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WATER POLLUTION AND NANOTECHNOLOGY: STATUS OF POLLUTION AND REMEDIATION, CHALLENGES AND FUTURE SCOPE

Faheem Ahamad and Rakesh Bhutiani

Limnology and Ecological Modelling Laboratory, Department of Zoology and Environmental Sciences, Gurukul Kangri (Deemed to be University), Haridwar-249404, Uttarakhand, India.

***Email id: : faheem.ahamad170390@gmail.com**

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Abstract

With growing contamination from domestic, agricultural, and industrial sectors, water pollution has become a serious global environmental concern. Emerging contaminants like heavy metals, microplastics, and pharmaceutical residues are frequently difficult to remove with traditional water treatment techniques. Due to its great efficiency, selectivity, and potential for widespread use, nanotechnology offers a viable approach to water filtration. The present chapter provides the state of water contamination with a focus on the main contaminants and their sources. The chapter explores the role of nanotechnology for water treatment. The findings of the chapter elucidate that besides national and international efforts, a large population of the world still don't have the access to clean water. Among all the emerging technologies, nanotechnology is cost-effective, and sustainable technology for the treatment of water and wastewater. The chapter also covers the drawbacks of water treatment using nanotechnology, including issues with cost, scalability, environmental impact, and regulations. To address global water security challenges, it concludes by outlining prospective

future research areas and the integration of nanotechnology with intelligent and sustainable water management techniques.

Keywords: Nanotechnology, scalability, sustainability, water crisis, disease.

Introduction

Water is one among the few irreplaceable natural resources of nature. The origin and development of human race take place after the existence of water on the earth (Baruahet al., 2016). Besides this water makes up a huge part of the body weight of both humans and plants. Water pollution is basically the change in the physical, chemical, and biological properties of the water that may cause harm to the health of living beings, material, property, and industrial processes. Water gets polluted due to indiscriminate dumping of untreated or partially treated wastewater on the ground or in aquatic bodies i.e. pond, lake, rivers etc. The polluted water is unsafe for the use of drinking, bathing, and irrigation purposes as it causes different problems for humans, aquatic life, and crops (Ahamad et al., 2023 & 24). Consumption of polluted water causes different diseases like cholera, typhoid, and mutations in human beings (Jain et al., 2016; Bhutianiet al., 2021). Aquatic bodies pollution causes the reduction in the population of aquatic organisms and plants. Pollutants from water bodies and soil enter in the food chain and then cause harm to the animals depending on the animal's size and toxic level of pollutants (Gehrke et al., 2015).

Water pollution is now a global issue affecting the health of humans, animals, and industries processes. About 2.2 billion people didn't have access to safe drinking water (Theron et al., 2008; Bora and Dutta, 2014; Kumar et al., 2014), challenging the fulfillment of sustainable development goals no 6 (Ahamad et al., 2023). Water related disease is the main cause of the death of about twelve million people every year (http://www.who.int/infectious-disease-report/pages/textonly.html).Along with organic, inorganic, and agrochemicals, microplastics is also reported in more than 70% of the samples.

Table 1: Showing the different water pollutants, their source and impacts.

Sr. No.	Water pollutant		Health impacts	Source
1	**Heavy Metals**	Lead (Pb)	Kidney dysfunction, neurological damage, developmental disorders	Agrochemicals, Electroplating industry, mining industry etc.
		Arsenic (As)	skin lesions, cancer, cardiovascular diseases	
		Mercury (Hg)	Effect on nervous system	
		Cadmium (Cd)	Damage to kidney and bones	
		Chromium (Cr)	Cancer	
2	**Organic Pollutants**	Agrochemicals (DDT, Glyphosate, Atrazine)	Toxic to aquatic life, Carcinogenic	Agricultural runoff and Industrial discharge
		Petrochemicals and Hydrocarbons (Benzene, Toluene, PAH)	Carcinogenic	
		Pharmaceuticals Chemicals (Antibiotics and Hormones)	Interrupts aquatic ecosystems	
		Endocrine-Disrupting Chemicals (Bisphenol A (BPA), Phthalates)	Disturb the hormonal balance as well as reproductive system	
3	**Microplastics**	Microbeads, cloth fibers,	Responsible for endocrine and immune system disruption, Contaminates food chains	Degradation of plastic waste and synthetic fishing gear, discharge from textile industry
4	**Pathogens**	Bacteria	Cholera, Dysentery	Discharge of untreated sewage,
		Viruses	Hepatitis A	

		Protozoa	Gastrointestinal infections	poor sanitation and flooding events
		Fungal & Algal Toxins	Algal blooms	

