrate into the respiratory tract from which they target various anatomical sites based on their aerodynamic size and other properties (Hartland et al., 2013).

The World Health Organization (WHO) Global Air Quality Guidelines (AQGs) have been adopted in numerous countries to protect public health from air pollution from six classic pollutants, namely, sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_2), nitrogen dioxide (NO_2), and particulate matter ($PM_{2.5}$ and PM_{10}). In addition, some air pollutants are associated with both health effects and global warming; hence, all efforts to improve air quality can enhance climate change mitigation and vice versa. About 80% of the global deaths attributed to PM2.5 exposure could be avoided if countries attain the updated annual AQG level (Table 10.1).

10.2 Source of Nanoparticles in the Air

10.2.1 Natural Sources of NPs

Human activity is responsible for around 10% of the overall aerosols found in the air; the remaining 90% are produced naturally (Sonwani & Saxena, 2021). Natural sources of nanoparticles include biogenic emissions, sea spray, forest fires, volcanic eruptions, landslides, and dust storms. They are also widely distributed in the environment (Goud et al., 2022). The natural inclination of NPs to react with clouds and air particles means that organic chemicals make up a significant fraction of atmospheric nanoparticles (Lee et al., 2019). Ambient air is high in nitrogen oxides, volatile organic compounds (VOCs), and primary organic aerosols from both

Table 10.1 Recommended 2021 Air Quality Guideline (AQG) levels

Pollutant	Averaging time	2021 AQG level
$PM_{2.5}$, μg/m^3	Annual	5
	24-h[a]	15
PM_{10}, μg/m^3	Annual	15
	24-h[a]	45
O_3, μg/m^3	Peak season[b]	60
	8-h[a]	100
NO_2, μg/m^3	Annual	10
	24-h[a]	25
SO_2, μg/m^3	24-h[a]	40
CO, mg/m^3	24-h[a]	4

μg microgram

[a]99th percentile (i.e., 3–4 exceedance days per year)
[b]Average of daily maximum 8-h mean O_3 concentration in the six consecutive months with the

highest 6-month running-average O_3 concentration. Note: Annual and peak season is long-term exposure, while 24 h and 8 h is short-term exposure

natural and man-made sources. These substances eventually combine to generate secondary biological aerosols (SOA) (Tiwari & Saxena, 2021). Biogenic unstable carbon-based compounds account for 10–40% of the bulk of biological aerosol in the world and produce around 90% of SOA generation (Cao et al., 2022). The chemical composition of nanoparticles differs substantially between regions due to various types of indigenous sources and their respective contributions.

In addition, incomplete incineration and geographical sources constitute the other major atmospheric sources of nanoparticle generation. The main combustion-generated sources are forest fires and volcanic eruptions, while the main geological sources are earthquakes, glaciers, dust storms, and volcanic eruptions (Leroy et al., 2022). According to Trejos et al. (2021), volcanic ash is essential to the worldwide movement of hazardous chemical species discharged together with particulates. Ash is a mixture of solid and liquid particle debris that is emitted during volcanic eruptions. It has an extremely complicated structure. Its composition varies throughout time as a result of chemical reactions and cooling. Volcanic ash nanoparticles (NPs) tend to have higher concentrations of harmful metals (Hg, Tl, Zn, Sn, Se, Te, Cd, Ag, Bi, Pb, and Ni) than comparable samples (Sonwani et al., 2021a).

10.2.2 A nthropogenic Sources of NPs

Man-made sources of NPs are more concentrated than natural sources in urban areas (Zhang et al., 2020b). There are two categories of anthropogenic sources: purposeful and unintentional. Unintentional sources include burning biomass, incinerating nonbiodegradable trash, and incomplete combustion from autos and industry. One of the intentional sources of NPs is the application of fertilizers and insecticides. NPs are further divided into main and secondary sources according to their place of origin. Industrialized emissions, mineral mining, energy generation, and transportation events are examples of primary sources. Primary sources might be mobile or fixed (Bhat et al., 2022).

