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Environmental Implications of Nanotechnology: A Concise Review on the Impact and Sustainability



Abstract: - The impact of Nanotechnology on the Environment is generally split into two aspects: the potential for nanotechnological innovations to improve the environment and, therefore, the possibly novel sort of pollution that nanotechnological materials might cause when released into the environment. Nanotechnology provides potential economic, societal, and environmental benefits. Nanotechnology has the potential to help reduce human footprints on the environment by providing solutions for energy consumption, pollution, and green gas emissions. Nanotechnology offers the potential for significant environmental benefits. It includes cleaner and more efficient industrial processes, improved technologies to detect and eliminate pollution by improving air, water, and soil quality, high-precision manufacturing by reducing the amount of waste, and clean, abundant power via more efficient solar cells. It also includes the removal of greenhouse gases and other pollutants from the atmosphere and decreased need for large industrial plants. While it is considered to be a positive effect of nanotechnology, there are certain negative effects of nanotechnology on the environment in many ways. It increases toxicological effects on the environment due to the uncertain shape, size, and chemical composition of the nanomaterials. It can be difficult to understand the risks of using nanomaterials and the effects of the resulting harm. It is required to perform an analysis of nanotechnology products at all stages to understand the hazards of nanomaterials. In this review paper, an overview of both the positive and negative impacts of nanotechnology on the environment is provided.

Keywords: Nanotechnology, Nanoparticles, Environmental impacts, Sustainability, Greenhouse gases

Introduction

Nanotechnology is the use of matter on a near-atomic scale to produce new structures, materials, and devices. The technology has the potential for scientific advancement in many sectors, such as medicine, consumer products, energy, materials, and manufacturing. Nanomaterials have dimensions between 1 and 100 nanometers. At this size, materials show unique properties that affect their chemical, physical, and biological performance. Researching, developing, and utilizing these properties is at the core of new technology [1]. Nanoparticle has a relatively larger surface area per unit mass, which is an essential factor to increase mechanical, physical, and chemical properties. Nanotechnological devices consume less energy, reduce material waste, and help in monitoring problems. Nanotechnology can also be considered to reduce and prevent the toxicity of nanoparticles in the environment more effectively [2]. Nanomaterials are rapidly becoming a part of our daily life in the form of food packaging, drug delivery systems, cosmetics, therapeutics, biosensors, and others [3,4]. Since their size scale is nearly equal to that of biological macromolecules and due to their antibacterial and odour-fighting properties, nanomaterials are extensively used for several commercial products such as wound dressing, detergents, or antimicrobial coatings [5,6]. Despite the clear advantages of these small materials, there are questions about how the nanoparticles used in daily life may affect the environment. One of the critical issues that has to be considered shortly, before the large fabrication of nanomaterials, is their impact on the environment. There are significant discussions regarding how the novel properties of nanomaterials could lead to adverse biological effects, with the potential to cause toxicity.

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Results And Discussion

Potential Environmental Effects

Potential environmental effects mean estimated environmental effects or pressure on the environment, resulting directly or indirectly from the use of nanotechnology under specified conditions of testing or use. Nanomaterials have a larger surface area than bulk materials, which can cause more destruction to the human being and the environment in comparison to the bulk materials. Therefore, the potential risk to society due to nanoparticles has attracted the attention of scientists, engineers, and policymakers working in this field. Nanoparticles are beneficial to modify the properties of polymeric composite materials and the environment in air pollution monitoring, and also to help reduce material consumption.

With the help of nanotechnology, it is possible to put a nanoscale coating on materials. The material will retain its initial strength longer and last longer. Carbon nanotubes have been used to increase the performance of data information systems. There are some considerations of potential risks that need to be considered before using nanoparticles. The significant problem of nanomaterials is the nanoparticle analysis methods. With the improvement of nanotechnology, new and novel nanomaterials are gradually being developed. The materials differ by shape and size, which are very important factors to determine the toxicity of the nanomaterials.

Positive Effects on The Environment

Nanotechnology has the potential to help in reducing human footprints on the environment by providing solutions for water quality, air pollution, and greenhouse emissions.

