LGU Journal of
LIFE SCIENCES

LGU Society of Life Sciences

DOI: https://doi.org/10.54692/lgujls.2024.0803xxx

Paper Submission: 4th Oct 2022; Paper Acceptance: 10th July 2024; Paper Publication: 10th Sep 2024

Review Article | LGU J. Life. Sci
Vol 8 Issue 3 July- Sep 2024 | ISSN 2519-9404
eISSN 2521-0130

Evaluating the Environmental Impact of Metal Oxide Nanoparticles: An Ecotoxicological Perspective

Fatima Tu Zahra*[1], Izza Taufiq[2], Ayesha Siddiqa[1]

1. Institute of Microbiology and Molecular Genetics, University of the Punjab, Lahore
2. National Centre of Excellence in Molecular Biology, University of the Punjab, Lahore

Corresponding Author's Email: fatimatuzahra2015@gmail.com

ABSTRACT: *Various nanoparticles (NPs) from the food industry, pharmaceuticals, cosmetics, and drugs significantly impact our daily lives. The association of these nanoparticles with the cellular environment adversely affects the normal functioning of cells and their components. For this review approximately 150 research papers were extensively reviewed, and 132 articles were included. This review examines the nanotoxicology of metal oxides and their effects at both in vivo and in vitro levels. It addresses factors related to the synthesis of biogenic metal oxide NPs, including size, concentration, and exposure methodologies. The primary goal is to understand the ecotoxicology of metal oxides, their risk evaluation, and public health implications. Offering a concise overview, this article discusses current understanding and future research avenues in nanoparticle biology. It highlights the complications and risks to public health posed by toxic metal oxides and emphasizes the importance of understanding the synthesis of nanoparticles to determine their physicochemical properties. Biological interactions of these NPs with the environment pose significant hazards to human health. Recent studies have advanced our knowledge of the emerging trends and prospects in nanoparticle ecotoxicology. This review provides a comprehensive outline of the objectives and domains of various toxicological impacts of nanoparticles, emphasizing a balanced approach to managing risks to ecosystems and human health.*

Keywords: *Bioremediation, Cytotoxicity, Drug delivery, Nanotoxicology*

INTRODUCTION

Nanotoxicology is a rapidly expanding research area focusing on the safety concerns of nanoparticles (NPs) and their wide applications across various disciplines. It primarily assesses the ecotoxicity and lethal impacts of NPs on human cells. NPs, ranging from 1 to 100 nm, are aggregates of atomic particles with unique properties due to their quantum-scale dimensions and significant surface area to volume ratio. These particles are often composed of inert elements such as zinc, magnesium, iron, copper, cobalt, tin, and gallium.

Research has shown that metal oxide NPs often consist of multiple metals, including titanium, iron, chromium, nickel, and zinc (Sanderson et al., 2014). NPs can cause severe biological effects, such as DNA damage and apoptosis due to free radical production (Tee et al., 2016). Additionally, exposure to toxic NPs can alter cell proliferation and lead to chronic health issues. The rapid development of new NPs with unique properties poses potential health risks to the environment.

Traditional methods for generating metal oxide NPs rely on physical and biochemical techniques that use expensive and hazardous chemicals, contributing to environmental harm (Seabra and Durán, 2015). Biogenic synthesis involves using capping agents to stabilize nanomaterials, improving biocompatibility and preventing aggregation. Various metal nanoparticles, including cobalt oxide, bismuth trioxide, copper oxide, iron oxide, tin oxide, gold, and silver NPs, have been extensively studied for their adverse effects on living systems and guidelines for safe use (Demir, 2021). The following section will briefly describe the biogenic synthesis of these metal oxide NPs and their environmental applications.

1. Types of NPs

Two major groups of NPs are classified according to their nature and origin. They are either naturally produced or artificially synthesized by a physical or a chemical process. These are generated through mechanisms taking place in nature or by engineered activities.

Nanoparticles (NPs) are naturally found in volcanic eruptions, deep oceans, forest fires, and crushed rocks such as silica (SiO2), titanium dioxide, iron oxides, and manganese oxides. Natural NPs are present in many living organisms, with examples including carbon nanotubes and fullerenes (Guo and Barnard, 2013). These NPs often have reproducible structures and are biocompatible, such as mesoporous silica nanoparticles (MSNs) and protein nanoparticles (Griffin et al., 2017). They can exist intracellularly or extracellularly, with viruses and liposomes being notable examples (Harish et al., 2022).

1.1. Mechanism of Action of Protein NPs

Protein nanoparticles (NPs) are extensively used in biological processes due to their high stability, making them effective for drug delivery. Besides stability, they also facilitate biodegradation and bioaccumulation (Herrera Estrada and Champion, 2015). Protein NPs are preferred over engineered NPs because they are non-antigenic, have lower immunogenicity and toxicity, and can be easily incorporated into various biopolymers.

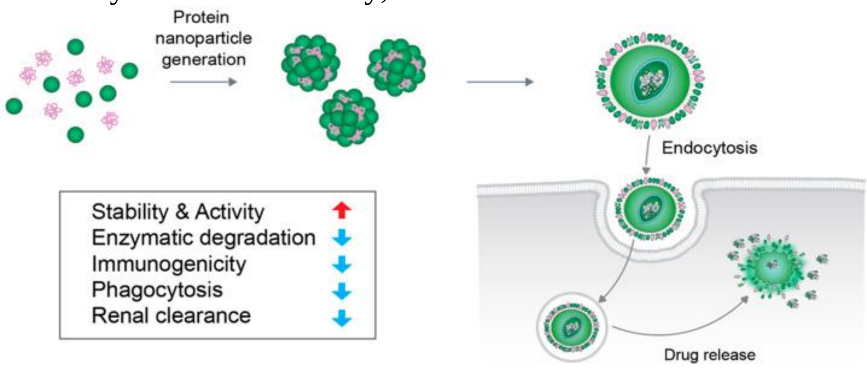

Fig. 1. The endocytosis process used for the delivery of various protein NPs and insoluble drugs in vivo (Hong et al., 2020)

Protein nanoparticles are also utilized for delivering non-soluble drugs within the internal cell region by the mechanism of endocytosis. These NPs show more protection from various processes like toxicity, degradation by enzymes, phagocytic reactions and endocytosis and hence increase the life and stability of the drug being introduced, as shown in Figure 1 (Hong et al., 2020). These protein NPs are prepared through a complex physical and chemical method following a self-assembly method.

