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NANOMATERIALS TOXICITY TO HUMANS AND PLANTS

VINAYATARI

Department of Biology, Faculty of Science and Technology, Universitas Airlangga, Surabaya, East Java, 60115, Indonesia.

GNANSANGEETHA D

Department of Chemistry, PSNA College of Engineering and Technology, Dindigul,
Tamil Nadu, 624 622, India.

KARTHIK KANNAN *

Chemical Science Department and the Radical Research Centre, Ariel University, Ariel 40700, Israel.
*Corresponding Author Email: *karthikkannanphotochem@gmail.com

Abstract

Nanotechnology is developing very fast and attracting great public interest in various fields such as agriculture, biomedicine, cosmetics, industry, pollution control, etc. In recent decades, research and development have developed rapidly to apply nanotechnology to solve many problems that make life easier. It is a great effort of researchers and scientists to overcome many challenges with the help of this new technology. However, there is much evidence of the adverse effects of nanomaterials on the environment, so they have become a new environmental problem under the title of “nanotoxicology". This review paper aims to summarise the effects of nanotechnology on plants and humans, sources, distribution, accumulation, bioavailability, and challenges for future sustainable development using current literature.

Keywords: Development, Human Being, Impact on Environment, Nanotechnology, Nanotoxicology, Sustainability, Toxicity.

INTRODUCTION

Nanotechnology has potential advantages in almost all fields due to its special physical and chemical properties such as small size (10-9, i.e., 1 billionth of a meter), hydrophobicity, lipophilicity, optics, electronics, magnetism, and large surface-to-volume ratio (K. R. B. Singh et al., 2020, L. Singh et al., 2017, Milovanovic et al., 2017). However, nanomaterials have a limited particle size of 1-100 nm (L. Singh et al., 2017, Milovanovic et al., 2017). Nanomaterials are environmentally friendly, clean, and cost-effective and have a wide range of applications in various fields such as environment, agriculture, biomedical, bio-labeling, and defense etc. (Borm et al., 2006,V. L. Colvin, 2003, K. R. B. Singh et al, 2020, L. Singh et al, 2017, Lewinski et al, 2008, Nikaeen et al, 2020, Ferrari, 2005, Tari et al, 2022). There are many benefits of nanomaterials to human health and the environment, including nanoremediation techniques, environmental monitoring sensors, bio-robotics, nano-drug delivery systems, nanoscale implants in medicine, nano-arrays, etc. (Maxine, 2011). Engineered nanoparticles (NP) are classified into five different subclasses, namely metal oxide NP, metal NP, semiconductors, carbonaceous NP, and nanopolymers (Handy RD, Owen R, 2008) (Ma X, Geiser-Lee J, Deng Y, 2010).

Nevertheless, nanomaterials have been shown to be toxic to the environment and humans (Buzea et al., 2007, Borm, 2005). The study of the toxicity of nanomaterials to

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human health and the environment is referred to as "nanotoxicology" (Buzea et al., 2007, Oberdorster, G., Oberdorster, E. and Oberdorster, 2005).

As the application of nanomaterials is rapidly increasing, the exposure is also increasing daily. Although these small, powerful materials offer many benefits, there are concerns about the behaviors of nanomaterials that may impact humans and the environment. The risk of nanomaterials can be understood by considering primarily the interaction between nanomaterials and environmental components and secondarily the interaction of nanomaterials with living systems (Donaldson, 2004). This critical review is a sincere attempt to explain the details of nanotoxicity to humans and their environment.

