



REVIEW PAPER



A REVIEW OF FUTURE PERSPECTIVES IN GREEN NANOTECHNOLOGY FOR POLLUTION CONTROL

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Abstract:

Green nanotechnology holds a lot of hope for future attempts to stop pollution. It makes use of eco-friendly processes to create nanomaterials that may be applied to a range of pollution remediation approaches, such as air, soil, and water cleaning. By removing certain pollutants from polluted settings, these materials are designed to improve the quality of the air, water, and soil. Globally, wastewater contamination is a serious hazard to both the environment and public health. This study aims to provide light on the evolution of nanotechnology, including both the present and next phases. High surface area-to-volume ratios and customizable physicochemical characteristics are two special benefits of nanotechnology that make it possible to create remediation solutions that are both extremely effective and reasonably priced. Current developments in this subject include a range of nanomaterials, such as nanoparticles, nanocomposites, and nanomembranes, that are intended to remove a variety of pollutants, including organic contaminants, microbes, and heavy metals. This study examines the current and potential applications of nanotechnology in the cleanup of wastewater pollutants. The current analysis examines the developing patterns and encouraging opportunities for enhancing wastewater pollution removal efficiency via the use of nanoscale materials and methods.

Keywords : Nanotechnology; Pollution Control; Catalysis; Environmental Remediation

1. Introduction

1.1. Importance and prospects for green nanotechnology in pollution control

Urbanization, increasing agriculture, and rapid industrialization have caused pollution of the air, water, and soil to reach a global disaster. There is a pressing need for transformative solutions since persistent hazardous pollutants, ranging from heavy metals and chlorinated organics to developing micro pollutants, resist conventional cleanup. Green nanotechnology, which makes use of environmentally friendly nanomaterial production and life-cycle-conscious design, has become a potential area for long-term pollution prevention. Green nanotechnology connects innovation with planetary stewardship by emphasizing biocompatibility, energy efficiency, recyclability, renewable resources, and minimum secondary environmental burden. [1]

1.2. Nanotechnology for agricultural soil remediation

The greatest threat to both the community and the environment is soil pollution brought on by a variety of man-made and natural activities. A technique to cleanup that shows promise is nanotechnology, which includes the use of nanoparticles. Many kinds of nanomaterials, such as nanobiosorbents and nanobiosurfactants, have demonstrated significant promise in soil remediation procedures. Remedial methods for soil pollution using nanotechnology are diverse. Techniques for immobilization and reduction reactions show how versatile nanoparticles are in reducing soil pollution. In agricultural soils, nanomicrobial-based bioremediation significantly improves the effectiveness of pollutant breakdown. Using several search engines, such as PubMed, Web of Science, and Google Scholar, a literature-based screening was carried out between 2010 and 2023.[2]

1.3. Treatment of industrial effluent: A case study of the pulp and paper industry

Chlorolignin, chlorophenols, furans, cyanide, and heavy metals are among the complex effluents produced by the pulp and paper industry. In order to properly treat these effluents, a thorough study published in ACS Omega (2024) emphasizes sustainable nanotechnological interventions such electrocoagulation, photocatalysis, nanocatalysts, nanoadsorbents, and nanocomposites. In comparison to traditional methods, innovations such as titanium-doped carbon-cellulose composites, porous nanofibers (such as Cu_2SnS_3 , CuO , SiO_2), and cellulose-supported ZnO , Co , Au , and Ag nanostructures quickly remove organic dyes and pollutants with improved adsorption and catalytic activity. [3] These results highlight the usefulness of biomass-derived supports in fusing advances in nanomaterials with problems at the industrial scale.

1.4. Nanomaterials across media: Water, soil, and beyond

Green nanotechnology's reach spans multiple environmental media:

1.4.1. Water treatment: In wastewater treatment, nanoadsorbents and hybrid systems are being investigated in addition to photocatalysis, taking advantage of high surface areas and functional group diversity. Green nanoparticles produced sustainably reduce chemical footprints and promote pollution decomposition.[4]

1.4.2. Soil remediation: The application of nanotechnology, which includes nanoparticles, is a promising remediation strategy. Many kinds of nanomaterials have demonstrated significant promise in soil remediation procedures, such as nanobiosorbents and nanobiosurfactants. There are several different ways to use nanotechnology to remediate soil pollution. The adaptability of nanomaterials in reducing soil pollution is demonstrated by reduction reactions and immobilization approaches. Bioremediation based on nanomicrobials improves the effectiveness of pollution breakdown in agricultural soils. [2]

1.4.3. Air pollution: Although less advanced, new initiatives investigate the use of nanoparticles for the absorption and degradation of air pollutants; nonetheless, safety and environmental effects are still being studied.