1.2. Engineered NPs

Such NPs are specifically manufactured and have a particular morphology and geometry e.g. quantum nano-dots, gold and silver NPs (Montano et al., 2014). Because of their definite shape and structure, they are easily made through chemical process. They are found in composition with other materials like a layer of gold or a central element such as gold covered with a shell made up of any other element like cobalt or silica (Flannery et al., 2015).

2. Metal Oxide NPs

2.1. Cobalt Oxide (Co_3O_4) Nanocrystals

Cobalt oxide nanocrystals have various applications due to their desirable properties, i.e. optical magnetic and electrochemical capabilities. They are used as supercapacitors in different kinds of devices for the purpose of storing energy. (Abdel Maksoud et al., 2021). For the biogenic formation of Co_3O_4 nanocrystals thermal and solvothermal decomposition routes are usually the main classical methods. A marine bacterium *Brevibacterium casei*, plays an important role in the production of NPs (Savi et al., 2021). Biogenic cobalt oxide NPs have proteins coated on their surface to conserve their identity. Furthermore, these proteins also aid in reduction of agglomeration of isolated NPs (Iravani and Varma, 2020).

2.2. Bismuth Trioxide (Bi_2O_3) NPs

Bismuth trioxide (Bi_2O_3) NPs have significant importance in our daily life. They are used as a semiconductor due to their visible photo sensitivity and enhanced photocatalytic activity. This metal oxide plays an effective role in wastewater treatment. Photocatalytic activity, low toxicity, chemical stability, the combination of visible photosensitivity and cost-effectiveness makes bismuth trioxide nanoparticles efficient for the treatment of waste water (Ahamed et al., 2019). They are used as an optoelectronic material e.g. gold, copper, aluminium and silver nanoparticles. They are obtained by adding toxic or organic solvents at an elevated temperature. Besides conventional chemical methods, *Fusarium oxysporum* is used as an alternate for the development of these nanocrystals (Zulkifli et al., 2018). However, the generation of bismuth trioxide NPs by biogenic synthesis is more environment friendly than conventional chemical methods.

2.3. Copper Oxide (CuO, Cu_2O) NPs

Copper oxide nanoparticles have wide array of applications in electric devices and ophthalmic treatments (Magdassi et al., 2010). They can also be used as good antimicrobial agent. At room temperature, Cu_2O nanoparticles with the diameter around 10–20 nanometer was made with the help of Baker's yeast *Saccharomyces cerevisiae*. Copper oxide nanoparticles are effective for reducing several bacterial and fungal strains. For example, *E. coli* and *A. niger*, respectively. These were obtained by the action of reductase enzyme which reduced copper sulfate. Several strains of fungi like *Penicillium aurantiogriseum*, *P. citrinum* and *P. waksmanii*, obtained from soil, are utilized in the biosynthesis of copper oxides.

2.4. Iron Oxide (Fe_2O_3, Fe_3O_4) Magnetic NPs

Iron oxide NPs have important applications in biomedical techniques including hyperthermia nuclear MRI and precise delivery of drugs. Biogenic techniques are mainly applied for obtaining iron oxide NPs rather than classical chemical methods. Iron oxide is reduced to iron by using a bacterium *Shewanella* strain HN-41, where pyruvate acts as an electron donor. The toxic effect of biogenic and commercial Fe_2O_3 nanoparticles was compared by observing hemagglutination and changes in morphology (Khalil et al., 2017). The capping agents of iron oxide present externally promotes structure stability and inhibit them from being aggregated.

2.5. Titanium Dioxide (TiO_2) NPs

Titanium dioxide nanoparticles have a vast variety of applications in biomedicine, environment and modern technology (Sagadevan et al., 2022). *Lactobacillus* sp. has been reported to be the main source of production of titanium dioxide NPs at room temperature. Yeast cells or *Lactobacillus* undergo interaction with $TiO(OH)_2$ and result in the production of these NPs using carbon and nitrogen sources (Khan et al., 2020).

2.6. Gold (Au) NPs

It has been shown by recent research studies that nano-sized gold particles possess antimicrobial activity. These have the ability to generate free oxygen radicals which are toxic to the environment as they result in production of ROS (Rajan et al., 2015). Artists have been utilizing their properties such as colloidal nature and radiant colors. Special properties, i.e. optical and electrical are possessed by these NPs because of their varying physical characteristics like morphology, diameter and surface composition. The significant usage of gold NPs in healthcare and diagnostics is due to their unique physical and chemical characteristics which can be utilized to detect biomolecules at minute concentrations.

2.7. Silver Oxide (Ag_2O) NPs

The medical fields of nanoscience and biomedicine mainly apply silver oxide nanoparticles which are essential for their research experiments (Wang et al., 2016). Several methodologies involving physiochemical and biological processes have been implemented to produce silver NPs. Studies have determined that Ag NPs possess extensive multifunctional properties, for example, as anti-inflammatory, antiviral, anticancer and antimicrobial agents (Gherasim et al., 2020). Biosynthetic silver NPs show high solubility, high stability and maximum yield (Gurunathan et al., 2015). Moreover, they have a well-defined size and morphology and are relatively less toxic and can therefore be used in green chemistry.

3. Effects of Metal Oxide NPs

Several mechanisms contribute to the toxicity of metal oxide nanoparticles (NPs) as they interact with cellular components, including DNA, proteins, mitochondria, and lysosomes, often generating reactive oxygen species (ROS) that disrupt cell function (Jamuna and Ravishankar, 2014). Co3O4 nanocrystals release cobalt ions, activating NADPH oxidase and producing ROS, leading to oxidative stress on lymphocytes and being lethal to human immune cells (Chattopadhyay et al., 2015; Savi et al., 2021). Bismuth trioxide NPs negatively affect mammalian cells and ecosystems, causing cytotoxic and genotoxic effects such as apoptosis and necrosis (Zulkifli et al., 2018; Mohamed et al., 2021). Copper oxide NPs induce DNA methylation, fragmentation, chromosomal damage, and lipid peroxidation.

