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Application of nanotechnology, nanofiltration, and water treatment a vision for the future

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ABSTRACT

New concepts and technologies are fast replacing the traditional methods of water distribution, supply and purification. Nanomaterials are well suited for water purification, disinfection and wastewater treatment applications as they have as large specific surface area, high reactivity, high degree of functionalization, size dependent properties, affinity for specific target contaminants, etc. Environmental science is moving at a rapid and drastic pace toward a newer realm and a newer visionary future. Rigid environmental regulations and zero-discharge norms has urged the scientific domain to devise new directions in novel separation processes and advanced oxidation processes. History of environmental science, scientific cognizance, and mankind's prowess will all go a long way in evolving new directions in the application of nanotechnology in drinking water treatment and industrial wastewater treatment. Nanofiltration and membrane separation processes in its truest sense is the only plausible solution to the varied problems of global drinking water crisis. In this treatise, the author deals strongly with deep and cogent insight the varied application of nanotechnology and nanofiltration in drinking water treatment. The author also delineates the recent scientific endeavour in the field of nanofiltration and other environmental and chemical separation processes with specific importance to water treatment. The path toward progress in the field of drinking water treatment evolve into new scientific and technological advancements. The author will also specifically deal with fouling phenomenon and the concept of concentration boundary layer. Drinking water crisis can only be solved if the scientific truth and scientific vision behind nanofiltration and other avenues of nanotechnology are truly realized. The challenge and vision behind this treatise and the immense urge to excel will surely open new dimensions of scientific understanding and scientific adjudication in years to come.

Keywords: nanotechnology; nanofiltration; drinking water.

INTRODUCTION

World stability can be considered to be dependent on availability of energy resources (e.g. Oil, petroleum, natural gas, nuclear fuel, etc.) and clean water. Clean water is essential and critical for all human activities ranging from simple household chores to the very complex industrial and agricultural processes. Direct available sources of clean water are very limited. Increasing population, intensive agriculture, rapid urbanization, and continuous industrial growth put a large stress on the demand for clean water. In order to satisfy this ever increasing demand for water, new methods and technologies need to be researched and developed.

Nanotechnology is one of the most rapidly emerging technologies. Advances in nanoscale science and engineering are providing immense opportunities to develop more cost effective and environmentally acceptable water purification processes. Nanomaterials are very well suited for water purification and waste water treatment owing to their unique and varied properties such as large specific surface area, high reactivity, high degree of functionalization, size dependent properties, affinity for specific target contaminants, etc. which render them excellent adsorbents, catalysts, and sensors. Nanocomposite membranes and filters combine separation and other functions to improve life and efficiency, and can be reused a number of times, thus making them eco-friendly. Antimicrobial nanoparticles can disinfect polluted water without formation of harmful Disinfection By-Products (DBPs).

In this review paper an overview of various water distribution and supply methods, water purification and treatment methods currently being in use and their drawbacks is given. Some new concepts regarding the same including a comprehensive study of various applications of nanotechnology in water purification and waste water treatment have been reviewed and presented.

Water is a mythical substance whose material existence is secondary compared to the symbolic value as it is manifested in our mind as the symbol of life. Sustainable supplies of clean water are vital to the world's health, environment and economy. Currently the human society is facing a tremendous crunch in meeting rising demands of potable water as the available supplies of freshwater are decreasing due to extended droughts, population growth, decline in water quality particularly of groundwater due to increasing groundwater and surface water pollution,

unabated flooding and increasing demands from a variety of competing users. Water being a prime natural resource, a basic human need and a precious national asset, its use needs appropriate planning, development and management. Increasing population coupled with overexploitation of surface and groundwater over the past few decades has resulted in water scarcity in various parts of the world. Wastewater is increasing significantly and in the absence of proper measures for treatment and management, the existing freshwater reserves are being polluted. Increased urbanization is driving an increase in per capita water consumption in towns and cities. Hence there is a need to recognize the requirement to manage existing water reserves in order to avoid future water strain. Today availability of safe drinking water is a concern. For almost all the water needs of the country, groundwater is by far the most important water resource. Worldwide, according to a United Nations Environment Programme (UNEP) study over 2 billion people depend on aquifers for their drinking water . 40 per cent of the world's food is produced by irrigated agriculture that relies largely on groundwater [1]. Groundwater constitutes about 95 per cent of the freshwater on our planet (discounting that locked in the polar ice caps), making it fundamental to human life and economic development. However the ever increasing scarcity of groundwater coupled with diminishing water quality has posed a serious threat to the population especially the rural community and has forced everyone to look at treatment of groundwater because clean water is fast becoming an endangered commodity. The unabated use has taken a serious toll on the availability of groundwater resources and as such the world is facing a severe crunch in the availability of groundwater. So we have no other option to move from "groundwater development" to "groundwater management" which means that we have to move towards optimal usage of groundwater which would be sustainable in the long run. Today the onus is on everybody to provide safe drinking water and for that water treatment processes need to be developed that are easy to implement, cost effective and sustainable in the long run.

