Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 4, Issue 3, 2026

IMPACT OF NANOPARTICLES ON HUMAN HEALTH IN PAKISTAN

Shahid Mahmood[*1], Razia Iqbal[*2], Kamza Andleeb[3], Memoona Kanwal[4], Maryum Mithu[5], Kalsoom Bibi[6]

[*1,* 2,3,4,5, 6] *Department of Zoology, University of Gujrat, Gujrat 50700, Pakistan*

[*1]shahid.mahmood@uog.edu.pk, [*2]razia.iqbal@uog.edu.pk

DOI: https://doi.org/10.5281/zenodo.18996532

Keywords
Nanotechnology; Nanoparticles; Oxidative stress; Inflammation; Genotoxicity

Article History
Received: 13 January 2026
Accepted: 25 February 2026
Published: 13 March 2026

Corresponding Author: *
Shahid Mahmood,
Razia Iqbal

Abstract
Nanotechnology is a rapid emerging field and has found application in medicine in a large-scale agriculture, industry as well as consumer products yet the rate of manufacturing and consumption of nanoparticles. The topic (NPs) has raised growing apprehensions regarding the potential adverse effects of such particles on human health. Nanotechnology is a fast-developing discipline, which has been used extensively in medicine, agriculture, industry, and consumer products but the pace of production and use of nanoparticles (NPs) has brought about increasing concerns about the possible negative impacts of these particles on human health. Nanoparticles, the size of which is generally between 1 and 100 nm, have distinct physicochemical properties including high surface area, high reactivity, and penetration of biological barriers which can have unexpected toxicological implications. The paper is a critical review of the sources, routes of exposure, toxicological pathways and health effects of nanoparticles with special reference to Pakistan. The primary route of human exposure to NPs is via the respiratory, oral, dermal, and occupational exposures (particularly in urban, industrial, and agricultural settings). There is evidence to show that nanoparticles cause toxicity through oxidative stress, inflammatory effects, mitochondrial pathology, and genotoxic effects, which lead to respiratory, cardiovascular, neurological, renal, and reproductive pathologies. Rapid urbanization, traffic emissions, industries, and the growing utilization of nano-enabled agrochemicals and pharmaceuticals are some of the major contributors to engineered and incidental nanoparticle exposure in Pakistan, and distinct monitoring and regulatory systems on nanoparticles are still scarce. This review provides global-based toxicological evidence with regional exposures to bring out the most pertinent public health and occupational risks of nanoparticles in Pakistan. Lastly, it also establishes the gaps that are of interest in the research and it also highlights the urgency of nano safety regulations, exposure surveillance, and evidence-based policymaking to ensure that nanotechnology continues to develop safely and sustainably in the country.

INTRODUCTION

Nanoparticles are minute particles between 1 and 100 nm in diameter, which are being widely employed in various sectors, e.g., medicine, engineering among others. Due to their distinct characteristics, including their small size, magnetic characteristics, quantum size effects, and a phenomenon called macroscopic quantum tunnelling effects, they will be important in the variety of potential applications (Kumah, Fopa et al. 2023, Roy, and Murugesan et al. 2023). The field nanotechnology has increased over the course of the twentieth and twenty first centuries, which has consequently increased the rate at which the number of new nanomaterials industrialized. It is probable that these new nanomaterials have been established because of their size-dependent, outstanding, physical, and chemical characteristics.

Nanotechnology is certainly playing a key role in the economy of most industries. Nanomaterials are characterized based on their express attributes of surface charge, surface area, surface coating, particle morphology, and level of agglomeration (Asmat ulu, Andalib et al. 2022). Some of the studies have reported cases of toxicity in the past 10 years as a result of nanomaterials (Bachand and Hayes 2016). The health complications are also increasing along with the demand of nanomaterials in various industries and domestic products. The toxicological methodology is instrumental in controlling the effects of many substances and products on human and environmental health (Qamar, Gulia et al. 2024).

According to epidemiological research, it is indicated that the ultrafine (nano-sized) portion of particulate air contamination has a stunning impact on the exacerbation of cardio-respiratory illness and a rise in morbidity (Pistorius, Stockmann-Juval et al. 2018). As a consequence, the adverse health effects of nanomaterials in the human environment are of great interest (Sahu and Hayes 2017). The interesting hypothesis is that nanoparticles have the potential to induce oxidative stress, chronic inflammation, and even genetic mutation leading to the pathogenesis of lung cancer, and the ability of a person to adapt and react to toxic substances determines the toxicity of a nanoparticle in this particular person (Wardoyo 2025).

In addition, the genetic make-up of a person is the determinant of the toxicity of a nanoparticle in an individual since it depends on how the individual can adapt and respond to that toxic substance (Kumah et al., 2023). NPs can be introduced into the human body through either unintended or intentional routes of entry through inhalation, dermal, oral, and injection. In both scenarios, NP success requires the capacity of NPs to penetrate biological barriers, including skin, gastrointestinal (GI) tract, or blood-brain barrier (Bakand & Hayes, 2016).

Different products based on nanotechnology including nano fertilizers, nano herbicides, nano pesticides, nano fungicides and nano insecticides have been developed in the recent years to control pest-related diseases. Nano pesticides are greatly applied in the farming, weed, and nutrient control in agriculture and in food manufacturing, packaging and preservation. Carbon, silver, silica and aluminosilicates nanoparticles are effective in the protection of plants in agricultural fields (Qasim et al., 2022). In order to know the impacts of the nanomaterials on occupational health, we should measure the respiratory toxicity of producing nanomaterials using inhalation tests, intratracheal instillation tests, and pharyngeal aspiration tests (Morimoto et al., 2013).

This review paper will critically assess the effects of nanoparticles on human health in Pakistan by incorporating the global toxicological evidence with the regional patterns of exposure and future uses of nanotechnology. As nanomaterials continue to grow exponentially in medicine, agriculture, processing of food, industry, and consumer goods, human exposures are growing via inhalation, ingestion, dermal exposures, and at workplaces. This review aims at discussing the key sources and applications of nanoparticles in Pakistan and the possibility of their effects on health, especially their contribution to oxidative stress, chronic inflammation, genotoxicity, respiratory and cardiovascular diseases, neurotoxicity, and carcinogenesis. The exposure to ultrafine particulate in urban setting, occupational hazards of industrial and agricultural laborers and the increasing application of nano-enabled agrochemicals are given special attention. Moreover, it attempts to evaluate the existing safety practices, regulatory issues, and risk assessment strategies applicable to nanomaterials and to identify the most important knowledge gaps and research priorities to guide the accomplishment of evidence-based policymaking, environmental surveillance, occupational health, and sustainable advancement of nanotechnology in Pakistan.

2. Classification and characterization of Nanoparticles

Nanoparticles have broad applications in both domestic and commercial aspects as the primary part of nanotechnology (Khan & Hossain, 2022). NPs can be of different shapes, sizes, and structures. They are spherical, conical, cylindrical, tubular, hollow core, spiral, or irregular. Nanoparticles might be crystalline, loose or agglomerated in shape. They can be uniform or made up of many layers (Joudeh & Linke, 2022).
Their applications are broad and classified into four groups: 1. in-organic-based nanoparticles, 2. Carbon based nano-particles, 3. Organic/polymer nanoparticles, 4. Composite based nanoparticles (Kumah et al., 2023).

