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Toxicity and Challenges of Nanomaterials and Their Impact on the Environment

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ABSTRACT

Nanomaterials (NMs) are those tiny materials that range from 1-100 nm. These materials show different characteristics in their physical and chemical forms in comparison to their bulk form. The use of nanomaterials is increasing day by day because of their enormous capabilities in the health sector as well as in other industries. There are currently few, if any, actual protocols for the disposal and characterization of these nanomaterials, which results in environmental toxicity. Heavy use of chemicals in the testing of nanomaterials has resulted in polluting our entire ecosystem. Inconsistent results of nanomaterial show that it is challenging to reduce the toxicity generated by it. In this review, we discuss the administration and use of nanomaterials in the agribusiness sector, in food, and, most importantly, in the environment, for purposes of protecting our plants and crops, dealing with incurable diseases, developing new tastes and textures in the food sector, sensations, identifying pathogenic organisms, and distribution systems where these minute particles can wreak havoc. Despite the potential benefits of nanomaterials, their unintentional harm to the environment and, in some cases, our health is making further development difficult. This article discusses the toxicity of nanomaterials and how they damage our environment, as well as the obstacles that come with overcoming them.

INTRODUCTION

Nanotechnology is an amalgamation of nano-sized (very minute size 1-100 nm) structured materials, analytical tools at the nanoscale, and nano-devices, into biological sciences for the development of new biomaterials and toolkits as well as for understanding life science. It's designed to help minimize man's impact on the environment by incorporating more sensible, effective, and low-cost modifications (Pathakoti et al. 2018). Despite ongoing progress in nanotechnology and nanomaterial discovery, understanding and knowledge on the possible effects of nanomaterials on health and the environment are still inadequate (Hutchison 2016). As nanomaterial is not easy to be analyzed after release into the environment, they can result in numerous types of atmospheric problems unless a proper curative plan is not executed. Engineered nanomaterials are generally manufactured with specific sizes and for specific purposes (Iavicoli et al. 2014). They are designed as their characteristic properties like physical and chemical attributes are different compared to their bulk conventional parts. Various types of nanomaterials find application in providing significant benefits to the environment. Furthermore, most nanomaterials have been discovered to have potential hazardous impacts on the environment, the most prevalent of which being nano plastics, which heavily pollute the ecosystem (Rai et al. 2020).

Plastic plays an important part in our general life. Plastic is known as polythene in the common language. Because of its lower cost and affordability, it is one of the most usable products in the modern era (Awoyera & Adesina 2020). However, it contributes to a large amount of pollution because of its non-degradable nature (Da Costa et al. 2016). It is further divided into subcategories like low-density polyethylene (LDPE) and high-density polyethylene (HDPE). Microplastics, which turn into nanoparticles of plastic over a long period of natural disintegration, are common contaminants that threaten our ecosystem and humans (Baztan et al. 2018). Microplastics are major prey for animals because they assume microplastics are their source of food, such as marine food, salt, and bottled water, as well as inhalation from the air and other surroundings.

Nano plastic has a unique property that depicts a high surface-to-volume ratio, which affects its degradation process. A high surface-to-volume ratio is a defining feature of nanotechnology (Bhushan 2017). This characteristic makes nanoparticles or plastic more harmful to the environment. Proper assessment should be done on nanomaterials that generate enough harm during the manufacturing process (Lee et al. 2013). Green nanotechnology is now seen to have the potential to reduce adverse environmental impact as well as harm to human health. Nano plastic agglomerates with chemicals and heavy metals via weaker links such as wander walls bonds, according to research (Herbort et al. 2018). As a result, when nanoparticles of plastic are moved from one compartment of the environment to another, harmful chemicals are released, making it impossible for marine species to survive (Del Saz-Salazar et al. 2009).