Emissions from mining operations, metallurgical and chemical industries, and thermal power plants are examples of stationary sources. One of the main sources of NPs is thermal power plants, particularly in metropolises where there are more of them than elsewhere, such as semirural/urban settlements. The majority of the mobility sources include ships, automobiles, airplanes, engines, submarines, and rockets launched into extra-atmospheric space (Sonwani et al., 2021b; Strambeanu et al., 2014). One of the main sources of NPs is vehicle exhaust, which is produced when fuel is not completely burned. As a result of a dramatic rise in the number of vehicles on the road, it is one of the core origins of air pollution (Sonwani et al., 2021a). In 2002, there were more over one billion vehicles on the planet, and the number has been gradually increasing ever since (Roosa, 2020).

Hydrocarbons (HCs), carbon monoxide (CO), sulfur oxides (SOx), nitrogen oxides (NOx), volatile organic compounds (VOCs), particulate matter (PM), and their secondary derived products are the main components of exhaust (Agarwal & Krishnamoorthi, 2023). The majority of particles found in automobile exhaust are within the sizes of 20–130 nm (diesel engines) and 20–60 nm (petrol engines). Fuel's sulfur content is a crucial factor since it sets off the PM production nucleation mode (Han et al., 2020). The discharges and ultrafine particles represent a major threat to the well-being of the environment due to their proven carcinogenic effects.

The mining and building industries are the second largest transmitters of anthropogenic nanoparticles to the atmosphere. Nanoparticles can be directly produced by surface excavation and mining through mine channels, but they can also be indirectly produced by decantation, sedimentation, and flotation (Silva et al., 2021). The amount of NPs in the atmosphere is also influenced by demolition techniques and meteorology. At demolition sites, one can find lead, wood, asbestos, fibers, glass, and other harmful particles in addition to dust. These particles have the ability to ascend high into the air and occasionally produce dust clouds that can spread widely impacting neighboring areas (Stevulova et al., 2022).

Pneumonia and, in extreme situations, cancer are brought on by inhalation of metal dust (nickel, chromium, and cobalt) and fumes (copper and zinc)—a condition that accounts for 15% of work-related risks (Nemery, 2022).

10.2.3 Trans-Boundary Movement of Nanoparticles

The migration of air contaminants is a significant driver in escalating the concentration of particulates in the atmosphere by augmenting the pollution load within a certain location, given that it carries an assortment of minerals and salts in addition to tiny particles, air mass migration from desert and ocean areas has a substantial impact on the quality of the air in secluded regions (Sonwani & Saxena, 2021). The burning of crop residues (CRB) is a major contributor to the deterioration of air quality in neighboring states due to trans-boundary movement. A significant portion of the emissions from CRB affect the air quality in the Indo-Gangetic Plains (IGP). The annual burning crop residues in IGP annually affect the air quality over the Arabian Sea coast and the south coast of India, with smoke columns reaching up to 2.5–3.5 kilometers (Sonwani et al., 2021a).

10.3 Mechanism of Exposure to Nanoparticles

10.3.1 Inhalation

The interior surface area of the human lungs ranges from 75 to 140 m^2, with approximately 3,00,106 alveoli (Wang et al., 2022a). The lungs are directly exposed to the external environment, and they serve as the primary point of entry for nanoparticles into the body. They are the main target site for studying the impacts of nanoparticles and are also regarded as significant (Garcia-Mouton et al., 2019). Breathing in air occurs through the nose and mouth, traveling down the throat, the tracheobronchial tree, and ultimately the alveoli. Particle passage is reliant on the respiratory airway's structure (Bake et al., 2019). NPs can disperse and collect in the alveolar section due to their tiny size and high retaining period. Some of them may even pass through the capillary endothelial cells and alveolar epithelium to enter the cardiovascular system as well as other internal organs. Moreover, electron imaging demonstrates that nanoparticles can penetrate the karyoplasm and cytoplasm of pulmonary mesothelial and epithelial cells in the lungs, as well as the inner and outer cellular compartments (Ferdous & Nemmar, 2020).

