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# Impact of Nanotechnology on the Environment: A Review

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## Abstract

The growing global population is causing an increase in energy and material consumption, which has an impact on the environment. Some of these repercussions include increased creation of solid waste, increased air pollution produced by automobiles and industrial facilities, contamination of surface and groundwater. Through the direct application of nanoparticles for the detection, prevention, and removal of pollutants as well as their indirect application through improved industrial design processes and the creation of environmentally friendly products, nanotechnology has the potential to improve the environment. Because of their enormous surface area and tiny size, nanoparticles exhibit greater reactivity. This property has many uses and advantages, but there are also potential hazards to workers and environmental safety. These dangers include the potential for long-term air suspension, build-up in the environment, ease of absorption, and harm to different bodily organs. This review has looked into how nanotechnology is used in water treatment, waste management, air pollution reduction, and nanomaterial safety.

**Keywords:** Nanotechnology; Environment; Contaminated Sites; Polluted Areas

## Introduction

Now a day's the world's greatest challenge today is improving living conditions for people while minimizing the impact of human activities on the planet's ecosystems (Salerno et al., 2008; Singh, 2023). Today there is a day-by-day increase in pollution due to industrial growth and a rapid increase in population. Nanotechnology can be defined as "technology on a nanoscale." Subsequently, a plethora of nanotechnology definitions have evolved. A variety of nanotechnology-based filtration techniques have proven effective in removing organic and inorganic contaminants; heavy metals such as mercury, lead, arsenic, and cadmium; and biological toxins such as cholera and typhoid (Sharifi et al., 2015). The field of nanotechnology has garnered considerable interest from scientists in areas such as nanocomposites, biocomposites, optical devices, biomedical devices, and electronics (Goyal et al., 2023; Dunphy et al., 2004; Wang et al., 2008; Sivakumar et al., 2023; Shanmugam et al., 2024). One of the most promising scientific developments of the future is nanotechnology. Nanotechnology uses different properties of nanomaterials, which have at least one diameter in the range of 1 nm to 100 nm, to produce nanoscale devices, components, and systems (Sahaym et al., 2008; Farokhzad et al., 2009; Gupta et al., 2022). Nanotechnology has directly involved various applications for the environment, engineering, biology, chemistry, computing, material science, military applications, and communications. In general, nanotechnology devices consume less energy, cost-effective, reduce material wastes quickly, and help in monitoring. Furthermore, nanotechnology is capable of reducing and preventing the toxicity of nanoparticles in the environment more effectively (Ghosh et al., 2019; Zhang et al., 2011; Rajpoot et al., 2021; Ali et al., 2021; Konar et al., Ghosh et al., 2020). There is an ever-growing range of nanoscale technologies that are presently being developed in nanotechnology.

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In addition to developing innovative methods for producing new products and substituting existing equipment, it also reformulates new chemicals and materials with improved performance, resulting in reduced energy and material consumption, reduced harm to the environment and remediation of the environment. "Green" manufacturing and environmental remediation are potential applications of nanotechnology (Roco et al., 2005; Mukherjee et al., 2018). However, nanotechnology may also allow for more sensitive monitoring of air, soil and water quality, allowing simultaneous measurements of multiple parameters (Figure 1) (Newberry, 2012; Qu et al., 2013; Singh et al., 2022).

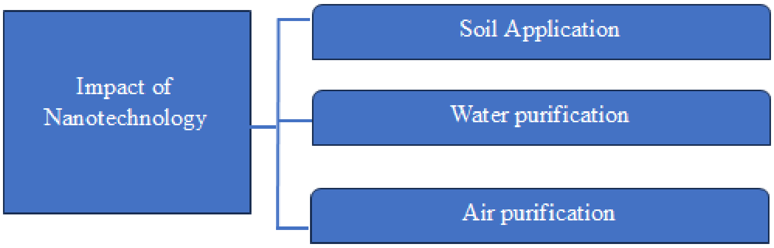

**Fig. 1.** Some important applications of nanotechnology in the Environment.

## Advances in nanotechnology

### *Impact of nanotechnology on water purification and wastewater treatment*

Water is an important life-supporting system and also the most vital component of life. Water pollution is one of the greatest challenges facing the world due to the rapid growth of population and industry. In the world, water is vital to all life and an essential resource for human civilization. The availability of affordable, clean, and safe water remains a major humanitarian challenge for the 21st century. Worldwide, some 780 million people still lack pure water sources (Qu et al., 2013).