TOXICOLOGY OF NANOMATERIALS

The branch of science that deals with the adverse effect of physical, chemical, and biological materials on living cells or living organisms, is called toxicology (Liu & Yu 2011). Nanotoxicology is a rapidly developing field in today's era (Khan & Shanker 2015). Despite the fact that nanoparticles (NPs) are always present in nature, major advances in their field of research have been made in bioremediation (Cecchin et al. 2017), paints (Goesmann & Feldmann 2010), coatings (Fierascu et al. 2019), electronics (Cardoso et al. 2018), fuel catalysts, water treatment (Kumar et al. 2014), and almost everywhere in human society (López-Serrano et al. 2014). Nanomaterials drugs offer a great advantage over general pharmaceutical formulations because of their clump-free, stable, and water-soluble properties (Malekhosseini et al. 2019). Especially nano plastics can cause more harm to biota than other micro and macro plastic because of their small size (Strungaru et al. 2019). It is a fact that plastic particles in the nano range are able to penetrate cell membranes (Bouwmeester et al. 2015). Aromatic hydrocarbons, polychlorinated biphenyls, and other additives exacerbate the impact of these chemicals on living beings. Nanoplastics can operate as pathogenic vectors for chemical and biological pollutants, causing poisoning in animals and humans (Jiang et al. 2020). Nanoparticle exposure in the environment and surroundings is shown in Fig1.

There are different ways by which microplastic and nano plastics enter our ecosystem. The direct way in which contamination is caused is through the application of plastic mulch in agricultural soils greenhouse buildings matter, raw material, and soil condition improver (Steinmetz et al. 2016). Because of their minute size, many nano plastics are retained in wastewater treatment reactors after being processed in a wastewater treatment facility, and the remainder ends up in generated sludge (Egirani et al. 2020).

Parameters that can affect the toxicity of nanoparticles: Various factors decide the fate of nanoparticles in the environment (Sajid et al. 2015). The morphology of the engineered nanoparticle is affected by the synthesis methods used and the changes in the synthesis procedure (Patra & Baek 2014). The composition of nano-sized particles stems from physical, chemical, mechanical, and biological processes. The physical process comprises the synthesis of the nanoparticles by different techniques like lithographic, ball milling, etching, and sputtering techniques, which focus on the breakdown of larger molecules into a material of suitable functional and morphological characteristics. The buildup of nanoparticles from non-complex molecular structures is done by the chemical process. These methods comprise deposition by chemical vaporization, condensation of atomic and molecular structures, spray with laser heating at controlled temperature conditions, and aerosol formation. There is a limited scien-

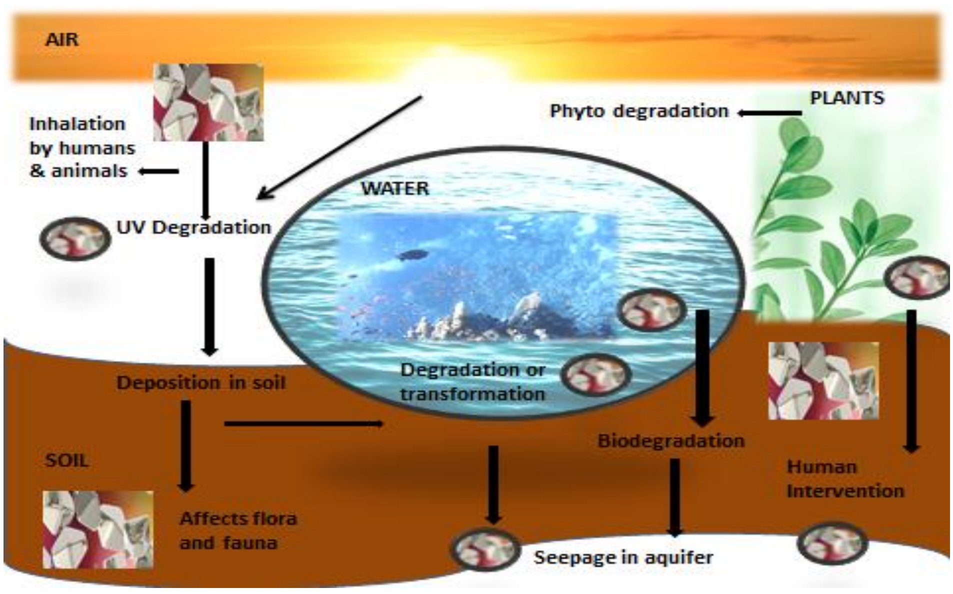


Fig. 1: Exposure of nanoparticles on animal health and environment.

tific understanding of reaction mechanisms and modeling characteristics associated with this factor mentioned below.