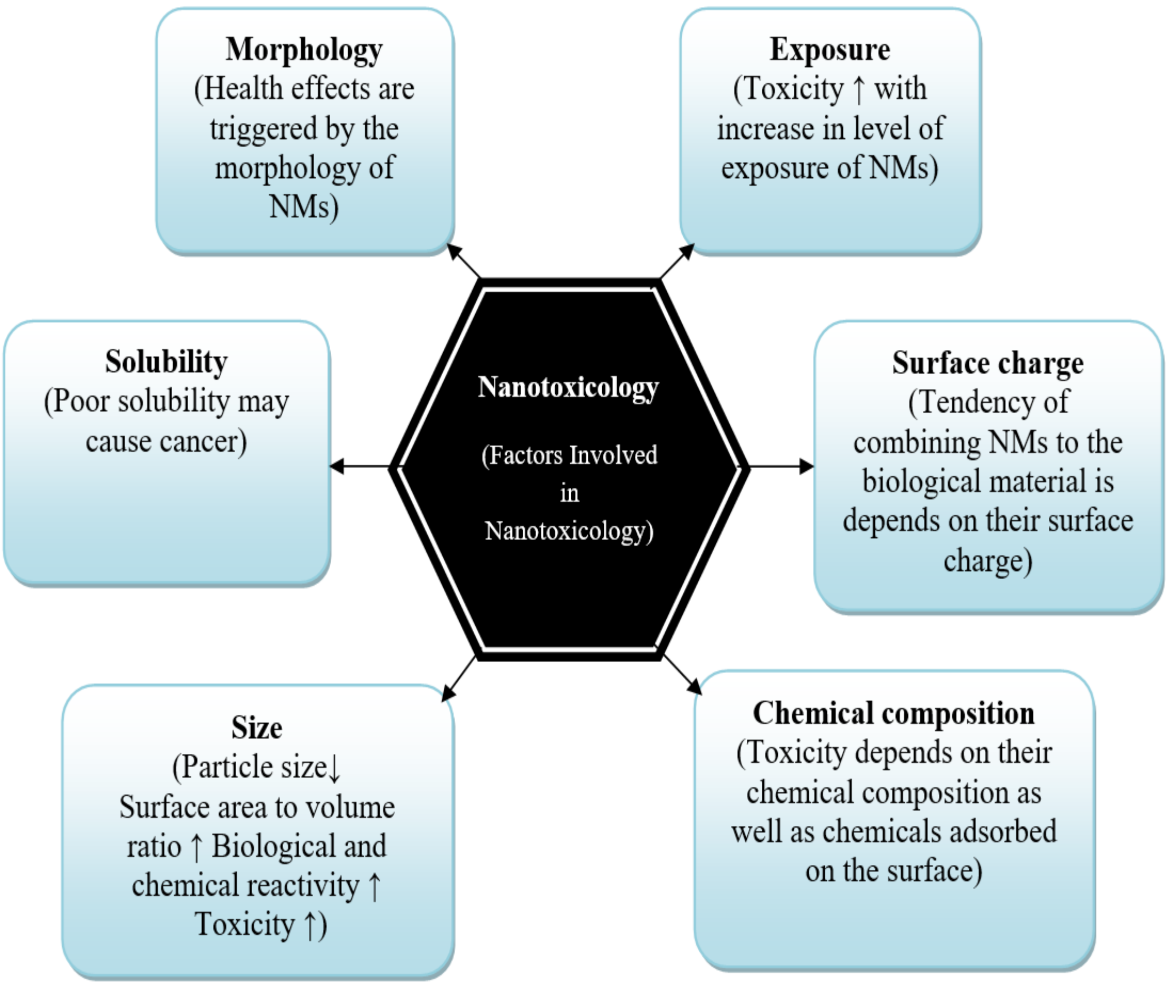

Figure 1: Factors involved in Nanotoxicology

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TRANSPORT AND FATE OF NANOMATERIALS

