

A Prevalent Analysis on Nanotechnology and Measures Being Taken to Diminish Nanopollution in Context of India: Review

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Abstract—Nanotechnology is one of the promising, newly, but highly expanding technology. With each day of research (R&D) on nanotechnology big amount of nanoparticle’s in the form of wastes are dumping in the different environmental matrices. Not only the world is facing lots of pollution oriented troubles right now but our negligence concerning nanomaterials is also playing a havoc role in the field of nanopollution. On this assessment, we discuss their applications in daily lifestyles, diverse entry routes of nanomaterials within the human body, and their toxicity. Furthermore, this paper discusses remedial techniques applying by various countries and our duty to make certain and comfortable disposal of nanowastes to reduce or put off untoward environmental and health influences. In short, this paper is a query of the available strategies for threat assessment and a chance to control to help in decreasing the occupational risks of potentially volatile engineered nanomaterials collectively with the control banding approach. The study provides a brief and well-organized report on nanotechnology that should be valuable to researchers, engineers, and scientists for future research projects. It is an attempt that can be saving and trying to convertible the world from the dangerous and fatal consequences of nanomaterials, by using the different methods adopted by different countries of the world especially in the context of India. For carrying out this study, relevant papers on

Nanotechnology from various research platforms are selected, identified and studied.

Key words—Nanoparticles, Nano pollution, Environmental matrices, Environmental effect, Nano wastes, Nanotoxicology.

I. INTRODUCTION

Nanotechnology is the fundamental technology of the world. Wherever we look we realize and find the effect of nanomaterial’s and nanotechnology. Nanotechnology is now considered as the most capable technology of the twenty-first century, and researchers have explored it as an innovative technology in various fields. Nanotechnology will attendant in a new era of productivity and prosperity, as seen by increased public funding for nanotechnology research and development over the last decade (Roco 2003, Gonzalez et al. 2013). A nanoparticle is a nano-object having all three external dimensions in the nanoscale, which is about 1 to 100 nm (ISO) i.e. 10^{-7} to 10^{-9} meter by Mansoori and Soelaiman (2005) or at least one dimension should be less than 100 nm (Laurent et al. 2010; Boverh et al. 2015). When we compare nanomaterials with other objects, we find that their size is very small presented in Fig.1.

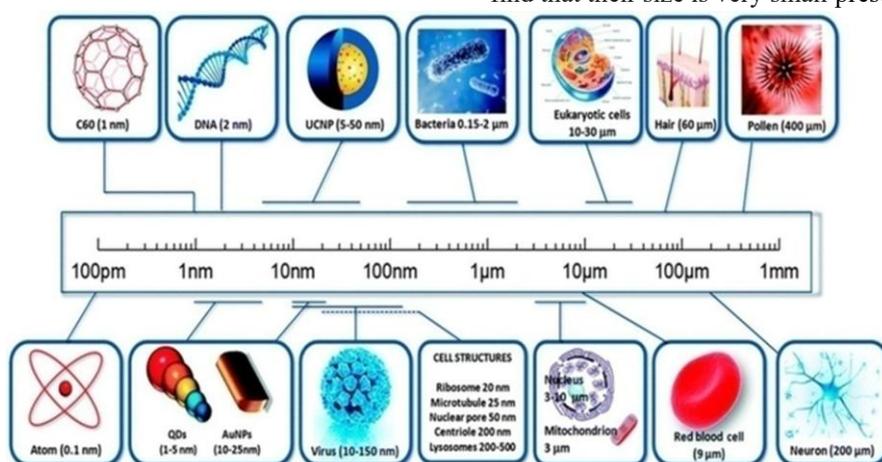


Fig. 1 a comparative analysis of nanomaterials based on their varying sizes. (Gnach et al. 2015)

We can understand the size of nanomaterials on comparing with

1. Meter (m): A standard unit of length.
2. Centimeter (cm): 1/100th of a meter. Example: The width of a finger.
3. Millimeter (mm): 1/1000th of a meter. Example: The thickness of a credit card.
4. Micrometer (μm): 1/1,000,000th of a meter. Example: A human hair is roughly 50-100 μm in diameter.
5. Nanometer (nm): 1/1,000,000,000th of a meter. Example: DNA double helix has a diameter of about 2 nm.

As a comparison, one must realize that a single human hair is 60,000 nm thicknesses and the DNA double helix has a radius of 1 nm) (Gnach et al. 2015). Depending on the overall shape nanomaterials can be 0D, 1D, 2D or 3D (Tiwari et al. 2012). The size of nanoparticles can affect the physio chemical properties of a substance like the optical properties. A 20 nm Gold (Au) looks wine red color, Platinum (Pt) looks yellowish gray, Silver (Ag) looks black and Palladium (Pd) appears dark black (Dreaden et al. 2012).

Origin of Nanomaterials and its concept:

The initiative of nanotechnology was taken firstly in 1959 by the physicist Richard P. Feynman during his speech “There are plenty of rooms at the bottom”. In this statement he expressed the capability to control the individual atoms and

molecules (Feynman 1960). After Richard Feynman signals, the entire world turned towards nanotechnology, and thereafter, almost all research began from this field. Dr. Norio Taniguchi, a Japanese scientist, coined the term nanotechnology in 1974 as “nanotechnology mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule” (Taniguchi et al. 1974). He conducted research on the top-down process and was awarded by the Nobel Prize. Dr. Eric Drexler is known as the father of nanotechnology. He developed the bottom-up approach and made nanotechnology useful for everyday life in favor of common people. After introduction of the word nanotechnology, there was a significant increase in the research of this field, and nanotechnology made its presence felt in every field (Drexler 1986). There is hardly any field where nanotechnology has not asserted its dominance. It can be said that nanotechnology is the backbone of the present era. It’s various important applications is seen in biology, biotechnology, nanotechnology, medicine, in high technology, in water purification systems, energy systems, food production methods, nutrition and large-scale infrastructure auto-fabrication etc.

Let, s take a look at what we have seen in the modern era through nanotechnology and how the progress is continued in nanoscience and nanotechnology in different fields of science Fig.2.