Sources and Types of Water Contaminants

Water gets polluted due to the discharge of untreated or partially treated wastewater of industries, municipalities, surface runoff, and agricultural runoff. Industrial waste contains different types of hazardous chemicals, metalsand radioactive materials (Barakat, 2011; Baruahet al., 2016). Runoff from agricultural fields possess different types of agrochemicals like pesticides, fungicides, fertilizers, rodenticides etc. The municipal discharge contains organic matter and pathogens. The discharge from nuclear reactors contains different radioactive materials which pollute both ground and water bodies for a long period. Leakage of oil from the ships is another major cause of water pollution in large water bodies like seas and oceans. Microplastics is another major cause which causes pollution of both ground and surface water (Gehrke et al., 2015). Leachate from the landfill sites possess harmful chemicals and other hazardous substances that cause soil and water pollution (Ruhelaet al., 2021). Besides all these anthropogenic reasons, water gets polluted due to some natural reasons. Various compounds of sulphur and mercury and other hazardous materials released from the volcanic eruptions that reached the water bodies and polluted the water bodies as well as ground (Madhura et al., 2019). Leaching of different heavy metals like arsenic, lead and fluoride due to various geological processes pollute groundwater. Surface runoff that possesses eroded soil is also a major reason for lakes, ponds, and rivers pollution (Bora and Dutta, 2014).

Water pollutants are of three types like physical, chemical, and biological. Physical pollutants include sediments, plastics, paper, pieces of clothingand pouches of daily use products. Chemical pollutants include heavy metals (arsenic, mercury, zinc etc.), agrochemicals (pesticides, herbicides etc.), pharmaceuticals chemicals (antibiotics, hormones

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etc.), nutrients (nitrate and phosphate), and petrochemicals (benzene, oil hydrocarbon etc.). Biological contaminants include algae, fungus, bacteria etc. (Sugunan and Dutta, 2008).

Need for Advanced Water Remediation Technologies

To fulfill the need of the continuously increasing population, urbanization, industrialization, agricultural land expansion is also increasing. All these activities lead to the increased use of water. The use of contaminated water can create health hazards and therefore the treatment of water is necessary. Various conventional methodologies were in use for the treatment of wastewater, but all these techniques are not successful for the reduction or elimination of emerging contaminants (microplastics, agrochemicals, pharmaceutical chemicals etc.) of water. Another drawback of conventional technologies is the requirement of high energy and chemicals (Khan et al., 2019). Therefore, for the complete treatment of water, the application of advanced water treatment technologies is essential. The advanced water treatment technologies are smart, ecofriendly, economically sound, and require less amount of energy as compared to conventional. Nanotechnology-based water treatment technologies also reduce the environmental footprint of water treatment. Nanotechnologies based water treatment, Advanced Oxidation Processes (AOPs), Membrane Technologies, and smart water treatment are some of the advanced methods of water treatment (Madhura et al., 2019).

Nanotechnology in Water Remediation

Nanotechnology is one among the various advanced techniques of water treatment. It is cost effective, eco-friendly and has a sustainable approach to water treatment. Technology can remove pollutants at nanoscale level (Bora and Dutta, 2014). The materials used for the treatment are first treated at nanoscale level. The high surface is to volume ratio make the nanoparticles more effective as it enhances the number of sites for pollutants bindings (Theron et al., 2008). The efficiency of the nanoparticles depends on their size. The less the size of the particle, the more the surface area is and high is the efficiency of those materials. The prepared nanoparticles can be customized according to the need i.e. for the reduction of heavy metals, the nanoparticles can be modified into magnetic nanoparticles(Sugunan and Dutta, 2008; Jain et al., 2016). Nanomaterials are categorized into carbon based, metal & metals oxide based, and Polymeric and Functionalized Nanomaterials (table 2).

Table 2: Categorization of nanomaterials (Source: Qu et al., 2013; Bora and Dutta, 2014; Gehrke et al., 2015).

Sr. No.	Category	Example	Use
A	**Carbon-Based Nanomaterials**	Carbon Nanotubes (CNTs)	Used for organic pollutants and heavy metal reduction
		Graphene and Graphene Oxide (GO)	Used for heavy metals, bacteria, viruses, dyes, and organic pollutants
B	**Metal and Metal Oxide Nanoparticles**	Nano-Iron (nZVI – Nanoscale Zero-Valent Iron)	Used for the reduction of hazardous metals like arsenic, chromium etc., from groundwater
		Iron Oxide Nanoparticles (Fe_3O_4, Magnetite)	Used for effective reduction of arsenic, lead, and cadmium
		Titanium Dioxide (TiO_2)Nanoparticles	Used for the reduction of organic pollutants with the help of UV light
		Silver Nanoparticles (AgNPs)	Used for the reduction microbial contamination
C	**Polymeric and Functionalized Nanomaterials**	Nanocomposite Membranes	Nanoparticles coated with polymer membrane enhanced the mechanical strength and antifouling property. Used for desalination and wastewater treatment.
		Molecularly Imprinted Polymers (MIPs)	Useful for the selective pollutant's reduction.
D	**Nanocomposite and Hybrid Materials**	GO-Fe_3O_4	Highly efficient for the removal of lead and arsenic.
		CNT-TiO_2	Used for photocatalytic degradation of heavy metals.