1. Size
2. Composition
3. Solubility and crystalline structure
4. Charge with surface characteristics
5. Attached functional groups
6. Agglomeration with impurities and porosity can potentially affect the total removal yield of the nanomaterial from the environmental contaminants (Das et al. 2018).

SOURCES OF NANOMATERIALS

Nanomaterials present in our environment come either from natural processes like volcanic explosions, forest fires, erosion of different soils, clay minerals, and dust storms (Bakshi et al. 2015) or from different anthropogenic activities including fossil fuel burning, mining, automobile traffic, and nanomaterial production, and wastewater release from industries (Kabir et al. 2018). Hydrophobicity, chemical, and physical resistance are the reasons, nanoparticle transports from one place to the other (Kettler et al. 2014). Our clothing, which is made of polyester, nylon, and acrylic fibers, is washed and laundered in wastewater treatment plants (Tiwari et al. 2020). Nanoparticles remain in the environment even after multiple treatments due to their small size and higher resistance power (Zhang 2015). Cosmetic products such as shampoos, soaps, and scrubs release high concentrations of nanoparticles because of the microbeads used and their fragmentation (Lehner et al. 2019). Even plastic tea bags which we use on daily basis in large amounts could release billions of nanoparticles (Auclair et al. 2020). Sources and applications of nanoparticles are compiled below in (Table 1).

Table 1: Sources of nanoparticles in the environment.

S. No.	Types	Applications	References
1	Natural	Volcanic eruption Forest fire Dust storm Soil erosion	(Strambeanu et al. 2015)
2	Intentional or engineered	Drug delivery Engineered nanomaterial Groundwater remediation Biomedical engineering Biosensors	(Sun et al. 2014)
3	Unintentional or incidental	Welding Vehicle exhaust Industrial processes Fuel burning Mining	(Hochella et al. 2019)

NANOMATERIALS OF DIFFERENT SUBSTANCES AND THEIR TOXICITY

Various types of nanomaterials are being used in everyday life including zinc oxide nanoparticles (ZnONPs), silica nanoparticles (SiO_2NPs), titanium dioxide nanoparticles (TiO_2NPs), silver nanoparticles (Ag-NPs), gold NPs (AuNPs), and polymeric nanoparticles (PNPs) (Sajid et al. 2015). Generally, these nanoparticles are for the drug delivery system in various parts of the body (Bharti et al. 2015). All interactions with harmful toxicological effects are caused by changes in the physicochemical and systemic properties of man-made nanoparticles (Gatoo et al. 2014).

ZnO nanoparticles (ZnO NP): Various types of cosmetics as sunscreens, food supplements like additives and color, pigments, and biosensors contain zinc oxide nanoparticles (ZnONPs) (Mirzaei & Darroudi 2017). The toxic effect of ZnO is seen in animal models and humans (Valdiglesias et al. 2013). Cytotoxicity and genotoxicity of ZnONPs have been studied in vitro as well as in vivo (Ng et al. 2017). Depending on the duration or dose, these ZnONPs have lower cell viability. Studies have found dose-dependent hepatotoxicity as well as an increase in oxidative stress because of increased levels of malondialdehyde (MDA) and decreased enzyme activity in the liver (Zhang 2015).

TiO_2 nanoparticles(TiO_2 NPs): TiO_2 is commonly used in beauty and skincare items as a pigment, a binder, and a UV absorber (Torbati & Javanbakht 2020). TiO_2 allows artificial medical implants and bone. Some scientists found the toxicity of TiO_2 nanoparticles through skin penetration in mice and skin of porcine post chronic exposure (Adachi et al. 2010). Other studies have observed in vitro cytotoxicity and genotoxicity of TiO_2NPs in different cell lines, in plants, and model organisms such as mice and zebra fishes (Bennett et al. 2012).

Silica nanoparticles(SiO_2 NPs): For a long time, the indefinite form of silica has been used as a food ingredient (Peters et al. 2012). The main purpose of SiO_2 nanoparticles in the food industry is to overcome flow or caking in powdered products. SiO_2 also have been used as a carrier of flavors as well as a thickener in paste-like substances (Guo et al. 2018). It is sometimes used to clear different beverages and lessen foaming. Various studies have reported the toxicity of SiO_2 nanoparticles as food additives on human gastrointestinal cells, thus enforcing their safety as food additives (Go et al. 2017). Scientists have also demonstrated that oral and intravenous administration of SiO_2 nanoparticles has a negative impact on biodistribution, excretion, and toxicity (Khlebtsov & Dykman 2011).