2.1 In-organic nanoparticles

This is the category of NPs that is not composed of carbon organic compounds (Joudeh and Linke 2022). Inorganic NPs are TMAT-AuNP, Ag-NP, Multi-walled carbon, nanotubes, TiO2, ZnS, CDs and Quantum dots. The silver, gold, zinc oxide (Zano), and titanium oxide (TiO2) NPs are employed in cosmetics due to their good drug delivery system, skin whitener and moisture absorber characteristics. Their application as therapeutic agents is due to their anticancer and antimicrobial properties (Bhatti, Shakeel et al. 2021).

2.2 Carbon based nanoparticles

Nanomaterials made of carbon (fullerenes, carbon nanotubes (CNTs) (particularly, single-walled carbon nanotubes (SWCNTs)) and graphene oxide (GO)) have a strong antimicrobial effect. Some studies have indicated the effective antimicrobial activity of the carbon nanostructures (Diaz, Minniti et al. 2015). The exposure of fullerene did not result in pulmonary inflammation and transient inflammation in the inhalation and intratracheal instillation experiments of well-characterized fullerenes. In comparison, inhalation research, a high concentration of multiwall carbon nanotubes (MWCNTs) and single-wall carbon nanotubes (SWCNTs) caused neutrophil inflammation or granulomatous structures into the lung, and intratracheal instillation of MWCNTs and SWCNTs caused sustained lung inflammation (Morimoto, Horie et al. 2013).

2.3 Organic nanoparticles

The formation of nanoparticles of complex organic molecule, in addition to the aforementioned elements of carbon and hydrogen, may also contain atoms of oxygen, sulfur, halogen, and is an important factor in biochemistry and nanomedicine (Utkina and Sergeev 2011). Dendrimers, liposomes, micelles, and protein complexes, including ferritin, are the most obvious representatives of this category (Joudeh and Linke 2022). The advantages of nanoparticles in medicine delivery, pollution, and developing new materials are made with the help of organic compounds and the nanoscale of these nanoparticles (Nawaz, Abdullah et al. 2025).

2.4 Nanoparticles based on composite

The composite nanoparticles can be explained as the nanomaterials of composite structure that are composed of two or more elements of nanoscale that have special physical and chemical characteristics. (Goswami and Zhao 2009). In the recent developments in the sphere of multifunctional composite materials (MFCMs), the use of composite materials has been noted. The advancement is under constant developments concerning advancements and substitution of metals despite the intense destructive and non-destructive tests, demonstrating the hardness and the life time of these materials. The current paper will examine the issues that are pertinent to the modern multi-functional composite materials (Ali and Andriana 2020).

3. Sources of Nanoparticles in Pakistan

Nanoparticles (NPs) are materials that are either engineered or naturally occurring with at least one dimension measuring less than 100 nm. The small size and high surface area of nanoparticles provide a distinct set of chemicals, physical, and biological properties, making them useful in applications such as medicine, agriculture, and industry. At the same time, the same properties may also lead to the release of nanoparticles into the environment and exposure of humans to them. Generally, sources of nanoparticles can be categorized as industrial, medical, agricultural, and consumer-related.

3.1 Industrial and Urban Sources

There are numerous contributions to the creation and release of engineered nanoparticles through industrial and urban activities that take place during the production process, through emissions, and through waste products. Pakistan has no nationwide NP emissions inventory; however, various studies indicate that the main sources of nanoparticles in the country include carbon nanoparticles (CNPs) produced and used in material science, environmental remediation, and biomedical research in the country, suggesting that there is industrial production and use of these engineered NPs. (Iqbal et al., 2022).

Although most nanoparticle synthesis activities in Pakistan have the aim of environmental sustainability, industrial synthesis activity continues to emit particulates which may serve as unintended sources of nanoparticles to the environment (Ullah et al., 2019; Ullah et al., 2025). The manufacturing and production of NP pollutes the environment through manufacturing and manufacturing waste, which is recorded and documented in sources of production and processing of nanomaterial. In Pakistan, montmorillonite clay is a natural nanomaterial that is being considered as industrial raw material in cosmetics, pharmaceutical, and water purification that is another source of nanoparticle exposure during production and use (Joravar et al., 2025).

3.2 Medical and Pharmaceutical Applications

In the medical research of Pakistan, nanoparticles are becoming increasingly popular to improve drug delivery systems, improve solubility, targeting, and delivery of therapeutics: Nanoparticles are being purposefully developed as a means of therapeutic delivery, diagnostics, and treatment, with Pakistani promotion in the healthcare and pharmaceutical sector (Abbas et al., 2025). Many papers report the treatment of cancer and other diseases with nanoparticle-based therapeutics, and the application of functionalized nanoparticles falls into the sphere of medical research in Pakistan (Nawaz et al., 2022). Pakistan reviews clearly refer to nanoparticles as the revolutionary in contemporary medicine, and the key focus is on diagnostics, cancer treatments, and personalized medicine (Naeem et al., 2023). Biogenic nanoparticles synthesized locally are also employed in the targeted drug delivery system, and they exhibit Pakistan research interest in the use of therapeutic nanoparticles (Atta-Ur-Rahman et al., 2024).

3.3 Agricultural Applications

In the agricultural sector, nanotechnology is expected to bring some change like the nano-fertilizer and other nano-enabled inputs. The sources are specific to Pakistan and are as follows: Nano-fertilizers are actively studied in Pakistan, and zinc oxide nanocomposites and chitosan-based nanocomposites can improve the nutrient uptake and crop yields (Ullah et al., 2025). Nano-Agri applications such as the use of biosynthesized nanoparticles in enhancing plant stress resilience are mentioned in the studies, which means that nano-Agri applications increase the nanoparticle concentration in agricultural environments (Javaid et al., 2025). The expanded information on Zano nanoparticles supports its application in the release of nutrients and enhanced plant growth that is a worldwide source of agricultural nanoparticle implementation in Pakistan (Hanif et al., 2024). Applications of Zano nanoparticles in agriculture, such as wheat, exhibit better crop production and nutrient bio fortification, which suggests their purposeful introduction into field farming technologies (Nazir et al., 2024). The expanded information on Zano nanoparticles supports its application in the release of nutrients and enhanced plant growth that is a worldwide source of agricultural nanoparticle implementation in Pakistan.

3.4 Consumer Products

Nano caustic materials are starting to be used more in consumer goods and as a result, they are likely to be released as nanoparticles when used, disposed of, and in the course of wear. Pakistan-specific and international evidence indicates: Nanoparticles in everyday life Reviews Nanoparticles in everyday life describe how nanoparticles are incorporated in consumer products, indicating the sources of nanoparticle exposures (Nawaz et al., 2024). Synthesis of nanoparticles through plants that play a role in remediation of the environment also finds its way into consumer products like antimicrobial coating and wastewater treatments (Riaz et al., 2025). According to general pollution research, cosmetic and industrial product nanoparticles may be released into the wastewater and soil when used or disposed off. According to a worldwide report conducted by Pakistani researchers, silver nanoparticles can be found in consumer goods like antimicrobial fabric, personal care items, and environmental clean-up instruments, which shows that there are many sources of nanoparticles (Shahzadi et al., 2025).