Now a day's Various technologies have been developed to remove these toxic chemicals and ions, including precipitation and co-precipitation, adsorption, coagulation, flocculation, ion exchange, RO, ED, membrane filtration, ultrafiltration, metal-organic frameworks (MOFs), graphene oxide (GO) and solvent extraction, but this technology is high cost, high energy consumption, incomplete metal removal, production of harmful waste products and slower process(Sing et al., 2022; Vieira et al., 2010; Shoshaa et al., 2023; Ghosh et al., 2021). Rural areas in developing countries such as India, Bangladesh, Pakistan, and Sri Lanka lack large power plants for distillation of water purification. However, Nanotechnology is a cost-effective, faster process and environmentally friendly water purification processes and it is new emerging technologies are replacing traditional water treatment methods (Kumar et al., 2014; Konar et al., 2011). Various nanomaterials are used in nanotechnology to produce filters and membranes, such as CNTs, dendrimers, nano-porous ceramics (clays), nanofibers, zeolites, and nano-ponges. A nanomaterial with high porosity offers active metal binding sites, a small size, regenerative properties after exhausting, and faster contaminant removal. Different nanomaterials such as ZnO, $TiO_2$, ZnO–$CeO_2$, and $TiO_2$ play an important role in the photodegradation of contaminants as well as wastewater treatment (Schwarzenbach et al., 2006; Ghosh et al., 2021).

### *Biosorption*

Now a day's water is polluted with various toxic substances such as arsenic, mercury, fluoride, lead, chromium, halogenated aromatics, nitrates, and phosphates. If this metal is present in trace amounts, it creates harmful diseases like cholera, brain damage, skin cancer, diarrhoea, diabetics, dysentery, hepatitis A, anorexia, typhoid and polio (Schwarzenbach et al., 2006; Ghosh et al., 2021). Biosorption is one of the best way for heavy metal removal from water; it is a physio-chemical process that links to metal and microbial cells. Biosorption combination of two words "bio" for biological which includes algae, fungi, yeasts, exhausted coffee, cork biomass, waste tea, seaweed, mustard seed cakes, and bacteria that are used to adsorb heavy metals ions present in water and "sorption" for adsorption of heavy metal ion (Schwarzenbach et al., 2006; Ghosh et al., 2021; Li et al., 2022). It has several advantages over conventional techniques, including: low cost, high efficiency, minimal chemical and biological sludge, no additional nutrients required, regeneration of the biosorbent, and metal possibility (Ali et al., 2008). The various biological species used to remove heavy metals are listed in Table 1.

**Table 1:** Adsorption of various metals by various biological species (Kumar et al., 2014; Minaeian et al., 20008; Abyar et al., 2012; Ghosh et al., 2023; Ghosh et al., 2021)

| **Name of Microorganisms** | **Heavy Metal Adsorbed** |
|---|---|
| *Chlorella emersonii* | Cd |
| *Ecklonia species* | Cu(II) |
| *Eschereria coli* | Cu, Hg, Cr, Ni |
| *Thiobacillus thiooxidans* | Zn, Cu |
| *Geobacillus themodenitrificans* | Cu, Zn. |
| *Cladophora fasicularis* | Cd, Hg, Pb |
| *Aspergillus fumigatus* | Ur(VI) |
| *Ascophyllum sargassum* | Pb, Cd |
| *Pseudomonas species* | Cr(VI), Cu(II), Cd(II), Ni(II) |
| *Bacillus polymyxa* | Cu |

### *Nano-Adsorption*

An adsorbent is a solid surface that captures molecules of an adsorbate (adsorbate). Nano-adsorption is affected by a variety of factors, including temperature, the nature of adsorbate and adsorbent, particle size, contact time, and chemical environment. Nanomaterials proved to have excellent heavy materials adsorbent properties. In 1956, a study reported that Mercury is a highly toxic substance and it caused Minamata disease, which can lead to memory loss. Common methods used for the removal of mercury contaminated from water is adsorption (Kumar et al., 2014; Sumesh et al., 2011; Robinson et al., 2002). Gold nanoparticles supported by alumina make great options for extracting mercury Hg (0) from water. Before doing this, $NaBH_4$ must reduce mercury ($Hg^{2+}$) to Hg(0) (Robinson et al., 2002).

