Nanotechnology and the Water Market: Applications and Health Effects

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ABSTRACT

Nanotechnology has enormous potential for creating cost-effective, simple, and efficient tools for addressing water-supply challenges while preventing the creation of potentially toxic byproducts. The success of these technologies using nanomaterials, however, will depend on whether the nanoparticles and fibers can be confined and isolated from human and environmental receptors and on assessments of the potential health and environmental risks if exposures do occur. To truly qualify as “green” technology, applications of nanotechnology will need to demonstrate that such exposures and potential concerns for health and environmental risk can be managed adequately. This paper describes some of these technologies, focusing on nanofiltration and disinfection, desalination, and environmental remediation, as well as implications to human health and the environment.

Keywords: filtration, desalination, disinfection, remediation, health effects

1 MOTIVATION

Safe and adequate supplies of water are vital for agriculture, industry, recreation, and human consumption. The World Health Organization (WHO) estimates that 2.4 billion people worldwide lack basic sanitation, and 3.4 million people, mainly children, die annually from water-related diseases [1]. Increasing challenges exist in maintaining sufficient clean water supplies due to extended drought, more stringent health-based standards (e.g., new 10-ppb arsenic standard in the U.S.), increasing populations and water demands worldwide, chemical and biological contamination threats, and potentially toxic byproducts from conventional treatments (e.g., from chlorination). Nanotechnology holds the promise of cost-effective and efficient solutions to these challenges, and will likely play a critical role in water-related technologies in the future.

2 NANOTECHNOLOGY APPLICATIONS IN THE WATER MARKET

The world market for water and wastewater is anticipated to increase from $287 billion in 2004 to $412 billion by 2010 [2]. Applications of nanotechnology in the water market include disinfection and filtration, real-time and remote monitoring, groundwater and subsurface treatment or remediation, and wastewater treatment and recycling (Table 1).

Nanotechnology	Example Application	Advantages
Alumina fibers	Disinfection, nanofiltration	Improved clogging resistance; high adsorption
Metals, semiconductors	Disinfection, nanofiltration, desalination	Generally recognized as safe
Zero-valent iron (ZVI)	Groundwater remediation	No toxic by-products; long-lasting; highly effective
Beads, resins	Remediation	Rapid adsorption; little solid waste; may be re-usable
Membranes, clays/zeolites	Wastewater recycling, desalination, purification	Can be selective for chemical; high surface area and adsorption
Capsules	Wastewater recycling, remediation	Re-usable; can be selectively engineered
Dendrimers	Wastewater recycling, remediation, filtration	High capacity for metals; able to self-assemble
Nanotubes	Purification, treatment	Can be selectively engineered
Composites	Treatment	Large surface area and adsorption capacity

Table 1: Examples of nanotechnology applied to the water market (details and citations provided in main text).

2.1 Nanofiltration and Disinfection

Nanofiltration is becoming more important in wastewater treatment as a pressure-driven membrane separation process [3,4], wherein disinfection and removal of solids, bacteria, and other materials is required. Current limitations in filtration technologies occur when properties of the membrane are exceeded and either allow the medium being filtered to pass through or prevent solution from passing due to fouling and clogging [3]. These limitations likely occur most frequently at the industrial level, where filtration needs involve high throughput of different solutions.

Nano-sized or nano-loaded membranes and filters working under principles of low-pressure reverse osmosis (RO) provide several advantages to filtration, including superior properties (e.g., high permeability and retention of organics), high surface area, and ability to accommodate high flow rates [3]. In addition, "smart" nanomembranes could contain embedded sensors to automatically change performance and sensitivity based on sensing of contaminant or solution differential across the membrane or could be engineered for selected effluents [3,5]. In particular, ceramic and nanoclay/zeolite membranes have the combined advantage of high chemical, mechanical, and thermal resistance and large surface area and absorption capacity through cation exchange; they also are relatively inert and can be engineered to be selective for a particular effluent [5–8]. Although generally expensive, their capacity for multiple use and regeneration would greatly reduce associated costs. Alumina nanofibers improve clogging resistance and fouling rates due to their highly electropositive surface, which attracts submicron and nano-sized particles [9]. In some applications, alumina nanofibers are equipped with charged polymer brushes or are pleated to increase surface area and adsorption capacity [9].

Nanometals and other semiconductor materials (e.g., titanium dioxide [TiO_2], palladium-coated gold or iron, and zinc oxide [ZnO]) also play a role in chemical degradation and disinfection, wherein reaction of the metals with ultraviolet light can oxidize harmful microorganisms [10–13]. This reaction generally results in oxidation of organic pollutants to carbon dioxide [10], and has been found to degrade phenol [10], toluene [5], *E. coli* [11,14], trichloroethylene (TCE) [13,15,16], polychlorinated biphenyls [16], carbon tetrachloride [17], and other volatile organic compounds [3,5]. These metals can also be doped to include various antibacterial metals (Ag, TiO_2, ZnO), to target certain agents [18]. An added benefit is that many metals used in these applications are generally recognized as safe and occur naturally in the environment.