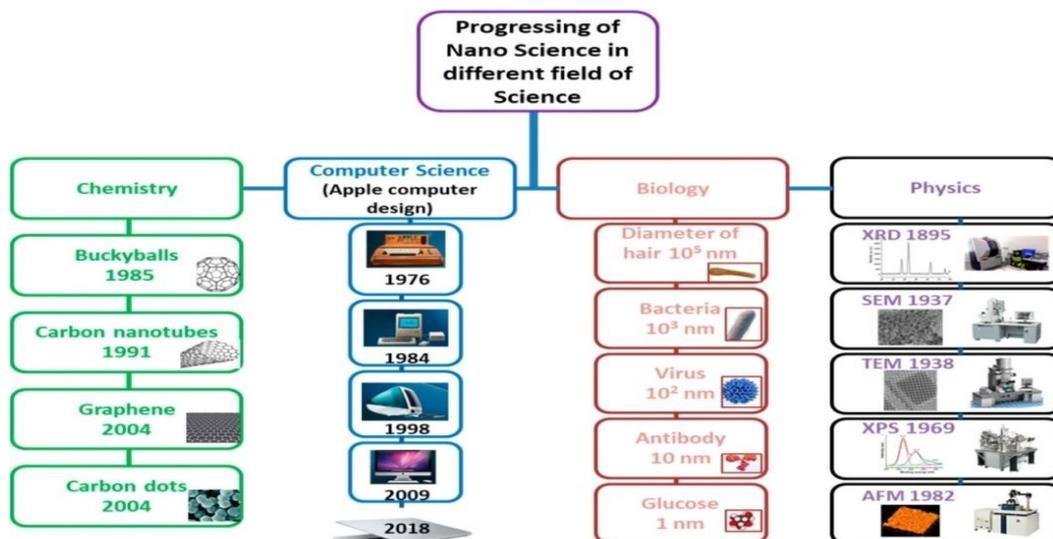


Fig. II Progressing of nanoscience in different fields of science. (Bayda et al. 2019)

As nanotechnology is a rising field, there is great contest regarding to what extent nanotechnology

will benefit or pose risks for human health. Due to massive use of nanotechnology and nanomaterials,

huge amount of nanoparticles are released and exposed to even all matrices of environment. Sometimes it is considered in the form of toxicity. The health impacts of nanotechnology are also seen on human health. Nanotechnology is noteworthy if potential negative effects of nanoparticles are overlooked which can't be.

II. NANOTECHNOLOGY CAN BE STUDIED IN VARIOUS ASPECTS:

2.1. *Nanotechnology serves as a significant form*

It is accommodating in the agricultural fields (in the form of fertilizers, herbicides and pesticides, soil feature regulation, wastewater management, and pathogen detection) (Kah et al. 2013), industrial food processing field (with enhanced food production having excellent market value, elevated nutritional and sensing property, improved safety, and better antimicrobial protection), in the field of electronics (for developing the sensors to measurement of the molecular level, reduce the size of electronic circuit and complexity and also reduce in total power consumption) by Liu and Fan (2001), in the field of medical (in the form of nanomedicine, nanoelectronic biosensors, clinically helpful devices), in the pharmaceutical industry that may include advanced drug delivery systems, new therapies, and in vivo imaging, (Sahoo et al. 2007), in the environmental safety fields through green nanotechnology (in achieving two goals: producing harmless nanomaterials, and producing nano-products that provide solutions to environmental problems and to make nanomaterials and nano-products without toxic ingredients, at low temperatures using less energy and renewable inputs wherever possible, and using life cycle thinking in all design and engineering stages) (Gottschalk et al. 2013), in the textile fields (as the understanding, manipulation, and control of matter such that the physical, chemical, and biological properties of the materials that can be engineered, synthesized, and altered to develop the next generation of improved materials, devices, structures, systems and to develop desired textile characteristics, such as high tensile strength, unique surface structure, soft hand, durability, water repellency, fire resistance, antimicrobial properties etc.), (Patra et al. 2018), in the daily life as consumer product applications (Roco 2003), in the field of food industry (in food include smart packaging, shelf-life extension, and improved

nutrient delivery) (Chaudhry et al. 2010), in the cosmetics industry (Wenqian Huang et al. 2020), energy production by Chu and Majumdar (2012), defense, rocketry (Lee et al. 2011; Barrak et al. 2016), CO₂ capturing (Ganesh et al. 2017; Ramacharyulu et al. 2015; Shaalan et al. 2016), gas sensing (Mansha et al. 2016; Rawal and Kaur, 2013; Ullah et al. 2017).

Smaller size of nanoparticles, gives larger surface area, and highly catalytic nature, nanomaterials have revealed outstanding results in various other areas, mainly in nanonutrients, crop productivity, and plant protection (herbicides and pesticides), as well as nano-packaging and nanosensors (Kah et al. 2013). Nanotechnology fundamentally contributes to achieving food security and improving crop production by enabling effective microbial, pest, and weed control with high economic value, security, and safety (Patra et al. 2018). It also plays a key role in food processing, food modification, enhancing food stability and sensing capabilities, prolonging shelf life, minimizing food losses, and ensuring food safety (Chaudhry et al. 2010; Mishra et al. 2020). Moreover, nanotechnology minimizes post-harvest losses by offering better stability, safety, and advanced packaging materials. Nanoparticles like silver, gold, zinc, titanium dioxide (TiO₂), zinc oxide (ZnO), silicon dioxide (SiO₂), and magnesium oxide (MgO) are commonly used in food processing due to their antimicrobial and preservation-enhancing properties by Momin and Jayakumar (2018).

Although benefits of nanotechnology are widely shown and cannot ignored, however the development of nanotechnologies has introduced significant amounts of manufactured nanoparticles into the ambient air and water in the form of pollutants, (Nemmar et al. 2001). Due to the smaller size it's been proven that nanomaterial's can input in the human body through numerous ports. Either in the form of insoluble and stable TiO₂, silver nanoparticles, gold nanoparticles and so on (Roberts 2009; Fakruddin et al. 2012; Banfield and Zhang 2001).

If we include both the advantages and harmful effects of nanomaterials and nanotechnology in the same paper then it will be a very lengthy discussion in one step so this paper will only mention its dark side and talk about measures taken by various

countries and especially in the context of India. Particularly the aim of this paper, to explore and shed light on the risks and hazards associated with application of nanotechnology in various fields, we will focus on what harms nanotechnology can reach or is reaching in the present time and in the future specifically to human health.

2.2 Nanotechnology as a threat

2.2.1 Health hazards due to nanomaterials

While nanoparticles are widely used for drug delivery and medical equipment, they also pose significant health risks due to their potential toxicity, including the induction of haemolysis, inflammation, and even cancer (Nel et al. 2006; Lewinski et al. 2008). The unique properties of nanoparticles mostly their high surface area to mass ratio and various shapes contribute to their discriminating reactivity and potential to interact harmfully with biomolecules in the human body by Fadeel & Garcia-Bennett (2010). Less soluble nanoparticles can accumulate in specific tissues, forming aggregates that may damage vital organs (Buzea et al. 2007).