4. Routes of Human Exposure to Nanoparticles (Silver, Lead, Zinc, Cadmium, and Gold)

Engineered metal nanoparticles have become a considerable human exposure in the industrial, medical, agricultural, and consumer products. Inhalation, ingestion, dermal contact, and occupational exposure are the main human exposures to nanoparticles of silver, lead, zinc, cadmium, and gold (De Matteis, 2017; Kumah et al., 2023). Through these exposure routes, the level of nanoparticle absorption, biodistribution and related toxicological consequences are defined.

4.1 Inhalation Route

One of the most significant exposure pathways of human exposure to metal nanoparticles, especially in the occupational and urban setting, is inhalation. Nanoparticles released into the air by industries and during combustion events, as well as during the work with nanomaterials, can reach deep into the respiratory tract (Xuan et al., 2023). Investigations have indicated that inhaled silver, gold, and zinc oxide nanoparticles are accumulated in the alveoli of the lungs which can later translocate into systemic circulation and get accumulated in the body in the liver, spleen, and kidneys (Hadrup et al., 2025). It has been experimentally demonstrated that lung inflammation and tissue remodeling results of inhaling lead oxide nanoparticles is a primary route of lead nanoparticle exposure (Dumka et al., 2017).

4.2 Ingestion Route

Another significant exposure pathway to nanoparticle is ingestion, especially ingested via contaminated food, drinking water and mouth to mouth. Nanoparticles have the ability to get to the gastrointestinal tract through food packaging, nano-enabled food additives, and environmental pollution (Kumah et al., 2023). It is demonstrated that, when taken orally, silver nanoparticles are partially absorbed across the intestinal epithelium and are distributed to systemic tissues (Ferdous & Nemer, 2020). On the same note, the food exposure to metal nanoparticles like zinc and cadmium may lead to long-term low-level build-ups in the body, and this issue is a cause of concern in the long-term health consequences (De Matteis, 2017).

4.3 Dermal Contact

Dermal exposure is caused by direct contact of the skin with consumer products of nanoparticles, medical devices, cosmetics and textiles. Despite the barrier provided by intact skin, nanoparticles can enter via hair follicles, through sweat glands or through broken skin (Ferdous and Nemer, 2020). Recurrent exposure of the skin to dermal exposure may also augment absorption of nanoparticle, particularly in the workplace where the skin is subjected to prolonged contact (Xuan et al., 2023). Research shows that in some circumstances, silver and zinc oxide nanoparticles could find their way into the systemic circulation after being exposed to the skin (De Matteis, 2017).

4.4 Occupational Exposure

Metal nanoparticles have a high risk of occupational exposure especially to workers dealing with nanomaterial production, processing and recycling sectors. Exposure in these conditions happens via combined inhalation, dermally, and by accidental ingestion (Hadrup et al., 2025). Systemic toxicity poses a greater risk to workers who are exposed to lead-based nanoparticles because of chronic inhalation and surface contamination (Dumka et al., 2017). The exposure is cumulative, and that is why the occupational exposure has to be extremely regulated and monitored (Fig 01).

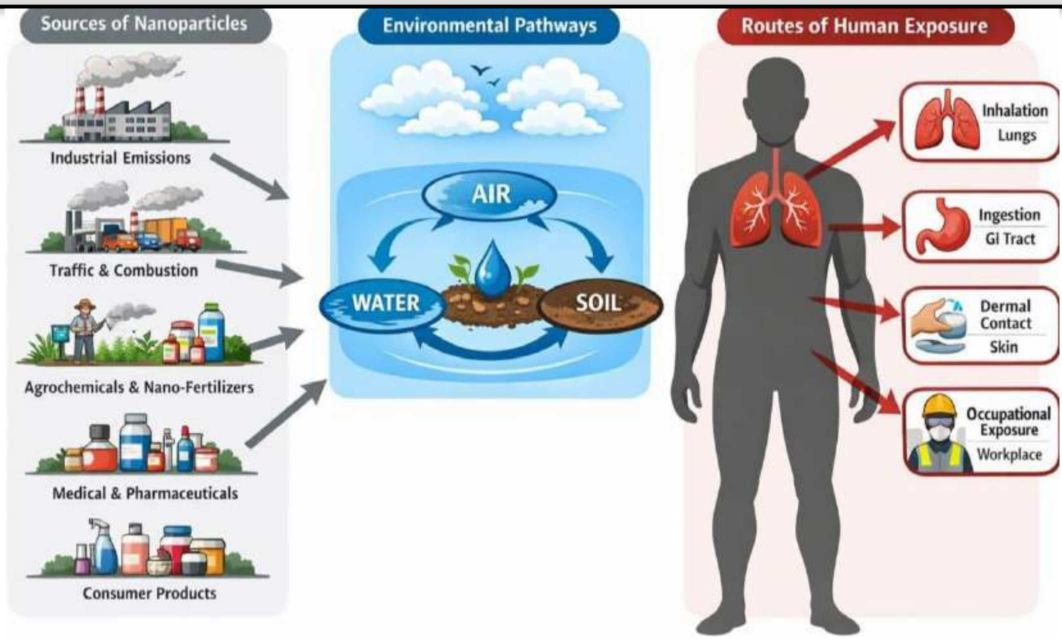

Fig. 01. Major Sources and Routes of Human Exposure to Nanoparticles

5. Mechanisms of Nanoparticles toxicity

In general, nanoparticles (NPs), which are particles with a length scale size of less than 100 nm, are associated with specific physicochemical characteristics such as high surface area, high surface reactivity and electronic characteristics. Although they could be useful in their biomedical and industrial uses, they are associated with the possibility of toxicological hazards (Nel et al., 2006; Oberholster et al., 2005).

5.1 Physicochemical Determinants of Toxicity

Nanoparticles are highly biological and their biological impact is closely dictated by their size, shape, their chemical composition, their surface charge and solubility. Nanoparticles that are smaller tend to be more active and cellular due to the high surface to volume ratio (Oberholster et al., 2005). Surface charge is also a determinant of toxicity, with positively charged nanoparticles having a stronger interaction with negatively charged cell membranes with the effect of destabilizing and leading to internalization of the membrane (Lynch et al., 2007). Moreover, carbon nanotubes having high aspect ratios may produce asbestos-like pathogenic implications due to frustrated phagocytosis and sustained stimulation of inflammatory systems (Poland et al., 2008).

5.2 Oxidative Stress and Reactive Oxygen Species (ROS) Generation

Oxidative stress is regarded as one of the key processes of the nanoparticle toxicity. The reactive oxygen species (ROS) may be produced by nanoparticles either directly by surface redox reactions, or indirectly by disrupting the mitochondrion (Nel et al., 2006). Overwhelming production of ROS overloads antioxidant defense mechanisms in cells, causing lipid peroxidation, protein oxidation and DNA damage (Fu et al., 2014). Nanoparticles made of metal (silver, zinc oxide, titanium dioxide, etc.) are especially related to the ROS-related cytotoxicity (Fu et al., 2014).