1.5. Emerging challenges and future directions

Several obstacles still exist despite encouraging advancements:

- **Cost and Scalability:** Green syntheses (such as cellulose supports and photocatalysts made from biomass) show promise, but achieving industrial scale will require addressing issues of cost-effectiveness, yield consistency, and reproducibility.[5]
- **Safety and Regulatory Oversight:** Little is known about the entire effects of implementing artificial nanoparticles on ecosystems' health and environment. Strong regulatory frameworks and thorough risk evaluations will be essential.[6]
- **Integration and Multifunctionality:** Multimedia hybrid systems that integrate sensing, adsorption, catalysis, and biodegradation are the way of the future. Intelligent, multipurpose nanostructures that can detect pollutants, remove them selectively, and monitor them in real time have the potential to completely transform remediation situations.[7]

1.6. Future road map

Green nanotechnology's potential for reducing pollution is expanding rapidly. However, a deliberate focus on scalability, safety, multifunctionality, and socio-regulatory alignment is necessary to transition from promising lab-scale systems to real-world environmental deployment. With the help of current developments and a foundation in sustainability, this chapter aims to map that course in order to imagine future environments where green nanotechnology provides resilient, fair, and clean environmental stewardship.

2. Current status of nanotechnology in pollution control

In the area of pollution control, nanotechnology has become a game-changing instrument, providing incredibly effective, economical, and sustainable answers to environmental problems. Through the creation of cutting-edge nanomaterials and nanoscale processes, it will be crucial in reducing pollution in soil, water, and air ecosystems by 2025.[2] In recent years, people have become more worried about how volatile organic compounds (VOCs) in the air affect health and the environment, which has sparked a lot of interest in studying the photocatalytic oxidation (PCO) of air pollutants.[8] Nanomaterials like carbon nanotubes (CNTs), metal oxide nanoparticles (such as TiO_2 and ZnO), and zero-valent iron (nZVI) are frequently employed in water pollution treatment to remove organic pollutants, dyes, and heavy metals. Nanoparticles are perfect for adsorbing or degrading contaminants because of their enormous surface areas, strong reactivity, and customized surface chemistry. For example, when exposed to UV light, titanium dioxide nanoparticles promote the photocatalytic breakdown of organic contaminants that are persistent in wastewater, providing an energy-efficient treatment technique. [9] Innovative point-of-use treatment methods are required due to the growing demand for freshwater and the growing contamination of distributed water sources, including surface water and stormwater. Solid oxidant-based advanced oxidation processes (AOPs) present a viable method for decentralized freshwater generation, but they are frequently constrained by nonselective radical reactions that break down contaminants and background water components. Here, sonicated carbon nanotubes (CNTs) that efficiently activate peroxymonosulfate are demonstrated, enabling selective contaminant degradation via dual nonradical pathways—singlet oxygen oxidation and direct electron transfer. Carbon nanotubes (CNTs) that efficiently activate peroxymonosulfate are

demonstrated, enabling selective contaminant degradation via dual nonradical pathways—singlet oxygen oxidation and direct electron transfer.[10]

Nanotechnology has also helped with air pollution control. Airborne pollutants are better captured and broken down by filters made of nanofibers and catalytic converters that incorporate nanomaterials. Car catalytic converters use cerium oxide and platinum nanoparticles to cut down on dangerous emissions like CO and NO_x. Additionally, real-time air quality monitoring is made possible by nanostructured sensors, which improves reactivity to pollution incidents.[11]

Nanotechnology-assisted soil remediation involves the use of nZVI particles to detoxify contaminated soils by changing heavy metals and chlorinated hydrocarbons into less dangerous forms. Furthermore, compared to conventional techniques, nanoparticles are being investigated for in-situ cleanup, which minimizes environmental disturbance. Notwithstanding its potential, the field has obstacles to overcome, such as the possible toxicity of nanoparticles, their environmental durability, and the absence of unified regulation. Because of worries about the ecotoxicological effects of nanomaterials, thorough risk evaluations and life-cycle analyses are required. However, frameworks for research and policy are progressively changing to guarantee safe implementation.