As a result, the use of nanotechnology in medicine should be approached with both caution and appreciation, balancing its remarkable benefits with its potential risks. Furthermore, toxic effects of nanoparticles are not limited to human health—they have also been observed in aquatic organisms and plant systems, highlighting their broader ecological impact (Handy et al. 2008). Most studies on nanotoxicity have focused on entry routes such as the respiratory tract, gastrointestinal tract, and skin pores to assess the health consequences of exposure (Oberdorster et al. 2005; Nel et al. 2006).

2.2.2 Nanotoxicology

Nanotoxicology is a field that studies the health risks of nanomaterials. Extremely small-sized nanoparticles are more readily taken up by the human body than larger particles (Donaldson et al. 2004; Oberdorster et al. 2005). Understanding how these nanoparticles behave once inside the organism is one of the significant challenges in this field. The behavior of nanoparticles largely depends on their size, shape, and surface reactivity with surrounding tissues (Nel et al. 2006; Fadeel et al. 2012). For example, nanoparticles may cause an overload on phagocytes, which are white blood cells responsible

for ingesting and destroying foreign matter. This overload can trigger trauma reactions, leading to inflammation and weakening the body's defenses against other pathogens (Borm et al. 2006).

Nanoparticles have the ability to accumulate in various organs, interact with biological processes, and rapidly adsorb onto cells, tissues, and macromolecules. This interaction can significantly influence regulatory mechanisms involving enzymes and other proteins, potentially leading to unforeseen biological effects. Due to the complexity and diversity of nanomaterials, it is challenging to generalize the health risks associated with their exposure (Fadeel et al. 2018). Each nanomaterial must be assessed on a case-by-case basis, taking into account its unique physicochemical properties (Fadeel & Garcia-Bennett 2010; Borm et al. 2006). As studies have shown, nanoparticles can induce oxidative stress, inflammation, and even genotoxic effects depending on their size, shape, surface chemistry, and route of exposure (Nel et al. 2006; Oberdorster et al. 2005). Moreover, their capacity to alter protein conformations and expose cryptic epitopes further complicates their toxicological profile (Lynch et al. 2006). Therefore, comprehensive evaluation is essential for understanding the potential health implications of engineered nanomaterials.

The National Institute for Occupational Safety and Health has conducted initial research on the effect of nanoparticles on workers engaged in the manufacturing or industrial use of nanomaterials (Current Intelligence Bulletin 63, 2012). The National Personal Protective Technology Laboratory of NIOSH, investing the filter penetration of nanoparticles on NIOSH-certified and EU marked respirators, as well as non-certified dust masks have been conducted by Zhuang and Viscusi (2011). Here it is found that the most acute particle size range was stuck between 30-100 nanometers. Other than this, chemical composition, shape, surface change, surface structure, solubility aggregation and presence or absence of functional groups of other chemicals are also influence the toxicity of nanomaterials (Shaffer and Rengasamy 2009; Rengasamy and Eimer 2011; Nel, et al. 2006). Study showed, TiO₂ particles was shown severe lung inflammation and lymph node trouble compared to BaSO₄ particles with lower surface area (Tran et al. 2000).

Higher surface area makes nanoparticles highly reactive, which could lead to stimulate unknown chemical reactions or to bond with toxins, allow them to enter cells other than the ones targeted.

The shape of nanoparticles plays a significant role in their respirability and inflammatory potential. Like single-walled carbon nanotubes (SWCNTs) have been shown to be carcinogenic and highly toxic, primarily due to their tendency to accumulate in biological systems at high doses. Moreover, they can cause oxidative stress, which is defined as an imbalance between the production of reactive oxygen species (free radicals) and the body's antioxidant defenses (Shvedova et al. 2003, 2005). The solubility of different nanoparticles is different, low solubility nanoparticles may cause the most health risks mainly after broken down and degradation. Moreover due to high reactivity and electrical charge, nanoparticles create situation inside the body where they come collect and form larger particles, called "particle aggregation" which is responsible to unknown reactions inside the cells by Fadeel and Garcia (2010).

Nanofibres (diameters < 1000 nm) can pose considerable health risks to humans, even with their wide range of medical applications, including wound dressings, artificial organ transplants, tissue engineering, antibacterial materials, and drug delivery (Hegde et al. 2005; Nanofiber Applications, 2004). In an animal study, silver nanofibres injected into the lungs of mice showed that particles larger than 5000 nm became lodged in the lungs and caused inflammation, while smaller particles were cleared away (BBC News, 2012). Additionally, asbestos fibers have been linked to mesothelioma, a type of lung cancer. However, it is still unclear whether the same effects occur in humans, as the study was conducted on mice.

Nanotechnology also works significantly in advanced drug delivery systems. However, their use is not without potential adverse effects that necessitate further investigation. Cationic nanoparticles, such as gold and polystyrene coated with various ligands for drug delivery, have been shown to induce hemolysis and promote blood clotting by De Jong and Borm (2008). Moreover, studies have reported that diesel exhaust particles (DEP) can change heart rate in hypertensive animal models, highlighting the cardiovascular

implications of nanoparticle exposure (Brook et al. 2010). High concentrations of both anionic and cationic nanoparticles are creating toxicity to the blood-brain barrier (BBB), raising concerns about their safety in central nervous system applications De Jong and Borm (2008). Furthermore, a positive correlation has been observed between nanoparticle exposure and the incidence of cardiovascular diseases, even though the precise mechanisms remain unclear. Studies showed that certain nanoparticles can enter the bloodstream via inhalation, potentially leading to increased thrombosis, though it remains uncertain whether this is due to pulmonary inflammation or direct particle translocation into the blood (Nemmar et al. 2002; Kreyling et al. 2006).

2.2.3 Nanotechnology as a Pollutant (Nanopollution)

Nanopollution is a term used to describe a group of particles generated by nano devices during manufacturing and increased by the use of nanomaterials and leading to sensitive environmental exposure. Limited information is available regarding their behavior in air, water, or soil. Nanoparticles loaded air makes environment toxic in particular is its individual chemical properties with Carbon Black nanoparticles causing more severe health effects compared to its other counterparts (Wilson et al. 2002).

