Applications of Nanotechnology for Environmental Management

C. K. JAIN*, R. D. SINGH, BABITA SHARMA AND VANDANA SAINI

National Institute of Hydrology, Roorkee – 247 667, India

**Email: ckj_1959@yahoo.co.in*

Abstract: *The availability and access to safe drinking water, especially amongst the poor is an issue that is accelerating with time. Many water sources are contaminated with both biological and chemical pollutants such as arsenic, fluoride, etc. New problems like organic contamination (pesticides, insecticides, etc.) and increasing salinity are affecting water sources extensively. Bacterial contamination in surface water and at points of use is a major cause of concern. Great strides have been made in applying nanotechnology in varying degrees of complexity in several fields – from space travel to cosmetics. Nanotechnology for safe water is an area that is being looked at globally and is also a priority concern in India. While there are several types of nanotechnology that are relevant to addressing safe water, there are some that may be more appropriate, affordable and sustainable for use among the poor. In this paper an attempt has been made to compile and evaluate recent advancements made in the application of nanotechnology in water sector to evaluate benefits and/or drawbacks of nanotechnology and its application in pollution remediation. Nanotechnologies can provide solutions to alleviate water problems, both in terms of detection and removal of contaminants. Also since small amounts of nonmaterial are used for purification, costs and waste generation are low, providing an effective and affordable water treatment solution to the poor.*

Keywords*: Nanotechnology, Drinking Water, Contaminants, Environmental Management*

1. Introduction:

Nanotechnology encompasses a broad range of tools, techniques and applications and is widely considered as one of the most significant technologies of the 21st century. Engineered nanomaterials are manufactured materials with a structure between approximately 1 nm to 100 nm. Their unique physico-chemical and surface properties contribute to the development of materials with novel properties and technical solutions to problems that have been challenging to solve with conventional technologies.

A large number of nanomaterials containing products are available in market including coatings, computers, clothing, cosmetics, sports equipment and medical devices. Nanotechnology has the potential to improve the environment, both through direct applications of nanomaterials to detect, prevent and remove pollutants, as well as indirectly by using nanotechnology to design cleaner industrial processes and create environmentally responsible products.

Over the past two decades, scientists and engineers have been mastering the complexity of working with nanoscale materials. Now, researchers have a somewhat clearer picture of how to create nanoscale materials with properties that never came into existence before. Products using nanoscale materials and processes are now available, e.g., anti-bacterial wound dressings use nanoscale silver, a nanoscale dry powder can neutralize gas, batteries for tools are being manufactured with nanoscale materials in order to deliver more power, more quickly with less heat, sunscreens containing nanoscale titanium dioxide or zinc oxide are transparent and reflect ultraviolet light to prevent sunburns [1].

2. Uses of Nanotechnology:

Nanotechnology is being used in various fields ranging from space travel to cosmetics. Various techniques and products based on nanoscale particles are available and can be categorized as i) Nano Films, ii) Nano Tubes, iii) Drug-Delivery Techniques, iv) Nanoscale Transistors and v) Water Filtration Techniques and these have been described below in brief [1].

2.1 Nano Films:

Different nanoscale materials can be used in thin films to make them water proof, anti-reflective, self-cleaning, ultraviolet or infrared-resistant, anti-fog, anti-microbial, scratch resistant or electrically conductive. Nano films are used now on eyeglasses, computer display and cameras to protect or treat the surfaces.

2.2 Nano Tubes:

Carbon nanotubes are allotropes of carbon with a cylindrical nanostructure. Nanotubes have been constructed with length-to-diameter ratio of up to 132,000,000:1, which is significantly larger than any other material. These cylindrical carbon molecules have unusual properties, which are valuable for nanotechnology, electronics, optics and other fields of materials science and technology. They exhibit extraordinary strength and unique electrical properties and are efficient conductors of heat. Their final usage, however, may be limited by their potential toxicity.

2.3 Drug-Delivery Techniques:

Dendriods are a type of nanostructure that can be shortly designed and manufactured for a wide variety of applications, including the treatment of cancer and other diseases. Dendriods carrying different materials and their branches can do several things simultaneously, such as recognising diseased cells, diagnosing diseased states (including cell death), drug delivery, reporting location, and reporting outcomes of therapy.

2.4 Nanoscale Transistors:

Transistors are electronic switching devices where a small amount of electricity is used like a gate to control the flow of larger amount of electricity. Transistors sizes have been decreasing, so computer have become more powerful. Until recently, the industry’s best commercial technology produced computer chips with transistors having 45-nanometer features. Recent announcements indicate that 32 nanometer feature technology soon will be here.