2.2 Monitoring

Nanoscale solid-state sensors are currently being developed by the University of California at Davis and the U.S. Environmental Protection Agency to provide real-time remote detection and to aid in facilitating the process of monitoring and treating pollutants [19]. These sensors can be engineered to be selective for certain chemicals—such as arsenic and chromium—allowing them to be more efficient than "broad range" monitoring devices. Other researchers, at Arizona State University, are developing high-performance, low-cost sensors to provide early warning and prevention of metal ion contamination using quantum effects exhibited by many nanoparticles for use in nanoelectrodes [20].

2.3 Desalination

Fresh water is important for sustaining all forms of life and it is becoming less available due to effects of global warming, environmental destruction, and loss of freshwater sources [2]. Up to 80% of the salt in surface waters results from natural erosion, although anthropogenic sources such as use of water softeners and land-use practices also contribute to concentrated salts [3]. Current desalination processes are expensive and time consuming, and are sensitive to fouling [3]. RO and multi-effects distillation are two types of desalination processes that could benefit from nanotechnology. These processes could include running salinated water through a series of membranes, distillation, and condensation to rapidly and effectively remove salts from water [3]. Nanoengineered membranes could be used for efficient and relatively cheap desalination of water supplies, and would offer the added benefit of being portable and easy to clean [8].

2.4 Groundwater Remediation

Nano-sized particles have been found to be efficient and expedient in groundwater remediation, without producing large volumes of waste or forming toxic by-products [17,21,22]. In addition, nanobeads and nanoresins have produced rapid absorption of different contaminants, with little waste generated they allow for multiple uses, making them highly cost-effective [23]. In some cases, nano-sized metals are incorporated into the resin beads to increase specificity, absorption, and stability [23]. Similarly, dendrimers, which are three-dimensional branched structures with a high degree of surface functionality and diversity, have a large capacity to trap metal ions, which can then be filtered out [24]. Dendrimers also have the ability to self-assemble, resulting in branching and increased surface area for adsorption. Nanocapsules (nanoparticle with a "hole" in it) or nanoemulsions could be engineered to contain a particular substance to be released under controlled conditions to treat a particular chemical or contaminant [25].

Zero-valent nano-iron (ZVI or Fe^0) has been particularly successful in groundwater remediation trials [17,21,22]. ZVI has been shown to be effective in dechlorination of organic solvents, transformation of fertilizers, detoxification of certain pesticides, and immobilization of contaminant metals [17,22,26,27]. In a pilot-scale study at Hunter's Point Shipyard in northern California, injection of ZVI resulted in removal of 99.1% of total chlorinated solvents and a 99.2% reduction in TCE concentrations over a period of three weeks (Figure 1) [26]. The formation of by-products often seen during traditional TCE destruction was not observed. In addition, metals present in the soil, such as manganese and arsenic, were not mobilized during treatment.

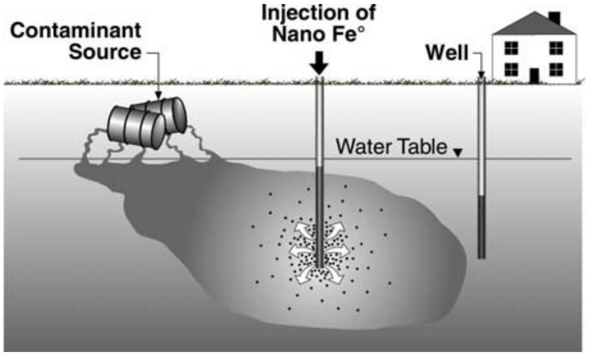

Figure 1. Example of a pilot-scale study of groundwater and subsurface treatment using ZVI (adapted from [27]).

2.5 Wastewater Treatment and Recycling

Many of the technologies described above can be used to treat and recycle wastewater. For example, systems that use nanoscale forms of TiO_2 and magnetic nanoparticles to decompose organic pollutants and remove salts and heavy metals from liquids enable the use of contaminated wastewater for irrigation and drinking [8,28]. Nanoelectrocatalytic systems could also be used to purify contaminated, salinated water for purposes of drinking and irrigation [8]. Nanomembranes could be functionalized to remove a particular component in the wastewater during treatment, prior to recycling. In addition, carbon nanotubes could be used for wastewater treatment. These nanotubes have been successful in filtering petroleum and treating contaminated drinking water [29].