Water Quality

Poor water quality can be improved by using Nanotechnology. Nano-sized materials like zinc oxide, titanium dioxide, and tungsten oxide make harmful pollutants inert [7]. Nanotechnology capable of neutralizing harmful materials is being used in wastewater treatment facilities around the world. Nanoparticles of molybdenum disulfide can be used to produce membranes that eliminate salt from water with one-fifth the energy of conventional desalination methods [8]. In the event of an oil spill, scientists have developed a nano-fabric capable of selectively absorbing oil [9]. All these innovations have the potential to improve the world's heavily polluted waterways. Various nanomaterials and nanotechnology-based processes/treatment methods for water and wastewater have been listed in Table 1.

TABLE 1

Various nanomaterials and nanotechnology-based processes/treatment methods for water and wastewater

Sr. No.	Nanomaterials	Example	Pollutant adsorbed	Adsorption capacity/Removal efficiency	Ref.
1	Graphene	Zirconia/laser-induced graphene	MB	Degradation 80% and 60% corresponding to	[10]

				dye concentrations of 5.0 and 10.0 mg L ⁻¹	
2	Nanofilters (NF)	CNT-ceramic composite NF	Yeast and heavy metals	98%, 100%	[11]
3	Metal NPs	Zinc-aluminium oxide NPs doped with lead (LD/Zn-AIO/NPs)	Methyl orange (MO)	200 mg/g, 99.60%	[12]
4	Polymer-based NAds	Nano adsorbents of iron-aluminium (Fe-Al) layered dual hydroxide/reduced GO (rGO) coated with sodium alginate (SA) (FAH-rGO/SA)	As	190.84 mg/g (FAH-rGO/SA-4), 151.29 mg/g (FAH-rGO/SA- 1), 115.39 mg/g, (FAH-rGO)	[13]
5	Magnetic Nads	Fe ₃ O ₄ /GO-COOH	Ca ²⁺ and Cu ²⁺	78.4% (Ca ²⁺) and 51% (Cu ²⁺)	[14]
6	Polymer-based nanocomposites	Polyaniline (PA) and polypyrrole-supported NiWO ₄ nanocomposites	CV and MB	94% degradation efficiency for both CV and MB	[15]
7	Heterostructured nanocomposite	Heterostructured nanocomposite	RB	100% photocatalytic degradation of RhB in 120 min	[16]

Air quality

Nanotechnology can be used to improve air quality. Nanoparticles are used to make precise sensors, like single-walled nanotubes or SWNTs etc. These sensors can detect minute, harmful pollutants in the air, like heavy metal ions and radioactive elements. SWNTs can detect nitrogen dioxide and ammonia gases at room temperature [17]. Other sensors can remove toxic gases from the air using nano-sized particles of gold or manganese oxide. Table 2 shows nanomaterials as adsorbents with the efficacy of adsorbed pollutants.

TABLE 2

Nanomaterials as an adsorbent with the efficacy of adsorbed pollutants.

Sr. No.	Adsorbent Nanomaterial	Adsorbed pollutants	Efficiency	Ref.
1	Zinc oxide-graphene	Rhodamine blue (RB)	42 mg/g	[18]
2	Graphene oxide	Lanthanum oxide (III)	85.67 mg/g	[19]