Nanomaterials have the potential to accumulate in specific "hot spots" through aggregation with minerals or interaction with organic substances. Like other pollutants, they can transfer from one organism to another and potentially move up the food chain. Due to the diverse nature, nanomaterials exhibit antibacterial or antiviral properties, while others have demonstrated harmful effects on invertebrates and fish, influencing their behavior, reproduction, and development. While nanotechnology remains a promising field, debate continues over the extent to which industrial and commercial applications of nanomaterials may impact organisms and ecosystems. The environmental impact of nanotechnology can be classified from two perspectives: its potential to contribute positively to environmental solutions and the novel types of pollution it might introduce if released into ecosystems (Handy et al. 2008).

There is a lack of research on soil systems and terrestrial species, making it unclear whether laboratory findings are applicable to real-world scenarios. Health and environmental issues intersect in the workplaces of companies engaged in producing or using nanomaterials in nanoscience and nanotechnology research. It is important to note that current workplace exposure standards for dusts cannot be directly applied to nanoparticle dusts due to their unique properties (Maynard et al. 2006).

III. COUNTRY-WISE OVERVIEW OF THE UTILIZATION OF NANOMATERIALS

(i) United States

U.S. is a global leader in nanotechnology innovation. In medicine, advanced nanomaterials are used for targeted drug delivery, cancer treatment, and regenerative therapies (National Nanotechnology Initiative). In electronics, the U.S. spearheads developments in semiconductor technology and nanoscale transistors and sensors. Energy research involves nanostructures for solar cells, next-generation batteries, and fuel cells. The military sector uses nanotechnology in lightweight armor, stealth coatings, and nanosensors (NNI 2020).

(ii) China

China leads globally in the manufacturing of bulk nanomaterials such as carbon nanotubes, graphene, and metallic nanoparticles (Zhou et al. 2020). It has made significant strides in energy applications like solar and battery technologies. Environmental uses include nanomaterials for air and water purification. The textile industry uses nanocoatings for stain resistance and antimicrobial properties (Liu et al. 2019).

(iii) European Union (EU)

The EU emphasizes sustainability, focusing on eco-friendly nanomaterials for renewable energy and environmental remediation (European Commission 2021). In healthcare, applications include diagnostics, drug delivery, and advanced prosthetics. The automotive industry incorporates lightweight nanocomposites to improve fuel efficiency. In agriculture, nanoscale fertilizers and pesticides aid in precision farming (Kah et al. 2018).

(iv) Japan

Japan is renowned for nanotechnology in electronics, especially semiconductors, displays, and high-performance batteries (Shimizu et al. 2020). In healthcare, nanomaterials are used in drug formulation and tissue engineering. Robotics incorporates nanocoatings and sensors for precision. The cosmetics industry uses nanoparticles in sunscreens and anti-aging products (Abe et al. 2017).

(v) India

India uses nanotechnology in agriculture for smart fertilizers and pesticide delivery (Chhipa 2019). Water purification systems using nanomaterials are deployed both in rural and urban areas. The healthcare sector is exploring affordable nanomedicine for diseases like tuberculosis and cancer. Energy applications include solar cells and biofuels (Kumar et al. 2021).

(vi) South Korea

South Korea is a leader in electronics, especially nanomaterials for OLEDs, semiconductors, and lithium-ion batteries (Lee et al. 2020). In healthcare, the country invests in nanomedicine and diagnostic biosensors. The automotive industry uses nanocomposites for lightweight design. Textile industries benefited by nanofiber innovations for high-performance wear.

(vii) Germany

Germany integrates nanocomposites in engineering sectors like automotive and aerospace (German Federal Ministry of Education and Research 2019). In healthcare, the focus is on targeted drug delivery and medical imaging. Energy applications include nanomaterials for hydrogen storage. The environmental sector benefits from nanotech in air and water purification.

(viii) United Kingdom

In the healthcare domain, nanotechnology supports cancer treatment, regenerative medicine, and diagnostic imaging (Royal Society 2020). Energy research focuses on nanomaterials for wind turbines and photovoltaics. The defense sector uses nanosensors and smart materials. Environmental nanotechnology addresses waste and water purification.

(ix) Russia

Russia emphasizes nanomaterials in defense and aerospace for light weight, durable materials (Skolkovo Foundation 2020). Health care applications include nanomedicine and biosensors. In energy, nanotech is used for enhanced oil recovery and renewable. Construction industries adopt nanocomposites for durability.

(x) Australia

Australia employs nanotechnology in healthcare, particularly in cancer diagnostics and therapies (Commonwealth Scientific and Industrial Research Organization CSIRO 2021). It also focuses on environmental sustainability, particularly in water purification. In mining, nanomaterials are used in mineral extraction. Energy research includes nanotech for solar panels and energy storage.

(xi) Brazil

In agriculture, Brazil uses nanotechnology to enhance crop productivity and develop smart fertilizers (De Lima et al. 2020). Energy applications involve nanomaterials in biofuel production. The healthcare sector uses nanotech for cost-effective diagnostic tools. Environmental efforts focus on water and air purification.

(xii) Middle East (UAE, Saudi Arabia, Israel)

These countries focus on energy, especially nanomaterials for solar technologies and desalination (Al-Kattan et al. 2021). Water management uses advanced nanofiltration. Health care investments target personalized nanomedicine. In construction, nano-enhanced materials are employed for insulation and durability.

Other Source: (OECD 2009; Fortune Business Insights 2024; the Business Research Stat Company 2024; IMARC Group 2024; WIPO Magazine 2009).

3.1. Mitigation Approach:

Several countries are adopting innovative approaches to mitigate the environmental impacts of nanomaterials. By combining regulation, advanced technologies, and sustainable practices, these efforts aim to harness the benefits of nanotechnology while minimizing its risks to ecosystems. Collaborative international research and standardized policies are essential for ensuring global environmental safety (OECD 2010).

For instance, the Australian Federal Government established a National Nanotechnology Strategy Taskforce under the Department of Industry, Tourism and Resources (DITR). The taskforce worked in the following areas:

- Compiling details of recent, ongoing, and planned research activities;
- Conducting a critical review of substantial existing work, with input from scientific experts in nanotechnology;
- Synthesizing the current state of knowledge relevant to professional health and safety (OH&S) in industries; and
- Identifying key gaps in knowledge and prioritizing areas for future research (Australian Government DITR, 2006).