3 IMPLICATIONS FOR HEALTH AND THE ENVIRONMENT

Although currently proposed treatments using nanotechnology are not expected to result in toxic by-products, as in chlorination, exposure to nanoparticles may be a concern because their small size allows them to remain in suspension in water. In addition, nanoparticles, again by virtue of their small size, may more readily cross biological membranes and barriers, where they can exert potentially toxic effects [30]. Other concerns are that even relatively inert substances may become more reactive, and thus toxic, by virtue of their small size and higher surface area. These issues must be considered from both a human health and environmental standpoint.

3.1 Environmental Issues

Nanoparticles may enter the environment either intentionally (e.g., ZVI) or accidentally, and the environment is the ultimate sink for these materials. In the environment, nanoparticles show enhanced dispersal and mobility due to their small size, and are thought to be more reactive. Nanoparticles could be liberated into water supplies, where exposure of humans and both aquatic and terrestrial organisms could occur. The presence of coatings, a surface charge, or other surface properties may result in enhanced interactions with bacteria, algae, and other microorganisms in the environment, and may result in bioaccumulation and possibly biomagnification up the food chain [31].

To minimize potential for exposure, nanotechnologies used in the water market should be evaluated for containment within a durable matrix (e.g., resin), such that any accidental release of the treatment product would not result in release of nanoparticles into the environment. In addition, it might be beneficial if the nanoparticles used were able to aggregate upon release, allowing for either rapid removal from the system (e.g., through filtration) once the desired treatment was achieved, or increasing the likelihood that the larger particle would fall out of solution. Several authors have demonstrated that metal-ethylenediaminetetraacetic acid complexes may result in chelation and subsequent extraction of nanometals used in treatment [32–34].

3.2 Human Health Issues

When evaluating human health, a four-step risk assessment process is generally used, which encompasses hazard identification, dose-response assessment (toxicity), exposure assessment, and risk characterization (Figure 2).

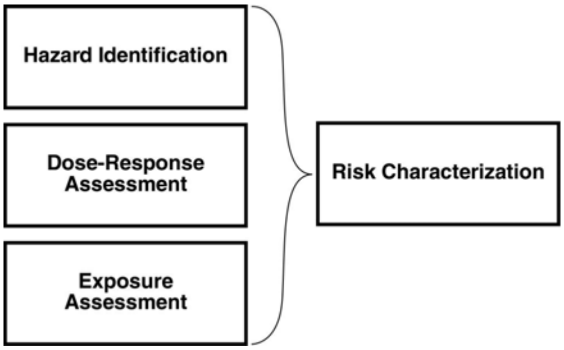

Figure 2. The risk assessment process (adapted from National Research Council, 1983).

Hazard identification considers issues related to the composition, size, structure, and presence of surface charges or coatings. In general, the hazards of novel materials will be less predictable than small-scale versions of known substances [35]. Relatively little is known about the toxicity or dose-response of nanomaterials, and information to date is from *in vivo* studies, primarily as short-term studies in rodents or bench-scale studies using isolated cells or tissues, using selected materials. The primary routes of exposure for humans are oral, dermal, and inhalation routes, with workers and academic researchers likely experiencing the highest exposures. Potential exposure to nanomaterials must be considered for the entire life cycle (e.g., from synthesis to disposal) of the material or product. For nanomaterials within products, assessment of the intrinsic material properties of the product will be necessary to evaluate the degree of containment over time. Finally, in risk characterization, uncertainties must be dealt with to fully understand health risks.

The available research indicates that toxicity cannot be predicted simply as a function of size. Rather, many factors are important for determining relative toxicity, including chemical composition and particle shape and structure [35,36]. Much of the scientific research indicates that toxicity may be related more to surface area than to mass [30], although smaller particles are not necessarily more toxic (Tsuji et al. 2006). Additional determinants of exposure and toxicity for nanomaterials in water applications include aggregation potential, surface charges, and, degree of containment [35–38]. The effect of these factors is likely material specific, and generalizations may be misleading. For example, aggregation may increase the size of particles beyond the nano range, but for at least one type of nanoparticle (C_{60} carbon, or fullerenes), aggregation increased solubility and toxicity to bacteria [39]. These factors will need to be considered in risk assessments and safety evaluations of these new technologies, and specific issues regarding the environment and human health are described further below.

4 CONCLUSIONS

Nanotechnology holds great promise for improving the efficacy and efficiency of water treatment. Most scientific reviews of nanomaterials have concluded that the risks associated with these substances can be managed, but due to the paucity of information regarding toxicity, more health and environmental effects research is needed. Some studies show that smaller particles are not necessarily more toxic, but the ability of these smaller particles to disperse and become mobile in both the environment and the human body must be evaluated. If nanomaterials are used in the water market for filtration, disinfection, and other treatment, product-specific implications should be considered, particularly for products that are designed to stay or otherwise degrade *in situ*.

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