3	Graphene nanoplatelets (GNP) and graphene magnetite (GM)	Emulsified oil	100 mg/g (GNP); 85 mg/g (GM)	[20]
4	Multiwalled carbon nanotube (MWCNT) carboxylic acid cysteamine	Amido Black 10B	131 mg/g	[21]
5	Hydrocomposite (HCP) of GO supported by chitosan (GO/CS-HCP)	Congo red (CR), Acid Red 1 (AR1), and reactive Red 2 (RR2)	43.06 mg/g (CR); 41.32 mg/g (AR1); 40.03 mg/g (RR2)	[22]
6	Graphene oxide hydrated manganese oxide nanocomposites	Lead (II)	553.6 mg/g	[23]
7	Thermally reduced graphene (TRG) and graphene nanoplatelets (GNP)	Oil	Batch adsorption: 1550 mg/g (TRG); 805 mg/g (GNP). Fixed bed column adsorption: 1100 mg/g (TRG); 850 mg/g (GNP)	[24]
8	Polyurethane (PU)/ graphene oxide (GO) electrospun membrane	MB and RB	109.88 mg/g (MB); 77.15 mg/g (RB)	[25]
9	MWCNTs (carboxyl functionalization)	Alkylbenzene sulfonates	168 mg/g	[26]
10	Magnetic ammonia functionalized MWCNTs	Methylene blue (MB)	178.57 mg/g	[27]
11	MWCNTs from activated carbon derived from wood sawdust, and doped with nickel-ferrites (Ni-Fe)	Metronidazole and levofloxacin	840.38 and 650.45 mg /g	[28]
12	Functionalized graphene nanosheets (FGNs)	Copper (II)	103.22 mg/g	[29]

Greenhouse Gas Emission

Greenhouse gases are responsible for global warming by increasing the average global temperature as they absorb and produce radiation in the thermal infrared range [30]. Nanotechnology can transform the technology into sustainable, green, and clean alternatives to deal with global warming and climate change consequences. Different nanoparticles are being developed to reduce greenhouse gas emissions. These nanomaterials with functionalized chemical groups (e.g., nanofilms, nanocomposites, nanofibers, metal-organic frameworks (MOFs), nanomembranes, CNTs, nano zeolites, nano silica, etc.) have great potential to capture greenhouse gases [31]. The fuel with nanoparticles has more fuel efficiency,

reducing the rate of greenhouse gas production [32]. Table 3 lists various nanomaterials used in greenhouse gas sequestration.

TABLE 3

Various nanomaterials are used in greenhouse gas sequestration.

Sr. No.	Nanomaterials	Captured greenhouse gases and adsorption efficiency/ capacity	Examples	Ref.
1	Graphene	58.9 wt% (CO ₂); 22.3 wt% (CH ₄); 0.40 wt% (H ₂)	Pillared graphene frameworks	[33]
2	Graphene	H ₂	Tetracyanoethylene (TCNE)-modified graphene	[34]
3	Graphene	CO ₂	Magnesium oxide nanoparticles (MONPs) with graphene oxide (GO)	[35]
4	Modified activated carbon	SO ₂ 161 mg/g	Bituminous coal + coking coal impregnated with pyrolusite powder	[36]
5	Mesoporous silica nanoparticles	CH ₄ (31% higher adsorption capacity) 412 mg CH ₄ /g	Ordered mesoporous carbon	[37]
6	Nano zeolites	CO ₂ (Adsorption increased 28% from 5.067 to 6.536 mmol/g)	CO ₂ (Adsorption increased 28% from 5.067 to 6.536 mmol/g)	[38]
7	Nano porous carbon materials, Carbon nanotubes	CO ₂ and CH ₄ (70% and 90%)	MWCNTs	[39]

Negative effects on the environment

Nanomaterials acquire unique properties owing to their nano size. These unique properties offer many commercial and domestic applications, including catalysis, medical applications, imaging, energy-based research, agriculture, and various environmental applications. Besides these applications, the toxicity of NPs has been a major issue for human beings. Nanomaterials may be toxic to living beings. If the properties of materials change dramatically in the nanoscale, then finely divided nano-sized materials may be more toxic than their macro counterpart. It is well known that the physical form of compounds significantly affects their toxicity. For example, asbestos is nontoxic in macro/bulk form but can cause lung cancer in its nano form[40]. On the other hand, CNTs and graphite can be toxic, even though there's no proof of excessive toxicity of CNTs. Studies have shown that lead NPs and tin NPs are stable, rigid, and nondegradable. Also, these NPs can enter plants, human organs, and tissues and show toxicological effects [41]. Nanomaterials can enter the body via skin absorption, inhalation, and ingestion skin absorption but inhalation is the dominant route for entry, and the respiratory system is the main target of these NPs [42]. The use of silver NPs is very common and causes harm to the aquatic environment by affecting fish, algae, bacteria, and other

aquatic organisms [43]. To avoid the toxicity of NPs, less toxic nanomaterials such as carbon-based (e.g., fullerene, CNTs, and graphene) NPs can be used as an alternative [43].