Iron oxide NPs (Fe_2O_3, Fe_3O_4) disrupt cell count, coagulation, cause inflammation, and damage various organs after inhalation (Valdiglesias et al., 2015; Chrishtop et al., 2021). Titanium dioxide NPs generate ROS, leading to genotoxicity, inflammation, cellular damage, and tumorigenesis. Gold NPs, in large amounts, reduce red blood cell count and cause anemia, spleen damage, and increased toxicity (Albanese and Chan, 2011). Silver NPs induce DNA damage, oxidative stress, and harmful effects on major organs (Antony et al., 2015; Bamal et al., 2021).

4. Applications of Metal Oxide NPs

Metal oxide NPs are widely used in biotechnology and biomedical sciences for sensing, imaging, gene and drug delivery, and surface functionalization (Falcaro et al., 2016; Savi et al., 2021). Cobalt oxide NPs are used for environmental remediation, including dye degradation and wastewater treatment (Anele et al., 2022). Bismuth trioxide NPs are applied in cosmetics, pharmaceuticals, industrial fields, cancer imaging, and wastewater treatment (Wang et al., 2016; Shahbazi et al., 2020). Copper oxide NPs are used in biomedical research, biosensing, and as fungicides and antibacterial agents (Verma and Kumar, 2019). Iron oxide NPs are utilized in drug delivery, molecular imaging, and wastewater treatment (Sangaiya and Jayaprakash, 2018; Gallo-Cordova et al., 2020).

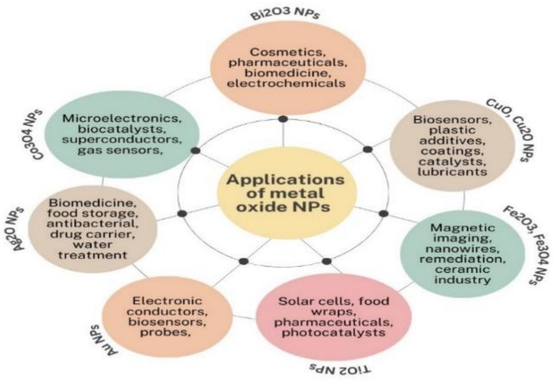

Fig. 2. Applications of metal oxide NPs in different sectors

TiO_2 NPs have vast applications in pharmaceutical products, food industries and cosmetics (Nadeem et al., 2018). These NPs also have immense industrial importance due to their usage as pesticides, for remediation of dyes, antibiotics and photocatalysts (Waghmode et al., 2019). Titanium dioxide is environmentally friendly because it has high chemical stability and non-toxicity. It can be used as an environment sanitizing agent due to its antifogging and self-cleaning properties (Waghmode et al., 2019).

Gold NPs have a broad spectrum applications, which include electronics, conductors, photodynamic therapy, biosensors, probes, diagnostic markers and catalyst for chemical reactions (Sýkora et al., 2010). Gold NPs have been shown to be effective for eradicating localized tumors. The extensive surface area relative to volume ratio enables these NPs to be used in surface coating. Different food items can be checked for their suitable consumption by using a colorimetric sensor made of Au NPs. Gold NPs have broad spectrum applications in the areas of water filtration, photothermal therapy, antimicrobial and the food industry. Gold NPs are known to be biocompatible due to their green synthesis (Küünal et al., 2018).

Several reviews and studies emphasize the widespread benefits in the industries of biomedicine, healthcare, food storage and ecosystem (Bapat et al., 2018). The antimicrobial activity of these NPs was reported against *E. coli*, in their cell walls. Various applications include biosensing, bioimaging, water treatment, textiles and as a drug carrier (Verma and Maheshwari, 2019). Silver NPs are found in containers used for food storage and packaging, purificants used in water and detergents. They are used as surfactants and oxidizing and bleaching agents.

Table 1. Effects and applications of various metal oxide NPs

Metal	Sources	Toxicological effects	Uses and applications	References
Co_3O_4 NPs	Aqueous extracts of leaves, medicinal plants, biotic compounds	ROS production, oxidative stress on lymphocytes, lethal to immune cells	Microelectronics, biocatalysts, superconductors, gas sensors, electronic ceramics, nanowires	(Mei et al., 2019; Savi et al., 2021)
Bi_2O_3 NPs	Smelting of ores, weathering of rocks, leaf extracts	Cytotoxicity, genotoxicity, apoptosis and necrosis of cells, cellular damage	Cosmetics, pharmaceuticals, biomedicine, electrochemical applications such as solid oxide fuel cells (SOFC), cancer imaging, photoconduction	(Jagdale et al., 2021)
CuO, Cu_2O NPs	Wood preservatives, mineral supplements, weathering of rocks	DNA methylation, DNA fragmentation, lipid peroxidation, chromosomal aberrations, micronucleus formation	Biosensors, electrochemical sensors, plastic additives, coatings, textiles, catalysts, lubricants	(Perreault et al., 2012)
Fe_2O_3, Fe_3O_4 NPs	Sedimentary rocks, iron mineral ores, atmospheric dust, aeolian deposits	Reduced cell viability, cell lysis, inflammation, generation of ROS, lipid peroxidation, DNA damage	Magnetic imaging, nanowires, coatings, resonance imaging, environmental remediation, glass and ceramic industry	(Attarilar et al., 2020)
TiO_2 NPs	Sand, mineral ores, atmospheric dust, soil, volcanic eruption, sea water, fire smoke	Oxidative stress leading to ROS production, pulmonary inflammation, carcinogenesis, tumor formation, genotoxicity, cellular damage	Solar cells, food wraps, medicines, pharmaceuticals, photocatalysts, agriculture, antibacterial coatings, cosmetics	(Waghmode et al., 2019; Banerjee and Thiagarajan, 2014)
Au NPs	Quartz, gold bearing mineral, gold mining, sedimentary rocks	Decrease in RBCs, decrease in body weight, lower spleen index, increased cytotoxicity, apoptosis, inflammatory immune responses	Electronic conductors, biosensors, diagnostic markers, probes, catalysts	(Daraee et al., 2016; Li et al., 2014)
Ag_2O NPs	Industrial effluents, leaching of metal tailings, sewage, ore processing, atmospheric deposition	DNA damage, cytokine induction, oxidative stress, organ damage, edema, epidermal hyperplasia, focal inflammation	Biomedicine, healthcare products, food storage, antibacterial agents, bioimaging, drug carrier, water treatment	(Prabhu and Poulose, 2012)

