

# Impact of Nanoparticles in Balancing the Ecosystem

Anju Surendranath <sup>1</sup>, Parayanthala Valappil Mohanan <sup>1,\*</sup> 

<sup>1</sup> Toxicology Division, Biomedical Technology Wing, Sree Chitra Tirunal Institute for Medical Sciences and Technology (Govt. of India), Trivandrum 695 012, Kerala, India

\* Correspondence: mohanpv10@gmail.com;

Scopus Author ID 7006010446

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**Abstract:** Nanotechnology has contributed enormous breakthroughs in various scientific and engineering disciplines, from basic researches to advanced product development. Rapid advancements in nanotechnology have accomplished a great quantum leap in the areas of medicine, environment, agriculture, and renewable energy. As a result, there has been a growing interest to substitute conventional materials with nanomaterials in almost all scientific disciplines globally. This economic success has left behind the possibilities of critical adverse effects these materials can impart to the environment and its dependants. Several debates were ongoing worldwide on the effect of nanoparticle released metal ions and their subsequent toxicological impacts. It's been anticipated that the increased application of nanoparticles will lead to abrupt unchecked emission of the same into various environmental strata. Therefore, despite these emerging advancements, the potential adverse effects these nanotechnological researchers can put forward also need a thorough investigation. This review article has highlighted the currently employed applications of engineered nanoparticles in agriculture technology and environmental restoration, adverse effects of its exposure to environmental flora and fauna, ecosystem toxicity, and related issues.

**Keywords:** nanoparticles; environmental fate; hazards; nanowaste; ecosystem balance.

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## 1. Introduction

Nanotechnology is concerned with the manipulation of matter on an atomic scale [1]. The as-formed nanomaterials possess one or more external dimensions that come within a scale of 1 to 100nm that exhibits unique properties when compared to their bulk counterparts [2]. It has been postulated that these materials show enhanced physicochemical characteristics such as better dispersibility, solubility, diffusivity, as well as optical and thermodynamic properties much forefront compared to bulk particles [3]. With these unique characteristics, over the past few decades, nanotechnology has given unlimited contributions in the fields of agriculture, food technology, material science, and even biomedical technology. While considering electronic and optoelectronic sectors, flexible, stretchable, and foldable electronics have revolutionized the electronics industry offering huge advancements in portable electronics [4]. Commercial applications have adapted various NPs like gold and silver NPs for targeted detection of various analytes such as proteins and nucleic acids that correspond to specific diseases [5, 6]. Better imaging and diagnostics tools have been designed with nanotechnological inventions that can be used for the detection of atherosclerotic plaques as well as thrombus or emboli in major arteries and veins [7]. These have benefitted the biomedical sector enormously. In renewable energy, the introduction of nanocatalysts greatly

enhanced the efficiency of fuel production from crude petroleum and natural gas[8]. Nanotechnology incorporated solar panels offer a better conversion potency of sunlight to household electricity [9]. Oil spill cleanup and wastewater treatment are other notable choices of nanotechnology in environmental remediation [10, 11]. Likewise, in almost all the sectors of science, technology, and environment, nanomaterials and nanotechnology has become better substitutes for conventional sources.

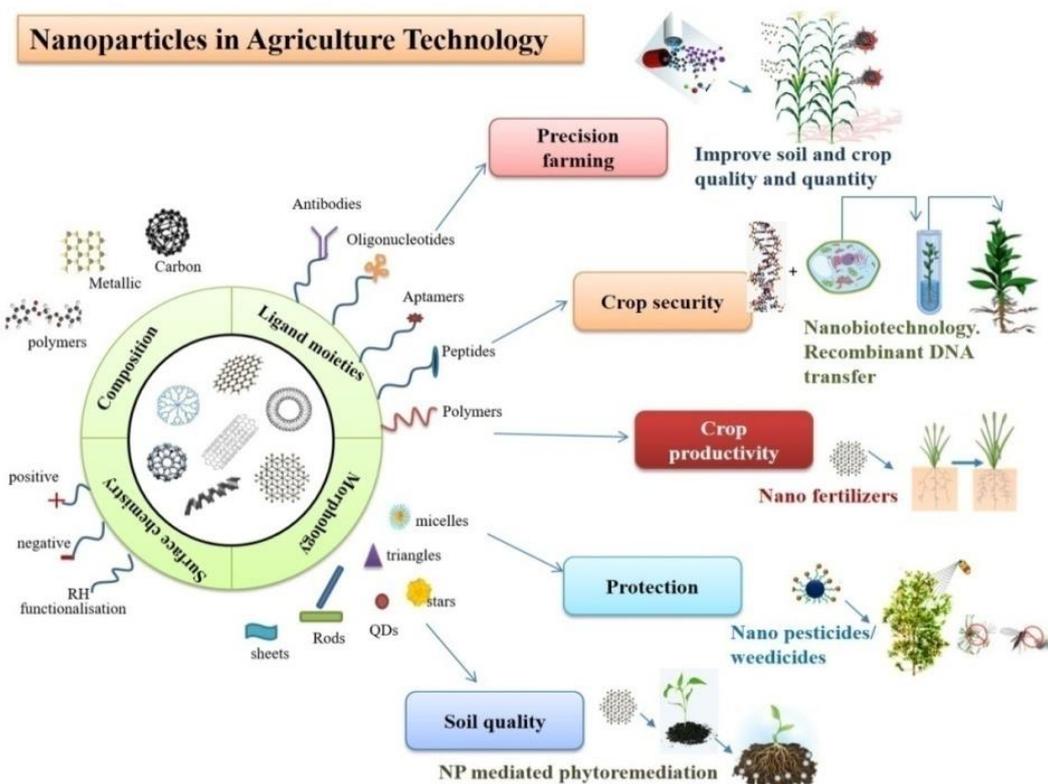
Today, the use of nanoparticles (NPs) has increased to an unprecedented manner in which almost all scientific disciplines substitute conventional materials with nanomaterials globally. Proper usage and disposal play a crucial role in avoiding the abrupt exposure of NPs into the environment and ecosystem. Once exposed to the environment, these NPs can circulate among various food webs in an ecosystem, which leads to bioaccumulation that can adversely affect its dependants [12]. The aquatic ecosystem is one of the major routes through which the NPs can reach various natural ecosystems [13]. Intact analysis of the various physicochemical properties of NPs and the subsequent nano-bio interactions is a necessary criterion to be followed before validating a nanomaterial safe for further applications [14]. Researches aimed at assessing the toxicological impacts of nanotechnology in living systems and further evaluation of their possible environmental adverse effect therefore sounds mandatory in the present scenario.