The respiratory system is responsible for gaseous exchange between the human body and its surroundings. It is one of the most vital systems in the human body and serves as an important entry port for nanomaterials into the human body and is the most common route of NP exposure. As humans breathe in air, NPs in the form of aerosols and powders can be easily inhaled into the respiratory tract (Yah et al., 2012). Once inhaled, particles are transported by the electrostatic force of the air from the upper respiratory tract to the lower respiratory tract. Larger NPs (>5 μm) are usually trapped by mucus in the upper respiratory tract and excreted via the body's lymphatic system (Fig. 10.1). On the other hand, smaller NPs escape from the mucociliary system and penetrate deep into the lung's alveoli where they are deposited in the alveolar epithelium or absorbed into the bloodstream (De Matteis & Rinaldi, 2018; Thu et al., 2023). In addition to the smaller-sized NPs, faster breathing rate, oral breathing, and existing lung disease can cause an increase in the penetration of NPs and deposition deep in the lungs.

10.3.2 Deposition

The aerodynamic diameter of the particle determines the location of nanoparticles dumping in the respiratory tract. The "saddle points" where the branching respiratory airways meet are where most of the bigger diameter fibers are deposited. As a

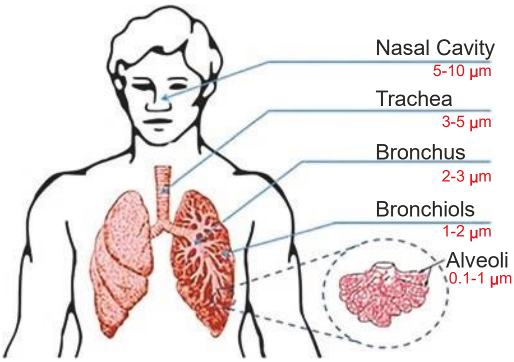

Fig. 10.1 Different size deposition of NPs in the airway after inhalation. (De Matteis & Rinaldi, 2018)

result, they can't enter the respiratory system deeply. Brownian motions primarily control deposition for smaller particles. Aerosol NPs of 20 nm size are shown to circumvent major clearance processes and deposit in the lung's alveolar region after 24 h of inhalation, according to data from energy-filtering transmission electron microscopy (EFTEM) (De Berardis et al., 2020; Si et al., 2021). The International Commission on Radiological Protection (ICRP) created a classical model that states that particulates with a diameter of less than 20 nm have a great likelihood of entering the alveolar section. Thus, by mucociliary escalation and macrophage activity, particles bigger than 20 nm in diameter are limited in the preceding regions of the respiratory tract. Prior to particles entering the pulmonary region, these responses aid in their removal from the tract (Bhat et al., 2022).

10.3.3 Clearance

Particle size, ventilator settings, and airway features are the main factors that influence deposition, but the physicochemical properties of the particulate matter ultimately decide how well it is cleared after it has been deposited. Due to impaction, bigger particles are dumped during inhalation at the intrathoracic bifurcations and extrathoracic area (nose and larynx). Mucus covers these upper respiratory airways. The primary route of clearance from the areas of the bronchus, trachea, and the upper bronchioles is the mucus layer, which traps the huge particles and transports them out by ciliary beating (Schneider-Daum et al., 2019). An effective ciliary beating cycle is facilitated by the periciliary layer, which lies beneath the outer viscoelastic mucus blanket. When the tips of the cilia come into contact with the mucus blanket, they beat in unison to speed up this layer (Hill et al., 2022). The mucus and NPs reach the pharynx, and they are eventually swallowed and continue to be processed inside the gastrointestinal system (Kaneko et al., 2020).

Tiny particles land in the bronchioles and alveoli after penetrating far into the lungs, where air velocity significantly drops (Ou et al., 2020). This is the location where macrophages engage in phagocytosis of the biogenic NPs such as bacteria, protozoa, and viruses where NPs undergo mucus transport (Joseph et al., 2023). Compared to mucociliary clearance, macrophage-associated clearance occurs far more slowly (Haque et al., 2020). The majority of these NPs move into connective tissue and then become involved in circulation of blood, which exposes them to macrophage populace in the non-alveolar area. Since surface macrophages are comparatively less effective at clearing NPs, interstitial and intravascular macrophages are primarily responsible for NP clearance. Numerous proteins and biomolecules are in contact with NPs upon their breathing in and deposition on the surfactant film with the underlying epithelium coating fluid (Garcia-Mouton et al., 2019).