5.3 Inflammatory responses

Nanoparticles have the ability to stimulate inflammatory agents, such as NF-kB and the MAPK cascade that led to the release of pro-inflammatory cytokines; TNF-a, IL-1b and IL-6 (Nel et al., 2006). The chronic stimulation of the immune system (especially macrophages) is another factor that leads to chronic inflammation and tissue damage (Donaldson et al., 2001). The partial phagocytosis of long or stiff nanomaterials can extend the effects of inflammatory responses and favors fibrotic response (Poland et al., 2008).

5.4 Genotoxicity and DNA

Nanoparticle can provoke the effects of pro-inflammatory cytokines; TNF-a, IL-1b and IL-6, by stimulating inflammatory agents, including NF-kB and MAPK cascade (Nel et al., 2006). Another cause of chronic inflammation and tissue destruction is the chronic stimulation of the immune system (particularly the macrophages) (Donaldson et al., 2001). The partial phagocytosis of long or stiff nanomaterials is able to prolong the outcome of inflammatory responses and preferential fibrotic response (Poland et al., 2008).

5.5 Cellular Uptake and Organelle Dysfunction

Cells can ingest nanoparticles by endocytosis, phagocytosis, and micropinocytosis based on its physicochemical properties (Xia et al., 2008). When absorbed, nanoparticles can be accumulated in the lysosomes and mitochondria, causing the permeabilization of the lysosomal membrane and dysfunction of mitochondria. Mitochondrial injury interferes with the synthesis of ATP and enhances the process of apoptosis through the intrinsic cell death pathways (Xia et al., 2008; Nel et al., 2006).

5.6 Apoptosis and Necrosis

Oxidative stress and damage to mitochondria induced by nanoparticles may also initiate intrinsic apoptotic processes, which are defined by the release of cytochrome c and the caspases (Fu et al., 2014). Under severe injury of cells, necrotic cell death can take place, and the membrane is ruptured to release intracellular contents that further enhance inflammation (Nel et al., 2006).

5.7 The Corona Formation of proteins and Immune Modulation

When nanoparticles are exposed to biological fluids, they quickly adsorb proteins onto their surface to create a protein corona which changes their biological identity, and interactions with cells (Lynch et al., 2007). Protein corona composition determines how nanoparticles are distributed in the body, how they are recognized by the immune system, whether they are ingested by cells or are toxic (Lynch et al., 2007).

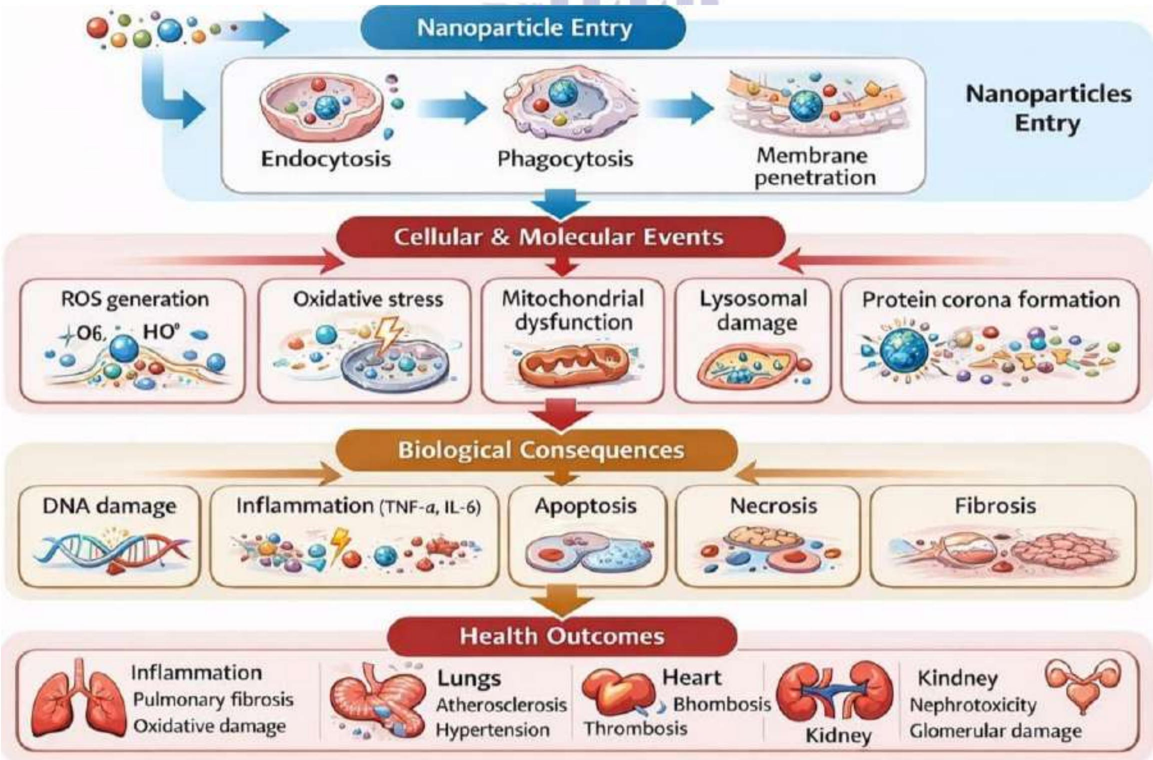

Fig. 02. Cellular and Molecular Mechanisms of Nanoparticles-Induced Toxicity

6. Impact of Nanoparticles on Human Health

Nanoparticles are being known for their negative impacts on human health. As because of their less visibility their effect is devastating. Their effect is becoming alarming in the coming years. Nanoparticles are not emerging naturally, human various activities tend to impose them in daily life (Rahman et al., 2013).

6.1 Impact on Respiratory System

Nanoparticles (NPs) mainly enter the body through the lungs, but they can also be inhaled, swallowed, or absorbed through the skin. Once inside, they can damage cells and organs like the liver, kidneys, and brain. The degree of their danger is compared to their particular size, figure, and chemical makeup, and the way that they react with our DNA and proteins. Due to such risks, it is essential to develop safer methods of making and using these particles by scientists. We should also determine biomarkers biological warning signs so that we can be able to detect any toxic effects on time. This is all the more significant in safeguarding employees handling such materials on a daily basis. Beyond the lungs, research shows that NPs can interfere with our hormones, immune system, and even lead to tumor growth. As nanotechnology grows globally, we need a complete understanding of its long-term impact on human health and nature.

Continuous study is the only way to balance these medical breakthroughs with our safety. Respiratory system includes organs nose, larynx, trachea, bronchi and lungs that tends to the exchange of gasses between the human body and atmosphere (Marcus, 2010). Deposition of nanoparticles in the respiratory system depends on their size shape and surface chemistry. Nanoparticles that are small in size more likely to settle in the lower system that interact with lungs as penetrate alveolar region (Zhang et al., 2022). Nano particles have the ability to change the characteristics of mucus layer composition or viscosity, which would hinder the effective release of trapped particles (Iya we and Murguia, 2018).

More over nanoparticles cause inflammation and infection as respiratory system becomes prone to the build-up of inhaled particles (Katari et al., 2024). Lung epithelial cells or immune cells get nanoparticles sometimes protein corona make them contagious for cells. As a result, it serves as a factor that take part to nanoparticles bad effects on respiratory system because of changed bioavailability as a result of protein corona development (Liu et al., 2020). Nanoparticles actively enter the circulatory system via intestinal system depending on their size, mode of dispersion and charge (Warheit and Says. 2015).