3.1.1 Key strategies utilized in various nations to tackle the environmental impact of nanotechnology consist of:

- Filtration and adsorption: Nano-enabled filters are used to remove nanoparticles from water and air, enhancing traditional treatment systems (Qu et al. 2013).
- Green synthesis: This involves producing biodegradable nanomaterials from natural, renewable sources to reduce environmental toxicity (Kharissova et al. 2013).
- Environmental monitoring: Nanosensors are increasingly being deployed for real-time pollution tracking, offering precise and continuous environmental data (Nowack et al. 2013).
- Recycling and waste management: Nations are implementing strategies to recover and reuse nanomaterials from industrial processes, minimizing nanopollution (OECD 2010).
- Soil and water remediation: Engineered nanomaterials, such as nano-zero-valent iron, are being used to detoxify contaminated environments and restore ecosystem health (Karn et al. 2009).

3.1.2. Government initiatives taken by various countries

Scientists around the world are making significant advancements in the field of nanotechnology. In 2003, more than 800 nanotechnology-related patents were granted, and this number increased to nearly 19,000 internationally by 2012 (Nanowerk 2013). The multilateral/bilateral cooperation play a major role in promoting cutting-edge basic R&D by

providing Indian scientists access to sophisticated equipment/facilities in advanced countries. India's early involvement with various international/ inter-governmental organizations, such as International Standards Organization (ISO), Organization for Economic Cooperation and Development (OECD), and IRGC, for the development of standards, safe lab practices and risk governance is quite significant (Kumar 2014).

Each country's utilization of nanomaterials reflects its economic priorities, industrial strengths, and societal needs. Global collaboration and regulation of nanotechnology are essential to ensure its sustainable and equitable use.

3.1.3 Worldwide Remedial techniques used for removal of nanomaterial pollution

A number of graphs fig.3 (types of remediation techniques used globally for Nanomaterials pollution removal , Smith, 2023), fig. 4 (Country wise remediation techniques for nanomaterials pollution removal, Environmental Science Institute 2023), and fig. 5 (Implementation levels of nanomaterial remediation techniques by countries. (Environmental Nanotech Research Group. 2023), viewing remedial techniques applying for removal of nanomaterial pollution by different methods worldwide. Here's a breakdown of countries excelling in this area. It represents the usage percentage of different methods, such as phytoremediation, bioremediation, adsorption, and membrane filtration, chemical treatment and advanced oxidation processes (Smith 2023).

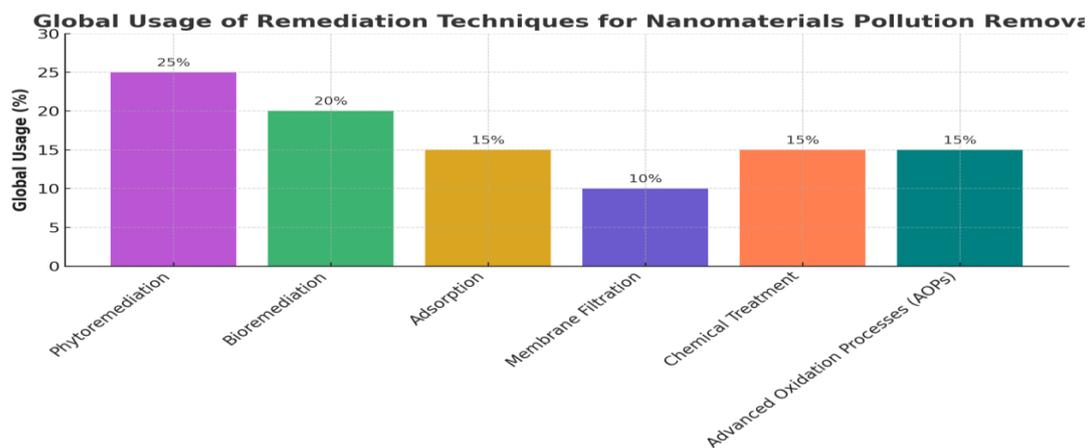


Fig. III Types of Remediation techniques used globally for Nanomaterials pollution removal (Smith, 2023)

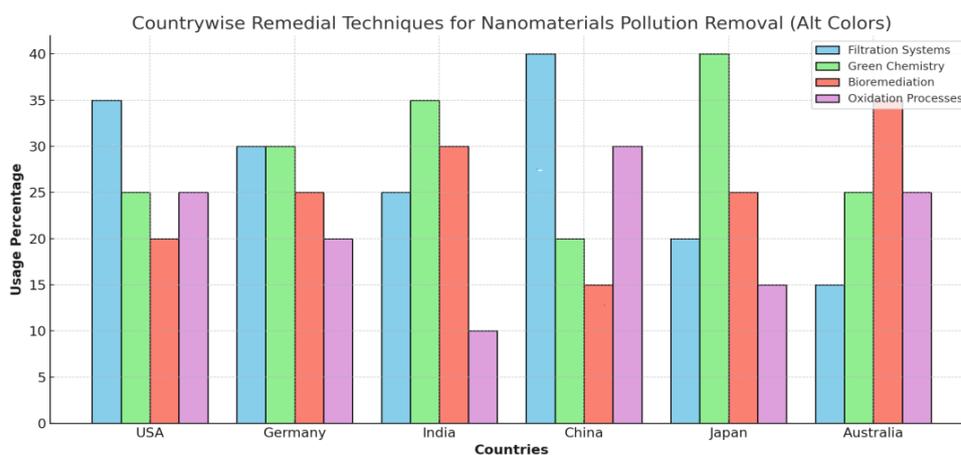


Fig. IV Country wise remediation techniques for nanomaterials pollution removal, Environmental Science Institute. (2023)

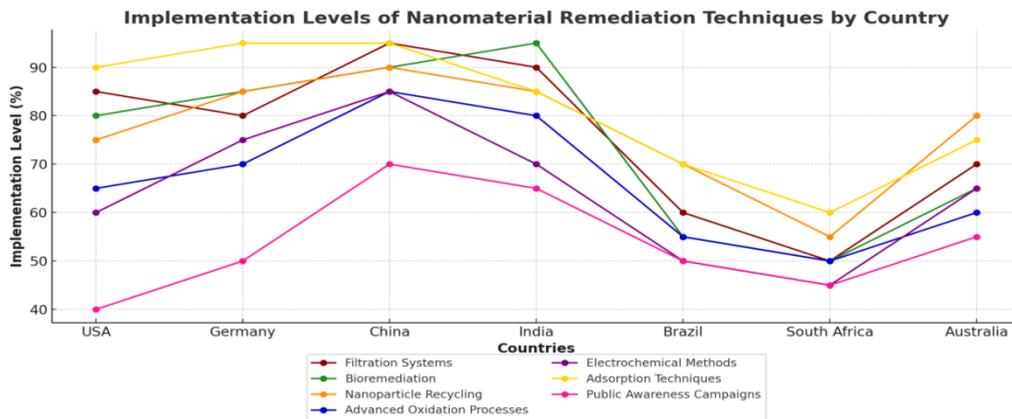


Fig. V Implementation levels of nanomaterial remediation techniques by countries. (Environmental Nanotech Research Group. 2023)