10.4 Consequences of Intake of Airborne Nanoparticles

The pseudo-stratified epithelium of the human lung makes up the lung-bloodstream barrier. The mucous layer covers the thin columnar epithelium, bronchial epithelium (3–5 mm), and bronchiolar epithelium (0.5–1 mm), which make up the airways (Armstead & Li, 2016). Many cell models were created and tested in order to investigate the combined impact of nanoparticles on the lungs, as lung tissue is composed of over 40 distinct cell types. The respiratory system's epithelium is the primary target of NP exposure. A549 cell lines, which are derived from human lung adenocarcinomas, are most frequently employed in toxicity testing, and Calu-3, 16HBE14o-, and BEAS-2B cell lines are utilized as models for the bronchial-b arrier system. The respiratory system is easily reached by smaller particles, which deposit at the distal portions of the respiratory tract, so the size of NPs and the harm they produce there are inversely correlated (Nho, 2020). The four major types of toxicological effects of nanoparticles (oxidative stress, inflammation, genotoxicity, and tumorigenicity) are discussed in the following sections.

10.4.1 Respiratory Injury

The responses to and lung detoxification of soluble and insoluble particulate matter differ significantly. In accordance with Khalaf et al. (2023), soluble nanoparticles enter the cardiovascular systems after dissolving in aqueous fluid. On the other hand, mucociliary escalator and macrophage phagocytosis are the methods used to eliminate the insoluble NPs (black carbon) (Osman et al., 2020). From research reports, insoluble particulates lead to increased lung tumors, inflammation, and tissue damage (Adeel et al., 2020). Lung damage results from the insoluble particulates accumulating more quickly than the ability of macrophages to clean them. As a result, the lungs' defense mechanisms are unable to function (Osman et al., 2020).

Additionally, it was found that the bronchoalveolar lavage fluid's shortened half-life of IL-1β and TGF-β1 induces acute lung inflammation. On the other hand, prolonged exposure results in the synthesis of collagen, which burdens the lungs and may lead to pulmonary fibrosis (Sun et al., 2020).

Lung burden-related health risks are closely linked to rising rates of early death, particularly in emerging countries. The rate of particle dumping, clearance, and residence time of the NPs all play a role in determining lung burden (Sun et al., 2020). Large mammals (humans and primates) have a slower rate of insoluble nanoparticle clearance and a higher propensity for reserved lung burden, which can move from the source alveolar dumping spots to the respiratory system's interstitial parts. These findings are supported by morphological observations and retrospective evidence. Long-term NP exposure results in a high rate of lung burden, which in turn supports lung tissue carcinogenesis (Sonwani et al., 2021a). Nonetheless, human exposure to this degree is uncommon, indicating a decreased risk of contracting the illness (Bouchama et al., 2022).

One of the most crucial channels for NPs to reach the body's various biological systems and for airborne contaminants to enter the body is through the respiratory system. Through the process of air particle diffusion, the reserved NPs in the lungs come into contact with the blood barrier of the alveoli, which is usually in-between the lungs' alveoli and the circulatory system's transferring vessels. This barrier aids in the exchange of stored gases in the alveoli with the whole body and vice versa. Through endocytosis in the alveolar epithelial cells, the trapped NPs permeate into these capillaries and are carried by blood to the other organs. A process known as endocytosis allows a cell to move particles into and out of the cell by creating vacuoles. The second route is the migration of these ultrafine particles via the nasal epithelial wall into the olfactory bulbs of neurons, which is how they get into the central nervous system (Kumar et al., 2022; Sonwani et al., 2021a). Nanoparticles can cause a variety of respiratory conditions when humans inhale it (Osman et al., 2020). The eight-largest hazard for the worldwide burden of disease is indoor air pollution caused by the burning of household fuels. The primary cause of indoor nanoparticle pollution in homes is smoke from biomass fuels and inefficient stoves which are mostly used in rural regions. Some of the main issues preventing rural residents from switching to modern stoves and environmentally friendly fuels include traditional practices, illiteracy, and ignorance (Altieri & Keen, 2019). Unprocessed biomass solid fuel is the most widely utilized fuel for home cooking in rural areas; it is reported to produce 50 times more emissions than gas cookers (Ravindra et al., 2019). Project Surya, which was implemented in India, recommended that upgraded cooking appliances be used by Indian homes as a way to mitigate black carbon emissions. As a result, it was advised that traditional cookstoves require more testing and better machinery (Sonwani et al., 2021a; Stoner et al., 2021). Such sustainable and environmentally friendly methods can lower the atmospheric concentration of NPs.