5. Sources of Metal Oxide NPs

Metal oxide NPs are formed through various biotic and abiotic methods. Major sources of metal oxide NPs include biogenic synthesis through biomineralization and other electrochemical methods. The details are as follows:

5.1. Natural Sources

For cobalt oxide, medicinal plants, aqueous extracts of leaves and biotic compounds are used for their synthesis (Shafey, 2020). Furthermore, smelting of mineral ores like bismite, bismuthinite are the major sources for the extraction of bismuth trioxide (Motakef-Kazemi and Yaqoubi, 2020). For copper oxide NPs, wood preservatives, inorganic compounds, vitamin and mineral supplements and weathering of rocks are the main sources for metal oxide NPs production (Alavi and Karimi, 2018). Iron oxide NPs are extracted from sedimentary rocks, iron mineral ores and aeolian deposits found in atmospheric dust. Titanium oxide NPs are obtained from sand, mineral ores, atmospheric dust, soil, volcanic eruptions, sea water and fire smoke.

5.2. Anthropogenic Sources

Anthropogenic NPs are made through human activities which are divided into two categories, i.e. the first category includes NPs without predetermined size and shows undefined chemistry (Strambeanu et al., 2014). For example, diesel exhaust, coal fly ash, welding fumes and combustion particulates. The second type of anthropogenic NPs is also known as engineered nanoparticles which have a particular size range of 1–100 nm. They are made up of pure materials with controlled surfaces (Chavali and Nikolova, 2019). For example, nanotubes made up of carbon, dendrimers, quantum dots, silver and gold nanocrystals as shown in Fig. 3 (Sadik, 2013).

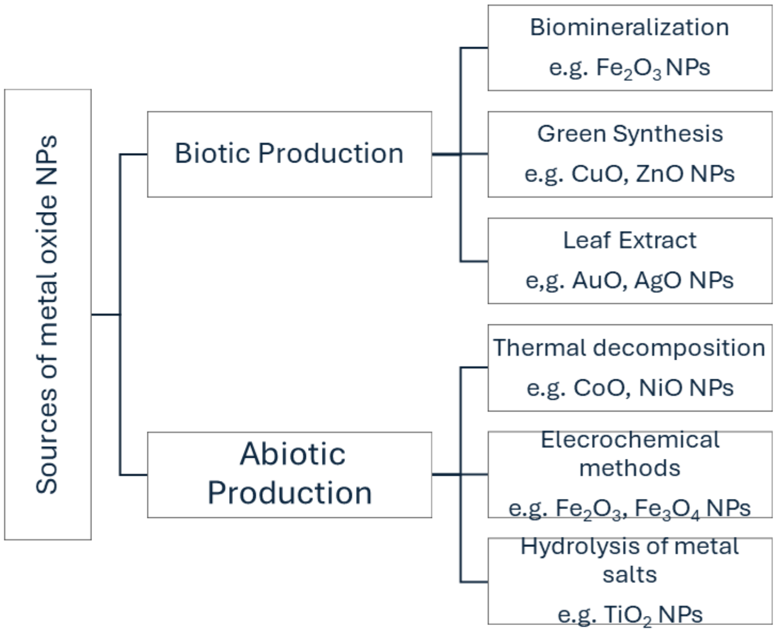

Fig. 3. Sources of metal oxide NPs

Metal oxide nanoparticles (NPs) have harmful impacts on both aquatic and terrestrial environments, altering the morphology and properties of natural flora and fauna through long-term exposure.

Aquatic Toxicity

Metal oxide NPs pose serious threats to aquatic organisms. For instance, nano TiO2 is toxic to Daphnia magna at levels greater than 100 mg/L. Photo-induced toxicity of nano TiO2 under UV exposure can cause fatal damage to marine plankton.

Terrestrial Toxicity

Nano TiO2 and other metal oxide NPs also impact terrestrial organisms. Studies show that nano TiO2 exposure causes DNA and mitochondrial damage in soil invertebrates like earthworms and nematodes, inhibiting reproduction (Samarasinghe et al., 2023). Nano CuO and nano NiO affect seed germination in cucumber, radish, and lettuce, while nano Co3O4 impacts root elongation of radish (Ahmad et al., 2023).

Relative Toxicity of Metal Oxide NPs

Research comparing the toxicity of various metal oxide NPs ranks CuO as the most toxic and TiO2 as the least toxic. The toxicity is assessed based on ROS production, lipid peroxidation, oxidative stress, and metal ion release (Sengul and Asmatulu, 2020). Experiments on Lactuca seeds and bacteria like S. aureus and E. coli confirm copper oxide's high toxicity (Sajjad et al., 2023).

Nanobioremediation

Nanoparticles play a crucial role in environmental remediation, effectively cleaning air, water, and soil. For example, iron oxide NPs are used to remove contaminants due to their high reactivity (Latif et al., 2020). Various NPs are employed in wastewater treatment through adsorption, degradation, and filtration (Naseem and Durrani, 2021).

Wastewater Treatment

Metal oxide NPs like iron oxide and cobalt are used to remove toxic elements from water, improving the hydrosphere (Abuhatab et al., 2020; Gautam et al., 2022).

Metal Oxide NPs and Microbes

Microorganisms can synthesize metal oxide NPs for environmental cleanup. Copper oxide NPs from Escherichia sp. degrade dyes, while iron oxide NPs from Aspergillus tubingensis remove heavy metals from contaminated water (Mandeep and Shukla, 2020; Yamini and Rajeswari, 2023).