Water contaminated with aluminum ($Al^{3+}$), arsenic ($As^{3+}$), cadmium ($Cd^{2+}$), and nickel ($Ni^{2+}$) has been purified using iron oxide ($\alpha$-$Fe_2O_3$) NPs. It was discovered that iron nanoparticles are positively charged at low pH values and negatively charged at relatively high pH values. Thus, electrostatic repulsion causes the metals to be repelled and eventually removed (Al-Saad et al., 2012). In 1991, Lijima first reported that CNTs possess outstanding mechanical, adsorption, and electrical qualities, a sizable specific surface area, and strong chemical stability. CNTs are made of hollow, cylindrical, rolled sheets of graphite that have lengths of a few Centimeters and outer diameters in the nanometer range (1–100 nm) (Collinson et al., 2013; Ghosh et al., 2023). Pillay et al., 2009; Kumar et al., 2014; Ghosh et al., 2023). Several reports of CNTs show that they can remove various heavy toxic metals from water like arsenate, fluoride, $Al^{3+}$, $As^{3+}$, and $Cd^{2+}$. An investigation by Wang et al. (2008) revealed that Ni(II) was adsorbed on oxidized MWCNTs. It was reported that 128 MWCNT-zirconia nanohybrids could remove arsenic and fluoride from drinking water (Li et al., 2005; Peng et al., 2005 Yang et al., 2009; Ghosh et al., 2020).

### *Impact of nanotechnology on air pollution abatement*

The industrialization of human cultures has led to an increase in the creation of dangerous air pollutants, including CO, SOx, NOx, and others. Due to various restrictions, some of the current methods for managing these contaminants are not cost-effective, while others result in the production of dangerous byproducts. Most of these techniques are unable to rid the environment of minuscule pollutants. Thus, it is imperative to offer a fresh, affordable approach to deal with this issue (Taran et al., 2021; Chen et al., 2008; Ghosh et al., 2020). One of the techniques currently employed worldwide in this area is nanotechnology. Utilizing nanotechnology to address environmental problems and lower air pollution includes the creation of nano-catalysts, nano-sensors, nanocomposites, nano-filters, and nano-biomaterials (Taran et al., 2021; Baraton et al., 2004; Fulekar et al., 2014).

### *Nanocatalysts*

Air filtration and the cleaning of vehicle exhaust gases are two other applications for nanostructured materials as environmental catalysts. Conventional metal or ceramic-based catalysts are highly expensive while having good efficiency. As a result, nanostructured catalysts have been proposed as a less expensive substitute for currently existing catalysts (Fulekar et al., 2014; Koga et al., 2010; Chaturvedi et al., 2012). Research has shown that the best material to absorb hazardous pollutants like dioxin and other pollutants emitted from incinerator furnace chimneys is carbon nanotubes. Dioxin is a hazardous consequence of numerous industrial operations that causes increased stability as well as long-term contamination of the air, land, water, and living things. Dioxins can cause cancer in certain cases, and the majority of them disrupt the human immune system (Taran et al., 2021; Zhou et al., 2015; Long et al., 2001).

Even though the production of this substance has been regulated in several nations recently, the environmental risks associated with it are still deemed to be serious. Although the best method for adsorbing harmful pollutants like dioxins is using carbon nanotubes, this comes at a considerable expense. Numerous research projects are focused on the low-cost carbon nanotube manufacturing process. Furthermore, the utilization of carbon nanotubes in computer displays lowers the amount of heavy metals that are consumed by them, which lessens environmental harm (Taran et al., 2021; Zhou et al., 2015; Long et al., 2001; Rafique et al., 2011).

### *Nanosensors*

The ongoing management of air pollution is one of the most crucial prerequisites. One of the more recent developments in this field is the ability of nano-sensors to recognize and react to physical stimuli at the nanoscale level. The two types of nano-sensors are materials with nanostructures and materials with nanoparticles. Both receptors and visual-spatial sensors are employed with nanoparticles, such as tiny spherical materials. Nanomaterials like porous silicon has been utilize to build nano-sensors, which are used to monitor biological and chemical interactions (Jimenez-Cadena et al. 2007; Peng et al., 2014). One concern associated with the industrial sector is the leakage of hazardous and noxious gas. These days, sensors mostly employed in the industry frequently pick up on these gases at low concentrations. This means that in order to produce sensors that are faster and more precise, new technologies must be used. This kind of sensor can absorb hazardous gas molecules since it is composed of single- or multilayer nanotubes (Jimenez-Cadena et al., 2007; Yuan et al., 2013; Kundu et al., 2020). Utilizing nano-sensors as smart dust is a novel application of them. By creating the first smart dust samples, the application and scientific stages of the usage of these sensors were closed. The primary goal of creating smart dust is to create a range of cutting-edge sensors in the form of extremely thin nano-computers. These silicon-based ultrafine particles have the ability to wirelessly transmit the gathered data to a central database within their structure(Fischer et al., 2009; Poddar et al., 2020; Taran et al., 2021).This type of sensor has a data transfer rate of at least one Kbps. These nano-sensors can get their energy from the sun and can float effortlessly in the air for hours at a time. Up to 20 Kilometreaway, smart dust can send information on temperature, pressure, humidity, and the concentration of chemicals in the air. It may also create circumstances that continuously reduce air pollution in a specific area (Fischer et al., 2009; Taran et al., 2021; Dickson et al., 2007).