Another significant cause of NP exposure is cigarette smoking. It is known that one cigarette releases around 8.8 × 109 nanoparticles. There have been few researches done on many types of particles found in cigarette smoke, perhaps due to the large concentrations of particles and their quick dilution in air. Research indicates that those who passively smoke have a higher body mass index (BMI), a higher incidence of malignancies, and a lower lung function compared to nonsmokers (Borch et al., 2019; khan et al., 2021). Passive smoking has been shown to have negative impacts on human carcinogen levels, as demonstrated by the elevated levels of 1,3-butadiene, particulate-bound 2,5-dimethylfuran (DMF) and benzene in nonsmokers exposed smoke from cigarette. Exposure to nanoparticles (NPs) poses a significant risk to occupational health, a concern that is spreading throughout emerging and underdeveloped countries. Traffic officers have been found to have higher incidences of cardiovascular and respiratory conditions as a result of their prolonged exposure to vehicle emissions (Bajaj et al., 2017; Rodrigues et al., 2022).

10.4.2 Effect of NPs on Reproductive System

The accumulation of NPs has been identified as one of the primary causes of the current increase in cases of infertility. According to Zhang et al. (2020a), an experimental investigation conducted on rats fed a high-fat diet demonstrates that the administration of silica NPs, frequently found in workplaces, led to lower sperm motility rates and concentration and raised the rates of sperm abnormalities. Significant sperm DNA integrity loss was noted as a result of TiO_2 NPs' genotoxic effects, which are demonstrated when they penetrate the barrier of blood-testis and induce cytotoxicity and inflammation (Santonastaso et al., 2019). NPs have an impact on the reproductive system through ovarian cell cytotoxicity, which disrupts the oogenesis process and ultimately leads to an excess of reactive oxygen species (ROS), apoptosis, and an imbalance in sex hormones in the body (Ferrante et al., 2022). An animal given MoO3 in a study displayed a marked reduction in the weight of both the uterus and the right ovary, which ultimately had a negative impact on the process of reproductive (Asadi et al., 2019). Therefore, nanoparticles play a crucial role in lowering birth rates and causing defects in children. These kinds of situations are frequently observed in urban locations in females exposed to air pollutants, notably particle matter (NPs) as a result of their daily lives.

10.4.3 Effect of NPs on Endocrine System

Over the past 50 years, epidemiological data have demonstrated a significant increase in immune system disorders, including altered growth and development processes, immune system disorders, neurological system disorders, reduced fertility, and the beginning of several major diseases, such as obesity, diabetes, testicular, prostate, and ovarian cancer. The increased exposure of the general public and workers to chemicals that act as endocrine disruptors (EDCs), which can have detrimental consequences by altering the hormonal and homeostatic systems, could be one explanation for the rise in these ailments (Iavicoli et al., 2013). A study demonstrates how giving male rats 150 μg/kg of zinc oxide nanoparticles caused a net imbalance by raising the T3 thyroid hormone and dropping the hormone that stimulates thyroid (Chong et al., 2021). Palladium nanoparticles have been demonstrated to have action on hormone receptors gradually, starting with overstimulation and stopping the indicator cascades (Leso et al., 2018). According to certain research, NP exposure makes diabetic wildlife more susceptible to the hormonal imbalance than the ones that are not diabetic (Salem, 2020).