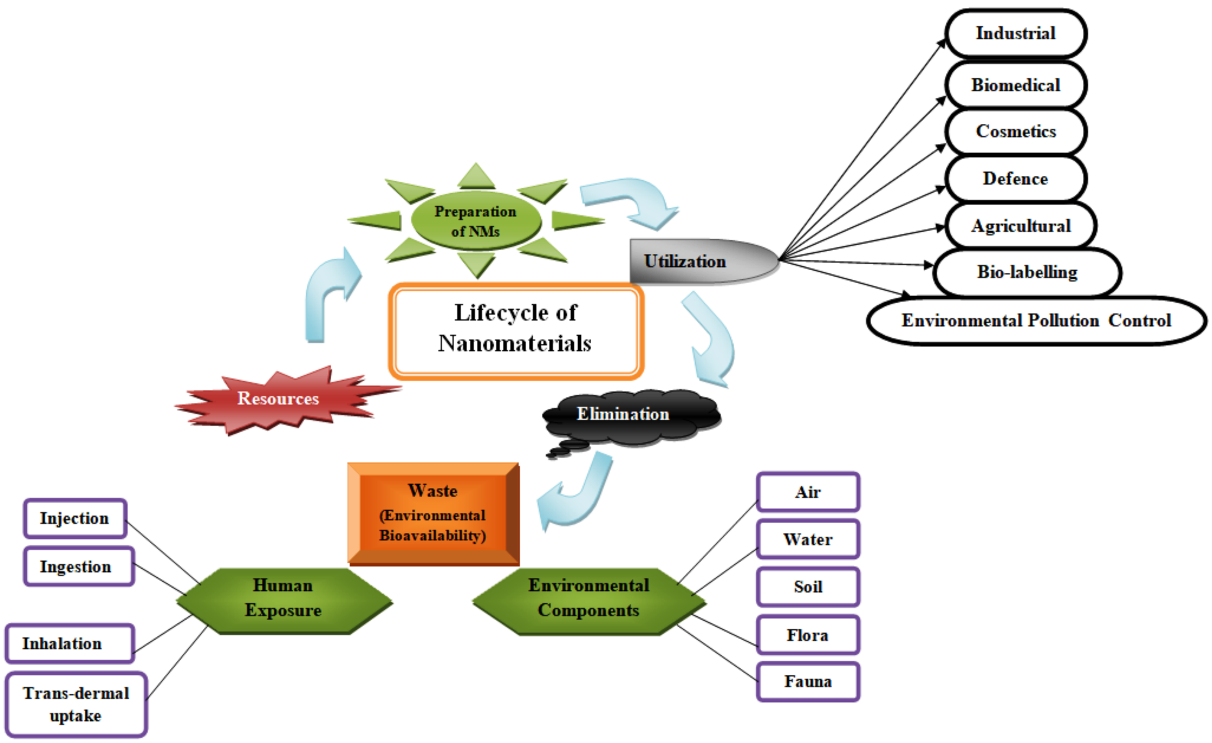

Figure 2: Transport of Nanomaterials

Figure 2 illustrates the sources, life cycle, and exposure and distribution of nanomaterials in the environment. Inorganic nanoparticles include metal nanoparticles such as Ag, Al, Au, Bi, Ce, Cu, Co, Fe, In, Mo, Ni, Sn, Ti, and Zn, as well as metal oxide nanoparticles such as ZnO, TiO_2, and ZnO. ZnO, TiO_2, CeO_2, AgO, AuO, SnO_2, ZrO_2, Al_2O_3, CuO, Cu_2O, FeO, In_2O_3, La_2O_3, MgO and NiO, etc (Rajput et al, 2018)(Faizan et al, 2020). Metal oxide nanoparticles are extensively used and studied for their toxic effects on flora and fauna activity and diversity. Because of their hazardous effects, metal nanoparticles have been used as biocides and nano-pesticides to destroy pests or microorganisms. Applying sewage sludge or industrial waste containing nanoparticles is the main source through which they enter the environment and subsequently accumulate in the ecosystem. Such nanoparticles, once released into the environment, could pose a serious threat to living organisms. Therefore, it is important to study the behavior of NPs in the environment (Rajput et al., 2018) (Shrestha, B., Acosta-Martinez, V., Cox, S.B., Green, M.J., Li, S., Cañas-Carrell, 2013).

In order to study the effects of nanoparticles, it is of great importance to understand the different factors that influence the behavior of nanoparticles in the environment. There are several factors that affect the behavior of nanoparticles in the environment, namely shape, size, size distribution, redox potential, surface and core chemistry of the particles,

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porosity, catalytic activity, crystallinity, surface charge, agglomeration state, etc (Figure 3).