## **2. Nanotechnology in agriculture**

One major concern the world globally facing today is food security to satisfy the needs of a vast population. According to reports, to fulfill the needs of 9 billion people, the world needs to produce 50% more food by 2050 [15]. The major hindrances associated with agricultural aspects such as food security, undernourished land, uncultivated areas, wastage and degradation of the shelf life of cultivated products, crop processing issues, and limitation of the agricultural practices need to be controlled to satisfy the food security of the entire population [16, 17]. With the drastic increase in a population explosion, the present global scenario greatly demands crop infrastructure and precision farming to satisfy the needs of the entire community without compromising both the quality and quantity of the nutrients. Currently employing strategies have greatly contributed to crop productivity enhancement, but the concurrent practice will lead to loss of soil fertility as well as the appearance of genetically resistant insects, pests, weeds, and newly emerged plant diseases, which leads to an unpredictable change in soil biota and ecosystem. Technological intervention is the only possible strategy that can be adopted to address these issues as the resources are limiting day by day. Therefore nanotechnology has evoked an impressive surge to surpass these hazardous effects at the same time providing an efficient outcome (Figure 1).

Nanoparticles with their unique functional characteristics can modulate physiological and biochemical pathways in plant systems such as respiration, photosynthesis, solute transport, nitrogen metabolism, etc. A wide range of ENPs has been developed in this context to improve agricultural productivity with the introduction of nano-fertilizers and nano-pesticide formulations. The United States Department of Agriculture-USDA, for the very first time in December 2002, proposed the world's first "roadmap" to apply nanotechnology in the field of agriculture and food [18]. NPs are reported to be active candidates for controlling membrane functionalities, modulator in the course of cellular biochemical interactions as well as a gatekeeper for entry and exit of micro/macronutrients. Thus they can either be a plant nutrient

provider, nano-fertilizer, or a phytoremediation agent. Various ENPs have been assessed for their ability to control physico-chemical pathways associated with plant biota also.



**Figure 1.** Applications of nanoparticles in agriculture technology.

### 2.1. Nanofertilizers and nanopesticides.

As potent nano fertilizers to improve crop productivity, alumina, single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (MWCNT), Zinc/Zinc oxides (ZnO) are mainly used, which are potentially tested in different crop varieties to prove the efficacy of the same [19]. Zero valent iron oxide NPs, cerium oxide NPs, as well as alumina nanocomposites, can be used as nano-fertilizer additives because they can activate plasma membrane  $H^+$  ATPase protein, enhance stromal functions, and control nutrient translocation from root to shoot. Due to the ability of augmentation of light reactions without any damage to the photosystem reactions, manganese NPs (Mn NPS) and copper NPs (Cu NPs) are proved to be effective candidates as micronutrient nano fertilizers [20]. Both have shown promising results in the carbon and nitrogen cycle, which are crucial in maintaining plant metabolism. In another study, ZnO NPs of 25 nm size at 1000ppm concentration was found to be effective for promoting plant growth, seed germination, and stem/ root elongation in peanuts [21]. Therefore colloidal ZnO NPs can be used as potent nano fertilizers. Titanium dioxide ( $TiO_2$ ) NPs have recently been investigated for the same, and it was reported that rutile  $TiO_2$  NPs had shown a considerable role in the germination and growth of spinach seedlings via improving its germination rate. Various factors affecting the growth and germination were found to be drastically elevated on  $TiO_2$  NPs treatment suggesting its applicability as efficient nano fertilizers to improve crop productivity and to maintain nutrient quality [22].

Nano alumina is another substitute for the same. Nano fertilizers may also constitute components such as silica NPs, Zn/ZnCdSe quantum dots (QDs), InP/ZnSe QDs, Mn/ZnSe QDs, nano zeolites, iron oxide NPs and gold nanorods [23]. Copper oxide NPs have shown their ability to protect the plant against bacterial (both gram-positive and gram-negative strains)

and fungal infections due to its inherent antimicrobial property. Cerium oxide NPs have shown an autophagy-mediated, antioxidant, and geno-protective role in plant cells, which can be utilized for the production of nano pesticides. NP based antifungal agents contribute to sustainable control in reducing major plant diseases. Graphene oxide (GO)/ silver NP composite was evaluated for this efficacy for the very first time recently. It was fabricated through interfacial electrostatic self-assembly, and the antifungal effect was monitored against phytopathogen *Fusariumgraminearum* both in *in vitro* as well as *in vivo* conditions [24]. The nanocomposite showed a 3-7 fold increased effect when compared to silver NPs alone concerning the prevention of fungal spore and hyphae germination. Moreover, the chemical reduction of GO mediated by fungal spores greatly contributes to the overall antimicrobial effect, which greatly imparts to its efficiency as a potent antimicrobial agent against a broad spectrum of pathogenic fungi. SiO<sub>2</sub> and ZnO NPs also contribute to the same due to inherent antimicrobial property either by rupturing bacterial or fungal cell wall or by coagulating with membrane proteins.

### *2.2. Plant metabolism and membrane functionalities.*

MWCNTs and SWCNTs, zinc, ZnO, TiO<sub>2</sub>, and alumina NPs were studied for their ability to promote seed germination and root growth. Promising results were exhibited by MWCNTs and SWCNTs with increased seed germination and improved crop productivity. The effect of rutile nano-TiO<sub>2</sub> on photochemical reactions of spinach chloroplast was studied, and the results suggest that several biochemical pathways sustaining photochemical reactions have drastically improved, such as chloroplast coupling, the activity of Mg<sup>2+</sup>ATPase, and chloroplast coupling factor-1-ATPase on the thylakoid membranes. These activations were suggestive for improved photosynthetic efficiency of spinach chloroplast [25]. TiO<sub>2</sub> and iron oxide NPs were studied for their ability to absorb and translocate phosphate ions from soil to make it available for plants for various synthetic pathways. It was proved that these formulations could be effectively applied as a good additive for nutrient management systems [26]. In another study, the photochemical reactions of spinach chloroplast were studied using rutile TiO<sub>2</sub> NPs, and the results showed that these NPs activate chloroplast photochemical reactions [25]. Likewise, Fe<sub>3</sub>O<sub>4</sub> NPs was studied for its ability to absorb, translocate, and accumulate the nutrient particles in plant tissues [27].

Au NPs and Se NPs will help to enhance the catalase activity as well as chlorophyll content in plants. Almost all the studies provide evidence for NPs mediated secondary plant metabolism up-regulation via the ROS trigger. Recognition of Ag NPs on the plasma membrane and subsequent membrane-bound NPs triggered Ca<sup>2+</sup> release, and ROS leads to the up-regulation of various protein synthesis signaling pathways. The subsequent MAP Kinase phosphorylation further activates various downstream signaling pathways for the transcriptional reprogramming of various secondary plant metabolites. This suggests ample evidence for the possibility of MAPK cascade in plants. Therefore, it is highly anticipated that the presence of NPs can bring about various additive or synergistic actions that regulate diverse plant metabolic processes.