Silver nanoparticles (Ag-NPs): Silver is well known for its antibacterial potential. Researchers found that silver has been used as a healing agent for a long time (Peng et al. 2012). To increase and use its potential, a silver particle (Ag) is used as a nanoparticle. Ag nanoparticles have been found to exhibit antiviral and antibacterial activities. Another application of silver-containing resin is to fill cavities and cover dental teeth, as well as in medical applications. In mice, researchers confirmed that ammonia and PVPs (polyvidone stabilized Ag nanoparticles) are non-cytotoxic at lower quantities (Saqib & Rahim 2016). Some researchers observed adverse effects of AgNPs on human cells and demonstrated that their cytotoxic and genotoxic effects act as a useful tool to control desirable angiogenesis which means the formation of new blood cells in an uncontrollable way (Gupta & Xie 2018).

Gold nanoparticles (Au-NPs): Gold nanoparticles are used to cap bio-functional moieties that have considerable biological activity, such as peptides and carbohydrates, to control and monitor various cell processes (Zhang et al. 2020). The application of AuNPs is also found in diagnosis due to their light returning ability and surface. Due to their significant potential in therapeutic and diagnostic purposes, AuNPs find great application in understanding toxic effects (Khan et al. 2014). Scientists studied the toxicity of AuNPs on immune dendrites that were obtained from mice bone marrow cells (Zhang et al. 2019).

TYPES OF NANOMATERIALS AND THEIR IMPACT ON THE ENVIRONMENT

Different categories of nanomaterials, classification and their structure are given in Table 2.

Nanomaterials then further classified according to their dimensions are -

- Zero-dimension (0D)
- One-dimension (1D)
- Two-dimensions (2D)
- Three-dimensions (3D).

Major counts of nano-particles are zero dimensions that include nanomaterial in the range of 1-100 nm. Unit dimension nanomaterials contain a thin needle or rod like-structure measure of 100 nm-10 μm and include nanotubes, nanorods, and nanowires (Ghassan et al. 2019). Two Dimensions nanomaterial comprises plate-like shapes including Nanocoatings, nanofilms, and nanolayers. 3D nanomaterials possess random dimensions and multilayer nano-crystalline structure (Yang et al. 2011**.** These nanomaterials usually include bulk powders, nanowire bundles, multi-nano layers, nanoparticles dispersions, and nanotubes (Saleem & Zaidi 2020).

ENVIRONMENTAL IMPACT OF NANOPARTICLES

Nanomaterial is generally released in the environment as waste from industries, directly into the land, water, air, soil through the remediation of contaminated fields. As technology advances, nanoparticles behave differently in different compartments of the environment.

Nanoparticle in the air: Nanoparticles present in the atmosphere can cover large distances from the point of their delivery or release, thus causing unmanageable exposure to humans as well as eco-toxicological effects on marine or terrestrial life (Ghadimi et al. 2020). The nanoparticles present in the terrestrial ecosystem spread rarely due to their immobile nature, yet they can travel into the human digestive system by gulping and swallowing or even contact with the skin (Berkowitz et al. 2014).

Nanoparticle in the soil: Nanoparticles can enter soils directly through pesticides and fertilizers, or indirectly through land and wastewater treatment materials such as sludges or biosolids (Courtois et al. 2020). Fertilizers are used to increase the productivity of the soil. Contrary outcomes of nanoparticles on biogeochemical cycles like in the nitrogen cycle have been found in some studies.