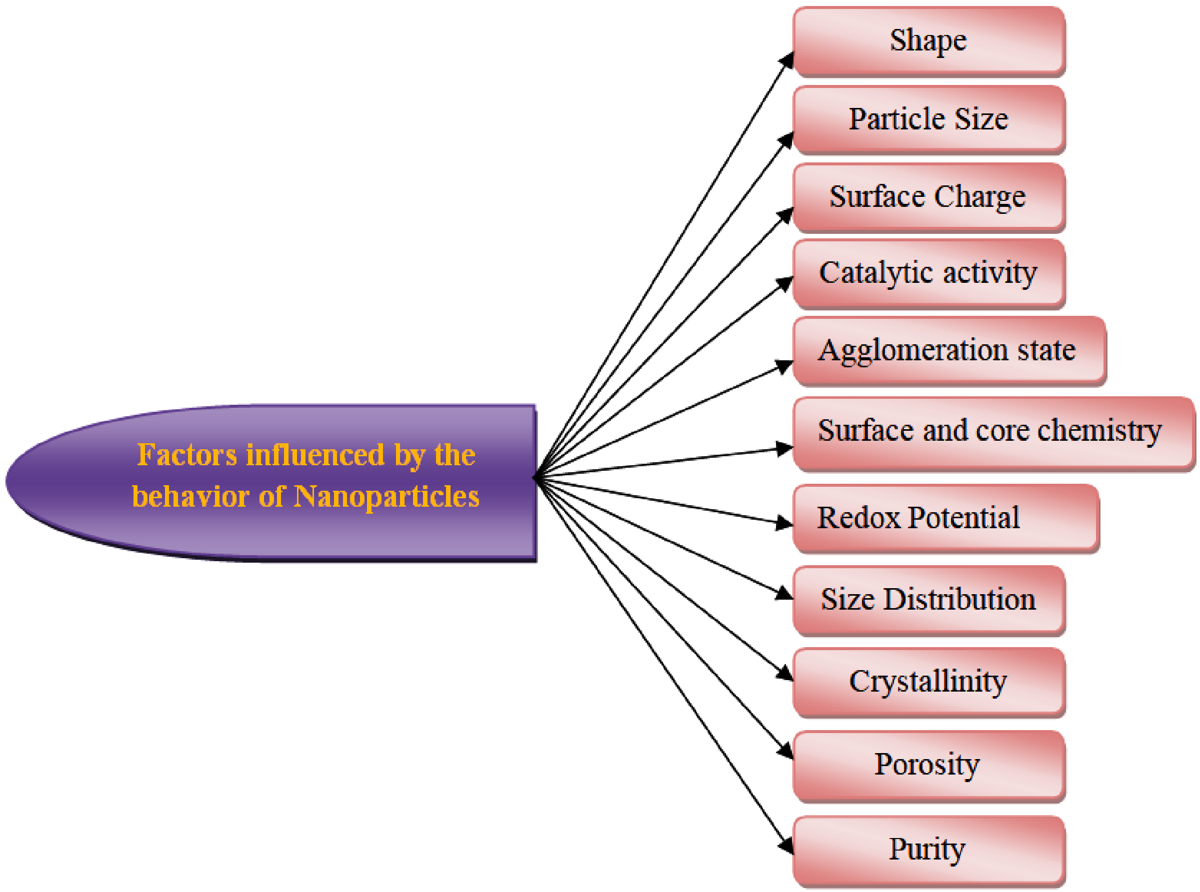

Figure 3: Factors Influenced by the Behavior of Nanoparticles

1. Impact of Nanoparticles on Plant Health

Although nanomaterials are extremely useful in various aspects of agriculture, some negative impacts of nanotechnology on crops and other agricultural activities have been reported (Bakht et al., 2020). Soil is the most important component of plant health and its nutrition (V. S. Tari & Patil, 2017b). However, the uncontrolled use of nanomaterials can have a negative impact on soil and plants. As mentioned earlier, NPs can be of both natural and anthropogenic origin. The plant has a natural tendency to absorb soil constituents (V. S. Tari & Patil, 2017b). Soil can be considered an important sink for NPs compared to the aquatic and atmospheric ecosystems (Keller, A.A., McFerran, S., Lazareva, A., Suh, 2013). The uptake of nanomaterials and their accumulation in plant cells is shown in Figure 4. It can affect important soil properties, namely plant protection, nutrition and maintenance, soil microflora and fauna, and overall plant health. Microflora and microfauna play an important role in the cycling of nutrients and minerals in soil

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(Bakht et al., 2020, Xueran Wang et al. 2023). The risk associated with nanomaterials increases exponentially because the behavior of nanomaterials and changes in their properties are uncertain as they interact with the environment and the weather conditions at any given time (Royal Society and The Royal Academy of Engineering, 2004) (Handy, R.D., Shaw, 2007).