To reduce the environmental impact of nanomaterial production, recent advancements have focused on the green synthesis of nanoparticles using biological agents. Furthermore, the accuracy of pollution monitoring and management techniques is being enhanced through the integration of nanotechnology, artificial intelligence, and remote sensing.[12] So, nanotechnology is at the forefront of innovative pollution control methods. Continued research, regulatory development, and public-private collaboration will be critical to fully realizing its potential while safeguarding environmental and human health.

Table 1: Examples of Nanomaterials Used in Pollution Control

Sr. No.	Nanomaterial	Application Area	Function	Reference
1.	TiO ₂	Air and Water Purification	Photocatalysis	[13]
2.	nZVI (Fe) NPs	Soil and groundwater remediation	Adsorption isotherm and redox reaction	[14]
3.	ZnO	Antibacterial coatings	Reactive Oxygen species generation	[15]
4.	Carbon Nanotubes	Water filtration	Adsorption of Heavy Metals	[16]
5.	Ag NPs	Disinfection	Antimicrobial action	[17]

The efficiency of these nanoparticles in eliminating pollutants, such as organic contaminants, heavy metals, dyes, and pathogens, is being extensively researched. However, a move toward greener alternatives is required due to worries about their toxicity and environmental permanence. As a result, researchers are exploring biodegradable and less toxic materials that can effectively degrade pollutants without causing harm to ecosystems. This shift not only aims to enhance pollutant removal efficiency but also to promote sustainability in nanotechnology applications. Sustainability in nanotechnology applications is becoming a pivotal aspect of research, as scientists seek to balance effective pollution remediation with ecological responsibility. By harnessing natural components and innovative designs, the development of these eco-friendly nanoparticles holds the promise of a cleaner and more sustainable future.[18] This future not only prioritizes environmental health but also encourages the

advancement of sustainable practices across various industries. As researchers continue to explore the potential of these eco-friendly nanoparticles, we can expect breakthroughs that significantly reduce the ecological footprint of traditional remediation methods. As these breakthroughs emerge, industries will likely adopt these innovative solutions, leading to a transformative shift in how we approach pollution control. By integrating eco-friendly nanoparticles into existing processes, we can pave the way for a more harmonious relationship between technology and the environment.

3. Green synthesis of nanomaterials

Many synthesis techniques have been developed in recent years, and many of them are used to prepare nanoparticles. These include solvothermal synthesis, sol-gel route, chemical vapour deposition (CVD) technique, hydrothermal technique, electro-deposition method, direct oxidation method, and green synthesis. However, because the harmful consequences of different chemical techniques have been eliminated, green synthesis has gained widespread support. Green synthesis, also known as phytosynthesis, is the term used to describe the synthesis of materials from plants. In phytosynthesis, plant extract is used as a stabilizing and capping agent as well as a reducing agent in the reaction mixture. The plant's biomolecules provide the final nanomaterials unique qualities and stunning features.[19]

This review includes various nanomaterials which synthesized by green method by using different green precursor and methods.