10.4.4 Effect of NPs on Neural System

The nervous tissues that comprise nervous system is composed of neurons and neuroglial cells (Rocha et al., 2020). Air pollutants enter the central nervous system (CNS) in various ways, however, the most common means is inhalation, in which substances can enter the brain through the blood-brain barrier, trigeminal nerve, olfactory bulb, the thalamus, and trigeminal nucleus, among other pathways. Nanoparticles (NPs) accumulate in many brain regions and alter gene expression that supports central nervous system growth and function, hence producing cytotoxic effects on neural cells (Vinod & Jena, 2021). Depression, inattention, and even cognitive impairment are indications of central nervous system dysfunction. Significant cytotoxicity is caused by ZnO NPs, which also cause apoptosis, changes in the cell cycle, a decrease in viability, and various forms of genetic damage, such as oxidative DNA impairment. Research indicates that inhaling manganese oxide causes inflammation in the brains of rats. In the mouse cortex and hippocampus, silver nanoparticles induce oxidative stress and upregulate genes linked to oxidative stress (Vinod & Jena, 2021).

10.4.5 Effect of NPs on Excretory System

The kidney is highly vulnerable to xenobiotic substances and the bioaccumulation of other toxins because each nephron in the kidney is equipped with a network of blood capillaries, which filter toxins from the blood. Following glomerular filtration, NPs typically gather in the proximal convoluted tubules (PCT), where endocytosis might cause tubular cells to internalize the particles. A study conducted on TH1 cells open to inorganic nanoparticles revealed that these cells had DNA damage in addition to an amplification of NP-induced nephrotoxicity (Sramkova et al., 2019). This will also cause chromosomal defects and genetic disorder. According to Naz et al. (2020), a particle's toxicity increases with its size. When exposed to SiO2 nanoparticles at dosage of 20–100 μg/ml, cells of the kidney experienced shrinking and nuclear condensation and that is an indicator of apoptosis, according to a study on HEK293 (cultured human embryonic kidney) cells. Additionally, oxidative stress induction and ROS generation in HEK293 cells suggest that nanoparticles may be nephrotoxic. Dysfunction in nephron elasticity brought on by impaired nephrotoxic potential can result in cerebral epilepsy (Sonwani et al., 2021a; Wang et al., 2022b). Additionally, the cytotoxicity of nanoparticles was assessed in the glomerular mesangial IP15 and epithelial proximal HK-2 cell lines. The tubular human renal cells and glomerular in the study were found to be cytotoxically affected by ZnO and CdS nanoparticles. Particle size, metal solubility, and metal composition were all connected to these effects (Pujalté et al., 2011; Sonwani et al., 2021a).

10.4.6 Effect of NPs on Cardiovascular System

NPs can enter human bodies by oral exposure to the gastrointestinal tract, which then travels to the circulatory system, or by inhaling (intranasal or intratracheal).

These may result in notable deviations from the system's typical operation. Some of the first effects of NPs on the cardiovascular system include elevated blood pressure, lowered heart rate, changed vascular tone, and malfunction (Cao & Luo, 2019; Yu et al., 2016). NPs can affect human bodies in a variety of ways, including vasodilation/vasoconstriction, angiogenic/antiangiogenic, prooxidant/antioxidant, cytotoxic, phagocytic, and apoptotic (Gonzalez et al., 2016). These effects depend on the physical characteristics, concentration, and retention period of the NPs. People who already have cardiovascular conditions are particularly vulnerable to these alterations. Because of the incorporation of NPs in the bloodstream, these individuals are more vulnerable to heart attacks, sudden cardiac arrests, and blood clot.

The simultaneous and opposing effects of silver nanoparticles (NPs) on blood composition, angiogenesis (vessel formation), and membrane permeability are shown in pacemakers, medications, and linked antibodies (Wang et al., 2022a). TiO2 NPs can accumulate in the heart after prolonged exposure, which can result in inflammation, cellular necrosis, sparse cardiac muscle fibers, and cardiac biochemical malfunction. An investigation on SiO2 NPs in aged rats revealed elevated Fbg levels and blood viscosity in addition to atrioventricular occlusion and myocardial ischemia injury (Yu et al., 2016).