CHALLENGES ASSOCIATED WITH ENVIRONMENT TOXICOLOGY OF NANOMATERIAL

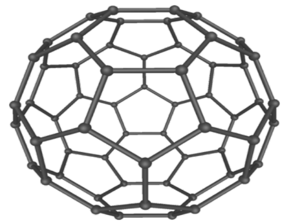
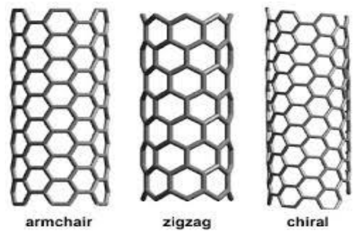
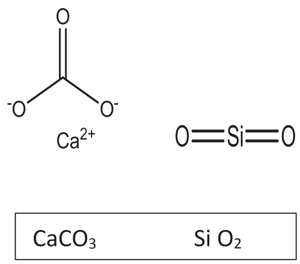
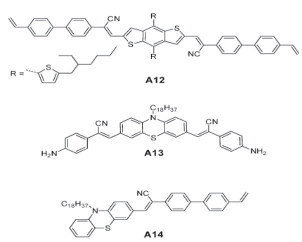
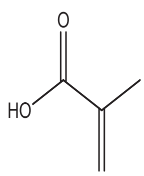
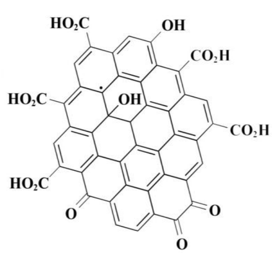
Analysis and assessments of different nanomaterials are limited due to a lack of knowledge and research in this field, as well as some inadequacies in regulating the spread of contamination by nanoparticles (Lai et al. 2018).

- Hazard and exposure evaluation- Hindrance in evaluating hazards posed by nanomaterials is a major issue due to the lack of standard protocols and methods to resolve them (Weinberg et al. 2011)
- Lack of informative data in the composition and profile of nanomaterials results in fewer testings and monitoring of facts for various NMs (Lead et al. 2018).
- Still, no methodology is available to recognize and identify the exposure of ENMs

CONCLUSION

Nanotechnology has gained significant importance in recent years owing to its widespread application and novelty. Although the majority of nanoparticles are utilized for a wide range of applications, their potential toxic hazards and consequences remain a major constraint to their advantage. The potential negative impacts of nanomaterials and nanoparticles in the environment have been studied by various researchers but major toxic effects of these NMs in the environment

Table 2: Types of nanomaterials.

Sr. No.	Type	Characteristics	Structure	References
1	Fullerenes	Interconnected carbon atoms Withstanding with extreme heat, still can regain its original shape. As hard or harder than diamond		(Castro et al. 2017)
2	Carbon-based	Single-walled or multiple walls 20 nm diameter E.g. Carbon nanotube		(Xin et al. 2019)
3	Inorganic	Pure metals or various inorganic products alloys Nanoscale distinguishes them from bulk material Display unique mechanical, electrical properties $CaCO_3$, SiO_2, AlOH, $SrCO_3$, TiO_2		(Wu 2017)
4	Organic	Contain both soluble and insoluble particles. Display catalytic properties not found in bulk material counterpart. Help drugs pass the blood-brain barrier.		(Lombardo et al. 2020)
5	Nanocapsules, nanoshells	Composed of insoluble organic polymers (methacrylic acid and PEG) Can bypass the digestive tract and act as pharmacologic vectors directly in the intestine.		(Bollhorst et al. 2017)
6	Quantum dots	Nanocrystals, artificial atom,1-10 nm in diameter Semiconductors, metal insulators, Magnetic matter or metallic oxides Fluorescent probe CdSe core with ZnS shell		(Yan et al. 2019)

along with adverse consequences on human health is a major cause of concern in coming years. Currently, current investigations using practical methodologies have proven the interactions of nanomaterials with various air surfaces, particularly plastics, restricting their bioavailability, reactivity, and toxicity, posing a risk to the environment. Despite increasing nanotechnology usage in industries, their ecological impacts are still in their infancy to combat them. The nature and composition of various nanomaterials used in fertilizers, and pesticides are often unclear, their utilization is widespread to cause contamination in soil and terrestrial habitat of plants as well.

Continued scientific input and knowledge are required to overcome the toxicological impacts of nanoparticles on the ecosystem and the environment. The long-term sustainability and prolonged exposure of nanoparticles in the environment require proper implementation and judicious regulations to combat toxic impacts. Assessment, risk, and evaluation of nanoparticles to understand potential toxicological impacts caused by them necessitated scientific understanding to learn their fate and action in the surrounding.

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