### *2.3. Micronutrient substitutes.*

Various metal-based NPs such as Ag NPs, TiO<sub>2</sub> NPs, Au NPs, Fe NPs, Cu NPs, FeS<sub>2</sub> NPs, ZnO NPs, etc. as well as carbon-based GO, fullerene NPs and carbon nanotubes are potent

seed priming agents and nutrient providers that promotes growth, seed germination and impart stress tolerance in plants [28]. A wide range of synthetic fertilizers offers micronutrients in NP formulations, which can be readily taken up by plants under any adverse conditions. Nano-encapsulated slow-release nutrient composites can offer the sustainable release of nutrients with minimal environmental hazards.

In a recent study, nano cerium functionalized straw biochar derived from maize straw was used for the evaluation of phosphorus bioavailability in mudflat-reclaimed soil [29]. Results of a recent study revealed the effects of nano TiO<sub>2</sub> and nano ZnO on grain yield of barley plants. It was reported that barley plants separately treated with chelated ZnO NPs during different stages of tillering, booting, and milky stages of germination revealed significant improvement in attaining maturity. Likewise, foliar application of nano TiO<sub>2</sub> enhanced chlorophyll content and straw yield [30]. Therefore, this can be an effective strategy for nutrient management in nutrient-deprived soil in semi-arid regions. Zero valent iron NPs (Fe NPs) are excellent phosphate ion adsorbents that help in the rapid uptake of phosphate ions from the soil. Micronutrient fortified supplements containing copper and manganese NPs have been evidenced for their light reaction augmentation efficiency during photosynthesis and showed promising results with carbon and nitrogen metabolism in plants [31]. Graphene is a renowned carbon allotrope, and depending on the dose and exposure limit, graphene NPs and graphene oxide NPs can be used for plant nutrient fortification via functioning as a carrier moiety for the slow release of plant micronutrients. The molecular mechanism and physiological effects of nano seed priming methods have not been impressively studied yet; therefore, many queries remaining are still not completely unveiled.

#### 2.4. Nanosensors in agriculture.

Nanosensors have found its application in agriculture for determining the adequate amount of crop activators and pesticides used for effective farming. They offer high sensitivity and selectivity in detecting pesticide residues present in soil and also detect soil nutrients, soil quality, toxins, pathological analysis, and moisture content in the soil. Optical nanosensors, wireless nanosensors, electrochemical nanosensors, bio-nanosensors, nanobarcode technology, etc. have transfigured agriculture and food technology with real-time sensing and multiplex sensing capabilities [32]. Enhanced sensing platforms were found to be contributed by metallic NPs like gold and silver, magnetic NPs like iron oxide, semiconductor QDs, carbon-containing NPs like fullerene, graphene, MWCNTs, and SWCNTs. An electrochemical acetylcholinesterase based biosensor made of platinum electrode modified ZnO nanocuboids have been recently developed for the effective detection of carbosulfan in rice [33].

Nanosensors are used to analyze the qualitative as well as quantitative appropriateness of farming soil in the context of soil fertility and microbial biota. Based on these, a plethora of nanosensors have been developed so far in the framework of nanotechnology. A polymer/ gold nanoparticle microsphere has been designed for the detection of malathion toxin in soil by Barahona *et al.*, [34] in which the colloidal gold NPs (40 nm) were conjugated to micrometer-sized polymer composite via surface functionalization with 2-aminoethanethiol. Thiolated gold NPs served as the sensing moiety for malathion, which will specifically target the aptamer sequences enabling detection up to 3µg/mL sensitivity via SERS technology. In another study, an electrochemical nanosensor has been designed to detect the presence of organophosphate and carbamate insecticides like chlorpyrifos and carbofuran in soil, in which cysteine functionalized 50 nm sized hollow gold NPs were used as the base targeting ligand. On to this

nanocomposite, enzyme acetylcholinesterase has been incorporated to effectively detect these toxins. The inhibition of this enzyme gives an idea about the quantitative assessment of chlorpyrifos and carbofuran [35].

Mercaptophenyl boronic acid-functionalized ZnSe QDs adhered to graphene/chitosan nanocomposite served as an excellent sensor for the detection of methyl parathion toxin in soil with a detection limit of even smaller than 0.2 nM [36]. In another study, mercaptopropionic acid (MPA) capped CdSe/ZnS core-shell QD based nanosensors have been developed, which enables imaging-based detection of even trace elements in soil [37]. Unchecked use of a huge amount of pesticides and fertilizers always leaves behind its severe toxic impacts on the soil and whereby it will contaminate the whole ecosystems in connection with it. Deltamethrin is a broad-spectrum weedicide widely used in agricultural lands that leave behind its prolonged consequences such as chronic toxicity, long persistence, and non-degradable nature in soil. To check the same, highly fluorescent silica NPs embedded CdTe QDs have been investigated that could check the traceability of this toxin up to the limit of even 0.16 µg/mL [38]. Also, for the detection of organophosphate based chemicals in soil and vegetables, amino acid-functionalized CNTs with immobilization of acetylcholinesterase were evidenced to be effective with a detection limit of up to 0.08nmoles [39].

Concanavalin A is a plant lectin that specifically blocks plant cell proliferation by targeting the glucose and mannose residues in plasma membrane receptors. For the sensitive detection of this concanavalin A, graphene oxide modified gold sensor chips have been fabricated, which detect the number of bound substrates by the surface plasmon resonance frequency of the detector [40]. In another study during the same period, an amperometric nano-immunosensor has been fabricated for the selective detection of carbofuran (2,3-dihydro-2,2-dimethylbenzofuran-7-yl methylcarbamate), which is a broad-spectrum weedicide used in agricultural fields. For this technology, they have designed a monoclonal antibody specific to this compound and adsorbed on to MWCNT/graphene nanosheet/ polyethyleneimine/gold NPs composite, and detection accomplished via simultaneous amperometric immunosensing [41]. Usually, in nanosensor designing, this concomitant strategy employing both electrochemical and immunological sensing techniques gives about reliable sensitivity, tractability, and acceptance.

### **3. NPs in the aquatic system and clearance of oil spillage**

Nanotechnology has enormously contributed to environmental protection via oil spillage degradation and petroleum product spillage control. One such example is the use of Ag NPs in reducing the accumulation of propylene oxide and other toxic by-products during the production of plastics, paints, and detergents. CF<sub>3</sub> functionalized silica aerogel, magnetic nanocomposites such as iron oxide NPs in organoclay, polymer-magnetic NPs composites, collagen/Fe<sub>3</sub>O<sub>4</sub>, carbon- metal nanoalloys as well as carbon-iron oxide nanocomposites can be used for these purposes. Recently manganese oxide nanowire-based membranes were fabricated intended for oil spillage clearance via filtration [42]. Likewise, various wettable nanomaterial-based products have been designed, fabricated, and applied to resolve oil spillage in water resources [43].