Implications for Environmental Management

Understanding the ecotoxicological impact of metal oxide NPs is crucial for environmental conservation and decision-making. Establishing safe exposure limits, incorporating nanomaterial-specific regulations, and effective risk communication are essential. Promoting interdisciplinary research and international cooperation can lead to innovative solutions for managing nanoparticle pollution (Navarro et al., 2008).

CONCLUSION

It was concluded metal oxide nanoparticles offer significant benefits in various applications such as bioremediation, drug delivery, and biomedicine, their potential toxicity cannot be overlooked. These nanoparticles pose risks including cellular and DNA damage, ROS formation, and inflammation, necessitating thorough toxicity evaluations before their use in diagnostics and therapies. Understanding and mitigating these risks is essential to harness their full potential while ensuring safety for humans and the environment.

ACKNOWLEDGEMENT

N/A

CONFLICT OF INTEREST

Authors declare no conflict of interest.

REFERENCES

1. Abdel Maksoud M, Fahim RA, Shalan AE, Abd Elkodous M, Olojede S, Osman AI, Farrell C, Al-Muhtaseb AAH, Awed A, Ashour A (2021). Advanced materials and technologies for supercapacitors used in energy conversion and storage: a review. Environ. Chem. Lett. 19: 375-439.
2. Abuhatab S, El-Qanni A, Al-Qalaq H, Hmoudah M, Al-Zerei W (2020). Effective adsorptive removal of Zn2+, Cu2+, and Cr3+ heavy metals from aqueous

solutions using silica-based embedded with NiO and MgO nanoparticles. J. Environ. Manage. 268: 110713.

3. Adachi K, Buseck PR (2010). Hosted and free-floating metal-bearing atmospheric nanoparticles in Mexico City. Environ. Sci. Technol. 44(7): 2299-2304.

4. Ahamed M, Akhtar MJ, Khan MM, Alrokayan SA, Alhadlaq HA (2019). Oxidative stress mediated cytotoxicity and apoptosis response of bismuth oxide (Bi2O3) nanoparticles in human breast cancer (MCF-7) cells. Chemosphere 216: 823-831.

5. Ahmad S, Pathak AK, Minj RP, Chaudhary S, Kumar A, Chalotra T, Raina N (2023). A Comprehensive Review of Nanoparticles Induced Stress and Toxicity in Plants. Univ. J. Green Chem. 11: 18-43.

6. Alavi M, Karimi N (2018). Characterization, antibacterial, total antioxidant, scavenging, reducing power and ion chelating activities of green synthesized silver, copper and titanium dioxide nanoparticles using Artemisia haussknechtii leaf extract. Artif. Cells Nanomed. Biotechnol. 46: 2066-2081.

7. Anele A, Obare S, Wei J (2022). Recent trends and advances of Co3O4 nanoparticles in environmental remediation of bacteria in wastewater. Nanomaterials 12: 1129.

8. Antony JJ, Sivalingam P, Chen B (2015). Toxicological effects of silver nanoparticles. Environ. Toxicol. Pharmacol. 40: 729-732.

9. Attarilar S, Yang J, Ebrahimi M, Wang Q, Liu J, Tang Y, Yang J (2020). The toxicity phenomenon and the related occurrence in metal and metal oxide nanoparticles: a brief review from the biomedical perspective. Front. Bioeng. Biotechnol. 8: 822.

10. Bamal D, Singh A, Chaudhary G, Kumar M, Singh M, Rani N, Mundlia P, Sehrawat AR (2021). Silver nanoparticles biosynthesis, characterization, antimicrobial activities, applications, cytotoxicity and safety issues: An updated review. J. Nanomater. 11: 2086.

11. Banerjee K, Thiagarajan P (2014). A review of titanium Di oxide nanoparticles-synthesis, applications and toxicity concerns. Nanoscience Nanotechnol. Asia 4: 132-143.

12. Bapat RA, Chaubal TV, Joshi CP, Bapat PR, Choudhury H, Pandey M, Gorain B, Kesharwani P (2018). An overview of application of silver nanoparticles for biomaterials in dentistry. Mater. Sci. Eng. C 91: 881-898.

13. Baranowska-Wójcik E, Szwajgier D, Oleszczuk P, Winiarska-Mieczan A (2020). Effects of titanium dioxide nanoparticles exposure on human health—a review. Biol. Trace Elem. Res. 193: 118-129.

14. Braunschweig J, Bosch J, Meckenstock RU (2013). Iron oxide nanoparticles in geomicrobiology: from biogeochemistry to bioremediation. New Biotechnol. 30: 793-802.
15. Bzdek BR, Pennington MR, Johnston MV (2012). Single particle chemical analysis of ambient ultrafine aerosol: A review. J. Aerosol Sci. 52: 109-120.
16. Chae H, Song D, Lee YG, Son T, Cho W, Pyun YB, Kim TY, Lee JH, Fabregat-Santiago F, Bisquert J (2014). Chemical effects of tin oxide nanoparticles in polymer electrolytes-based dye-sensitized solar cells. J. Phys. Chem. C 118: 16510-16517.