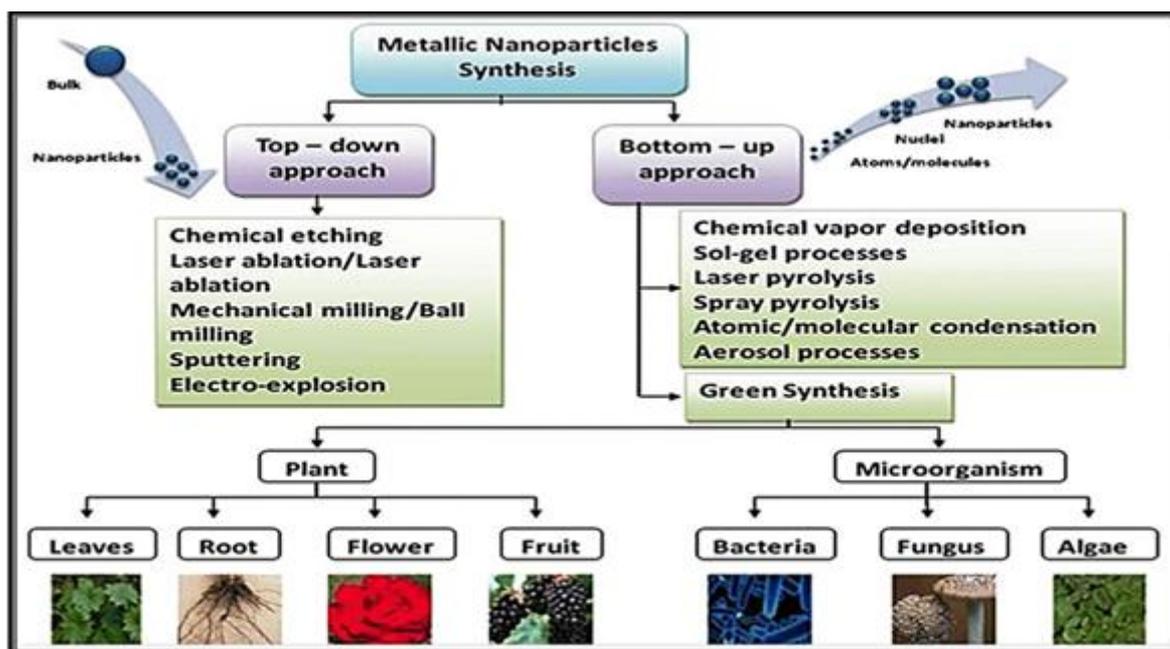


Figure 1: Different synthetic approaches available for the preparation of nanoparticles. Reproduced with permission from [20]. Copyright under the creative commons attribution license

Table 2: Green Synthesis of Nanoparticles with their Applications

Sr. No.	Nano-particle	Green precursor	Size	Shape	Applications	Ref.
1.	TiO ₂	leaves of Aloe barbadensis miller plant	10-15 nm	Spherical	Photoanode; for dye-sensitized solar cells	[21]
		<i>Morus nigra</i> Leaves		Irregular shape	Biological potential	[22]
		leaf extracts of <i>Jatropha curcas</i> L	13 nm	Spherical	Waste water treatment	[23]
		lemon peel extract	20 to 180 nm	Spherical	Optical and Photocatalytic properties	[24]
2.	Ag NPs	<i>Podocarpus macrophyllus</i>	13-20 nm	Spherical	Targeting GBM and LGG brain cancer	[25]
		<i>Breynia nivosa</i>	15-20 nm	Spherical	Biomedical applications	[26]
		<i>Ocimum species</i>	5- 70 nm	Spherical	Assessment of Anticancer potential	[27]
		<i>Brassica carinata microgreen</i>	Average 35 nm	Spherical	Antimicrobial activities	[28]
3.	ZnO	<i>Sansevieria trifasciata</i>	30 nm	Spherical & hexagonal	High performance Asymmetric Supercapacitors	[29]
		<i>Aerapersica Aqueous-Root Extract</i>	20-25 nm	Not specific	Antioxidant and Anti-Inflammatory	[15]
		<i>Rhus coriaria extract</i>	15-20 nm	Spherical & hexagonal	Anticancer activity against triple-negative breast cancer cells	[30]
4.	n ZVI (Fe ⁰)	0.2 M iron chloride and oak leaf extract	10- 100 nm	Spherical	Degradation of Sulphacitamide	[31]
		Three plant extracts including <i>Rosa damascene</i> (RD), <i>Thymus vulgaris</i> (TV), and <i>Urtica dioica</i> (UD)	Average 100 nm	Spherical	Removal of Cr(VI) from aqueous solution	[14]
		<i>Palm Petiole Extract</i>	70-75 nm	Irregular shape	Removal of Cr(VI) from water	[32]
		<i>Ricinus Communis Seeds Extract</i>	10-30 nm	Irregular shape	Treatment of Methylene Blue-Polluted Water	[33]