Studies have shown that gold NPs embedded mesoporous manganese oxide catalysts can be suggestive for clearing volatile organic compounds such as toluene, hexane, acetaldehyde, etc. [44]. On to the graphitic structures on CNTs, organic compounds having functional groups like -OH, -COOH, and -NH<sub>2</sub> can bind. This typical interaction can be used

for removing most of the toxic organic moieties from oil spillages [45]. Organic molecules with a typical gelling property offer a cheap and environmentally friendly approach for oil spill cleanup. Some studies, therefore, reported the efficacy of 'supergelators', which are organic NPs formulations when sprayed on contaminated water would get roll up into 50-100nm bundle nanofibres. This will eventually fabricate a web to trap the crude oil and petroleum fragments.

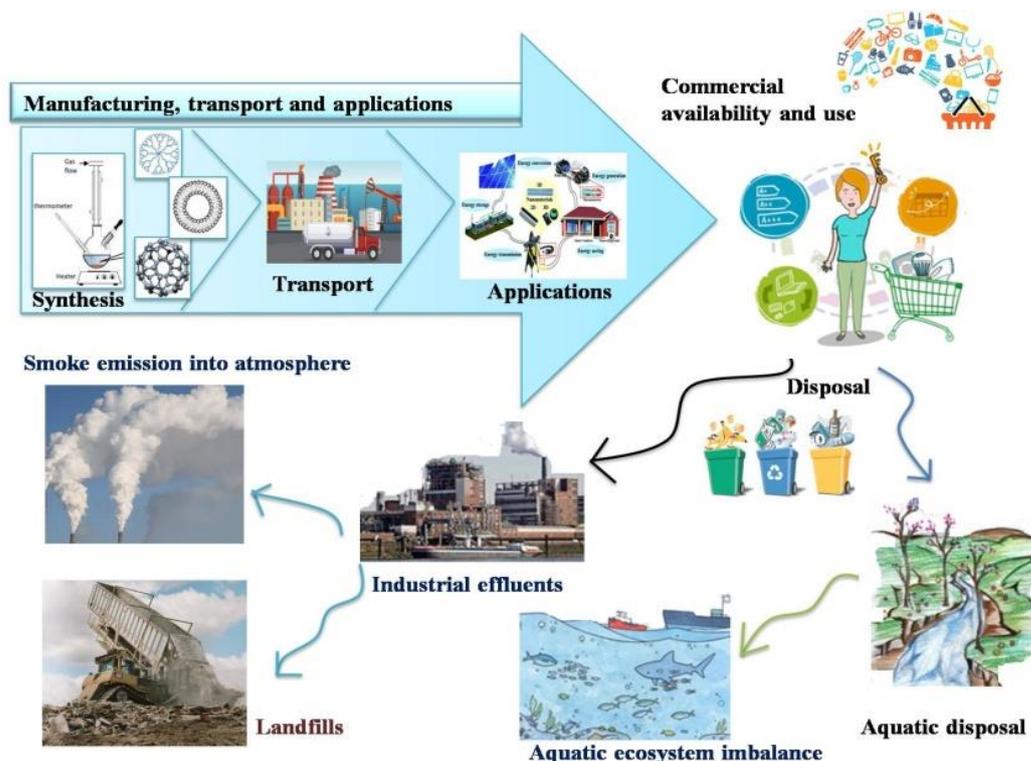
#### **4. Renewable energy**

In accordance with a report that came in 'International Energy Outlook, 2007', the worldwide consumption of marketed energy is anticipated to rise to 57% by 2030 [46]. This foresees the necessity of advanced renewable energy-based technologies for the sustainable utilization of energy sources. Nanotechnology marked a remarkable abrupt regarding this with the introduction of CNTs, fullerene, and perovskite like QDs for photovoltaic devices that generate electricity via the conversion of photons absorbed from the sun. CNTs are sought to be the substitute material in various solar cell technologies like silicon-based and organic dye-sensitized solar cells with improved efficiency. Conventional graphite electrodes are replaced by CNTs in batteries. In electric transmission grids, wires having CNTs are used as it has high electrical conductivity.

In transformers, fluids containing NPs can be used as coolants at the same time, improving the efficiency of transformers. Nano-engineered polymer matrix and plasmonic cavities can be used in the designing of high-efficiency light bulbs. Another recent idea under keen development is to update the incandescent bulbs by entrapping the conventional filament with some crystalline NPs that can convert infrared rays to visible light [47]. Li-ion batteries (LIBs) and Na-ion batteries (SIBs) are highly demanding rechargeable energy storage systems for portable electronic consumables. Graphene and transition metal-based NPs have been used as anodes for these energy storage systems. CNTs can be used to replace silicon in microprocessors allowing manufacturers to develop denser 3D chips having faster processing speed. Very recently, the University of Missouri researchers have developed nanomaterial-based antennas called 'Nantennas' that capture both IR and visible light to generate thin-film solar sheets giving 90% efficiency than currently employed solar panels. Nanocones made of ZnO were reported to boost-up the efficiency of conventional solar cells. Very recently, University of Texas researchers have developed carbon nano- supercapacitors called 'Nanosponges', which is efficient in storing static energy and can deliver energy even faster than conventional chemical-based batteries. Piezo electronic nanofibres are another class of flexible materials that can easily generate electric current when meager mechanical stress is applied to it, which can be effectively used for energy scavenging applications. Thus nanotechnology has brought about huge significant breakthroughs in the field of renewable energy to effectively challenge the issues of energy starving the economy.

#### **5. Exposure to the ecosystem**

It has been foreseen that the abrupt application possibility of NPs opens up a wide diversification in various emission sources of these into the environment. Three emission circumstances are generally considered with NPs exposure to the environment. They are (i) release during NPs raw material synthesis and product development (ii) release during its use, and (iii) release after its disposal or waste handling (Figure 2).



**Figure 2.** Possible ways of nanoparticle exposure into different ecosystem habitats.

According to reports,  $\text{TiO}_2$  and  $\text{SiO}_2$  are the most relevant materials in terms of worldwide productivity, which was followed by oxides of Ce, Fe, Al, Zn, and CNTs [48]. Studies have reported that most of the NPs exposure happened during its usage and after disposal, but while during production, mere quantities have been exposed to the environment. Also, disposal of NPs and other chemicals from chemical laboratories without taking proper precautions is another source. Depending on the type of application, these are either directly released into natural ecosystems or indirectly via sewage treatment plants or waste streams, causing a delayed-release into the environment. NPs in paints, fabrics, and personal health care products, including sunscreens and cosmetics, will eventually enter land and water bodies directly and get deposited [49]. The adverse effects will depend on nature and chemical composition of the material. It was reported that the dominating emission strategy for  $\text{TiO}_2$  NP release was associated with accumulation in sewage treatment plants during wastewater purification, which ultimately gets released into the soil [50]. While during incineration, chances are high for NPs accumulation in air. Approximately 30% of  $\text{TiO}_2$  emissions get deposited in these ways. ZnO NPs are commonly employed in the cosmetic and medical industries. A high chance of emission via water resources was found for ZnO NPs also. But CNTs are found to be mainly released into the atmosphere during its production and usage, and approximately 90% of CNTs are found to be accumulated in the soil, and some sediment can be seen in the air also [51]. According to global reports, the majority of NPs exposure to the environment is via landfills and soil (80%) followed by emission into the aquatic environment and air.