17. Chattopadhyay S, Dash SK, Tripathy S, Das B, Mandal D, Pramanik P, Roy S (2015). Toxicity of cobalt oxide nanoparticles to normal cells; an in vitro and in vivo study. Chem. Biol. Interact. 226: 58-71.
18. Chavali MS, Nikolova MP (2019). Metal oxide nanoparticles and their applications in nanotechnology. SN Appl. Sci. 1: 607.
19. Chrishtop VV, Mironov VA, Prilepskii AY, Nikonorova VG, Vinogradov VV (2021). Organ-specific toxicity of magnetic iron oxide-based nanoparticles. Nanotoxicology 15: 167-204.
20. Daraee H, Eatemadi A, Abbasi E, Fekri Aval S, Kouhi M, Akbarzadeh A (2016). Application of gold nanoparticles in biomedical and drug delivery. Artif. Cells Nanomed. Biotechnol. 44: 410-422.
21. Dasari TP, Pathakoti K, Hwang HM (2013). Determination of the mechanism of photoinduced toxicity of selected metal oxide nanoparticles (ZnO, CuO, Co3O4 and TiO2) to E. coli bacteria. J. Environ. Sci. 25: 882-888.
22. Demir E (2021). A review on nanotoxicity and nanogenotoxicity of different shapes of nanomaterials. J. Appl. Toxicol. 41: 118-147.
23. Donovan AR, Adams CD, Ma Y, Stephan C, Eichholz T, Shi H (2016). Single particle ICP-MS characterization of titanium dioxide, silver, and gold nanoparticles during drinking water treatment. Chemosphere 144: 148-153.
24. Ejileugha C, Ezejiofor AN, Ezealisiji KM, Orisakwe OE (2022). Metal oxide nanoparticles in oil drilling: Aquatic toxicological concerns. J. Hazard. Mater. Adv. 7: 100116.
25. Falcaro P, Ricco R, Yazdi A, Imaz I, Furukawa S, Maspoch D, Ameloot R, Evans JD, Doonan CJ (2016). Application of metal and metal oxide nanoparticles@ MOFs. Coord. Chem. Rev. 307: 237-254.
26. Flannery M, Desai TG, Matsoukas T, Lotfizadeh S,

Oehlschlaeger MA (2015). Passivation and Stabilization of Aluminum Nanoparticles for Energetic Materials. J. Nanomater. 2015: 682153.

27. Gallo-Cordova Á, Espinosa A, Serrano A, Gutiérrez L, Menéndez N, del Puerto Morales M, Mazarío E (2020). New insights into the structural analysis of maghemite and (MFe2O4, M= Co, Zn) ferrite nanoparticles synthesized by a microwave-assisted polyol process. Mater. Chem. Front. 4: 3063-3073.
28. Gautam PK, Banerjee S, Samanta SK (2022). Chapter 7 - Sustainable approaches for synthesis of biogenic magnetic nanoparticles and their water remediation applications. In J. R. Koduru, et al. (Eds.), Sustainable Nanotechnology for Environmental Remediation. Elsevier: 157-178.
29. Gherasim O, Puiu RA, Bîrcă AC, Burdușel AC, Grumezescu AM (2020). An updated review on silver nanoparticles in biomedicine. Nanomaterials 10: 2318.
30. Ghosh N, Ghosh R, Babu SP (2021). Nanotechnology in microalgae for biofuel production and CO2 sequestration: A review. Environ. Chem. Lett. 19: 2777-2796.
31. Griffin S, Masood MI, Nasim MJ, Sarfraz M, Ebokaiwe AP, Schäfer KH, Keck CM, Jacob C (2017). Natural nanoparticles: a particular matter inspired by nature. Antioxidants 7: 3.
32. Guo H, Barnard AS (2013). Naturally occurring iron oxide nanoparticles: morphology, surface chemistry and environmental stability. J. Mater. Chem. A 1: 27-42.
33. Gurunathan S, Han JW, Kim ES, Park JH, Kim JH (2015). Reduction of graphene oxide by resveratrol: a novel and simple biological method for the synthesis of an effective anticancer nanotherapeutic molecule. Int. J. Nanomed. 4: 2951-2969.
34. Handy RD, Owen R, Valsami-Jones E (2008). The ecotoxicology of nanoparticles and nanomaterials: current status, knowledge gaps, challenges, and future needs. Ecotoxicology 17: 315-325.
35. Harish V, Tewari D, Gaur M, Yadav AB, Swaroop S, Bechelany M, Barhoum A (2022). Review on nanoparticles and nanostructured materials: bioimaging, biosensing, drug delivery, tissue engineering, antimicrobial, and agro-food applications. Nanomaterials 12: 457.
36. Herrera Estrada LP, Champion JA (2015). Protein nanoparticles for therapeutic protein delivery. Biomater. Sci. 3: 787-799.
37. Hong S, Choi DW, Kim HN, Park CG, Lee W, Park HH (2020). Protein-based

nanoparticles as drug delivery systems. Pharmaceutics 12: 604.

38. Hu C, Hou J, Zhu Y, Lin D (2020). Multigenerational exposure to TiO2 nanoparticles in soil stimulates stress resistance and longevity of survived C. elegans via activating insulin/IGF-like signaling. Environ. Pollut. 263: 114376.

39. Hussain I, Singh N, Singh A, Singh H, Singh S (2016). Green synthesis of nanoparticles and its potential application. Biotechnol. Lett. 38: 545-560.

40. Hwang GH, Han WK, Kim SJ, Hong SJ, Park JS, Park HJ, Kang SG (2009). An electrochemical preparation of bismuth nanoparticles by reduction of bismuth oxide nanoparticles and their application as an environmental sensor. J. Ceram. Process. Res. 10: 190-194.

41. Iravani S, Varma RS (2020). Sustainable synthesis of cobalt and cobalt oxide nanoparticles and their catalytic and biomedical applications. Green Chem. 22: 2643-2661.

42. Jagdale P, Serino G, Oza G, Audenino AL, Bignardi C, Tagliaferro A, Alvarez-Gayosso C (2021). Physical characterization of bismuth oxide nanoparticle based ceramic composite for future biomedical application. J. Mater. 14: 1626.

43. Jamuna BA, Ravishankar RV (2014). Environmental risk, human health, and toxic effects of nanoparticles. Nanomater. Environ. Prot. 1: 523-535.

44. Jeng HA, Swanson J (2006). Toxicity of metal oxide nanoparticles in mammalian cells. J. Environ. Sci. Health A 41: 2699-2711.

45. Jiang Z, Shan K, Song J, Liu J, Rajendran S, Pugazhendhi A, Jacob JA, Chen B (2019). Toxic effects of magnetic nanoparticles on normal cells and organs. Life Sci. 220: 156-161.

46. Jung H, Park H, Kim J, Lee JH, Hur HG, Myung NV, Choi H (2007). Preparation of biotic and abiotic iron oxide nanoparticles (IOnPs) and their properties and applications in heterogeneous catalytic oxidation. Environ. Sci. Technol. 41: 4741-4747.