4. Mechanisms of pollution control via nanomaterials

4.1 Adsorption

Adsorption is a surface phenomenon in which organic and inorganic materials adhere to the surface of an adsorbent due to physical-chemical forces, primarily electrostatic and van der Waals interactions. In order to ensure waste removal, an efficient adsorbent needs to have a high adsorption capacity in addition to being inert, biocompatible, and resistant to mechanical pressures. Adsorption processes are affected by temperature, pH, pollutant concentration, contact time, particle size, and the physical and chemical properties of the adsorbate and adsorbent. For instance, an increase in temperature can enhance adsorption capacity in endothermic reactions, and pH can affect adsorption capacity by changing the surface groups on the adsorbent and the pollutant charge.[34] A common wastewater treatment method for eliminating impurities from aqueous solutions is adsorption. These include organic pollutants, heavy metals, colors, nutrients, and pathogens. Significant advancements in the adsorption capacities and specificities of recently developed adsorbents, as well as a better understanding of adsorption mechanisms and kinetics, have been made during the last ten years. The use of nanotechnology has led to significant advancements in the creation of adsorbents by enabling the production of materials at the nanoscale with special qualities including large surface area, adjustable pore size and shape, and functional groups. It is possible for nanomaterials to function as independent adsorbents or as essential building blocks for composite adsorbents. Carbon nanotubes, graphene, metal oxides, metal-organic frameworks, zeolites, and magnetic nanoparticles are a few examples of nanomaterials that have been extensively researched for adsorption applications.[35]

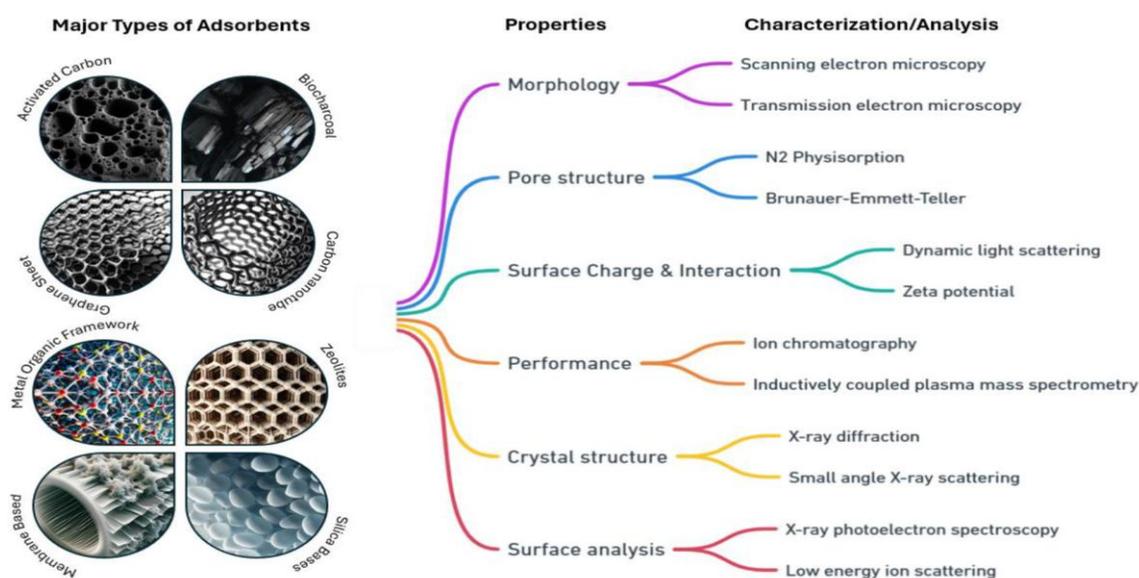


Figure 2: Key adsorbent types, their properties and techniques used for respective characterization.

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4.1.1 Photocatalysis

Photon absorption and electron-hole pair excitation, Separation and migration of photogenerated charge carriers, and Surface catalytic chemical redox reactions are examples of photocatalysis processes. Each of these processes is critical for photocatalytic systems' efficiency. In the first place, efficient light harvesting guarantees that the

materials collect enough photons to generate electron-hole pairs efficiently. For these electron-hole pairs to be delivered to the intended reaction location, charge separation and transfer procedures are essential for preventing recombination. [36]