## 6. Impact of ecosystem balance

Most of the NPs discharged into the environment were provided with a path to enter into soil biota like microbes and thereby enter into the food chain, eventually disturbing the ecosystem balance. Coastal runoff and surface deposition are the major contributors to aquatic

ecosystem contamination that will subsequently lead to marine ecosystem imbalance. Some metallic NPs, like Molybdenum, can easily mimic the active site prosthetic groups of certain microbes and can deprive the enzymatic activity. The general adverse effects include oxidative stress and related biomarker expression, inflammation, etc. The release of NPs to aquatic ecosystems may impose a greater threat to aquatic flora and fauna (Table 1).

**Table 1.** Depicted various currently employed nanoparticles, their environmental exposure sources, possible environmental adverse effects, and suggestive toxic responses in the living system.

Nanoparticles/ size	Environmental source	Environmental Impacts	Toxic response in the living system	References
ZnO NPs 20-50 nm	Cosmetic products, bactericidal agents, pharmaceuticals, textiles, photocatalysts, food packaging	Extremely toxic to various aquatic trophic levels, zebrafish embryo damage	ROS generation, DNA damage in the zebrafish embryo, leaching of Zn <sup>2+</sup> ions leads to neurotoxicity	[52, 53]
TiO <sub>2</sub> NPs 100 nm	Cosmetics, coatings, catalysis, water purification, UV protector, medical devices, dental restoration	Down regulation of radical scavengers in aquatic organisms, growth inhibition of freshwater algae, oxidative stress, micronuclei formation, and DNA breaks	Inflammatory cytokine upregulation, apoptotic gene activation, inhibition of heat shock proteins, and neuroinflammation	[54, 55]
CNTs (MWCNTs and SWCNTs) 100 nm	Renewable energy sources, batteries, solar cells, sporting equipment, lubricants, water treatment plants	Mild indirect effect on aquatic organisms and soil microbes, negative impact on algal growth, toxic effects on freshwater aquatic invertebrates	MWCNTs show the carcinogenic effect, SWCNTs can be uptaken by macrophages immediately from circulation, lung toxicity, ALT/AST/GSH levels increased in the liver of SWCNT treated animal	[56, 57]
Fullerene NPs 20-100 nm	Volcanic eruption, coal mining, automobiles, burning of fuels, lubricants	The graded concentration of C60/C70 fullerenes on embryonic zebrafish showed up to 100% mortality, malformations, and pericardial edema. Effects on soil nematodes and aquatic ecosystem	DNA strand breakage, micronuclei formation, and chromosomal aberration were observed in some <i>in vitro</i> studies. Stimulate platelet aggregation	[58, 59, 60]
Graphene NPs 20-100 nm	Coal mining, automobiles, burning of fuels, lubricants, research activities	Loss of organelle membrane potential in aquatic microbes, negative impact on microbial biota	Dose dependant toxicity in animal cells, lung granuloma, kidney malfunctioning, hepatic problems associated with oxidative stress	[61, 62]
Silver (Ag NPs) 10-100 nm	Antimicrobials and cosmetic products, toothpaste, shampoo, sanitizer sprays, detergents, soaps, dental products, and medical devices	Toxic responses were observed in aquatic organisms. Undergoes multiple transformations when released into the environment, causing adverse impacts to flora and fauna	Alterations in nonspecific immune responses, alterations in cell signaling, apoptosis, necrosis, oxidative stress	[63, 64]
Gold (Au NPs) 10-50 nm	Beauty care products, sunscreens, therapeutic agents, imaging agents, photovoltaic, wastewater treatment	Affects reproduction and fertility in daphnia, mammals, and fishes. Bio-toxicity and necrosis in exposed plants	Size-dependent accumulation in different organs, positively charged Au NPs showed more cytotoxicity, accumulation in the liver, causing oxidative stress. 15-50 nm can effectively cross BBB	[65, 66]

Nanoparticles/ size	Environmental source	Environmental Impacts	Toxic response in the living system	References
Arsenic/ Cadmium/ Lead NPs 1-20 nm	Conventional quantum dots, solar cells, research activities,	Extremely toxic to airborne, waterborne, and soilborne pathogens and microbial biota, cause severe inflammation in other ecosystem species, drinking water contamination agents	Fatal respiratory and kidney problems, renal tubular dysfunction, carcinogenic, oxidative stress, inflammatory biomarker gene upregulation	[67, 68]
Quantum dots 1-10 nm	Photoluminescence based medical applications, photovoltaics, optoelectronics, energy storage, drug delivery, sensors	Induce toxicity and food chain transfer in aquatic algae and Ceriodaphniadubia species. Disrupts ions channels	Endothelial toxicity by activation of mitochondria, easy penetration into BBB and placental barrier, neurotoxicity, nephrotoxicity, hepatotoxicity. Heavy metal leaching leads to severe toxic effects.	[69, 70]
Silica NPs 50- 100 nm	Food additives, adsorbents, thickeners, flavoring agents, paints, varnish	A fibrotic lung disease called silicosis as an occupational hazard, emphysema, pulmonary tuberculosis, lung cancer to living beings. Toxic to aquatic and terrestrial flora and fauna	Increased level of ROS secretion, induction of inflammatory biomarker genes like IL-1, IL-6, IL-8, and TNF-alpha, hepatotoxicity, immunotoxicity, autophagy	[71, 72]
Polymeric NPs 50- 100 nm	Paints, varnish, plastics, textiles, fertilizers, food adulterants, and preservatives	Impart toxicity in aquatic organism via biotransformation, accumulation, and migration along with the food web	Oxidative stress, inflammation, fibrosis, alteration in cellular morphology	[73, 74]

Various studies have reported that MWCNTs and fullerene NPs can elicit toxic responses and inhibit the growth of zebrafish embryos and *Xenopus tropicalistadpoles*[75]. The most commonly used NPs, such as Ag, TiO<sub>2</sub>, and ZnO NPs are subsequently released into water bodies, causing serious concerns about the safety of the aquatic environments and its dependants [76]. QDs like cadmium tellurium (CdTe) could generate ROS leading to inflammation and lipid peroxidation to freshwater mussels, especially by damaging their gills. Leaching of heavy metals leads to heavy metal intoxication that will directly affect aquatic fauna and indirectly affect human life by consuming them.