6.2 Impact on Cardiovascular System

Nanotechnology is transforming the cardiovascular care by allowing the detection of disease earlier and. more specific therapies that have lesser side effects. These nanoparticles are able to deliver drugs hence their ability to do so. They have the potential to treat up to damaged heart tissue and enhance medical imaging, directly to the damaged heart tissue. To half the cardiovascular diseases better than conventional means. They are especially applied in targeted delivery of drugs, gene therapy and the development of tissue repairing scaffolds. A significant strength is that nanoparticles are directed directly into the blood and tissues, enabling them to be done away with easily by the body after their duty is accomplished.

Research highlights their cardioprotective effects, which involve repair of cardiac cells, decrease the heart size. Tissue damage (infarct size) and supporting in the growth of stem cells (Bernacki et al., 2008). Researches indicate that these advantages are. It is frequently dose-dependent, that is, the better the dose of medicine. While the indications are overwhelmingly favorable, and scientists continue to attempt to define which one in particular. The most efficient with respect to various patients is nanoparticles and interventions. Nanoparticles find it difficult to get to the brain as the blood-brain barrier (BBB) and the body immune system prevent or eliminate them. Though the dose can be raised, it poses a risk during the long term. Poisoning and overworking the natural systems of body clearance. Scientists rearrange this by using special coats to conceal them to the immune system or magnetic fields and orders to safely direct with ultrasound or magnetic fields them across the obstacle to their target (Bernacki et al., 2008).

6.3 Effect of nanoparticles on Brain

Nanoparticles the Brain is also affected by nanoparticles. Researchers are coming up with superior nanoparticles to address the great incidence of brain tumors such as gliomas and meningiomas. It can be done by employing iron oxide or polymeric particles that are coated with special. By targeting molecules, physicians will be able to enhance MRI and fluorescence imaging in order to see tumors better clearly. These micro-deliveries, which may be constructed out of biodegradable substances such as PLGA, are effective at penetrating the blood-brain barrier to transport chemotherapy drugs to the cancer (Teleanu et al., 2018). This targeted therapy greatly minimizes the size of tumors and spares the healthy brain tissue the severe treatment chemicals. One of the most innovative approaches is called theragnostic nanoparticles, and they enable physicians to diagnose and treat a tumor at the same time. These are all-in-one particles which rely on light sensitive materials to take a visual image and photothermal therapy which involves heat generated by lasers to physically destroy cancer cells.

By integrating delivery, imaging, and heat treatment on the same platform, such nanomedicines can provide a combination of all three. Greater and more accurate substitute to conventional neurosurgery and radiation (Teleanu et al., 2018).

6.4 Nano particles in food items

Food supplements and other applications of nanoparticles in order to enhance the absorption of nutrients also make use of them additives that result in further development of packaging and enhances the capacity to absorb nutrients (Sufian et al.,2017). Silver nanoparticles in stuffed material also found in food packaging material beverages (Warheit and Sayes. 2015). Topical drug delivery is delivered in different nanocarriers, which are selected depending on the outcome either deep skin permeation to induce transdermal effects or to the skin organelles such as hair follicles. NLCs and SLNs are lipid nanoparticles that are commonly used to deliver to NLCs have a greater drug loading capacity than skin organelles (SLNs). Vesicular nanoparticles such as transferosomes and ectosomes are more appropriate in transdermal delivery owing to they are more likely to penetrate the deeper layers of the skin whereas the polymeric nanoparticles are more appropriate to drugs that are not easily soluble are employed using nanocrystals and water-soluble drugs and wound healing dissolve. The type of nanocarrier to select is dependent on the aim of the study (permeation) improvement vs. focused delivery) and the pharmaceutical characteristics. Nanocarriers this term refers to small delivery systems (below 500 nm) to enhance the absorption of drugs across the skin (Sufian et al., 2017). They work by defending the medicine, discharging it gradually, and attacking particular regions such as hair follicles to treat. Such diseases as acne or baldness. Although this approach permits greater penetration and greater length long-term outcomes, scientists have yet to surmount such issues as drug solubility and skin heterogeneity to render these treatments effective to the full extent. The choice of an appropriate nanocarrier is dependent on the purpose of the study (permeation enhancement and targeted delivery) and the characteristics of the drug (Warheit and Sayes. 2015).

6.5 Renal problems cause by NPs

Kidney disease manifests in 750 million individuals but the treatment is usually unequal because of the social and political factors (Crews et al., 2019). An overactive immune system is a great cause of destruction. It is attacked by (the complement system) which assails the unprotected filters in the kidney. To fix this, scientists are making nanoparticles that are able to find and treat the disease simultaneously, better medicine that has fewer side effects (Chin et al., 2020).

The size and distribution of a nanoparticles are the most important characteristics of nanoparticles since it determines the behavior of the particles travels through the body, their safety and their target accessibility. These factors also control capacity of the particle to hold medicine and thus the rate at which it is released. Because of their tiny scale, nanoparticles tend to be more stable and effective in drug delivery as compared to larger microparticles (Yand et al., 2017). Man-made nanoparticles are a challenge to analyze because of their tiny scale. In order to accomplish this, scientists employ a number of special instruments: DLS and TEM to size and shape, UV-vis and FT-IR to verify their chemical properties and XRD to examine their internal structure. Such tests are used to make certain that the particles are properly constructed to be used medically.

Nanotechnology is a dominant discipline that unites science, medicine, and engineering together to develop superior medical equipment. This technology has altered how we manage clinical treating and surgeries. It has enhanced the delivery of drugs, recovery of damaged tissues and development of superior diagnostic tests, nanomedicine is much influencing the way we have been detecting and treating diseases (Chandarana et al., 2018). FDA has already approved more than 100 nanomedicines that apply the use of small carriers such as the use of fat bubbles or proteins in order to transfer drugs safely and effectively. Such smart medicines assist in the delivery of treatments hard-to-reach regions, such as the brain, but minimizing the amount of unwanted side effects.

This technology is now a foundation of modern healthcare, driving all the things, such as cancer treatments to mRNA vaccines (Mozaffar. 2018). Nanotechnology promises to provide strong novel methods of diagnosis and treatment of diseases such as cancer and kidney failure. Although it is already benefiting patients, we are yet to discover more researches to unlock its potential full healing potential. This area is the key towards creating safer and more effective medicine towards the most severe diseases of the world (Bhardwaj and Burgess. 2010; Ma et al., 2020).

6.6 Neurological impact of NPs

Alzheimer and Parkinson are neurodegenerative diseases that are becoming increasingly widespread age, and the brain cells are forgotten gradually or movement difficulties arise. These conditions are they are often caused by the aggregation of proteins (with misshapen shapes) into toxic amyloid fibrils. To find early, these clumps can be identified by scientists with the help of magnetic and metallic nanoparticles which serve as high-tech beacons for medical imaging. To treat the disease, biodegradable nanoparticles (such as PLGA or chitosan) are used as miniature delivery trucks that can be used to deliver genetic antibodies or drugs straight into the brain. These particles are useful in Alzheimer solubilize or inhibit the formation of the clumps of the protein.