2.5 Water Filtration Techniques:

Scientists are experimenting with carbon nanotubes based membranes for water desalination and nanoscale sensors to identify contaminants in water system. Other nanoscale materials that have great potential to filter and purify water include nanoscale titanium dioxide, which is used in sunscreen and which has been shown to neutralize bacteria.

3. Nanotechnology in Water Sector:

Although, nanotechnology is being applied in many areas (e.g., medicine, energy, agriculture, etc.) but from a human development perspective water purification has been identified as a high priority area in water sector. Given the importance of clean water to people in developed and developing countries, various researchers and organizations are utilizing the potential application of nanotechnology to solve technical challenges associated with the removal of various contaminants from water. Researchers claim that these technologies offer more effective, efficient, durable and affordable solutions to removing specific types of contaminants from water. A wide range of water treatment devices that incorporate nanotechnology is already available in the market and many others are in advanced stages of development. These nanotechnology applications include:

i) Nanofiltration and desalination technologies using zeolite, attapulgite clay and polymer filters;
ii) Nanocatalysts and magnetic nanoparticles; and
iii) Nanosensors for the detection of contaminants.

3.1 Nanofiltration and Desalination:

Nanofiltration membrane technology is widely used for removal of dissolved salts from salty water, removal of micro pollutants, water softening and wastewater treatment. Nanofiltration membranes selectively reject substances, which enables the removal of harmful pollutants and retention of nutrients present in water that are required for the normal functioning of the body. It is expected that nanotechnology will contribute to improvements in membrane technology that will drive down the costs of desalination, which is currently a significant impediment to wider adoption of desalination technology. Source materials for nanofilters include naturally occurring zeolites and attapulgite clays, which can now be manipulated on the nanoscale to allow for greater control over pore size of filter membranes. Attempts are also being made for developing new classes of nanoporous polymeric materials that are more effective than conventional polymer filters.

3.2 Nanocatalysts and Magnetic Nanoparticles:

It is expected that nanocatalysts and magnetic nanoparticles will enable the use of heavily polluted water for drinking, sanitation and irrigation. Catalytic particles can chemically degrade pollutants instead of simply moving them somewhere else, including pollutants for which existing technologies are inefficient or cost prohibitive. Magnetic nanoparticles, when coated with different compounds that have a selective affinity for diverse contaminating substances, can be used to remove pollutants, including arsenic, from water.

3.3 Nanosensors:

Nanosensors based technologies are being developed that combine micro- and nanofabrication technology to create small, portable and highly accurate sensors to detect chemical and biochemical parameters in water. Several research consortia are field testing devices that incorporate nanosensor technology to detect pollutants in water. Nanotechnology is also playing an increasingly important role in the development of biosensors [2,3,4]. Sensitivity and other attributes of biosensors can be improved by using nanomaterials in their construction. The use of these nanomaterials has allowed the introduction of many new signal transduction technologies in biosensors. Because of their submicron size, nanosensors, nanoprobes and other nanosystems are revolutionizing the fields of chemical and biological analysis, to enable rapid analysis of multiple substances in vivo [5].

4.0 Recent Case Studies:

Recent studies have shown that nanomaterials are highly promising in water purification process due to their unique properties like higher surface area per unit volume, ease with which they can be anchored onto solid matrices and the ability to functionalize with different functional groups to enhance their affinity towards target molecules [6,7,8]. The unique and novel properties of nanoparticles make them well suited for treating water. Nanotechnology offers an opportunity to refine and optimise current techniques, and to provide new and novel methods of purifying water. Nanotechnology has introduced a new generation of water filters and purification systems. Research on nano catalysts like silver, iron, titanium dioxide and carbon nanofiltration membranes for water treatment applications is fast growing.

Chloro-organics are a major class of contaminants at many waste sites and several nanomaterials have been applied to aid in their remediation. The iron nanoparticle technology has received considerable attention for its potential applications in ground water treatment and site remediation. Recent studies have demonstrated the efficacy of zero-valent iron nanoparticles for the transformation of halogenated organic contaminants and heavy metals. Zero-valent iron has been used successfully in the past to remediate ground water by construction of a permeable reactive barrier (iron wall) of zero-valent iron to intercept and dechlorinate chlorinated hydrocarbons such as trichloroethylene in ground water plumes. Laboratory studies indicate that a wider range of chlorinated hydrocarbons may be dechlorinated using various nanoscale iron particles (principally by abiotic means, with zero-valent iron serving as the bulk reducing agent), including chlorinated methanes, ethanes, benzenes and polychlorinated biphenyls. Nanoscale zero-valent iron may not only treat aqueous dissolved chlorinated solvents in situ, but also may remediate the dense nonaqueous phase liquid (DNAPL) sources of these contaminants within aquifers [9].