LCA (life cycle assessment) is a good criterion for the assessment of the effects of materials on the environment [44]. However, in the LCA of NPs, there is uncertainty and a vast data gap in material properties, potential toxicity, bioavailability, mobility, and bioaccumulation [45]. Hence, improvement is required for better analysis through the LCA of nanomaterials.

Regulation of Nanotechnology

Nanotechnology, being a new and developing technology, needs specific regulations and guidelines for safe handling and use. Due to toxic nanomaterial findings, regulations were set to ensure safe and efficient nanotechnology.

- (i) In 1976, the United States law, The Toxic Substances Control Act, or TSCA, gave the U.S. Environmental Protection Agency (EPA) the authority to require record keeping, testing, reporting, and regulation of the use of chemical substances. Nanomaterials are also regulated under the TSCA as "chemical substances"[46]. India lacks any specific law for toxic chemicals like the Toxic Substances Control Act in the United States; therefore, TO make India a technology-favoured nation, the government must focus on making new laws and policies for nanomaterial use and commercialization.
- (ii) The EPA required all companies that manufactured or processed nanomaterials between 2014 and 2017 to provide information on the type and amount of nanotechnology used [47]. Today, all new kinds of nanotechnology have to be reported to the EPA for review before getting into the market [48]. The EPA makes use of this information to evaluate the capability environmental consequences of nanotechnology and to regulate the discharge of nanomaterials into the environment.
- (iii) In India, "Guidelines and Best Practices for Safe Handling of Nano-materials in Research Laboratories and Industries" is provided by the Department of science and technology (DST). In 2001, the Government of India launched nanoscience with DST and Nano Mission, and in 2007 Government of India launched the Nano Science and Technology Initiative.
- (iv) The Hazardous Waste Rule 2008 for Management, Handling, and Transportation is also important for handling nanotechnology waste.
- (v) In 2006, for nano-safety concerns and regulatory aspects, an international forum, OECD (Organisation for Economic Cooperation and Development, Paris) on Manufactured Nanomaterials (WPMN) was established. The WPMN (secondary body of the OECD chemical committee) leads an international programme for the health and safety aspects of NPs and chemicals[49].
- (vi) The Canada-U.S. Regulatory Cooperative Council (RCC) was established in 2011. Through the RCC's Nanotechnology Initiative, the U.S. and Canada advanced a nanotechnology work plan, which set up ongoing regulatory coordination and information sharing between the two nations for nanotechnology.
- (vii) The National Nanotechnology Characterization Laboratory, USA, and the Nanotechnology Research Coordination Group, UK, have taken initiatives for nanotoxicity testing and reference materials [50].
- (viii) The International Alliance for Nano Environment and Human Health and Safety Harmonization is developing protocols for nanotoxicity testing [51].

Conclusion

Nanotechnology offers a wide range of applications in the environment, agriculture, food, and energy sectors. Nanotechnology can handle the nanotechnological products and processes that are considered the most effective and innovative tools to achieve sustainability goals. Nanostructured materials such as nano zeolites, nano silica, nano lubricants, nanocomposites, functionalized nanomaterials, nanocatalysts, and nano coatings, etc., have vast possibilities in sequestration and reduction of

greenhouse gases, wastewater treatment, biofuel production, and environmental remediation using a sustainable approach. International policies on climate change and their implementation at the world to regional levels are needed at the hour. Further, nanotechnology has a huge capacity to create sustainable techniques, products, and approaches to fight the consequences of climate change. It can be concluded that nanotechnology has emerged as one of the potential technologies providing sustainable solutions and alternatives to conventional methods. Problems always exist with new, unproven technology. Nanomaterials may also assist in cleaning certain environmental wastes, but pollute the environment in other ways. Choosing the right and novel nanomaterials in the right manner is one of the most important parameters for the future direction of nanotechnology.

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