### *Nanofilters*

Filters are the most often used technology for reducing air pollution. Particles stay inside a filter's porous structure, which allows gas to pass through (Taran et al., 2021). Three methods are used by the membrane to remove particles from the filter: direct particle contact with the filter structure, the application of inertia force when the gas direction changes and the electric charge effect between the particle and the filter structure. The primary drawback of filters is the pressure drop they cause, which must be overcome with a lot of energy. With pores between 1 and 10 nm, nanofilters are more efficient than traditional filters at removing various types of bacteria, viruses, and organic pollutants (Sutherland et al., 2011; Schäfer et al., 2005). The ability to extract carbon dioxide from other gases is enhanced by carbon nanotube-based membranes. Compared to other gas separation technologies, carbon nanotubes have a gas-trapping rate of more than 100 times (Taran et al., 2021; Kulavi et al., 2021). They are therefore appropriate for large-scale disconnection. Carbon nanotube-based membranes do not have these drawbacks, in contrast to traditional membranes where the quantity of gas moving through a membrane is inversely related to the quality of gas separation. Many businesses can employ nanomembrane technology to separate and purify gases and polluted vapor, as well as to stop their release into the environment (Skoulidas et al., Zhang et al., 2015).

### *Nanocoatings*

Compared to conventional coatings, nanostructured coatings exhibit superior adherence and the production of unique surface characteristics. Applied to various surfaces, nanocoatings provide improved chemical, mechanical, and thermal resistance as well as self-cleaning qualities [38]. Their thickness ranges from several microns. The quantity of raw materials needed to replace these structures is decreased by the increased characteristics. They also result in less energy being used and less need for detergent consumption. Therefore, using nanocoatings results in a decrease in the amount of pollutants that are produced (Yaghoubi et al., 2010; Deepak et al., 2015; Nasrollahi et al., 2014).

### *Impact of nanotechnology on soil management*

In addition to being the most essential part of the terrestrial ecosystem, soil is a significant life-supporting system. Soil is essential for the growth of plants and the generation of food, but it also controls important planetary processes that support life on Earth (Bakshi et al., 2020; Hodson et al., 2010; Banwart, 2011). Maintaining the earth's equilibrium and environmental processes, as well as ensuring food security and agricultural productivity, depend heavily on managing soil health (Bakshi et al., 2020; Nandi et al., 2023).

A major environmental issue that presents a significant challenge to agricultural production and food security in the current environment is soil contamination and deterioration. A number of issues, including overgrazing, soil erosion, deforestation, a drop in soil fertility, and urbanization, can cause soil degradation (Lal et al., 2015; Leon et al., 2014; Khan et al., 2017). Therefore, eating products cultivated on contaminated soils may have detrimental effects on one's health, or the pollutants may contaminate food chains and enter the body through ingestion. Because they are therefore unfit for growing crops, the majority of these contaminated and polluted fields are abandoned, which drastically reduces agricultural output. Every year that goes by, soils get more and more degraded and polluted, which reduces the amount of land that can be used for agriculture. Therefore, we must simultaneously prevent additional damage to the land and restore the already degraded land while meeting the growing need for food from an ever-increasing human population on a rapidly diminishing landscape. Thus, it is necessary to combine prevention with cleanup and repair of this contaminated land (Hodson, 2010).

### *Applications and uses of nanotechnology in soil remediation*

With rapid advancement and expanding application fields across all dimensions, nanotechnology is regarded as a unique technology. When matter is designed, measured, and manipulated at the atomic, molecular, macromolecular, and micromolecular scales, a substance known as nanotechnology is created that has distinct features that are not present in the original bulk material (Hodson et al., 2010; Khan et al., 2017). The particles produced in this way are known as nanoparticles (NPs) or engineered nanoparticles (ENPs). Particles with at least one exterior dimension ranging from 1 to 100 nm are referred to as ENPs. Applications for nanotechnology can be found in many different fields, including agriculture, food (nutrients) production and packaging, pharmaceuticals, medical diagnostics, pesticide encapsulation using nanotechnology, genetic material delivery in plants, medicine delivery in humans, and cancer treatment, among many others. Aside from this, the remediation of environmental compartments including soil and water has been one of its most anticipated uses (Halder et al., 2023; Thuesombat et al., 2014). These include pollutant-contaminated soil remediation, groundwater purification, and wastewater treatment (Bakshi et al., 2020; De Oliveira et al., 2014). The growing use of nano-based tools, materials, and techniques for environmental cleanup may be the result of a pressing need for technology that is quicker to produce results without adding to the cleanup process's burden by leaving behind residues or environmental persistence. This technology should also be more readily available, cheaper, and cleaner (Cai et al., 2019). Because heavy metals, pesticides, and persistent organic pollutants (POPs) are mostly nonbiodegradable in nature, there is growing consideration for the use of nanoparticles (NPs) or nanomaterials including nanoparticles for the rehabilitation of soil affected by these chemicals. Nanomaterials for the degradation of pesticides and POP, nanomaterials for the conversion of heavy metals to less toxic forms, nano-based sensors for the detection of pesticide residue in soil, and nanomaterial-assisted phytoremediation or bioremediation of contaminated soil are just a few of the nanotechnology-based applications being used for soil remediation (Bakshi et al., 2020; Das et al., 2020).