Several other remedial measures using nano zerovalent iron (nZVI) has also been reported [10]. Applications of nanoscale zerovalent iron (nZVI) for removal of metal cations in water indicate that nZVI has much larger capacity than conventional materials for the sequestration of Zn(II), Cd(II), Pb(II), Ni(II), Cu(II), and Ag(I). Characterizations with high-resolution X-ray photoelectron spectroscopy (HR-XPS) confirm that the iron nanoparticles have a core-shell structure, which leads to exceptional properties for concurrent sorption and reductive precipitation of metal ions.

In addition to zero-valent iron, other nanosized materials such as metalloporphyrinogens have been tested for degradation of tetrachlorethylene, trichloroethylene and carbon tetrachloride under anaerobic conditions [11]. Titanium oxide based nanomaterials have also been developed for potential use in the photocatalytic degradation of various chlorinated compounds [12].

Enhanced retention or solubilization of a contaminant may be helpful in a remediation setting. Nanomaterials may be useful in decreasing sequestration of hydrophobic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), bound to soils and sediments. The release of these contaminants from sediments and soils could make them more accessible to *in situ* biodegradation. For example, nanomaterials made from poly(ethylene) glycol modified urethane acrylate have been used to enhance the bioavailability of phenanthrene [13].

Metal remediation has also been proposed, using zero-valent iron and other classes of nanomaterials. Nanoparticles such as poly(amidoamine) dendrimers can serve as chelating agents, and can be further enhanced for ultrafiltration of a variety of metal ions, viz., Cu(II), Ag(I), Fe(III), etc. by attaching functional groups such as primary amines, carboxylates and hydroxymates [14]. Other research indicates that arsenite and arsenate may be precipitated in the subsurface using zero-valent iron, making arsenic less mobile [15]. Self-assembled monolayers on mesoporous supports (SAMMS) are nanoporous ceramic materials that have been developed to remove mercury or radionuclides from wastewater.

Manganese dioxide nanowhiskers (MDN), prepared by the reduction of potassium permanganate by ethyl alcohol has been investigated as an adsorbent for Hg(II) removal from aqueous medium. The nanostructured MnO_2 prepared through the reduction of potassium permanganate by ethyl alcohol is a very effective adsorbent for Hg(II) removal from aqueous medium and chlor-alkali industrial effluent [16].

Recently, noble metal nanoparticles have emerged as potential materials for water purification. Gold nanoparticles loaded on alumina have been shown to remove Hg(II) after its reduction to Hg(0), followed by amalgamation [17]. An uptake capacity of 4.065 g per 1 g of gold nanoparticle has been reported. However, the uptake was significantly reduced when Hg(II) was used directly. Gold nanorod-based determination of Hg(II) in water has been reported up to parts per trillion [18]. Chemical interaction of heavy metal ions such as Hg(II), Hg(I), Pb(II) and Cd(II) with naked and protected silver nanoparticles have also been reported [19]. From these perspectives, noble metal nanoparticle-based adsorbent systems provide a viable practical solution to drinking water purification.

Nanomaterials have also been studied for their ability to remove metal contaminants from air. Silica-titania nanocomposites can be used for elemental mercury removal from vapors such as those coming from combustion sources, with silica serving to enhance adsorption and titania to photocatalytically oxidize elemental mercury to the less volatile mercuric oxide [20]. Other authors have demonstrated nanostructured silica can sorb other metals generated in combustion environments, such as lead and cadmium [21,22]. Certain nanostructured sorbent processes can be used to prevent emission of nanoparticles and create byproducts that are useful nanomaterials [23].

5. Risks of Nanotechnology:

While much attention has been focused on the potential benefits of water treatment devices that incorporate nanotechnology, a growing number of people are advocating for more research to assess the potential human health and environmental risks of nanotechnologies. Although there are a limited number of research studies on the potential human health and environmental risks of nanotechologies, some research indicates that the unique properties of nanomaterials (e.g., size, shape, reactivity, conductivity) may cause them to be toxic. Because research on the impacts of nanomaterials is limited, risk experts are looking to the results of studies with incidental and natural nanoscale particles and studies with airborne ultrafine particles as the basis for the expanding field of nanotoxicology. Development of nanotechnology must be undertaken with care to avoid accidents. Once a nanotechnology-based manufacturing technology is created, it must be administered with even more care and irresponsible use of molecular manufacturing should be avoided. The challenges related to assessing and managing the potential risks of nanoscale materials are relevant to people in both developed and developing countries. Therefore, it is imperative that information about potential risks and risk management approaches is shared widely.