The potential risk associated with these materials depends on their size, morphology, solubility, and agglomeration tendency. Asbestos is one classic example, which is a naturally occurring silicate-based NPs that consists of long fibrous crystals. Each fiber constitutes millions of microscopic minute fibrils that possibly get released into the environment during abrasion. This can evoke serious adverse effects, and in some circumstances, this can be fatal also [77]. Global estimation of NPs emission indicates that soil and landfills (approximately 60-90%) account for the largest share, followed by subsequent release into aquatic environments and air [78]. It is quite likely that these will get transformed to larger aggregates and further dissolve, oxidize or reduce to even more toxic by-products thereafter. Such estimations can put forward the possible exposure limit that can be used to potentially analyze the severity of further environmental implications [79]. Currently, no effective strategies are available for the detection of nano waste in the aquatic ecosystem; the only way is proper disposal. Likewise, various structural and functional changes and challenges can happen in

both aquatic as well as terrestrial biota, but neither the underlying cause nor the mechanisms driving these challenges have been completely understood.

## 7. Ecotoxicity

### 7.1. Soil ecosystem (bacteria, fungi).

Industrial spills, land spills, and sewage sludge contribute major routes for NPs exposure in the soil ecosystem. This will, in turn, alter the soil composition, pH, and nutrient availability in soil. Metal and metal oxide NPs constitute more than 11 million tons of overall NPs production. These NPs can enter into soil microbes by endocytosis or by penetrating microbial cell walls. Once enter inside the cell, these NPs can alter the catalytic activity of enzymes by promoting protein denaturation or by changing the chemical composition of active catalytic sites of enzymes. The release of metal ions and subsequent ROS production will lead to oxidative stress-mediated biochemical responses inside the cell [80]. Ag NPs have been reported to reduce bacterial enzyme activity in two major soil bacterial strains, *Bacillus cereus*, and *Pseudomonas stutzeri*.

Oxidative stress response genes like *katB*, *pykA* genes were found to be overexpressed in the bacterial cells after NPs exposure. Altogether, an altered bacterial transcriptional response was found as a consequence of Ag NP exposure [81]. The release of toxic metal ions and subsequent interaction of these metal ions with microbial cells accounts for another major contribution of NPs induced toxicity. Mostly, these released ions such as Cr, As, Cu, Fe, Hg, and Cd interact with cellular proteins generating ROS mediated oxidative stress response. Alterations in the normal redox state of cells lead to an abrupt imbalance between ROS generation and the ROS detoxification efficiency of cells. These will eventually lead to free radical-mediated membrane protein denaturation, membrane destabilization, and DNA fragmentation. Metallic NPs like Arsenic containing compounds tend to agglomerate the natural antioxidants such as glutathione (GSH) present inside the cell by forming covalent bonds with sulfur causing thiol oxidation. This will hamper the activity of GSH dependant enzymes such as glutathione peroxidase, GSH-S-transferase, and glutathione reductase [82]. One study reported that upon exposure to ionic  $Ag^{2+}$ , activation of bacterial DNA conglomeration defense genes happens that severely compromised bacterial replication system [83].

Chen *et al.* [84] successfully demonstrated the impact of  $TiO_2$  NPs with photosynthetic bacterial light-harvesting complex (LH2), which confirmed the structural deterioration of the protein complex. Later on, Sinha and Khare [85] proposed conceptual proofs for the same, stating the involvement of electrostatic, hydrophobic, and hydrogen bonding interactions between NPs and proteins, leading to irreversible protein inactivation. Positively charged NPs like Au, Ag NPs can get entrapped into the negatively charged peptidoglycan layer on the walls of gram-positive bacteria like *s.aureus*, causing membrane disruption. This will enhance ROS production and increase mechanical stress on the membrane leading to membrane depolarization [86]. Some NPs like Gallium and Chromium will interfere with nutrient assimilation pathways in soil microbes. Chromium can cause sulfur starvation in *S.cerevisiae* cells by interfering with sulfur uptake and assimilation. This is due to the high affinity of chromium towards the active site of sulfur transporter enzymes *Sul1* and *Sul2* [87]. Similarly, while coming to mycorrhizas and rhizobia, the concentration of NPs in the soil is a critical factor driving the NP-mycorrhiza/ rhizobia interactions [88]. Least toxic NPs like  $ZnO$ ,  $TiO_2$

can become inhibitory in action at higher concentrations, and on the other hand, highly toxic metallic NPs like Ag NPs can be stimulatory at even lower concentrations. ZnO NPs were found to critically affect fungal colonization in the roots of legume plants. A well-defined species dependant bactericidal action was elicited by ZnO NPs in N<sub>2</sub>-fixing bacterium *Sinorhizobium meliloti*; however, different strains of E.coli was found to be extremely resistant to these metallic NPs [89].

### 7.2. Aquatic ecosystem (fishes and larvae).

Polluted water bodies and destroyed aquatic ecosystem has become one among the serious threats of industrialization. Analyzing several studies, it has been confirmed that most of the lethal cases are due to NP accumulation leading to oxidative stress-related pathophysiology. Many shreds of evidence suggest that NPs can cause a range of sublethal effects on aquatic organisms' organ pathology (gill, liver, intestine, brain), inhibition of Na<sup>+</sup>/K<sup>+</sup> ATPase system, essential trace elemental composition, etc. Different NPs elicit responses differently. Yet then, in general, it will result in ROS production due to NP aggregation characterized by subsequent loss of plasma membrane and subcellular organelle integrity as well as DNA damage. Metallic NPs, including Au, Ag, Mg, Mn, Co, Cu, Ti, Si, Fe, and Al, are well studied about the possibility of contaminating the aquatic ecosystem and its dependants.

Usenko *et al.* [90] reported that with exposure of 200mg/ml of C60, C70 fullerenes; zebrafish larvae showed incurable malformations such as pericardial edema, gill damage, and even increased mortality whilst higher concentrations. CNTs of 20nm size dispersed in SDS solvent were known to impart dose-dependent increase in ventilation rate, hyperplasia, excess mucus secretion, and altered gill pathology in Rainbow trout (*Oncorhynchus mykiss*) species [91]. Thus carbon-based NPs were also found to be good contributors towards aquatic biota toxicity. Nano TiO<sub>2</sub> and nano Al<sub>2</sub>O<sub>3</sub> were found to impose detrimental effects on the chemotactic response of ciliates *Paramecium caudatum*, the growth of unicellular algae *Chlorella Vulgaris beijer*, and the mortality of crustacean *Daphnia magna straus* [92]. Several studies revealed the selective dependence of NPs toxicity on their size, chemical composition, and concentration. In some studies, the toxic effect of TiO<sub>2</sub> exposed at a concentration of 1mg/mL for 48h was found to cause edema in the gills of fishes and that for nano Cu was characterized by proliferation of epithelial cells and gill filament edema [93].