India is a vast country having diversified geological, climatological and topographic set-up, giving rise to divergent groundwater situations in different parts of the country. Unsustainable uses of resources and indiscriminate applications of pesticides, fertilizers, industrial pollutants are continuously disturbing the status of purity of groundwater. Shallow aquifers generally suffer from agrochemicals, domestic and industrial waste pollution. Major water pollutants include microbes (like intestinal pathogens and viruses), nutrients (like phosphates and nitrates), heavy metals and metalloids (like arsenic, lead, mercury), organic chemicals (like DDT, lubricants, industrial solvents), oil, sediments and heat. Virtually all industrial and goods-producing activities generate pollutants as unwanted by-products. Heavy metals can contaminate the aquifer and subsequently can bioaccumulate in the tissues of humans and other organisms. For example, more than 100 million people are living in the arsenic affected districts of India and Bangladesh. 9 districts out of 19 in West Bengal, 78 blocks and around 3150 villages are affected with arsenic- contaminated groundwater [2]. Pollutants can take years to reach the aquifers, but, once it reaches the water source, it is very difficult and costly to remove the pollutants. More than 80% of sewage in developing countries is discharged without proper treatment which can pollute the river systems, lakes and coastal water bodies [3].

In the present context the recent advancement of nanoscale science and engineering is opening up a hitherto unknown and novel gateway to the development and deployment of water purification processes which are in tune with the above mentioned parameters. Nanoscience is the study of phenomenon and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale [4]. Nanotechnology is the design, characterization, production and applications of structures, devices and systems by controlling shape and size at nanometer scale. In recent years, a great deal of attention has been focused onto the applicability of nanostructured materials as adsorbents or catalysts in order to remove toxic and harmful substances from wastewater [5]. Nano-materials had gained special attention since last decade because the materials of such kind posses unique properties than the bulk materials. Like different nano materials, single and multi metal or doped metal oxides are also subject of much interest since that materials posses high surface-to-volume ratio, enhanced magnetic property, special catalytic properties etc [6]. Consequently, different methods viz. chemical precipitation, sol-gel, vapour deposition, solvo thermal, solid state reaction etc were adopted for the synthesis of specified oxides by various workers [7]. Nano- enabled technologies for water treatment are already on the market. Nanofiltration currently seeming to be the most mature and eco-friendly technology and many more are on their way of development and applications. The environmental fate and toxicity of any material are critical issues in choice of materials for water purification. Nanotechnology while being questionably better than other techniques used in water treatment, the knowledge about the environmental fate, transport and toxicity of nanomaterials is still inadequate.

The high surface area and surface reactivity compared with granular forms enable the nanoparticles to remediate more material at a higher rate and with a lower generation of hazardous by-products. Advances in nanoscale science and engineering suggest that many of the current problems involving water quality could be resolved or greatly diminished by using nanosorbents, nanocatalysts, bioactive nanoparticles, nanostructured catalytic membranes, nanotubes, magnetic nanoparticles, granules, flake, high surface area metal particle supramolecular assemblies with characteristic length scales of 9-10 nm including clusters, micromolecules, nanoparticles and colloids have a significant impact on water quality in natural environment [8]. The defining factor which characterizes the capability of nanoparticles as a versatile water remediation tool includes their very small particle sizes (1–100 nm) in comparison to a typical bacterial cell which has a diameter on the order of 1 μm (1000 nm). Hence nanoparticles can be transported effectively by the groundwater flow. They can also remain in suspension for sufficient time in order to launch an in situ treatment sphere. As a result, nanoparticles can be anchored onto a solid matrix such as a conventional water treatment material like activated carbon and/or zeolite for enhanced water treatment [9].

Current Scenario

Current methods in water distribution and supply and in various purification and treatment methods are very much inefficient and give rise to large costs. These methods focus on processing water on a bulk basis which is the cause of this rise in costs and inefficiency. The water purification and treatment methods are very well capable of providing good quality clean water, but these methods are not environmentally friendly for they create large amounts of waste products which are carcinogenic and harmful to the environment. The drawbacks of the current methods are the driving force for the research and development of various new methods and technologies.