A comparative analysis indicates that India has made significant progress in addressing nanopollution, initially employing green chemistry approaches, followed by bioremediation, the implementation of filtration systems, and finally, oxidation processes. In contrast, China ranks highest in utilizing filtration systems, Japan leads in green chemistry initiatives, and Australia excels in bioremediation strategies by Sharma and Li (2022). Most of the countries utilizing advanced tools to tackle environmental issues such as climate change, biodiversity loss, pollution, and resource management (Vinuesa et al. 2020).

3.1.4 Efforts being made by India

India has been actively working on various remediation techniques to tackle nanopollution. Here's an overview of the status of key remediation strategies of India. (Kumar and Sharma 2021; MoEFCC 2023).

(i) Filtration Systems

- Implementation: Moderate to high in urban areas and industrial sectors.
- Focus: Development of advanced filtration systems, especially for water and air purification.
- Challenges: High cost and lack of widespread accessibility in rural areas by Patel and Rajput (2020).

(ii) Bioremediation

- Implementation: High, particularly in agriculture and wastewater treatment.
- Focus: Use of microorganisms and plants to degrade or sequester nanoparticles.

- Challenges: Limited scalability and research on long-term effects (Gupta, & Diwan 2017; Singh, and Kalamdhad 2022).

(iii) Nanoparticle Recycling

- Implementation: Moderate, mostly in research and pilot projects.
- Focus: Recovery of nanoparticles from industrial waste and e-waste.
- Challenges: Lack of robust infrastructure for recycling and awareness (NITI Aayog 2022; Sharma et al. 2021).

(iv) Advanced Oxidation Processes (AOPs)

- Implementation: High in industrial wastewater treatment.
- Focus: Use of techniques like photocatalysis and ozonation to degrade pollutants.
- Challenges: High energy consumption and operational costs. By Mishra and Goswami (2020).

(v) Electrochemical Methods

- Implementation: Moderate in wastewater management.
- Focus: Use of electrochemical cells to remove contaminants.
- Challenges: Limited adoption due to cost and complexity. By Saxena and Yadav (2019).

(vi) Adsorption Techniques

- Implementation: High, particularly in water purification.
- Focus: Use of activated carbon, nanomaterials, and other adsorbents to remove pollutants.

- Challenges: Disposal of used adsorbents and cost-effectiveness. By Kumar and Singh (2020).

(vii) Public Awareness Campaigns

- Implementation: Moderate, mainly driven by government and NGOs.
- Focus: Education on the risks of nanopollution and sustainable practices.
- Challenges: Reaching rural and underserved communities. (CSE India 2023; NGT 2022).

India's efforts in adopting advanced technologies like nanotechnology and AI are significant; however, challenges such as high costs, limited infrastructure, and a lack of widespread awareness hinder broader implementation. Increased investments in research, public-private partnerships, and educational initiatives could accelerate progress (Mishra et al. 2021).

India has shown significant initiative in addressing nanopollution, particularly in urban and industrial zones. Through a combination of policy measures, targeted research, and the deployment of emerging technologies, India is actively working to mitigate nanopollution across various environmental matrices. However, broader adoption of these interventions remains limited due to high implementation costs, infrastructural deficits, and insufficient public outreach (Ministry of Environment, Forest and Climate Change, (MoEFCC) 2024).

Key actions have included the development of national standards for nanomaterials, monitoring frameworks in collaboration with academic institutions, and pilot projects in pollution hotspots. Urban centers have seen initiatives focused on air and water purification using nanotechnology-based filters, while industrial areas have begun implementing nanosensors to track pollutant levels in real time. Despite these advances, further progress hinges on sustained funding, inter-institutional research collaborations, and scalable

public-private partnerships aimed at cost-effective, sustainable solutions (MoEFCC 2024).

3.2 National Policy & Regulatory Framework in India.

3.2.1 Nano Mission – Department of Science & Technology (DST):

Launched in 2007, the Nano Mission aims to promote research and development in nanoscience and nanotechnology in India.

Guidelines for Safe Handling of Nanomaterials:

Draft guidelines formulate under the Nano Mission to attend to environmental, health, and safety impacts of nanomaterials.

Nanotechnology Regulations in India:

An overview of the importance of implementing nanotechnology regulations in India, emphasizing the role of DST and the Nano Mission Council.

3.2.2 Research & Monitoring: Environmental Monitoring in Nanotoxicology by CSIR-NEERI's, and IITs.

The National Environmental Engineering Research Institute (NEERI) conducts extensive research in environmental science and engineering, including air and water quality monitoring. A brainstorming event hosted by CSIR-NEERI focusing on sustainable energy transitions, including discussions on emission control and waste valorization. The Indian Institute of Soil Science (IISS) focuses on soil chemistry, fertility, and biology, researching numerous methods to maintain soil biodiversity and manage nutrient and water levels in India. Various IITs are engaged in research on nanotoxicology, assessing the environmental and health impacts of nanomaterials.

3.2.3 Sector-Specific Efforts (Table 1)

Nanopollution mitigation in India requires a multi-pronged approach encompassing technological advancement regulatory frame work and public awareness. Efforts taken by different sectors are shown in table 1.

(Table 1) Summary Table of Matrix-Wise Measures for Nanopollution Mitigation in India.

Matrix	Measures Taken	Explanation/Notes
Air	- Nano-filters - Industrial emissions monitoring - TiO ₂ photocatalytic coatings	Advanced filtration systems, including nanomaterials, are being used in air purifiers and industry. (Goyal & Tyagi, 2024; Guo et al., 2024).