In the case of Parkinson, they provide expert medicines or even microRNA to assist in healing the damaged areas and motor skills. Moreover, some special particles such as cerium oxide are shields that shield the healthy brain cells against stress chemical and inhibition of additional cell death (Saleh, T.A.; Gupta. 2018). A stroke is an emergency that may lead to death because of the blocked blood vessel (ischemic), or a ruptured one (hemorrhagic). The most popular type are the ischemic strokes which cause a quick death in brain cells death and inflammation, but there are very limited choices of treatment at present. To tackle this, Investigators are coming up with intelligent nanoparticles, including liposomes and PLGA polymers carry targeted drugs, which are more capable of bypassing the blood-brain barrier (Eaglesham et al., 2020).

Such nanoparticles are being designed to carry some targeting ligands such as chlorotoxin so that they can access the damaged location accurately. There are even some systems that track the healing with the help of magnetic iron oxide cells or transfer genetic material (siRNA) which assists in healing the blood vessels of the brain. By improving survival in cells and alleviation of inflammation, these nanotechnologies provide a bright future of both. Immediately treat strokes, and promote long-term recovery (Hausen, M. & Striding et al., 2019). Nanoparticles are of special health hazards since their small size enables them to evade biological thromboses and clogging occur in such essential organs as the brain and liver.

Their main damage cause is through initiating oxidative stress and chronic inflammation that may result in the mutation of DNA and organ damage dysfunction. Exposure occurs through inhalation, ingestion, or skin contact, with toxicity levels heavily influenced by a particle's specific shape, **size,** and surface charge**.** While they offer breakthrough potential in medicine**,** their ability to interact at a cellular level requires careful monitoring to prevent long-term respiratory and cardiovascular diseases.

Table 01: Biological impact of Nanoparticles on different organ Systems

Organ System	Common Nanoparticles	Primary Biological Impact	Treatment	References
Respiratory system	Cabron nanotubes, Silica, Titanium dioxide	Inflammation, pulmonary fibrosis, oxidative stress, and DNA damage in lung tissue	Pulmonary surfactant replacement therapy	(Xia et al., 2009)
Integumentary system	Silver (Ag), Zinc oxide (ZNO), Quantum dots	Penetration of dermal layers causing localized irritation, cytotoxicity, and potential systemic absorption	Topical antioxidant gel	(Xia et al., 2009)
Renal system	Gold (Au), Cadmium-based NPs, silica	Accumulation in glomerulus, nephrotoxicity, and impaired filtration functions	Hydration and diuretics pH-sensitive nano micelles	(Zia et al., 2023)
Neurological system	Manganese, Copper, Silver	Crossing of the blood brain barrier leads to neuroinflammation and potential triggers for neurodegenerative diseases	Minimizing blood brain barrier penetration	(Zia et al., 2023)
Cardiovascular system	Carbon black, Iron oxide, Polystyrene	Altered heart rate variability, increased blood pressure, and risk of atherosclerosis or sticky blood (thrombosis)	Stains and ACE inhibitors, thrombolytic agents, treatment relies on neuroprotective agents like ZL006	(Iqbal et al., 2023)
Digestive System	Silver, Titanium dioxide, Plastic NPs	Alteration of gut microbiota, inflammation of the intestinal lining, and malabsorption	Oral adsorbent	(Iqbal et al., 2023)
Reproductive System	Gold, Silver, Cerium oxide	Disruption of the blood-testis barrier, reduced sperm motility, and potential development toxicity in embryos	Ceasing exposure to prevent further damage to Leydig and Sertoli cells, antioxidant therapy is used to mitigate NP	(Ghasemi Yeh & Mohammadi-Samani, 2020)

7. Nanoparticle-specific environmental and public health implications in Pakistan

Though, nanoparticle-specific environmental monitoring is still underdeveloped in Pakistan, the growing industrialization, automobile emission, and the implementation of nanotechnology-related products indicate the possibility that engineered and incidental nanoparticles will spread to the environment. The nanoparticle size range includes ultrafine particles (≤100 nm), which are also known to have a high reactivity, deeper pulmonary deposition, and translocation capability being systemic (Oberholster et al., 2005; Nel et al., 2006). The large surface area-volume ratio of nanoparticles enables them to produce reactive oxygen species (ROS) and in this way induce oxidative stress, inflammation and cellular damage (Nel et al., 2006; Donaldson et al., 2001).

Combustion-generated ultrafine particles that result due to traffic, brick kilns, and industrial sources are the main sources of urban air pollution in Pakistan (Gutt Kunda & Gurjar, 2012). Despite the fact that the majority of local monitoring measures PM2.5 as the mass concentration, ultrafine particles are a large proportion of aerosols of combustion, and can be disproportionately toxic because of their nanoscale size (Heal et al., 2012). Since it has been reported that nanoparticles can be translocated in population of the most polluted Pakistani cities through the lungs to the systemic circulation and therefore to the secondary organs of the body like the heart and brain (Oberholster et al., 2005). The Pakistani population in high pollution cities can be exposed to cardiopulmonary and neurological impacts of nanoparticles.

In Pakistan, the major source of urban air pollution is the combustion-based ultrafine particles which come as a result of traffic emissions, brick kilns and industry (Gutt Kunda and Gurjar, 2012). Though the majority of local measurements are performed on PM2.5 mass concentration, ultrafine particles can form a large portion of combustion aerosols and can be a disproportionate source of toxicity because they are nanoscale in size (Heal et al., 2012). Considering that nanoparticles have been reported to translocate out of the lungs to other areas of the body and potentially to secondary organs like the heart and brain (Oberholster et al., 2005), people living in heavily polluted cities of Pakistan could be susceptible to the occurrence of cardiopulmonary and neurological effects of nanoparticles. Another area of concern is occupational exposure. The international studies have proved that exposure of a person to metal nanoparticles at workplaces can lead to pulmonary inflammation and systemic oxidative stress (Donaldson et al., 2001). Nevertheless, the occupational health surveillance information on nanoparticles in Pakistan is limited and mostly non-existent, which is a significant gap in research.

Not only are incidental nanoparticles produced due to combustion, but engineered nanoparticles (silver, titanium dioxide, and zinc oxide) are now being used in consumer products, cosmetics, pharmaceuticals, and agricultural inputs all over the world (Buzea et al., 2007). Although little information is available on production and environmental discharge in Pakistan, the increasing trend in importation and use of nanotechnology-based materials may imply possible environmental buildup and human contact. In the absence of regulatory frameworks or environmental surveillance mechanisms that are specific to nanoparticles, it is difficult to estimate long term ecological and human health hazards. In general, due to the lack of systematic nanoparticles monitoring in Pakistan and high background concentrations of combustion-generated ultrafine particles, there is a necessity of specific environmental surveillance, biomonitoring research, and developing regulatory frameworks to gain better insight into the specific health impacts associated with nanoparticles.

8. Current Challenges

Although the existence of air pollution and inhalation of particles in Pakistan has been established, there is still limited systematic data regarding engineered nanoparticles (ENPs) and ultrafine particles (PM0.1). In Pakistan, the majority of air quality research on PM2.5 and PM10, which are commonly found in nanoparticles (less than 100 nm), are not well-characterized in a national monitoring program (Irfan, Munir, Akbar, and Zafar, 2025). This restricts the possibility of measuring the actual human exposure to nanoparticles in the ambient air and the possibility of a good assessment of the health risks. Moreover, although international toxicological studies have reported how nanoparticles cause oxidative stress, inflammation, and cellular damage, localized toxicological evidence of the linkage between environmental exposure of nanoparticles and their effects on the health of Pakistani populations remains absent (Kumah et al., 2023).