Anatase TiO<sub>2</sub> NPs (5nm) exposed goldfish (*Carassius auratus*) skin cells tended to induce detrimental genotoxic effects and become unresponsive to photo stimuli. In a similar study, Ag NPs (5-20nm) of 100µg/mL concentration exposure for 72h showed dose-dependent mortality and malformations in zebrafish embryos, whereas 1mg/mL exposure in adult zebrafish showed brain seizures and organ malformations [94]. ZnO NPs also showed dose dependant toxicity and related effects in various aquatic invertebrates. 20nm average-sized ZnO NPs and 60 nm-sized SiO<sub>2</sub> NPs caused severe oxidative stress in zebrafish embryos, which leads to prolonged hatching time of embryos with increased mortality rate. Metallic NPs were reported to be more toxic and least excretable when compared to non-metallic NPs in which they tend to accumulate in major organs causing severe lesions and seizures, leading to increased mortality of aquatic fauna. In another study, Selenium NPs of average size 30nm were found to elicit acute toxic responses than selenite powder, causing persistent gill damage to Japanese medaka (*Oryzias latipes*) [95].

Nanosilver was found to cause concentration dependant increase in mortality with tail and spinal cord truncation and cardiac malformations, which lead to increased mortality to fish

larvae. Metallic NPs like TiO<sub>2</sub> showed a concentration dependant oxidative stress-mediated toxicity to marine planktonic species. One such study by Ma *et al.* [96] highlighted this fact stating the effect of TiO<sub>2</sub> NPs in the planktonic crustacean *Daphnia Magna* and Japanese rice fish larva. Both the species were treated with varying concentrations of NP for varying periods of 48 and 96h, respectively. The study effectively revealed the pronounced phototoxic effect accounts for ROS generation induced toxicity of TiO<sub>2</sub> NPs in these planktonic species. The physiological effects of NPs on aquatic ecosystem dependants are a relatively underexplored area of research. Although the dataset is rather limited, there is a strong enough indication from the existing reports that NPs are critically toxic to aquatic fauna rather than the dissolved bulk metal counterparts.

### 7.3. Terrestrial biota (phytotoxicity).

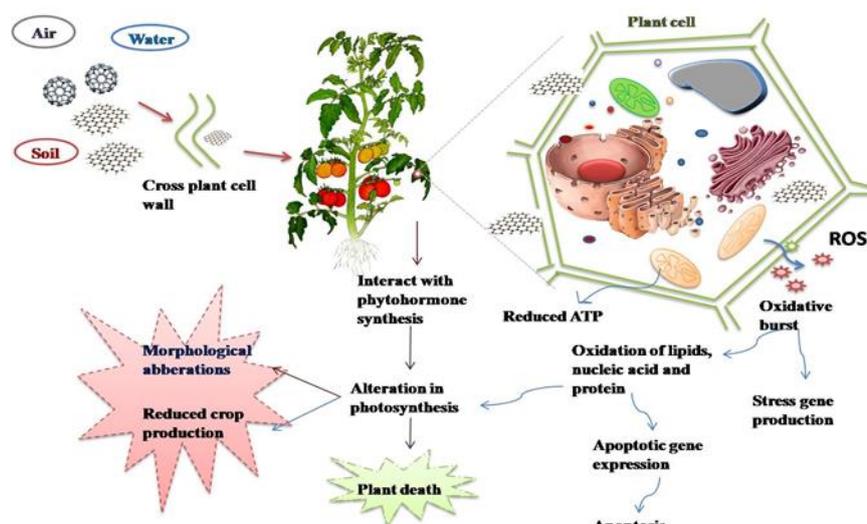
ENPs designed for nano-agriculture and biotechnological applications are sometimes processed to uptake by plants. A certain degree of phytotoxicity has been exhibited by almost all NPs in a concentration dependant manner. The internalization of NPs by plants is usually mediated by clathrin dependant endocytosis, and in some cases, clathrin-independent pathways are also studied. In the clathrin dependant pathway, NPs can bind to clathrin proteins on the cell surface and get invaginated inside the cell. Reports suggest that the possible clathrin-independent pathways include (i) caveolae and lipid-raft mediated uptake, (ii) fluid-phase endocytosis, and (iii) phagocytosis [97]. Various adverse pathophysiology can be observed in plants after NP uptake (Figure 3).

Subsequently, its transport and bioaccumulation via the food chain is an indispensable concept. This bioaccumulation and tropic transfer of ENPs has been documented about the aquatic ecosystem in several studies but very much restricted to terrestrial plant biota. ENPs that are intentionally applied for bioremediation purposes or to enrich soil nutrition can deposit on the leaves or other aerial parts of plants leading to stromal penetration and impose an unrecovered effect on the metabolic processes in plants. Rico *et al.* [98] reported the effect of nano Al<sub>2</sub>O<sub>3</sub> on *Glycine max*, *Z. mays*, *C. sativus*, *B. oleracea*, and *Daucus carota* plants and observed that root elongation was suppressed in all crop variants with a significant level of phytotoxicity. A comparative study of nano and bulk counterparts of Fe<sub>2</sub>O<sub>3</sub> and CuO on ryegrass showed the tendency of nanoformulations to impart more phytotoxicity when compared to the bulk formulation. This is because of the tendency of NPs to be effectively taken up by cells rather than sticking on to the surface and thereby generating ROS and oxidative stress [99]. In a study by Canas *et al.*, [100], the nanotoxicological effect of ENPs on a broad spectrum of plants has been evaluated in which they found that metal oxides of rare earth metals impose no effect on seed germination of *C. sativus*, *B. oleracea*, *B. napus*, and *Lycopersicon esculentum* species.

It was reported that nano La<sub>2</sub>O<sub>3</sub>, Yb<sub>2</sub>O<sub>3</sub>, and Gd<sub>2</sub>O<sub>3</sub> inhibited seedling elongation to a very mild extent in all the species, whereas CeO<sub>2</sub> was relatively inert in imposing even such mild changes. Contradictory results were obtained with CNTs in which the exposed seedlings were found to drastically inhibit root elongation and seedling germination. Nano TiO<sub>2</sub> mediated phytotoxicity was evidenced for the DNA damage detected in *N. tabatum* plants, which is evidence for ENP mediated genotoxic effects in terrestrial plants. It was reported that nano TiO<sub>2</sub> induced micronuclei formation and DNA laddering in root cells of *A. Cepa* plants [101].

Nano ZnO and SiO<sub>2</sub> were reported to be toxic to seed coats and also regulate the gating of aquaporins, which are membrane proteins that translocate water molecules across cell walls

on plants. Likewise, MWCNTs can upregulate gene expression of these aquaporins, whereby translocation of excess water leading to whole plant destruction. For instance, different variants of fullerenes like hydrophilic C60 fullerol (25nm) and hydrophobic C70 fullerenes (100nm) underwent thorough check for its presence in between the cell wall and plasma membrane of *A. cepa* plants. It was found that hydrophobic C70 fullerenes were aggregated at the interface showing clear-cut Evidence for the ability of NPs to penetrate through the surface that is even smaller than their size with an increased permeability effect. In conclusion, almost all the NPs can directly or indirectly affect plant metabolic processes whereby hamper processes like photosynthesis pathways, growth, and differentiation, pollen generation, vascular tissue proliferation, etc.