Water	- Nanofiltration - Adsorption (e.g., activated carbon, silver nanoparticles) - Bio-remediation	Technologies using nanomaterials help to remove heavy metals, microbes, and organic pollutants. (Ghosh et al., 2022; Khan & Ullah, 2024; Reddy et al., 2023).
Soil	- Biochar application - Phytoremediation - Monitoring of nano-fertilizers and pesticides	Use of plant-based remediation and amendments to manage nanoparticle accumulation and toxicity. (Bharagava & Saxena, 2024; Shah & Singh, 2024).
Industry	- Hazardous waste management rules - Promotion of green synthesis methods	Regulations for proper disposal of nanomaterial waste and cleaner production techniques. (Department of Science & Technology 2017; NEERI, 2023).
Policy	- Nano Mission - Environmental Impact Assessment (EIA) integration - CPCB guidelines	Policy mechanisms being developed to incorporate nanomaterial risk assessment into national planning. (Department of Science & Technology, 2007; Central Pollution Control Board, 2023).
Research	- Nanotoxicology studies - Development of nano-biosensors - Risk assessment frameworks	Ongoing R&D to study effects on human health, animals, and ecosystems; monitoring tools are evolving. (Singh et al., 2023; Lewinski et al., 2011; Times of India, March 2024,).

(Table I) Summary Table of Matrix-Wise Measures for Nanopollution Mitigation in India

A. Agriculture and Soil Health

- Guidelines under development for nano-fertilizers and nano-pesticides by ICAR (Indian Council of Agricultural Research). Field studies to evaluate nanoparticle leaching into soil and groundwater. ICAR promotes studies on nano fertilizers to enhance soil health, crop productivity and operation of drones for fertilizer/pesticide spraying, integrating nano fertilizers.
- Nanotechnology for Sustainable Agriculture: Nanomaterials are being explored to enhance soil quality and crop productivity by influencing the soil microbiome and nutrient availability.
- Nano-Bioremediation: Combining nanotechnology with bioremediation techniques offers solutions for reducing pollutants in groundwater, wastewater, and sediments contaminated with heavy metals and organic compounds.
- Nano Fertilizers: Advancing agricultural efficiency/discusses the role of nano fertilizers in sustainable agriculture and their potential to improve nutrient use efficiency.

B. Air Quality Management

- Advances in Nanomaterials for Air Filtration: Explores research on nanomaterials for air

filtration, covering diverse techniques and applications. Electrospun, Nanofibers with Antibacterial and Antioxidant Activities: Highlights the potential of electro spun nanofibers in air purification devices due to their enhanced antibacterial and filtration performance.

- Improvement of Air Quality Using Nanomaterials and Nanotechnology discusses the use of nanosorbents in air purifiers and filters to remove toxic gases from the air.
- Technological Interventions in Delhi: To combat severe air pollution, Delhi's Winter Action Plan includes measures like drone monitoring, artificial rain through cloud seeding, and anti-dust campaigns.

C. Wastewater Treatment

- Solar Water Purification with Photocatalytic Nanocomposite Filter: Demonstrates the use of titanium dioxide nanowires-based photocatalytic filters for water decontamination using sunlight.
- Nano-Bioremediation for Wastewater Treatment: Exploring cutting-edge techniques combining nanotechnology and bioremediation for wastewater treatment.

D. Healthcare and Pharmaceuticals

- Central Drugs Standard Control Organization (CDSCO) is working on regulations for nano-drugs and their environmental disposal.
- Promotion of green synthesis methods for nanoparticle production to minimize waste.

E. Industry and Manufacturing

- Mandating Environmental Management Plans (EMPs) in industries that manufacture or use nanoparticles.
- Encouraging zero liquid discharge (ZLD) systems in high-risk sectors like paints, textiles, and electronics.

F. Awareness, Training, and Collaboration

- Workshops and training programs for environmental regulators and industry stakeholders.

- Collaboration with international bodies like OECD and ISO for best practices.
- Citizen science initiatives and public awareness campaigns about responsible use and disposal of nano-enabled products.

Though India is making progress in addressing nanopollution, but several technical, infrastructural, and policy-related barriers are preventing it from performing at its best. Here are challenges Hindering India’s effectiveness in nanopollution control. Here are some comparative studies are carried out through different tables: table 2 (Global Technical Issues in Nanotechnology), table 3 (Technical Issues in Nanotechnology – India), table 4 (Key problem areas and their impact on nanopollution management in India).

(Table II) Global Technical Issues in Nanotechnology (Maynard, 2015; OECD, 2021)

Issue	Description
Toxicity and Safety	Limited understanding of long-term effects of nanoparticles on human health and the environment.
Standardization	Lack of global standards for manufacturing, testing, and usage.
Regulation	Regulatory frameworks differ by country; many nations lack specific nano-focused laws.
Characterization	Difficulty in characterizing nanomaterials due to their small size and complex behavior.
Scale-up Challenges	Moving from lab-scale to commercial-scale production frequently faces reproducibility issues.
Lifecycle Analysis	Inadequate tools to assess the environmental impact throughout the lifecycle of nanomaterials.
Waste Management	Nano-waste poses unique disposal challenges and is not covered by conventional waste treatment.

(Table II) Global Technical Issues in Nanotechnology (Maynard, 2015; OECD, 2021)

(Table III) Technical Issues in Nanotechnology – India (DST, Government of India, 2020; Sharma, & Li, 2022; Bhushan, 2010).

Issue	Description
Infrastructure Gap	Lack of state-of-the-art infrastructure for high-end nano research and production.
Human Resource Development	Shortage of skilled personnel in interdisciplinary nanosciences.
Policy Implementation	Weak coordination between research institutions, regulatory bodies, and industries.
Limited Toxicological Research	Few Indian institutions conduct systematic studies on nanoparticle toxicity.
Import Dependency	Dependence on imported high-end instruments and precursors.
Funding Constraints	Contradictory and limited funding for long-term research and product development.
Public Awareness	Lack of public engagement and understanding of nanotechnology risks and benefits.

(Table III) Technical Issues in Nanotechnology – India (DST, Government of India, 2020; Sharma, & Li, 2022; Bhushan, 2010).

(Table IV) Key Problem Areas and Their Impact on Nanopollution Management in India

Problem Area	Impact
Absence of nano-specific laws	Weak enforcement mechanisms
Inadequate infrastructure	Limited detection and cleanup efforts
Low public and industry awareness	Unsafe handling and practices
Fragmented research efforts	Ineffective policy implementation
Insufficient remediation funding	Limited progress in solutions
Shortage of trained personnel	Lack of technical expertise

(Table IV) Key Problem Areas and Their Impact on Nanopollution Management in India

Fig. 6 is showing severity of technical challenges in nanotechnology: when we compare India with Global level . Scheme to visually represent the rigorously of each technical issue (Rated on a scale from 1 to 5): (OECD, 2021; DST, Government of India, 2020).