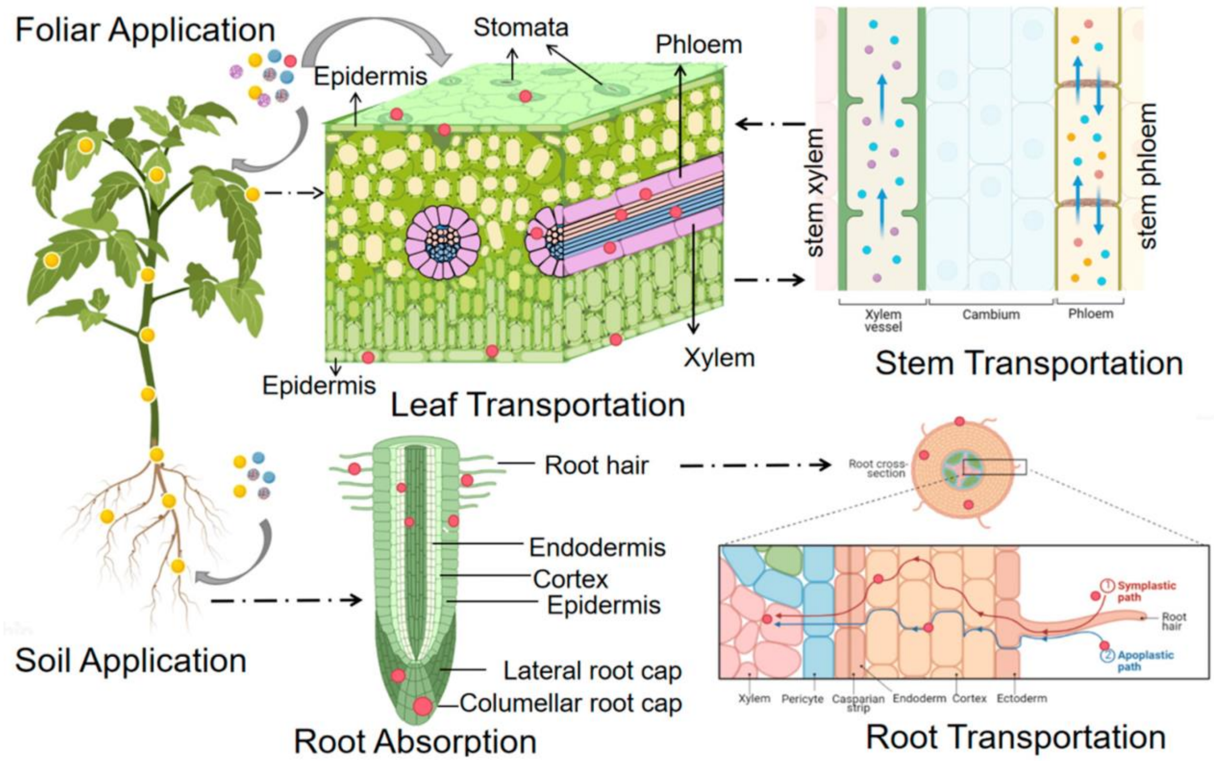

Figure 4: Schematic Diagram of the Uptake of Nanoparticles in the Plant Cell

(Source: Xueran Wang et al. 2023)

Sometimes the number of NPs is more or less, but these NPs can be useful or toxic. Beneficial NPs always help to promote microbial growth and nutrient cycling and improve the overall quality of the soil. Soil microbes are resistant to NPs, so there is no negative impact on their functions. However, when microbes are not resistant to NPs, they can alter various functions of microbes, ultimately reducing their numbers and diversity (Simonin, M., Richaume, 2015). Therefore, soil health can be maintained through proper management of nanomaterial use, which can ultimately ensure human and environmental health and improve crop production. Thus, depending on the size, category, nature, and quantity of nanoparticles, they can have positive and negative effects on plants (Bakht et al., 2020). High and low concentrations of AgNPs have negative and positive effects on barley root length, respectively, under hydroponic conditions (Gruyer, N., Dorais, M., Bastien, C., Dassylva, N., Triffault-Bouchet, 2013). However, in another study with AgNPs, it was found that the growth of corn and beans was stronger at a lower

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concentration of AgNPs than at a higher concentration (Salama, 2012). From these examples, it can be concluded that the effects of AgNPs depend on the concentration supplied to the plants in the field.

Some other negative effects of NPs have been noted, namely, decrease in chlorophyll content, photosynthetic rate, germination potential, increase and enlargement of plant roots, etc. (Tripathi, D.K., Tripathi, A., Singh, S., Singh, Y., Vishwakarma, K., Yadav, 2017). NPs have been found to be present in various parts of the plant and sometimes found in the edible parts of the plants (Bakht et al., 2020).

Wang, X.P., Li, Q.Q., Pei (2018) conducted an experiment to investigate the effects of zinc oxide nanoparticles on the growth, photosynthetic properties, and antioxidant enzymes of *Solanumly copersicum* L., i.e., tomato plant, and found that ZnO NPs are likely to reduce chlorophyll and damage the photochemical system, ultimately leading to low photosynthesis and reduced biomass. The supernatant of ZnO NPs suspensions showed no negative effects on tomato growth, despite the presence of a small amount of Zn++. Zn is a micronutrient for plants that plays an important role in protein synthesis through the activation of enzymatic reactions (V. S. Tari & Patil, 2017a, Eneida A. Pérez Velasco, Rebeca Betancourt Galindo & José A. González Fuentes, Bertha A. Puente Urbina, 2020). However, the positive side of ZnO NPs is that it promotes the transcription of genes related to antioxidant capacity, increasing the plant defense response by enhancing antioxidant enzyme activities (Wang, X.P., Li, Q.Q., Pei, 2018).

Table 1: Impact of different Nanoparticles on Plant Health

Sr. No.	Metal oxide NPs	Plant Species	Impact	Reference
1	ZnO	Maize and Rice	No effect on seed germination, it inhibits root elongation; NPs are more toxic than their corresponding microparts.	(Yang, Z., Chen, J., Dou, R., Gao, X., Mao, C., Wang, 2015)
		Arachishypogaea	Root and shoot length increased by 3% and 32%, respectively, at 1000 ppm; root and shoot length decreased by 18% and 25%, respectively, at 2000 ppm.	(Prasad et al. 2012)
		HordeumvulgareL .	Shoot length, root length, number of roots and shoot weight increased.	(Plaksenkova et al., 2020)
		Brassica nigra	Impairment of germination and seedling growth showed an increase in antioxidant activities and non-enzymatic antioxidants.	(Zafar, H., Ali, A., Ali, J.S., Haq, I.U., Zia, 2016)
		Arabidopsis	Plant growth reduced by 20–80%, Chl a and b reduced by up to 50%, expression of Chl synthesis genes and photosystem structure genes inhibited, increase in carotenoid synthesis genes detected.	(Wang, X., Yang, X., Chen, S., Li, Q., Wang, Q.W., Hou, C., Gao, 2015)
		*Solanumlycopersicum*L.	Significant inhibition of tomato root and shoot growth, decreased chlorophyll a	(Wang, X.P., Li, Q.Q., Pei, 2018)