Water Distribution and Supply

More than 71% of Earth’s surface is covered by water, but still the total available freshwater for direct use is very less. Fig. 1 shows the water distribution on the Earth’s surface [10]. About 97% of all water present on Earth is in the oceans and hence cannot be used for human activities directly. The remaining 3% is the freshwater available for use. Of this 3%, around 68.7% is locked up in glaciers and icecaps. Of the remaining, nearly 30% is groundwater which contains many pollutants, organic and inorganic, due to industrial, agricultural and domestic waste disposal. Thus, rivers and lakes that supply surface water for human uses only constitute about 0.007% of total water on Earth. In other words, if all the Earth's freshwater were stored in a 5-liter container, available fresh water would not quite fill a teaspoon [11].

Water Purification

Current water purification methods can control the organic and inorganic wastes from water and can purifyit to a high degree of purity. These methods use physical separation methods (e.g. membranes and filters) and chemical purification methods (e.g. chemical disinfection, chemical precipitation, etc.). Membrane and filter processes are better than the chemical methods as toxic products are avoided but, the major drawback of these methods is membrane and filter fouling. Bacteria and other impurities build up on the surface and clog the membranes over time leading to costly clean-up and replacements. Membrane fouling results in higher energy demands on the pumping system. The chemical methods produce toxic reactive complexes which then are incinerated or compressed and used in landfilling. Both these methods are harmful to the environment and cause ecological imbalance.

Nanotechnology

Water Purification and Waste water Treatment Nanotechnology has many potential applications in wastewater treatment and purification. Membranes using nanomaterials composites with selective absorption of target pollutants, improved permeability to increase flux and better functionality can be developed. Nanocomposite membranes can be structured so as to reduce energy requirements as by improving resistance to fouling. Use of 'functional nanomaterials' to combine two or more processes such as separation and degradation of retentate increase the efficiency of the purification and waste treatment systems. Nanotechnology applications focus on increasing durability and reusability of membranes to cut costs of replacement of filters and membranes. Nanomaterials have a broad range of physicochemical properties make them particularly attractive as separation and reactive media for water purification. Functional nanomaterials can be used to build high- performance, small-scale or point-of-use systems to increase the robustness of water supply networks, for water systems not connected to a central network, and for emergency response following catastrophic events.

Nanofiltration:

Membrane processes such as nanofiltration (NF) are emerging as key contributors to water purification [12]. Nanofiltration membranes (NF membranes) are widely used in water treatment for drinking water or wastewater treatment. It is a low pressure membrane process that separates materials in the 0.001-0.1 micrometer size. NF membranes are pressure-driven membranes with properties between those of reverse osmosis and ultra filtration membranes and have pore sizes between 0.2 and 4 nm. NF membranes have been shown to remove turbidity, microorganisms and inorganic ions such as Ca and Na. They are used for softening of groundwater (reduction in water hardness), for removal of dissolved organic matter and trace pollutants from surface water, for waste water treatment (removal of organic and inorganic pollutants and organic carbon) and for pretreatment in seawater desalination. Bruggen & Vandercasteele (2003) have studied the use of nanofiltration to remove cations, natural organic matter, biological contaminants, organic pollutants, nitrates and arsenic from groundwater and surface water[13] . Favre-Reguillon et al. (2003) found that nanofiltration can be used to remove minute quantities of U(VI) from seawater . Mohsen et al. (2003) have evaluated the use of nanofiltration to desalinate water [14]. They found that nanofiltration in combination with reverse osmosis could effectively render brackish water potable. An improvement in water quality was shown by Peltier et al. (2003) for a large water distribution system using nanofiltration [15]. Carbon nanotubes filters are also gaining prominence in water treatment processes. Srivastava et al. (2004) recently reported the successful fabrication of carbon nanotube filters [16]. These new filtration membranes consist of hollow cylinders with radially aligned carbon nanotube walls. They showed that the filters were effective at removing bacteria (Escherichia coli and Staphylococus aureus) from contaminated water[17]. The carbon nanotube filters are readily cleaned by ultrasonication and autoclaving.