10.4.7 Effect of Nanoparticles on the Digestive System

The stomach, intestines, and esophagus make up the majority of the digestive system, sometimes referred to as the gastrointestinal tract. The most common ways that NP enters the gut are through food or water consumption (Huang & Tang, 2021). According to Polet et al. (2020), the presence of silver nanoparticles raises interleukin- 8 levels, which are directly related to inflammation and increased mucus formation. Certain NPs can disrupt the mucus and epithelial cell layers in blood vessels by escaping the junctions between intestinal epithelial cells, depending on their size. Moreover, they ultimately gather in the intestinal lamina propria, where they impair goblet cell activity (Ejazi et al., 2023). The rate of NP buildup increases if an individual already has underlying medical disorders such Crohn's disease or ulcerative colitis, which causes intestinal inflammation. Cancer of the colon and other carcinomas can arise from the elevated toxicity levels (Wang et al., 2022a).

10.4.8 Oxidative Stress

The main effect of nanotoxicity is oxidative stress, which is brought forth by an imbalance between antioxidants and free radicals in the body. As a result, extra free radicals with an irregular number of electrons unintentionally react with other molecules to cause an imbalance in the respiratory system (Yahya et al., 2019). One of the key oxidative processes that lead to lung damage in humans is the generation of ROS. According to Flores-López et al. (2019), NPs' action in the cell's mitochondrial electron transport chain is what causes the overproduction of ROS.

Carbon NPs are known to influence mitochondrial processes, while metallic NPs cause Fenton-type reactions that result in free radical-mediated toxicity (Canaparo et al., 2020). The surface groups' catalytic activity determines how much ROS is created by a specific NP. About 10% of the molecules in a particle with a size of 30 nm are expressed, compared to only about 20% and 50% of the molecules in particles with a size of 10 and 3 nm, respectively. The organism experiences oxidative stress when reactive oxygen species (ROS) are produced excessively or when antioxidant defense mechanisms are compromised.

10.4.9 Inflammation

There are two types of immune systems in humans: innate and adaptive. The first defense against any foreign particle that enters the body is the innate immune system. The much more sophisticated and potent adaptive immune system is triggered if the innate immune system is unable to neutralize the foreign particle (antigen) on its own. The body's dendritic cells are responsible for this activation (Keselowsky et al., 2020). Because they are foreign particles, nanoparticles also trigger the activation of dendritic cells, which release ROS, chemokines, and cytokines and stimulate naïve T-cells and different inflammasomes. The zeta potential (ξP) of a particle is a well-known indicator of its capacity to induce inflammation. The electric potential generated by the interaction of charged groups (found on a particle's surface) with the suspension medium is known as the zeta potential (ξP) (Sonwani et al., 2021a). Because the human body's medium is acidic, a particle's solubility in the medium will increase if it has more positively charged groups on its surface. This will increase the particle's contact with macrophages, which will cause inflammation (Karakashev et al., 2022). In these fluids, magnesium and zinc oxide nanoparticles exhibit great solubility. An additional indicator of inflammation in the body is the quantity of white blood cells (WBCs) in blood. When the white blood cell count rises above normal, it indicates inflammation and a decline in immunity. NPs that are inhaled cause the production of pro-inflammatory hormones upon deposition in the lungs, where they come into contact with alveolar macrophages, which are the primary immune system. The dormant macrophages are aroused to promote the delivery of several pro-inflammatory cytokines to the site of injury as a result (Sonwani et al., 2021b).

The respiratory tract's cilia are destroyed as a result of inflammation, which makes it more difficult for mucus to pass through cilia and trap dirt and infectious pathogens. Additionally, inflammation causes epithelial injury by rupturing the epithelial barrier separating the bloodstream from the lung surface. This compromises blood and oxygen circulation within the body, clotting, and reduced lung function. Pulmonary fibrosis, lung cancer, chronic obstructive pulmonary disease, asthma, and cystic fibrosis are all characterized by inflammation of the lung tissue and pneumonia (Poore & Zemanick, 2023). The primary causes of death for patients with chronic lung illnesses are different forms of pulmonary fibrosis. Additionally, inflammation causes blood clot, which triggers the thrombosis cascade at several sites. These events ultimately result in issues with the cardiovascular system, disrupt the heart's rhythm, and raise the body's risk of cardiac arrest (Stark & Massberg, 2021).