### *Sustainable agriculture practices and nanotechnology*

The primary source of food and energy needed for human sustenance is agriculture (Thuesombat et al., 2014). The quickening pace of human population growth, the advancement of technology, and the avaricious need for lifestyle changes have led to increased resource exploitation in agriculture and environmental deterioration. In this sense, maintaining crop output and environmental sustainability through sustainable agriculture is the final resort. Sustainable crop production refers to the prudent use of the natural resources used in crop production so as to prolong the crops' useful life for society. Numerous applications of nanotechnology have been made for the sustainable production of agricultural crops. These include waste management, improving soil hydrophilicity, efficiently and precisely delivering fertilizers and pesticides to crop plants, and editing genes for biotechnological purposes (Ditta et al., 2020; Husen et al., 2020).In addition to revolutionizing sustainable crop production, these technologies have also improved soil health by enhancing the characteristics of the soil microbiome and have transformed the livestock and fisheries industries. The primary components of the majority of manufactured nanoparticles are silicon and carbon. As the most abundant element on Earth, carbon has been successfully used as a carrier, sensor, and scaffold material in biotic and abiotic stress environments, including those involving nutrients, temperature, salinity, pH, insect pests, weeds, pathogens, and so forth. Examples of these environments include carbon nanotubes (CNTs) and single-layered graphene (Ditta et al., 2020; Das et al., 2020; Ditta, 2019). Agricultural nanotechnology encompasses materials that are bioactive, biocompatible, bio-inert, and possess antimicrobial capabilities in addition to carbon-based nanoparticles. These comprise inorganic metals and metal oxides as well as biological and organic substances including liposomes, dendrimers, and amino acid chains. Other solutions include hybrid nano-entities made of peptide dendrimers and organic polymeric materials. In conclusion, agricultural crop production could be completely transformed by nanotechnology in a targeted, effective, and comprehensive way (Ditta et al., 2020; Ditta, 2019; Mukherjee et al., 2022).

### *Nano-fertilizers*

By supplementing nutrients alone or in combination with adsorbents with nano-dimension, nano-fertilisers are created. A product known as "nano-fertiliser" provides nutrients to crops in three different ways: it can be supplied as nanoscale particles or emulsions, covered in a thin layer of protective polymer film, or encapsulated inside nanomaterials like nanotubes or nanoporous materials (Nagula et al., 2016). Nanotechnologies can be applied to agrochemical products directly, or they can integrate with other ingredients. To put it another way, the nutrients can be given as particles or emulsions of nanoscale dimensions, or they can be enclosed inside nanoporous materials. In order to improve nutrient use efficiency, decrease soil toxicity, minimize the potential side effects of overdosing, and lower the cost of frequent application, these implications aim to deliver nano-agrochemical products in a targeted manner and release them sustainably in response to biological demand and environmental stimuli (Husen et al., 2020; Rai et al., 2012; Naderi et al., 2013; Anu et al., 2009; Burman et al., 2013).

## Conclusions

Nanotechnology inventions should be assessed unprejudiced following national and global requirements. The use of nanotechnology will continue to be developed, a benefit to society and a way to improve the environment and be cost-effective. Nanoscale materials and products will be more functional, cheaper to manufacture, more energy-efficient, and clean to use. In addition, several issues regarding human safety, the environment, and the ecosystem remain unresolved. Many factors could influence the success of nanotechnology. These factors include market demand, risk assessments and supervision, profit margins, environmental benefits, and many other technologies competing with it. However, nanotechnology is the safest technique for environmental cleaning and has a good impact on the environment.

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PG, AK, SH, SDS and JK conceived the concept, wrote and approved the manuscript.

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