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			and b content, and decreased photosynthetic efficiency.	
		Schoenoplectusta bernaemontani	Roots tended to accumulate ZnONPs, translocation from root to shoot was limited.	(Zhang, D., Hua, T., Xiao, F., Chen, C., Gersberg, R.M., Liu, Y., Stuckey, 2015)
		Pisumsativum L.	Chlorophyll content decreased by 77% at 500 ppm.	(Mukherjee, A., et al. 2014)
		Tomatoseedling	Epibrassinolide improved plant tolerance to ZnO NPs. helps reduce excess zinc content.	(Li, M., Ahammed, G.J., Li, C., Bao, X., Yu, J., Huang, C., Yin, H., Zhou, 2016)
		Glycine max (L.)	Root length, surface area and volume decreased by 89%, 88% and 87% at 500 ppm, while stem length, surface area and diameter decreased by 76%, 82% and 25%, respectively.	(Yoon, S.J., et al. 2014)
		MedicagosativaL., and *Sinorhizobium Meliloti* (symbiotic Association)	Root and shoot biomass decreased by 80%, and ZnO-NPs showed lower toxicity compared to Zn chloride.	(Bandyopadhyay, S., Peralta-Videa, J.R., Plascencia-Villa, G., José-Yacamán, M. &Torresdey, 2012)
		Cucumissativa	Showed inhibition of root growth.	(de la Rosa et al., 2013)
		Triticumaestivum	Reduction of Chl a synthesis and thus reduction of photosynthetic activity.	(Ramesh M, Palanisamy K, 2014)
		Brassica napus	Reduction of germination and simultaneous inhibition of root growth.	(Zafar et al., 2016)
2	AgO	*Lactucasativa L.*	Under shaking conditions, increased inhibition of root growth was observed.	(Kong et al., 2021)
		Raphanussativus L.	Decreased inhibition of root growth was observed under shaking conditions.	(Kong et al., 2021)
		Loliummultifolium, *Eruca sativa*, and *Zea mays*	Root and shoot length increased at low concentrations and decreased at relatively high concentrations.	(Vannini et al., 2013)
		Sorghum bicolor	Root growth, root length and biomass decreased.	(Borm et al., 2006)
		Baccopamonnieri	Caused cracks in the epidermis and root cap.	(Vannini et al., 2013)
		Vignaradiata	Impairment of seed germination.	(Fageria NK, Baligar VC, 1990)
		Triticumaestivum	Reduction in growth, decrease in shoot weight, and increase in biomass.	(Jasim et al., 2017)
3	Al_2O_3	*Nicotianatabacum*	Impairment of overall plant growth and development.	(Foy CD, 1982)
		*Hibiscus sabdariffa*L.	Priming seeds with 0.05, 0.1, and 0.5% Al2O3NPs resulted in decreases in fresh weight and dry weight, root and shoot length, leaf area, Chl a, b, and	(Abdel et al., 2020)

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			carotenoid content, proteins, amino acids, soluble sugars, and defense enzyme activities. Hence, adverse effects.	
4	FeON Ps	*Arabidopsis thaliana*	Shows inhibition in development.	(Fageria NK, Baligar VC, 1990)
5	Fe_3O_4	*Triticum aestivum*	-NPs exposure did not alter germination, plant growth, and chlorophyll content. -Plant exposed to NPs showed a favorable response to prevent oxidative damage.	Lannone et al., 2016
		Zeamays	-Germination index was observed to be higher with 20 and 50 mg/L nanoparticles treatment whereas decreases with 100 mg/L treatment.	Li et al., 2016
6	CdO	*Hordeum Vulgare*	-No change in total chlorophyll concentration, with minor change in Fv/Fm with (3) treatment. -Increase in total amino acids in all three cases with maximum in (3) treatment.	Vecerova et al., 2016
7	NiO	*Solanum lycopersicum*	-NiO induce apoptosis in tomato root cells. -Increase in ROS, antioxidants, and mitochondrial membrane potential. -Trigger the release of caspase-3 proteases from mitochondria.	Faisal et al., 2013
		Hordeum Vulgare	-Increase in lipid peroxidation, superoxide anion radicle, and cell death. -Decrease in leaf surface area, chlorophyll, and carotenoids.	Soares et al., 2016
8	CeO_2	*Oryza sativa*	-Under NPs influence, rice grain contains less Fe, S, prolamin, glutelin, lauric acid, valeric acid, and starch in comparison to control. -NPs could compromise the quality of rice grain.	Rico et al., 2013
		Transgenic cotton (Bt – 29317)	-Reduction in Zn, Mg, Fe, and P levels in Xylem sap. -Conventional cotton was more sustainable to CeO_2 nanoparticles stress in comparison to transgenic cotton.	Nihan et al., 2015
		Solanum lycopersicum	-At 250 mg/kg coated nanoparticles increased total chlorophyll, chl-a, and chl-b. -At 500 mg/kg coated and bare nanoparticles increased steam length by 13 and 9% respectively.	Barrios et al., 2016
		Phaseolus Vulgaris	-Natural organic matter influences the behavior of nanoparticles in the soils. -Nanoparticles increased antioxidant enzyme activities in the aerial tissues.	Manjumdar et al., 2016