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Nanoparticles reduce the pollutants due to adsorption, catalytic degradation, and antimicrobial action. Nanoparticles enhance the membranes resistant against fouling. Nanotechnology based water purification systems are efficient to remove the large range of pollutants, consume less amount of energy, and sustainable. Scalability, final disposal and lack of regulatory guidelines regarding the use of nanoparticles for environmental remediation (Lovern and Klaper, 2006). Nanoparticles work in both modes, i.e. remove some pollutants completely and sometimes change the state of the pollutants as the more toxic hexa-chromium is converted to less toxic trivalent chromium ion by nanoscale zero-valent iron (nZVI) particle. Chitosan-based nanoparticles are biodegradable and highly efficient for the removal of lead and mercury. Similarly, MIPs are highly efficient for the removal of copper and nickel. Organic pollutants are removed from water by adsorption (pollutants get attached to the surface of nanoparticle), photocatalytic degradation (breaking down of organic matter in the presence of lights), Fenton process (oxidation of organic matter by hydroxyl radical), and bio-nano catalysis (enzymatic degradation) method (Bora and Dutta, 2014). In case of microbial contamination, the nanoparticle attached to the cell membrane of microbes and disrupts the membrane which results death of microbe. Another method of microbial decontamination is the oxidation of microbial cell membrane with the help of reactive oxygen species (ROS). Metal based nanoparticles are attached to the cell of microbes and make them enabled. Nanoparticles also reduce the formation of biofilms by preventing the attachments of microbes. Reverse Osmosis (RO) membrane impregnated with graphene oxide (GO) enhances the water flux and durability of the membrane. Similarly, the impregnation of CNTs enhances the permeability and helps in reducing the fouling property of the membrane. The combined nano electrode and TiO_2-based systems effectively remove the pharmachemicals, microplastics and endocrine disruptors from the wastewater. Nanocoating of the membranes helps in reducing scaling property and thereby increases the lifespan of the membranes (Mouchetet al., 2008).

Challenges of Nano-Based Water Remediation

Although nanotechnology is reported efficient for water treatment by various authors around the world simultaneously several drawbacks are also reported (Petersen et al., 2011; Clemente et al., 2012; Asghari et al., 2012; Qu et al., 2013;Gehrke et al., 2015; She et al., 2016; Madhura et al., 2019). Nanomaterials got clogged because of aggregation of molecules which reduce the available surface area of and thereby reduce the cumulative efficiency of the materials (Hyung and Kim, 2009; Madhura et al., 2019). Photocatalysis, a nano based technology, demands high energy making it unsuitable in the context of sustainability (Bora and Dutta, 2014). Toxicity of nano materials such as silver nanoparticles and metal oxide-based particles cause harm to the environment when discharged. Proper toxicity assessment before the use and then careful discharge will eliminate this challenge. Some nano materials used for water treatment persist in the water and enter the food chain and in the long-term cause harm to the health of living beings. Practicing biodegradable materials for water treatment completely reduces the risk of persistence. Generation of secondary products is a critical drawback of nano technology-based water treatment processes. High production cost is another drawback of this technology.

Future Scope

The research is going on to enhance the lifespan of the membrane and reduce the fouling property. Researchers around the globe are working on ecofriendly bio nanoparticles to build hybrid nanotechnology for water treatment. To reduce the risk of toxicity and the cost of production, synthesis of biobased nano particles is in development. Use of artificial intelligence with nanomaterials helps in the real time water quality monitoring and in the development of smart water filtration system. Advancement in MIPs is another milestone in the development of pollutants, specifically water purification systems. Recovery of valued materials form waste with the help of nano adsorbents helps in the achievement of zero liquid discharge (ZLD) policy.

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Conclusion

The main aim of the present chapter is to study the status of water pollution and remediation technologies with a special focus on the role of nanotechnology for water and wastewater treatment. Various websites and research platforms were visited for literature review. After a thorough review of the existing literature, it was found that access to clean is still a dream to a huge number of people around the globe. Various conventional and non-conventional technologies are in use for the treatment of water and wastewater. Due to high demand of energy, the use of conventional is decreased while the use of non-conventional technologies is increasing. Among them nanotechnology is playing an important role due to its cost, low demand of energy, and sustainability. Although membrane fouling, scalability, and toxicity are some of the big challenges for the successful use of this technology. Research are also needed to overcome all the drawbacks reported in the literature.

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