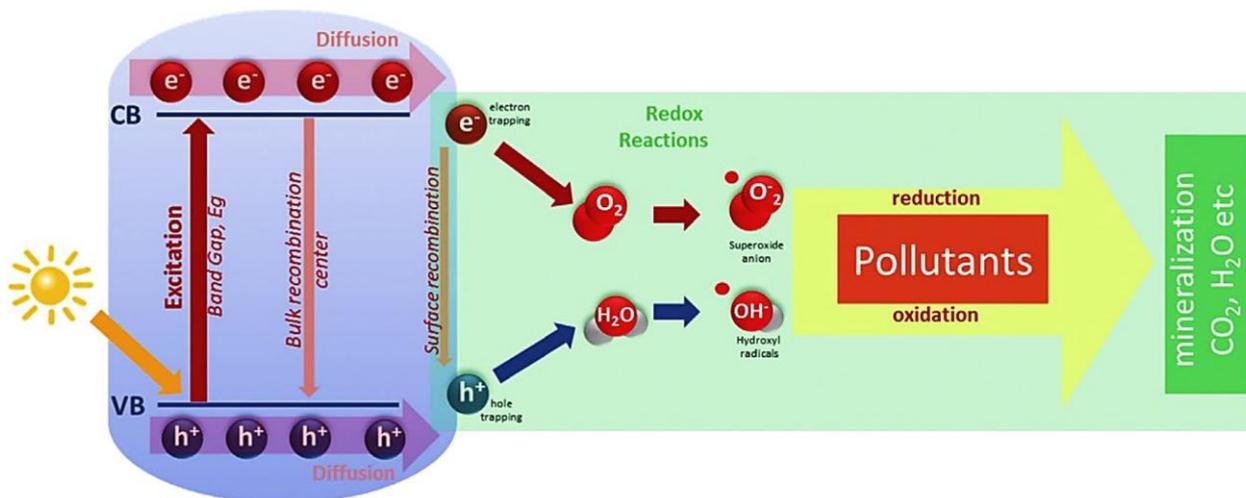


Figure 3: General mechanism of photocatalytic degradation of pollutants in presence of NPs.

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5. Emerging trends in nanotechnology

5.1. smart nanomaterials: Responsive to environmental stimuli (pH, light, temperature) for targeted action. Their unique physicochemical properties and multifunctional capabilities have made smart nanomaterials (NMs) a game-changing instrument in the biomedical field. In the biomedical industry, nanoparticles (NPs) have long been recognized as drug carriers that help get past biological barriers and lower the dosages of medications that need to be administered. Certain NPs have the ability to interact with external stimuli, like electromagnetic radiation, to produce intriguing effects (like hyperthermia) or even alter how the biological system interacts with the electromagnetic field (like electroporation). Because of these factors, the applications of nanomaterials are currently being thoroughly researched, particularly for medications that exhibit significant adverse effects, for which a lower effective dose necessitates the discovery of substitutes.[38]

5.2. Bio-nano hybrid systems: Combining enzymes or microbes with nanomaterials to enhance degradation.

5.3. Nano-enabled sensors: Real-time monitoring of pollutants at ultra-low concentrations. With broad implications for individualized education and mental health therapies, nano-biosensors (NBs) are emerging as revolutionary tools for real-time cognitive monitoring. These sensors integrate effective nanomaterials (NMs) with bioelectrical signal detection, giving them unique sensitivity to physiological indicators such as cortisol, dopamine, serotonin, lactate, and heart rate variability. By enabling dynamic assessments of student engagement, cognitive load, and mental states in educational contexts, NBs provide flexible learning environments that may be tailored to meet the needs of each person. In a similar vein, they facilitate the early detection of mood, anxiety, and stress issues in mental health, enabling timely interventions. This innovative device encourages self-awareness and resilience by giving users immediate feedback so they can develop healthy coping mechanisms. [39]