9	TiO_2	*Allium cepa*	Concentration dependent increase in genotoxicity.	Demir et al., 2014
		Linum usitatissimum	-Reduction in root biomass and root length. -Reduction in seed germination after 24 h.	Clement et al., 2013
		Zea mays	Leaf growth inhibition and transpiration via physical effects on root water transport.	Asli and Neuman, 2009
		Hydrilla Verticillata	-Increase in catalase and glutathione reductase activity. -10 mg/L concentration has shown increase in hydrogen peroxide level.	Okupink and pfugmacher 2016
10	CuO	*Raphanus sativus* *Lolium perenne* *Lolium rigidum*	The DNA damage was found to be increased (DNA lesions compound) with an increase in concentration of nanoparticles.	Atha et al., 2012
		Elodea nuttallii	-Ultraviolet (UV) radiation treatment increases the Cu concentration in shoot. -UV irradiation enhances the phytotoxic effect of nanoparticles.	Regier et al., 2015
		Lemna minor	-Increase in peroxides, catalase, superoxide dismutase activity. -Increase in lipid peroxidation. -Inhibition of plant growth.	Song et al., 2016
		Wheat	-Inhibition of root elongation by CuO nanoparticles (> 10 mg/kg). -Exposure resulted in root hair proliferation and shortening of the zones of division and elongation.	Adamast et al., 2017

2. Impact of Nanomaterials on Human Health

The toxicological effects of nanomaterials are studied by Ray et al, 2009, V. Colvin, 2008, Bakht et al, 2020). Nanotechnology enables the creation of devices, materials, and systems by controlling substances at the atomic and molecular level to exploit new phenomena and properties (Ray et al., 2009). The source of nanoparticle (NP) generation is not always the laboratory in institutions and industry, but there are some natural sources of NPS such as aerosols, pollen grains, ultrafine particles from smoke, dust, and other air pollutants (V. Colvin, 2008). According to BCC Research, it was estimated that the global consumption of NPS will increase from 225,060 Mt to about 585,000 Mt from 2014 to 2019 (BCC Research, 2014) (Faizan et al., 2020).

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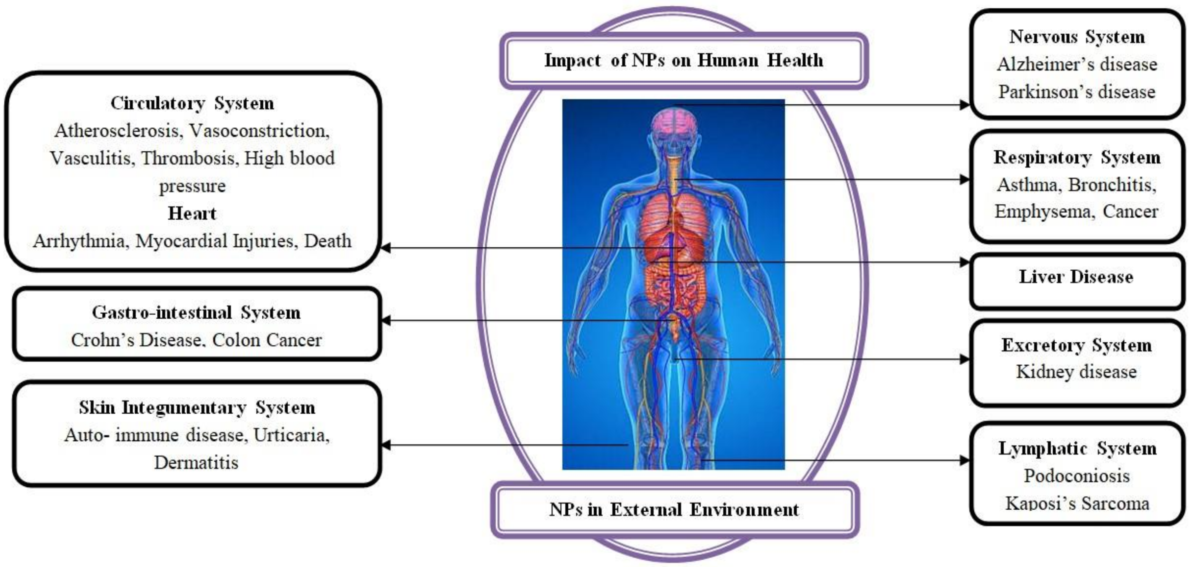