The lack of regular monitoring is also applicable to occupational environments: the workers in the metallurgical setting, welding, and construction are probably exposed to nano-sized particles during the high-temperature processes, but no occupational health studies of nanoparticles have been carried out in Pakistan (Irfan et al., 2025). The other challenge is the methodological one: most studies fail to include standardized characterization of nanoparticles (size distribution, surface chemistry, number concentration) to compare findings across regions, or include them to integrate findings into regulatory frameworks (Kumah et al., 2023; Oberholster, Oberholster, and Oberholster, 2005). Furthermore, the regulatory policies in the country of Pakistan are based on the conventional ways of measuring particulate mass (PM2.5, PM10) and there are no explicit policies or exposure limits of nanoparticles or ultrafine particles, which complicates the process of protecting the environment (Irfan et al., 2025). Collectively, these issues highlight key research shortcomings in environmental surveillance, exposure assessment, toxicology, occupational health surveillance, and regulatory science that should be filled to adequately assess and control the risks of nanoparticles in Pakistan.

9. Conclusion

Exposure to nanoparticles has a major effect on human health as it is able to penetrate biological barriers cause oxidative stress, chronic inflammation and genotoxicity in major organ structures, as well as respiratory, cardiovascular and nervous systems. While these materials offer medicine and industry have revolutionary advantages, their characteristic physicochemical characteristics like the large surface-volume ratio can cause deep tissue accumulation causing long term ones such pathologies as pulmonary fibrosis or neurodegeneration. There is a gap in the future that is critical in Pakistan due to the lack of a dedicated regulatory system, and standardized nano safety regulations, abandoning the fast-developing textile and pharmaceutical industries to inadequate toxicity monitoring. In order to overcome these issues, it is suggested that Pakistan provides a National Nano safety Task Force to come up with compulsory safety measures, including the implementation of high-efficiency particulate air (HEPA) filtration systems and the application of special purpose Personal to prevent Infection Control Protective Equipment (PPE), such as N95 or N99 respirators and nitrile gloves by inhalation and by the skin. Moreover, occupational health should be implemented monitoring and raising general awareness by using organizations such as the Pakistan Council of Science and Technology are critical measures so that technological innovation will not undermine the future livelihood of the people.

REFERENCES

Abbas, T., Kanwar, F., Tariq, H., & Malik, M. R. (2025). Nanoparticles in drug delivery systems: Challenges, innovations and surface modification for targeted therapeutics. Indus Journal of Bioscience Research, 3(1), 325–336. https://doi.org/10.70749/ijbr.v3i1.507

Aysa, N. H., Almutairi, R. S., & Hamza, L. F. (2024). A critical assessment of the harmful effects of nanoparticles on the respiratory system. Pakistan Journal of Life & Social Sciences, 22(1).

Asmat ulu, E., et al. (2022). Impact of nanomaterials on human health: A review. Environmental Chemistry Letters, 20(4), 2509–2529.

Atta-Ur-Rahman, A., Balqees, K., Hasnain, M., et al. (2024). Biosynthesized nanoparticles as advanced nanocarriers for targeted therapeutic interventions. Biological and Clinical Sciences Research Journal. https://doi.org/10.54112/bcsrj.v2024i1.1152

Bachand, S., & Hayes, A. (2016). Toxicological considerations, toxicity assessment, and risk management of inhaled nanoparticles. International Journal of Molecular Sciences, 17(6), 929. https://doi.org/10.3390/ijms17060929

Bhatti, R., et al. (2021). Inorganic nanoparticles: Toxic effects, mechanisms of cytotoxicity and phytochemical interactions. Advanced Pharmaceutical Bulletin, 12(4), 757.

Bellinger, D. C., & Bellinger, A. M. (2006). Childhood lead poisoning: The torturous path from science to policy. Journal of Clinical Investigation, 116(4), 853–857. https://doi.org/10.1172/JCI28232

Dal Zotto, R., Descalzi, G., & Scan Setti, G. (n.d.). The problem of lead exposure in the Piedmont: From the workplace to the general environment [Article in Italian].

Diza, S. M., et al. (2015). Antimicrobial activity of carbon-based nanoparticles. Advanced Pharmaceutical Bulletin, 5(1), 19.

Donaldson, K., Stone, V., Clouter, A., Renwick, L., & Macnee, W. (2001). Ultrafine particles. Occupational and Environmental Medicine, 58(3), 211–216. https://doi.org/10.1136/oem.58.3.211

Filippelli, G. M., & Laidlaw, M. A. (2010). The impact of soil lead on children's health: A case for action. Environmental Health Perspectives, 118(3), A105–A106. https://doi.org/10.1289/ehp.0901756

Fu, P. P., Xia, Q., Hwang, H. M., Ray, P. C., & Yu, H. (2014). Mechanisms of nanotoxicity: Generation of reactive oxygen species. Journal of Food and Drug Analysis, 22(1), 64–75. https://doi.org/10.1016/j.jfda.2014.01.005

Gamely, P. S. Fleming, G., Walton, M., & Gouldens, T. (2022). Human health effects from exposure to lead: A review of the current literature. American Journal of Biomedical and Life Sciences, 10(5), 135–145. https://doi.org/10.11648/j.ajbls.20221005.12

Ghasemi Yeh, P., & Mohammadi-Samani, S. (2020). Potential of nanoparticles as permeation enhancers and targeted delivery options for skin: Advantages and disadvantages. Drug Design, Development and Therapy, 3271–3289.

Gutt Kunda, S. K., & Gurjar, B. R. (2012). Role of meteorology in seasonality of air pollution in megacity Delhi, India. Environmental Monitoring and Assessment, 184, 3199–3211. https://doi.org/10.1007/s10661-011-2182-8

Hanif, S., Javed, R., & Cheema, M. (2024). Harnessing the potential of zinc oxide nanoparticles and their derivatives as nano fertilizers: Trends and perspectives. Planta. https://doi.org/10.1016/j.plana.2024.100110

Hanna-Attisha, M., LaChance, J., Sadler, R. C., & Schnepp, A. C. (2016). Elevated blood lead levels in children associated with the Flint drinking water crisis: A spatial analysis of risk and public health response. American Journal of Public Health, 106(2), 283–290. https://doi.org/10.2105/AJPH.2015.303003

Iqbal, T., Razzaq, B., Tahseen, A., & Bashir, A. (2022). A review on carbon nanoparticles (CNPs): Synthesis, mechanism of antimicrobial action, applications and toxicity effect. Pakistan Journal of Scientific & Industrial Research Series A: Physical Sciences. https://doi.org/10.52763/PJSIR.PHYS.SCI.65.2.2022.189.198

Irfan, F., Munir, R., Akbar, S., & Zafar, R. (2025). Assessment and critical review of PM0.1 pollution in Pakistan. Journal of Engineering, Science and Technological Trends, 2(3), 1–4. https://doi.org/10.64060/jestt.v2i3.4

Javaid, A. (2025). From biosynthesis to abiotic stress resilience in crops. Indus Journal of Bioscience Research.