47. Khalil AT, Ovais M, Ullah I, Ali M, Shinwari ZK, Maaza M (2017). Biosynthesis of iron oxide (Fe2O3) nanoparticles via aqueous extracts of Sageretia thea (Osbeck.) and their pharmacognostic properties. Green Chem. Lett. Rev. 10: 186-201.

48. Khan MR, Fromm KM, Rizvi TF, Giese B, Ahamad F, Turner RJ, Füeg M, Marsili E (2020). Metal nanoparticle–microbe interactions: synthesis and antimicrobial effects. Part. Part. Syst. Charact. 37: 1900419.

49. Kiser M, Westerhoff P, Benn T, Wang Y, Perez-Rivera J, Hristovski K (2009). Titanium nanomaterial removal and release from wastewater treatment plants.

Environ. Sci. Technol. 43: 6757-6763.
50. Ko KS, Kong IC (2014). Toxic effects of nanoparticles on bioluminescence activity, seed germination, and gene mutation. Appl. Microbiol. Biotechnol. 98: 3295-3303.
51. Kushwaha M, Mishra A, Goel D, Shankar S (2023). Nanotechnological approach for the abatement of environmental pollution: a way forward toward a clean environment. Biotechnol. Environ. Remediation 2: 221-247.
52. Küünal S, Rauwel P, Rauwel E (2018). Plant extract mediated synthesis of nanoparticles. In: Emerging applications of nanoparticles and architecture nanostructures. Elsevier: 411-446.
53. Latif A, Sheng D, Sun K, Si Y, Azeem M, Abbas A, Bilal M (2020). Remediation of heavy metals polluted environment using Fe-based nanoparticles: mechanisms, influencing factors, and environmental implications. Environ. Pollut. 264: 114728.
54. Li C, Zhang Y, Wang M, Zhang Y, Chen G, Li L, Wu D, Wang Q (2014). In vivo real-time visualization of tissue blood flow and angiogenesis using Ag2S quantum dots in the NIR-II window. Biomater. Res. 35: 393-400.
55. Magdassi S, Grouchko M, and Kamyshny A (2010). Copper nanoparticles for printed electronics: Routes towards achieving oxidation stability. Materials. 3(9): 4626-4638.
56. Mandeep and Shukla P (2020). Microbial nanotechnology for bioremediation of industrial wastewater [Mini Review]. Front. Microbiol. 1: 11.
57. Mei J, Liao T, Ayoko GA, Bell J, and Sun Z (2019). Cobalt oxide-based nanoarchitectures for electrochemical energy applications. Prog. Mater. Sci. 103: 596-677.
58. Mohamed AE, Celik A, Yetkin D, and Guler G (2021). Bismuth oxide nanoparticle: The potential of apoptotic and genetic damage on MDBK cell line. Nanomed. Nanotechnol. 1(1): 1-5.
59. Montano MD, Lowry GV, von der Kammer F, Blue J, and Ranville JF (2014). Current status and future direction for examining engineered nanoparticles in natural systems. Environ. Chem. 11(4): 351-366.
60. Moore T, Hennessy EM, Myles J, Johnson SJ, Draper ES, Costeloe KL, and Marlow N (2012). Neurological and developmental outcome in extremely preterm children born in England in 1995 and 2006: the EPICure studies. BMJ: 345.
61. Motakef-Kazemi N, and Yaqoubi M (2020). Green synthesis and characterization of bismuth oxide nanoparticle using Mentha pulegium extract. Iran. J. Pharm. Res. IJPR. 19(2): 70.
62. Nadeem M, Tungmunnithum D, Hano C,

Abbasi BH , Hashmi SS, Ahmad W, and Zahir A. (2018). The current trends in the green syntheses of titanium oxide nanoparticles and their applications. Green Chem. Lett. Rev. 11(4): 492-502.

63. Naseem T, and Durrani T (2021). The role of some important metal oxide nanoparticles for wastewater and antibacterial applications: A review. Environ. Chem. Ecotoxicol. 3: 59-75.

64. Navarro E, Piccapietra F, Wagner B, Marconi F, Kaegi R, Odzak N, Behra R. (2008). Toxicity of silver nanoparticles to Chlamydomonas reinhardtii. Environ. Sci. Technol. 42(23): 8959-8964.

65. Nizamuddin S, Siddiqui M, Mubarak N, Baloch HA, Abdullah E, Mazari SA, Tanksale A (2019). Iron oxide nanomaterials for the removal of heavy metals and dyes from wastewater. Nanoscale Mater. Water Purif: 447-472.

66. Nowack B, and Bucheli TD (2007). Occurrence, behavior and effects of nanoparticles in the environment. Environ. Pollut. 150(1): 5-22.

67. Oukarroum A, Bras S, Perreaul F, and Popovic R (2012). Inhibitory effects of silver nanoparticles in two green algae, Chlorella vulgaris and Dunaliella tertiolecta. Ecotoxicol. Environ. Saf. 78: 80-85.

68. Perreault F, Melegari SP, da Costa CH, Rossetto AL, Popovic R, and Matias WG (2012). Genotoxic effects of copper oxide nanoparticles in Neuro 2A cell cultures. Sci. Total Environ. 441: 117-124.

69. Prabhu S, and Poulose EK (2012). Silver nanoparticles: mechanism of antimicrobial action, synthesis, medical applications, and toxicity effects. Int. Nano Lett. 2: 1-10.

70. Rahman MM, Uddin J, Asiri AM, and Rahman MR (2024). Toxicity of nanoparticles: Recent advances and new perspectives.

71. Rajan, A., Vilas, V., and Philip, D. (2015). Studies on catalytic, antioxidant, antibacterial and anticancer activities of biogenic gold nanoparticles. J. Mol. Liq., 212, 331-339.

72. Rajput VD, Minkina T, Sushkova S, Chokheli V, and Soldatov M (2019). Toxicity assessment of metal oxide nanoparticles on terrestrial plants. Compr. Anal. Chem. Elsevier 87: 189-207.