Figure 5: Impact of Nanomaterials on Human Health

Table 2: Impact of different nanoparticles on human health

Sr. No.	Metal Oxide NPs	Biomarker/model used	Toxicity/harmful impacts of nanoparticles	References
1	CuO	Lung adenocarcinoma cells (A549)	-Reduces cell viability -Induces membrane damage dose-dependent -Oxidative stress -ROS generation	Jing et al.,
		Human skin epidermal cell line (HaCaT)	-Decrease in cell viability. -Apoptosis -Necrosis -Include DNA damage mediated by oxidative stress	
2	Bi_2O_3	MCF-7 cancer cell line	-Reduces cell viability -Induces membrane damage dose-dependent -Oxidative stress -ROS generation	Ahamed et al.,
		HepG2 human hepatocarcinoma cells CaCo2 human colorectal adenocarcinoma cells A549 human lung carcinoma cells	-Induces apoptosis in HepG2 -Induces necrosis in A549 & CaCo-2	Abudayyak et al.,
3	Ni, NiO	Human bronchial epithelial cell line (BEAS-2B)	-Nickel causes no effect on cell transformation (ability to form colonies in soft agar) or cell motility	Gliga et al.,

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		Human bronchial epithelial cells (HBEC)	-Causes a release of inflammatory cytokines from exposed macrophages	Ãkerlund et al.,
		Hep-2 & MCF-7 cells	-Apoptosis -Cytotoxicity -ROS generation -Oxidative stress -Generation and oxidative stress	Siddiqui et al.,
4	CeO_2	A549 cancer cell line	-Generation of oxidative DNA damage -Causes tightness of the lung cell monolayer -Dose-dependent cellular response	Rothen-Rutishauser et al.,
		Human dermal fibroblasts	-Genotoxicity -ROS production -Lower doses of CeO_2 did not induce significant cytotoxicity.	Benameur et al.,
5	Fe_3O_4	Human adipose tissue derived stromal cells (hAScs)	-No effect on the physiological functions on hAScs	Radeloff et al.
	Pd/Fe_3O_4	Human colon adenocarcinoma cells (CaCo2)	-No ignition of ROS production -Little impact on the viability of CaCo2 cells -No toxicity effect	Hildebrand et al.,
6	TiO_2	Human astrocytoma and Human fibroblasts	-Induces cell death -Apoptosis -Necrosis	Lai et al.,
	TiO_2 & multiwall carbon nanotubes (MWCNT)	Human bronchial epithelial (HBEC-3KT) cell line	-Low cytotoxicity in short term tests -Cell proliferation affected in long-term exposure	Phuyal et al.,
7	SiO_2	A549 cells	Lower concentration: -Induction of reactive oxygen species -Membrane damage	Akhtar et al.,
8	Single wall carbon nanotubes (SWCNTs)	Human Caucasian colon (CaCo-2) adenocarcinoma cell line	-Increase in lactate dehydrogenase (LDH) leakage -Protein content only modified at higher concentration	Jos et al.,
		A549 cells	-Low oxidative stress -Cell responses are strongly dependent on the vehicle used for dispersion	Herzog et al.,

CONCLUSION

The effects of manufactured nanomaterials on the environment and human health have not yet been fully researched. The studies and research are still ongoing. Whatever studies have been done in the past are compiled in this review, which has a strong opinion that “nanotechnology is like a coin that has two sides,” i.e., nanotechnology has very successful and interesting applications in various fields. It is a warning to researchers, scientists, and industrialists that they need to think about these crucial issues before the massive production of nanomaterials. The study of the behaviour of nanoparticles (NP) during biodegradation in the cell and the cellular responses such as the accumulation of NP in the cell, gene alterations, disruption of organelles, etc., must be evaluated before massive production and dissemination. Therefore, it is crucial to evaluate the toxicity of nanomaterials, transformation in the environment and intracellular behavior, etc., before distributing the manufactured nanomaterials for daily use. Nano-toxicology research will enable researchers to understand how nanomaterials affect the environment and human health so that their undesirable properties can be modified. This review aims to fill a knowledge gap in understanding the toxicity of nanomaterials to humans and their effects on the environment. However, it is very important that scientists, researchers, developers, and industrialists also focus on the other side of the coin when developing nanomaterials to minimize their impact on the environment and health.

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