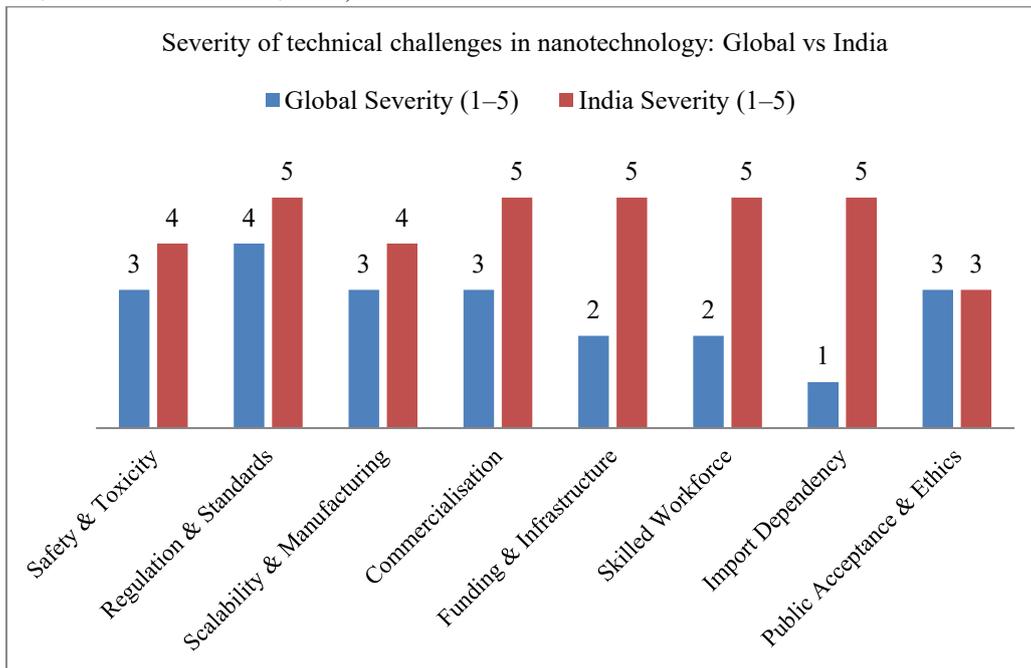


Fig. VI Severity of technical challenges in nanotechnology: Global vs India (OECD, 2021; DST, Government of India, 2020).

1. Lack of Specific Regulations and Standards

- India lacks dedicated and enforceable regulations for nanomaterials and their environmental impact.
- No uniform safety protocols for the disposal, handling, or life-cycle analysis of nanoparticles by Sharma and Li (2022)

2. Inadequate Infrastructure and Monitoring

- Limited advanced labs and sensors for real-time detection and monitoring of nanopollution.
- Many industrial and research sectors still use conventional pollution control systems that don't address nanoscale pollutants (DST 2020).

3. Low Public and Industrial Awareness

- There is limited understanding among industries and the general public about the dangers of nanopollution.
- As a result, best practices are not followed in manufacturing, waste handling, or disposal.

4. Fragmented Research and Policy Implementation

- Research in nanotechnology is not always aligned with environmental safety.
- Policies developed under India's nanomission focus more on innovation than regulation or sustainability (OECD 2021).

5. Insufficient Funding for Environmental Nanotoxicology

- Most funding is directed toward product development (e.g., nano-agriculture, nano-medicine).
- Environmental impact studies and remediation research are underfunded and under-prioritized.

6. Lack of Trained Human Resources

- India faces a notable shortage of professionals with expertise in nanotoxicology, environmental nanochemistry and nano-safety.
- This includes a deficit in trained toxicologists and risk assessors who can evaluate the environmental and health impacts of nanoparticles.
- Without skilled human resources, the development, enforcement, and monitoring of nano-specific safety protocols remain inadequate (Kumar et al. 2020; Singh and Sharma 2021).
- The lack of interdisciplinary training and coordinated academic programs has further contributed to gaps in nano-risk governance.

Suggested Improvements:

- India should develop nanopollution-specific regulations and policies.
- Development and Investment should be done in advanced infrastructure and monitoring tools.
- India should promote interdisciplinary research focused on safety and sustainability.
- India should provide more and more training and awareness programs for industry and academia.

IV. CONCLUSION

In this review, we presented a detail overview about nanotechnology its application, what consequences of overuse of nanotechnology, what measures are taken globally and in India. There is no doubt that nanotechnology has gifted a new world to human, nanotechnology is as long as and doing best as new solutions for the basic need. Without which we cannot think about modern era, yet we cannot ignore the problems that will arise in our future due to nanotechnology. However much of the disadvantages in its application is yet to be

researched as whatever little information is available only comes from inhaled nanoparticles. If not researched thoroughly, the risk of nanoparticles could increase significantly, as it has already been demonstrated in lab rats which resulted in lung inflammation and blood clotting. Furthermore, the high surface area of nanoparticles makes them particularly sensitive when it comes to reactivity, which inside the human body could trigger unwanted reactions in turn causing damage to cells and organs. Therefore the subject of nanoparticles should be treated with caution, especially when it comes to application on humans in order to allow for safer usage in medicine. However nanotechnology is useful for all fields of life but still there are various and severe health hazards concern due to their unstoppable use and discharge to natural environment.

V. RECOMMENDATION

- It is crucial to address environmental concerns before using nanomaterials on a large scale, particularly those containing heavy metals, as they pose significant risks to environmental and human health and can adversely impact all forms of life.
- The limited awareness, infrastructural constraints, and lack of nanoparticle-specific guidelines further hinder India's capability to address potential environmental and health risks posed by nanomaterials. Therefore, while India has made scientific advancements in nanotechnology, its governance mechanisms and protective measures for nanopollution remain significantly underdeveloped by global standards.
- Present policy study concludes that a policy need to be formulated based on training and the commitment of the protection of mankind and environment through R&D within an effective policy and legislative framework.
- Scientists, governments, civil society organizations, and the general public will need to collaborate across sectors to assess the significance and adverse effects of nanoparticles on human beings and on the living world. Everyone should work together so that nanotechnology remains a useful

technology and provides convenience to humans and not harm them.

- More and more studies must be conducted in quantitative as well as qualitative access for nanowaste, so that the proper management of nanowastes takes place. Proper methods of treatment of nanowaste need to be developed for the safety of human health and environment as well.

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