73. Revell P (2006). The biological effects of nanoparticles. Nanotechnol. Percept. 2(3): 283-298.

74. Sadik OA (2013). Anthropogenic nanoparticles in the environment. Environ. Sci. Processes Impacts. 15(1): 19-20.

75. Sagadevan S, Imteyaz S, Murugan B, Anita L, Sridewi N, Weldegebrieal GK (2022). A comprehensive review on green synthesis, characterization, and applications of biogenic bismuth

nanoparticles. Int. J. Energy Res. 46(4): 4909-4932.

76. Saleh TA, Wahab MA, and Mahtab A (2020). Environmental applications of nanoparticles and their mechanisms of action and factors influencing their toxicology. Comp. Biochem. Physiol. Part C Toxicol. Pharmacol: 109682.
77. Sajjad H, Sajjad A, Haya RT, Khan MM, Zia M (2023). Copper oxide nanoparticles: In vitro and in vivo toxicity, mechanisms of action and factors influencing their toxicology. Comp. Biochem. Physiol. C Toxicol. Pharmacol. 109682.
78. Samarasinghe SV, Krishnan K, Aitken R J, Naidu R, and Megharaj M (2023). Chronic effects of TiO2 and ZnO nanoparticles to earthworm Eisenia fetida. Environ. Chem. Ecotoxicol. 5: 129-134.
79. Sanderson P, Delgado-Saborit JM, and Harrison RM (2014). A review of chemical and physical characterisation of atmospheric metallic nanoparticles. Atmos. Environ. 94: 353-365.
80. Sangaiya P, and Jayaprakash R (2018). A review on iron oxide nanoparticles and their biomedical applications. J. Supercond. Nov. Magn. 31(11): 3397-3413.
81. Savi M, Bocchi L, Cacciani F, Vilella R, Buschini A, Perotti A, Frati C (2021). Cobalt oxide nanoparticles induce oxidative stress and alter electromechanical function in rat ventricular myocytes. Part. Fibre Toxicol. 18:1-17.
82. Seabra AB, and Durán N (2015). Nanotoxicology of metal oxide nanoparticles. Metals 5(2): 934-975.
83. Sengul Ab, and Asmatulu E (2020). Toxicity of metal and metal oxide nanoparticles: A review. Environ. Chem. Lett. 18(5): 1659-1683.
84. Shafey A (2020). Green synthesis of metal and metal oxide nanoparticles from plant leaf extracts and their applications: A review. Green Process. Synth. 9(1): 304-339.
85. Shahbazi MA, Faghfouri L, Ferreira MP, Figueiredo P, Maleki H, Sefat F, Santos HA (2020). The versatile biomedical applications of bismuth-based nanoparticles and composites: Therapeutic, diagnostic, biosensing, and regenerative properties. Chem. Soc. Rev. 49(4): 1253-1321.
86. Siddiqi KS, and Husen A (2017). Plant response to engineered metal oxide nanoparticles. Nanoscale Res. Lett. 12: 1-18.
87. Stark WJ (2011) Nanoparticles in biological systems. Angew. Chem. Int. Ed. 50(6): 1242-1258.
88. Strambeanu N, Demetrovici L, Dragos D (2014). Anthropogenic sources of nanoparticles. In: Nanoparticles'

Promises and Risks: Characterization, Manipulation, and Potential Hazards to Humanity and the Environment. Springer: 21-54.

89. Stuchinskaya T, Moreno M, Cook MJ, Edwards DR, and Russell DA (2011). Targeted photodynamic therapy of breast cancer cells using antibody-phthalocyanine-gold nanoparticle conjugates. Photochem. Photobiol. Sci. 10(5): 822-831.

90. Sýkora D, Kašička V, Mikšík I, Řezanka P, Záruba K, Matějka P, and Král V (2010). Application of gold nanoparticles in separation sciences. J. Sep. Sci. 33(3): 372-387.

91. Tee JK, Ong CN, Bay BH, Ho HK, and Leong DT (2016). Oxidative stress by inorganic nanoparticles. Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol. 8(3): 414-438.

92. Tolocka MP, Lake DA, Johnston MV, and Wexler AS (2004). Number concentrations of fine and ultrafine particles containing metals. Atmos. Environ. 38(20): 3263-3273.

93. Valdiglesias V, Kiliç G, Costa C, Fernández-Bertólez N, Pásaro E, Teixeira J P, and Laffon B (2015). Effects of iron oxide nanoparticles: cytotoxicity, genotoxicity, developmental toxicity, and neurotoxicity. Environ. Mol. Mutagen. 56(2): 125-148.

94. Verma N, and Kumar N (2019). Synthesis and Biomedical Applications of Copper Oxide Nanoparticles: An Expanding Horizon. ACS Biomater. Sci. Eng. 5(3): 1170-1188.

95. Verma P, and Maheshwari SK (2019). Applications of Silver nanoparticles in diverse sectors. Int. J. Nano Dimens.10(1): 18-36.

96. Waghmod MS, Gunjal AB, Mulla JA, Patil NN, and Nawani NN (2019). Studies on the titanium dioxide nanoparticles: Biosynthesis, applications and remediation. SN Appl. Sci. 1(4): 310.

97. Wan R, Mo Y, Feng L, Chien S, Tollerud DJ, and Zhang Q (2012). DNA damage caused by metal nanoparticles: involvement of oxidative stress and activation of ATM. Chem. Res. Toxicol. 25(7): 1402-1411.

98. Wang T, Huang D, Yang Z, Xu S, He G, Li X, Zhang L (2016). A review on graphene-based gas/vapor sensors with unique properties and potential applications. Nano-Micro Lett. 8: 95-119.

99. Yamini V, and Rajeswari VD (2023). Effective bio-mediated nanoparticles for bioremediation of toxic metal ions from wastewater– A review. J. Environ. Nanotechnol. 12(2): 12-33.

100. Zhang XD, Wu HY, Wu D, Wang YY, Chang JH, Zhai ZB, Fan FY (2010). Toxicologic effects of gold nanoparticles in vivo by different administration routes. Int. J. Nanomed: 771-781.