Joudeh, N., & Linke, D. (2022). Nanoparticle classification, physicochemical properties, characterization, and applications: A comprehensive review for biologists. Journal of Nanobiotechnology, 20(1), 262.

Joravar, N., Farhan, S., Chaudhary, M. M. & Khizer, Z. (2025). A new source of natural nanomaterial in Pakistan for industrial applications [Preprint]. ResearchGate.

Khan, S., & Hossain, M. K. (2022). Classification and properties of nanoparticles. In Nanoparticle-based polymer composites (pp. 15–54). Elsevier.

Kumah, E. A., Fopa, R. D., Hariti, S., Boadu, P., Zohoori, F. V., & Pak, T. (2023). Human and environmental impacts of nanoparticles: A scoping review of the current literature. BMC Public Health, 23(1), 1059. https://doi.org/10.1186/s12889-023-15914-4

Laidlaw, M. A., Filippelli, G. M., et al. (2005). Lead exposure via dermal contact: Implications for public health. Environmental Science & Technology, 39(2), 56–61. https://doi.org/10.1021/es049069y

Lanphear, B. P., Burgoon, D. A., Rust, S. W., Eberly, S., & Galka, W. (1998). Environmental exposures to lead and urban children's blood lead levels. Environmental Research, 76(2), 120–130. https://doi.org/10.1006/enrs.1997.3801

Lanphear, B. P., Hornung, R., Khoury, J., et al. (2005). Low-level environmental lead exposure and children's intellectual function: An international pooled analysis. New England Journal of Medicine, 348(16), 1517–1526. https://doi.org/10.1056/NEJMoa022848

Letourneau, G. G., & Gagne, D. J. (1992). Blood led level in children living close to a smelter area: 10 years later. Canadian Journal of Public Health, 83(3), 221–225. PMID: 1303638

Morimoto, Y., Horie, M., Kobayashi, N., Shinohara, N., & Shimada, M. (2013). Inhalation toxicity assessment of carbon-based nanoparticles. Accounts of Chemical Research, 46(3), 770–781.

Murata, K., Iwata, T., Yamamoto, M., & Kobayashi, E. (2015). Elevated lead in workers of battery recycling: Occupational study. Industrial Health, 53(1), 73–82. https://doi.org/10.2486/indhealth.2014-0108

Naeem, Z., Rana, T., & Javaid, S. (2023). Evaluating frontiers in nanotechnology: A review of novel nanoparticle technology in drug delivery systems. Currents in Pharmaceutical Research. https://doi.org/10.32350/cpr.11.03

Nawaz, A., et al. (2025). Usage of organic compounds and nanoparticles in everyday life. Indus Journal of Bioscience Research, 3(1), 271–279.

Nazir, M. A. (2024). Zinc oxide nano-fertilizer differentially affects wheat physiology. Scientific Reports. https://doi.org/10.1038/s41598-024-63987-9

Nel, A., Xia, T., Medler, L., & Li, N. (2006). Toxic potential of materials at the nano level. Science, 311(5761), 622–627. https://doi.org/10.1126/science.1114397

Oberholster, G., Oberholster, E., & Oberholster, J. (2005). Nanotoxicology: An emerging discipline evolving from studies of ultrafine particles. Environmental Health Perspectives, 113(7), 823–839. https://doi.org/10.1289/ehp.7339

Patrick, L. (2006). Lead toxicity, a review of the literature. Part 1: Exposure, evaluation, and treatment. Alternative Medicine Review, 11(1), 2–22. https://pubmed.ncbi.nlm.nih.gov/16597190/

Poland, C. A., Duffin, R., Kinloch, I., et al. (2008). Carbon nanotubes introduced into the abdominal cavity show asbestos-like pathogenicity. Nature Nanotechnology, 3(7), 423–428. https://doi.org/10.1038/nnano.2008.111

Pistorius, A., et al. (2018). Nanomaterial exposure, toxicity, and impact on human health. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 10(5), e1513. https://doi.org/10.1002/wnan.1513

Qamar, W., et al. (2024). An insight into impact of nanomaterials toxicity on human health. Peer, 12, e17807.

Qasim, M., Akhtar, W., Haseeb, M., Sajjad, H., & Rasheed, M. (2022). Potential role of nanoparticles in plants protection. Life Sci J, 19(2), 31–38.

Riaz, M., Ikhlas, K., Safia, G., et al. (2025). Plant-mediated synthesis of Zn-Ag nanocomposites for multifunctional wastewater treatment. Indus Journal of Bioscience Research, 3(8), 68–75. https://doi.org/10.70749/ijbr.v3i8.1993

Roy, B., et al. (2023). Impact of nanoparticles on human health and disease. Nepal Journal of Epidemiology, 13(4), 1294.

Sahu, S. C., & Hayes, A. W. (2017). Toxicity of nanomaterials found in human environment: A literature review. Toxicology Research and Application, 1, 2397847317726352.

Schneider-Foschi, E. K., & Reyes-Ortega, F. (2021). Advantages and disadvantages of using magnetic nanoparticles for the treatment of complicated ocular disorders. Pharmaceutics, 13(8), 1157.

Shahzadi, S., Fatima, S., Ain, Q., et al. (2025). A review on green synthesis of silver nanoparticles using plant extracts. RSC Advances, 15, 3858–3903. https://doi.org/10.1039/D4RA07519F

Teleman, D. M., Chircop, C., Grumezescu, A. M., Volceanov, A., & Teleman, R. I. (2018). Impact of nanoparticles on brain health: An up-to-date overview. Journal of Clinical Medicine, 7(12), 490.

Ullah, N., Khan, A., Younis, T., Maqbool, H., Iqbal, M., Ali, M., & Shinwari, Z. K. (2025). Advances in nanocomposite-based fertilizers for sustainable agricultural practices. Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences, 62(1), 1–18. https://doi.org/10.53560/PPASB(62-1)1071

Wardoyo, S. (2025). Adverse effects of nanoparticles on humans. Journal of Occupational Health, 67(1).

Wang, M., Liang, B., Zhang, W., Chen, K., Zhang, Y., Zhou, H., Cheng, Y., Liu, H., Zhong, X., Li, Y., & Liu, Y. (2019). Dietary lead exposure and associated health risks in Guangzhou, China. International Journal of Environmental Research and Public Health, 16(8), 1417. https://doi.org/10.3390/ijerph16081417

Xia, T., Li, N., & Nel, A. E. (2009). Potential health impact of nanoparticles. Annual Review of Public Health, 30, 137–150. https://doi.org/10.1146/annurev.publhealth.031308.100155

Zaremba, S., et al. (2017). Dermal lead contamination in households near contaminated industrial sites. Journal of Environmental Monitoring, 19(2), 233–244. https://doi.org/10.1039/c6em00512a

Zia, S., Islam Aqib, A., Muneer, A., Fatima, M., Atta, K., Kausar, T., Zaheer, C.-N. F., Ahmad, I., Saeed, M., & Shafique, A. (2023). Insights into nanoparticles-induced neurotoxicity and coping strategies. Frontiers in Neuroscience, 17, 1127460.