Role of nanomaterials in water treatment and purification:

Nanomaterials are fast emerging as potent candidates for water treatment in place of conventional technologies which, notwithstanding their efficacy, are often very expensive and time consuming. This would be in particular, immensely beneficial for developing nations like India and Bangladesh where cost of implementation of any new removal process could become an important criterion in determining its success. Qualitatively speaking nanomaterials can be substituted for conventional materials that require more raw materials, are more energy intensive to produce or are known to be environmentally harmful. Employing green chemistry principles for the production of nanoparticles can lead to a great reduction in waste generation, less hazardous chemical syntheses, and an inherently safer chemistry in general. However, to substantiate these claims more quantitative data is required and whether replacing traditional materials with nanoparticles does indeed result in lower energy and material consumption and prevention of unwanted or unanticipated side effects is still open to debate. There is also a wide debate about the safety of nanoparticles and their potential impact on the environment. There is fervent hope that nanotechnology can play a significant role in providing clean water to the developing countries in an efficient, cheap and sustainable way. On the other hand, the potential adverse effects of nanoparticles cannot be overlooked either. For instance the catalytic activity of a nanoparticle can be advantageous when used for the degradation of pollutants, but can trigger a toxic response when taken up by a cell. So this Janus face of nanotechnology can prove to be a hurdle in its widespread adoption. However as mentioned before nanotechnology can step in a big way in lowering the cost and hence become more effective than current techniques for the removal of contaminants from water in the long run. In this perspective nanoparticles can be used as potent sorbents as separation media, as catalysts for photochemical destruction of contaminants; nanosized zerovalent iron used for the removal of metals and organic compounds from water and nanofiltration membranes.

Removal of nanoparticles after water treatment:

The use of nanoparticles in environmental applications will invariably lead to the release of nanoparticles into the environment. Assessing their potential risks in the environment requires an understanding of their mobility,bioavailability, toxicity and persistence. Little is known about the possible exposure of aquatic and terrestrial life to nanoparticles in water and soil. The rapidly growing use of engineered nanoparticles in a variety of industrial scenarios and their potential for wastewater purification and drinking water treatment raise the inevitable question how these nanoparticles can be removed in the urban water cycle. Traditional methods for the removal of particulate matter during wastewater treatment that have been in vogue include sedimentation and filtration. However, due to the small sizes of nanoparticles the sedimentation velocities are relatively low and significant sedimentation will not occur as long as there is no formation of larger aggregates [18]. Common technologies such as flocculation might be inappropriate to remove nanoparticles from water, which points to the need of finding new solutions to the problem. Till now, membrane filtration (e.g. nanofiltration and reverse osmosis) has been already applied for the removal of pathogens from water [19]. Hence, this technique can also be used for the removal of nanoparticles. Most nanoparticles in technical applications today are functionalized in nature and therefore studies using virgin nanoparticles may not be relevant for assessing the behaviour of the actually used particles. Functionalization is often used to decrease agglomeration and therefore increase mobility of particles. Unfortunately little is known to date about the influence of functionalization on the behaviour of nanoparticles in the environment.

Conclusion:

While nanotechnology is considered to be the new buzzword by many in the scientific community, information regarding the subject remains largely dispersed and fragmented due to the relative novelty of the technology. But the increasing trends of researches which have been discussed so far have made it clear that nanotechnology holds an immense potential to be developed into a very potent water treatment tool of the 21st century. In fact nanomaterials and their various incarnations are the drivers for the nanotechnology revolution. Nanoparticles in particular will have important impacts on various fields of environmental technology and engineering not least in water treatment. However most oftechniques for the treatment of wastewater involving nanotechnology so far have only been investigated in laboratory scale and not all of them are likely to be feasible alternatives for existing treatment technologies mainly perhaps due to economic reasons. This makes it difficult to predict what the future holds for us at this stage concerning this nascent technology. Also the incorporation of nanomaterials into existing water purification systems is another key challenge. Membrane processes such as RO, NF are becoming the standardised water purification techniques for public utilities and industry because they are flexible, scalable, modular and relatively easy to operate and maintain. Thus further laboratory investigations and pilot scale testing will be needed to integrate novel nanostructured membranes into existing water purification systems. Also the environmental fate and toxicity of a material are areas of concern in material selection and design for water purification. Not much is known about the environmental fate, transport and toxicity of nanomaterials. Thus it should be borne in mind that nanotechnology can become a double edged sword and each positive and desired property of nanomaterials could pose a risk to the environment. Thus a careful weighing up of the opportunities and risks of nanotechnology with respect to their impact on the environment is therefore needed. No systematic investigations regarding the stability of nanomaterials in natural and engineered environmental systems have been carried out till date to the best of our knowledge. On a positive note, due to their extremely high potential in combination with the high specificity, nanoparticles can be developed into ideal candidates for water treatment and may contribute to solving future challenges in the area of water treatment technologies. Thus nanotechnology holds a lot of promise in the remediation of groundwater and for this there is further scope in research and development.

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