5.1 Environmental Risks:

In free form, nanoparticles can be released in the air or water during production (or production accidents) or as waste byproduct of production and ultimately accumulate in the soil, water or plant life. While we are more interested in researching and developing the possible benefits of nanotechnology, we also has the obligation and mandate to protect human health and safeguard the environment by better understanding and addressing potential risks from exposure to nanoscale materials and products containing nanoscale materials.

5.2 Health Risks:

Health and environmental issues are combined in the work place of companies engaged in producing or using nanomaterials and in the laboratories engaged in nanoscience and nanotechnology research. It is safe to say that current work place exposure standards for dusts cannot be applied directly to nanoparticle dusts. To properly assess the health hazards of engineered nanoparticles, the whole life cycle of these particles needs to be evaluated, including their fabrication, storage and distribution, application and potential abuse and disposal. The impact on humans and/or the environment may vary at different stages of the life cycle.

6. Opportunities and Challenges:

The rapid development of nanotechnology and the increasing production of nanomaterials and nanoproducts present both opportunities and challenges. Using nanomaterials in applications that advance green chemistry and engineering and lead to the development of new environmental sensors and remediation technologies may provide us with new tools for preventing, identifying and solving environmental problems. In addition, at this early juncture in nanotechnology’s development, we have the opportunity to develop approaches that will allow us to produce, use, recycle and eventually dispose of nanomaterials in ways that protect human health and safeguard the natural environment. The integration and synergy of nanotechnology, biotechnology, information technology and cognitive technology will present opportunities as well as challenges to regulatory agencies. To take advantage of these opportunities and to meet the challenge of ensuring the environmentally safe and sustainable development of nanotechnology, we must understand both the potential benefits and the potential impacts of nanomaterials and nanoproducts.

Nanotechnology has the potential to contribute to long-term water quality, availability and viability of water resources, such as through advanced filtration that enables more water reuse, recycling and desalinization. For example, nanotechnology-based flow-through capacitors (FTC) have been designed that desalt seawater using one-tenth the energy of state-of-the art reverse osmosis and one-hundredth of the energy of distillation systems. The projected capital and operation costs of FTC-based systems are expected to be one-third less than conventional osmosis systems.

Applications potentially extend even more broadly to ecological health. One long-term challenge to water quality is the build-up of nutrients and toxic substances due to runoff from agriculture. In general with current practices, about 150% of nitrogen required for plant uptake is applied as fertilizer [24]. Fertilizers and pesticides that incorporate nanotechnology may result in less agricultural and lawn/garden runoff of nitrogen, phosphorous and toxic substances, which is potentially an important emerging application for nanotechnology that can contribute to sustainability. These potential applications are still in the early research stage [25]. Applications involving dispersive uses of nanomaterials in water have the potential for wide exposures to aquatic life and humans. Therefore, it is important to understand the toxicity and environmental fate of these nanomaterials.

7. Conclusion:

Nanotechnology research is being conducted in a broad spectrum of areas relevant to water treatment, including filters, catalysts, magnetic nanoparticles and sensors. Several research publications in the last few years have clearly indicated the possible role of nanotechnology in providing clean water in developing countries. Nanofiltration membrane technology is widely applied for removal of dissolved salts from salty water, removal of micro pollutants, water softening and wastewater treatment. Researchers are also exploring how nanocatalysts such as titanium dioxide and iron nanoparticles can be used to degrade organic pollutants and remove salts and heavy metals from water. Magnetic nanoparticles are also being developed to adsorb metals and organic compounds. When coated with different compounds that have a selective affinity for diverse contaminating substances, magnetic nanoparticles could be used to remove pollutants, including arsenic, from water. This class of technologies seems especially suited for decomposing organic pollutants and removing salts and heavy metals from water. We must continue to undertake, collaborate and support research to better understand and apply information regarding environmental applications of nanomaterials. We must also continue to undertake, collaborate and support research to better understand and apply information regarding nanomaterials, e.g., chemical and physical identification and characterization, environmental fate, environmental detection and analysis, potential releases and human exposures, human health effects assessment and ecological effects assessment.

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