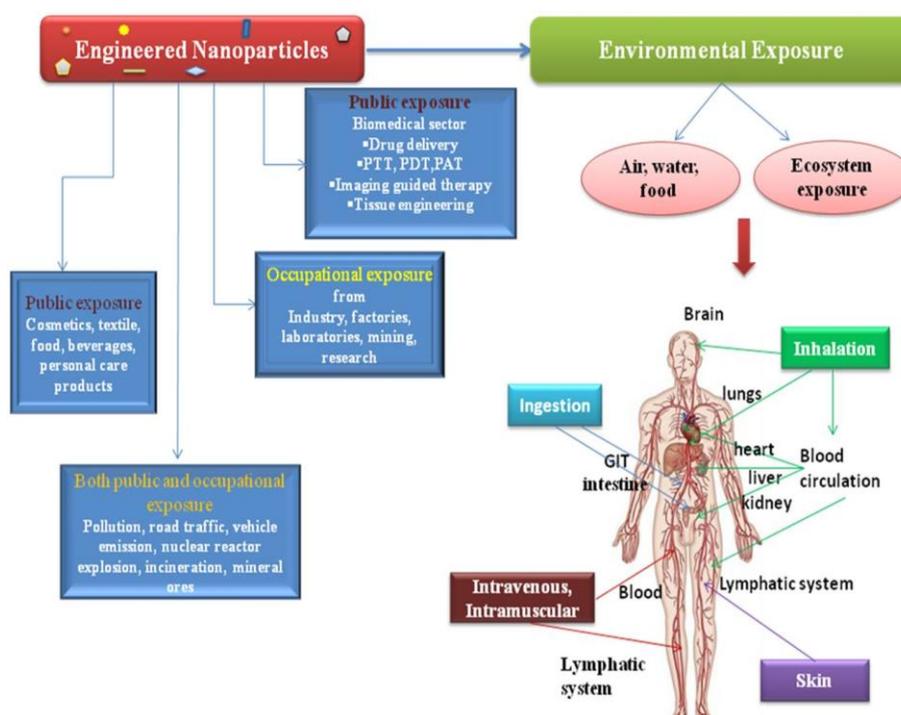
**Figure 3.** Adverse effects of nanoparticle uptake in plants.

## 8. Occupational exposure of NPs

Exposure of NPs from the environment to humans can be explained in various ways, and the foremost among them is the occupational exposure of NPs. Occupational activities with substantial probabilities of workplace exposure involve energy, healthcare, construction, chemical industry, automobile/aerospace industry as well as applied electronics. Considering the most possible exposure routes, occupational cohorts are likely to have faster magnitude exposure that may occur via ingestion, inhalation, and skin absorption (Figure 4). Among these, inhalation routes have received a global outreach for workplace hazards. During both synthesis and recovery processes in commercial NPs production, increased chances of occupational exposure can happen mainly through various routes. Airborne exposure is the most prevailing one. The likelihood of inhalation occurs during high-temperature evaporation and gas-phase flame pyrolysis that can lead to direct leakage from reactors causing drastic respiratory hazards. Especially, generating NPs in a non-enclosed environment will increase the chances of direct entry into the atmosphere, which directly or indirectly harm the dependants. Aerosolization of NPs can occur during these conditions. Working with NPs in colloidal or liquid media without taking proper precautionary measures will increase the risk of skin exposure. Among the largely commercialized NPs, asbestos, TiO<sub>2</sub>, ZnO, CNTs, carbon black, fullerenes, Aluminium oxides (AlO<sub>x</sub>), CeO<sub>2</sub>, Silver, Iron, Silica, and Gold are the serious contributors to this scenario

[102]. Due to increased application in the cosmetic, plastic, and textile industry, TiO<sub>2</sub> contributes more to this growing occupational exposure hazards.

Nano formulations are potentially responsible for the drastic adverse effects of TiO<sub>2</sub>. Cardiopulmonary defects and carcinogenicity are the most prevailing outcomes of TiO<sub>2</sub> NP exposure. Ultrafine nanoformulations are found to be more potent in elucidating toxic responses. ZnO and CNTs the preceding ones after TiO<sub>2</sub> related to occupational exposure of NPs. CNTs were proved to be able to behave similarly to asbestos when deposited in the lungs resulting in acute pulmonary inflammation leading to the onset of pulmonary fibrosis. Various *in vivo* studies have reported the ability of MWCNTs in evoking similar responses to that of asbestos mediated pathogenicity in experimental mice and rats even with acute exposure. Skin sensitivity and eye irritation are the prevailing clinical conditions associated with gold and silver NPs. Increased chances of NPs exposure can likely occur during spillage of products, handling errors during recovery and packaging, cleaning and maintenance activities, direct leakage from reactors, and during various post-production processes. The use of proper and adequate precautionary strategies is, therefore, necessary. A combination of exposure assessment and animal toxicological examination is, therefore, a mandatory criterion for meaningful occupational health and safety recommendations.



**Figure 4.** Occupational exposure of nanoparticles and nanoparticle-mediated adverse effects in humans.

## 9. Conclusion

Nanotechnology has become in the limelight of various interdisciplinary researches from the past few decades owing to their intriguingly appealing characteristics. It has considerably revolutionized many technological inventions, especially in electronics, optoelectronics, environmental remediation, agriculture, to even biomedical technology. Development, usage, and potential release of NPs have run ahead of possible risks they impose on the environment. Uncertainty about factual data on NPs contamination and their distribution in the environment always demands quantitative ecological risk assessments. Various federal agencies, including the foremost Environmental Protection Agency (EPA) have tentatively

cataloged the following research essentialities including characterization, possible transformation, environmental fate, dosage assessment, ecological impact, human health effect analysis as well as the assessment of NPs life cycle as a major criterion to follow before the validation of any NPs safe for application. It is essential to study at least its release, uptake, and mode of toxicity in organisms. The post-production life cycle assessment and possible toxicological risk analysis is an unavoidable factor also. , The lack of strict regulations and policies regarding the usage and disposal of NPs, has become a great threat to the environment. The impact of NPs under sthe current and future exposure extremities on various levels of ecosystems needs to be elucidated further. On the other side, their functions and interactions across multiple concurrent ecosystems need special attention. Particularly, NPs having longer half-life in the ecosystem are susceptible to long-term deposition in various environmental sediments. They need special focus as they are likely to cause more potential harm to both aquatic and terrestrial biota. Nonetheless, various analytical techniques are still under development to much effectively detect and characterize NPs quantification in complex environmental strata, but its efficacy in proper management is still a controversial topic. Nanotechnology is growing in an unforeseen exponential manner, and it is also an authentic fact that issues related to notoriously difficult nano waste disposal will grow at an even faster rate if unchecked.

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## Conflicts of Interest

The authors declare no conflict of interest.

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