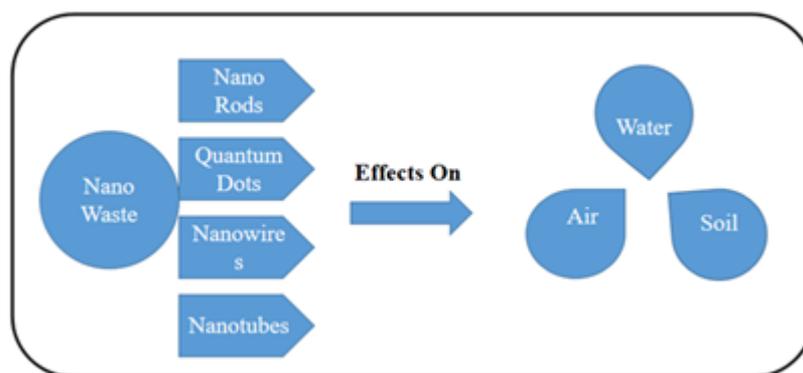


Figure 5: Effects of Nano waste on Environment

6. Future directions

In order to address the challenges outlined in the Sustainable Development Goals (SDGs), the United Nations has divided the risks facing the globe into 17 categories, each with distinct goals. To guarantee the implementation of these measures, science and technology were widely used as conduits. Sustainability science, in this sense, looks for ways that the research community may help address issues related to sustainable development. Specifically, it has been acknowledged that nanotechnology is a crucial instrument for offering innovative and successful approaches to achieving the SDGs.[40]

6.1. Development of multifunctional nanomaterials

Multifunctional nanomaterials for pollution control have recently produced flexible platforms that combine remediation, sensing, and recovery in a synergistic way. According to a study presented at the American Chemical Society, multifunctional carbon-metal nanohybrids efficiently break down organic contaminants while permitting environmental monitoring and catalytic regeneration, underscoring its promise for environmentally friendly remediation systems.[41] In addition to these, improved spherical metal oxides (SMOs) with porous, yolk-shell, and hollow morphologies have been developed for the photocatalytic destruction of antimicrobial contaminants. These structures improve degradation efficiency by increasing mass transfer, light usage, and reactive oxygen species production.[42] Furthermore, a thorough analysis demonstrates how metal oxide and carbon-based nanoparticles (like graphene, ZnO, TiO₂, and CNTs) have remarkable adsorption strengths (removal rates ranging from approximately 60% to 99%) and several other functions, such as antimicrobial activity, which allow for simultaneous adsorption, disinfection, and catalytic degradation in wastewater systems.[43]

The ability of multifunctional nanomaterials for air filtration to concurrently capture, sense, regenerate, and degrade airborne contaminants has demonstrated extraordinary adaptability in recent years. One noteworthy example is a graphene-enhanced ceramic filter medium (GeFM) that can capture more than 95% of particulate matter and microorganisms larger than 1 μm while allowing for self-cleaning through Joule heating above 300 °C to break down trapped organic and microbial contaminants, regenerating filter function and improving longevity and safety.[44] Similarly, Ag-doped TiO₂ embedded in electrospun silk nanofibers exhibits multifunctionality by providing antibacterial activity, photocatalytic destruction of organic pollutants, and efficient air filtration.[45] Collectively, these developments show a strategic move toward smart air purification technologies that combine operational regeneration, active pollutant destruction, and structural filtration into cohesive nanostructures, offering more effective, long-lasting, and adaptable defenses against airborne pollutants. These advancements highlight the trend toward multifunctional, structurally complex nanomaterials that combine adsorption,

photodegradation, sensing, and regeneration, providing comprehensive, effective methods for managing a variety of contaminants in environmental remediation.

Conclusion

Growing environmental problems brought on by urbanization, industry, and population expansion have made the creation of novel and sustainable pollution control systems necessary. The multidisciplinary field of green nanotechnology, which combines the ideas of green chemistry and Nano science, has the potential to revolutionize pollution control in a way that is more economical, environmentally responsible, and efficient. Looking ahead, it seems not only promising but also necessary to strategically integrate green nanotechnology into waste management, pollution prevention, and environmental rehabilitation. The potential to create nanoparticles with particular qualities to identify, break down, or eliminate contaminants at trace amounts is one of the most alluring features of green nanotechnology. Advanced nanomaterials with enormous promise for treating pollutants in the air, water, and soil include metal-organic frameworks (MOFs), carbon-based nanostructures, green-synthesized nanoparticles, and biodegradable polymer nanocomposites. In comparison to traditional methods, their high surface area, responsiveness, and functional adaptability provide improved performance with smaller environmental impacts.

However, there are still a number of obstacles in the way of the widespread use and commercialization of green nanotechnology. It is necessary to fully address issues with Nano toxicity, long-term environmental effects, regulatory uncertainties, and public acceptance. Life-cycle assessments, biosafety analyses, and the creation of thorough recommendations for the responsible use and disposal of nanomaterials must be the main areas of future research. To guarantee comprehensive and useful solutions, it is also critical to encourage interdisciplinary cooperation among material scientists, environmental engineers, legislators, and industrial stakeholders.

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