10.4.10 Genotoxicity

Direct NP-DNA contact or indirect oxidative stress or inflammatory responses are two ways that NPs might cause genotoxicity. Two categories of genotoxicity can be distinguished: primary and secondary genotoxicity, based on several research and their ensuing impacts. When minuscule particles penetrate the nucleus and alter DNA, this is known as primary genotoxicity. The cascade of DNA repair is connected to another important indirect mechanism. According to Vecchiotti et al. (2021), oxidative stress and inflammation brought on by NPs are the causes of secondary genotoxicity. Adenine and guanine undergo hydroxylation during DNA oxidation, which causes mutagenic changes and the creation of DNA adducts. DNA adducts are the product of covalent modifications to DNA caused by specific carcinogens. Particulate carcinogens can penetrate cellular membranes and the nucleus directly. Examples of such substances include asbestos and crystalline silica. They subsequently cause dysfunctionalities by interfering with many components of the mitotic spindle's operation and process. All biological functions, including mitosis, DNA replication, and DNA transcription into mRNA, can be interfered with by these foreign particles. Nanoparticles cause phagocytes (neutrophils, macrophages, etc.) to produce reactive oxygen species (ROS), which damages DNA and causes mutagenesis in nearby cells (Shukla et al., 2021). The induction of inflammation by diesel exhaust particle exposure results in epigenetic modifications, such as disruptions in DNA repair, adduct formation, gene expression impairment, and cell proliferation (Quezada-Maldonado et al., 2021).

10.4.11 Tumorigenicity

The MAPK/ERK pathway, sometimes referred to as the Ras-Raf-MEK-ERK pathway, is a network of proteins in a cell that transmits a signal between a surface receptor and the DNA located in the nucleus. Epidermal growth factor receptor (EGFR) is a cell surface receptor, and the signaling molecule that binds to it initiates the signal (Lin et al., 2020). Extracellular ligands, like epidermal growth factors, attach to this receptor in its normal state, phosphorylate it, activate it, and initiate a series of docking proteins that eventually produce mRNA, which is then translated into other proteins. Here, ROS and occasionally direct NanoPs interact with these receptors, and because of the altered DNA coding, aberrant proteins may or may not arise. One of the key steps in the development of many cancers is the possibility of a protein in the pathway becoming stuck in the "on" or "off" position due to mutation. The body's concentration of 8-hydroxy-2′-deoxyguanosine (8-OHdG) is largely increased by the introduction of NPs. Tumors can arise from G-to-T transversion mutations caused by 8-OHdG in important genes that are known to play a role in the genesis of cancer (Guo et al., 2021). As a result, there is a clear correlation between an elevated level of 8-OHdG and the development of carcinogenicity, which reduces immunity. Caveolin-1 overexpression and p53 inactivation are additional routes. NPs cause p53 inactivation by lowering phosphate levels in cells, which is necessary to activate proteins and raise the risk of tumor development (Kornberg et al., 2019).

10.5 Conclusion

A recent increase in the forms and variety of air pollutants has been attributed to urbanization, industrialization, and other human activities. A consequence of this is the increased burden of sickness brought on by pollutants that harm both the environment and humans. The benefits of nanoparticles (NPs), like high reactivity, small size, and great capacity, may turn into deadly aspects if they cause detrimental and toxic effects on cells that are not seen in micron-sized counterparts. Additionally, at that size, the optical properties also predominate, which emphasizes the significance of these materials in photocatalytic applications. It can be helpful to utilize synthetic methods to regulate the precise size, shape, and magnetic characteristics of NPs. Even though NPs have a wide range of applications, their uncontrolled use and discharge into the environment raise certain health risks. These issues should be taken into account while developing more environmentally friendly and convenient ways to employ NPs. Ongoing research and its benefits offer hope for new product breakthroughs. It is feasible to create artificial "living-like" or "nano-bot" entities that can remove heavy metals and dangerous toxins from surroundings. Therefore, the environment and industry will advance with the widespread use of these organisms and products.

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