Nano Technology in Water Treatment

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Abstract— **The third world war will be for water is said by researchers. The long-term development of the global water situation is closely connected to the growth of the world population and global climate change. Constant growth of the world's population, which is forecasted to be nearly doubled from 3.4 billion in 2009 to 6.3 billion people in 2050, is attended by a predicted needed growth of agriculture production of 70%, by 2050. Currently, 64 billion cubic meters of fresh water are progressively consumed each year. A group of leading climate impact researchers have shown that climate change possibly exacerbates the regional and global water scarcity. They predict that global warming of 2°C above present temperatures will confront an additional approximately 15% of the global population with a severe decrease in water resources and will increase the number of people living under absolute water scarcity (<500 m^3 per capita per year) by at least another 40% compared with the effect of population growth alone. The adaptation of highly advanced nanotechnology to traditional process engineering offers new opportunities for development of advanced water and wastewater technology processes. Here, an overview of recent advances in nanotechnologies for water and wastewater processes is provided, including nanobased materials, processes, and their applications. Besides the promising technological enhancements, the limitations of nanotechnology for water applications, such as laws and regulations as well as potential health risks, are reported.**

Key words: carbon-based nanoadsorbents, carbon nanotubes (CNTs), metal-based nanoadsorbents, polymeric nanoadsorbents, zeolites.

I. INTRODUCTION

NANOBASED MATERIALS, PROCESSES, AND APPLICATIONS

Nanomaterials have unique size-dependent properties related to their high specific surface area and discontinuous properties. These specific nanobased characteristics allow the development of novel high-tech materials for more efficient water and wastewater treatment processes, namely membranes, adsorption materials, nanocatalysts, functionalized surfaces, coatings, and reagents.

Adsorption

Solids that are used to adsorb gases or dissolved substances are called adsorbents, and the adsorbed molecules are usually referred to collectively as the adsorbate.4 Due to their high specific surface area, nanoadsorbents show a considerably higher rate of adsorption for organic compounds compared with granular or powdered activated carbon. They have great potential for novel, more efficient, and faster decontamination processes aimed at removal of organic and inorganic pollutants like heavy metals and micropollutants. In addition to saving of adsorbent materials, the superior process efficacy enables implementation of more compact water and wastewater treatment devices with smaller footprints, particularly for decentralized applications and point-of-use systems. Current research activities mainly focus on the following types of nanoadsorbents:

- carbon-based nanoadsorbents ie, carbon nanotubes (CNTs)
- metal-based nanoadsorbents
- polymeric nanoadsorbents
- zeolites.

Carbon nanotubes

CNTs are allotropes of carbon with a cylindrical nanostructure. Depending on their manufacturing process, CNTs are categorized as single-walled nanotubes and multiwalled nanotubes, respectively. Besides having a high specific surface area, CNTs possess highly assessable adsorption sites and an adjustable surface chemistry. Due to their hydrophobic surface, CNTs have to be stabilized in aqueous suspension in order to avoid aggregation that reduces the active surface. They can be used for adsorption of persistent contaminants as well as to preconcentrate and detect contaminants.5 Metal ions are adsorbable by CNTs through electrostatic attraction and chemical bonding.6 Although chemical oxidation occurs, no toxic byproducts are produced, which is an important advantage over conventional disinfection processes like chlorination and ozonation.7 They can be simply regenerated through appropriate adjustments of operating conditions, like pH shift.

Conventional desalination methods are energy-consuming and technically demanding, whereas adsorption-based techniques are simple and easy to use for point-of-use water purification devices, yet their capacity to remove salts is limited. Yan et al8 developed plasma-modified ultralong CNTs that feature an ultrahigh specific adsorption capacity for salt (exceeding 400% by weight) that is two orders of magnitude higher when compared with conventional carbon-based water treatment systems.

Although CNTs have significant advantages over activated carbon, their use on an industrial scale for large municipal water and wastewater treatment plants is not expected in the midterm because of high production costs.10 Point-of-use

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applications that require small quantities of CNTs are more competitive; for example, for the elimination of heavily degradable contaminants such as many antibiotics and pharmaceuticals.11–13

Polymeric nanoadsorbents

Polymeric nanoadsorbents such as dendrimers (repetitively branched molecules) are utilizable for removing organics and heavy metals. Organic compounds can be adsorbed by the interior hydrophobic shells, whereas heavy metals can be adsorbed by the tailored exterior branches.14 Diallo et al15integrated dendrimers in an ultrafiltration device in order to remove copper from water. Nearly all copper ions were recovered by use of this combined dendrimer-ultrafiltration system. The adsorbent is regenerated simply through a pH shift. Sadeghi-Kiakhani et al16 produced a highly efficient bioadsorbent for the removal of anionic compounds such as dye from textile wastewater by preparing a combined chitosan-dendrimer nanostructure. The bioadsorbent is biodegradable, biocompatible, and nontoxic. They achieve removal rates of certain dyes up to 99%.

Zeolites

Zeolites in combination with silver atoms have been known since the early 1980s.17 Zeolite has a very porous structure in which nanoparticles such as silver ions can be embedded. There they are released from the zeolite matrix by exchange with other cations in solution. Egger et al18 compared various materials containing nanosilver, including zeolites. When used for sanitary purposes, the silver attacks microbes and inhibits their growth, as shown by Agion® (Sciessent LLC, Wakefield, MA, USA).19 A small amount of silver ions is released from the metallic surface when placed in contact with liquids. The success of this composition in water disinfection was shown once again by Petrik et al.20 The Water Research Commission Report No KV 297/12 shows the innovative use of zeolites as an adsorbing platform for silver nanoparticles as a source of silver ions for a disinfectant. Another possibility is applying zeolites themselves as nanoparticles, as shown by Tiwari et al, who prepared nanozeolites by laser-induced fragmentation of zeolite Linde type A microparticles and Jung et al, who used nanozeolites in sequencing batch reactors for waste water treatment.21,22

Properties, applications, and innovative approaches of nanoadsorbents

Both CNTs and nanometals (see section on Nanometals and nanometal oxides) are highly effective nanoadsorbents for the removal of heavy metals such as arsenic. With regard to this application field, nanometals and zeolites benefit from their cost-effectiveness and compatibility with existing water treatment systems since they can be implemented in pellets and beads for fixed absorbers. In contrast, the production of CNTs is very costly, and additional technical devices, for example, membrane filtration plants, have to be integrated in order to make absolutely sure that no nanoparticles are discharged into the aqueous environment. A major advantage of CNTs in terms of micropollutant removal is their strong adsorption capacity for polar organic compounds due to the diverse interactions between contaminants and CNTs. Whereas CNTs and nanometals are commercially available for diverse applications, market entry of polymeric nanoadsorbents is ongoing. From the point of view of process efficacy, polymeric nanoadsorbents are highly advanced materials allowing both removal of heavy metals as well as organic contaminants within one process step. The major limitation of this novel adsorption technology is the technically demanding and cost-intensive production process for polymeric dendrimers that has to be improved.

Nanometals and nanometal oxides

Nanoscale metal oxides are promising alternatives to activated carbon and effective adsorbents to remove heavy metals and radionuclides. As well as having a high specific surface area, they feature a short intraparticle diffusion distance and are compressible without a significant reduction of surface area. Some of these nanoscale metal oxides (eg, nanomaghemite and nanomagnetite) are superparamagnetic, which facilitates separation and recovery by a low-gradient magnetic field. They can be employed for adsorptive media filters and slurry reactors.13 Nano iron hydroxide [α-FeO(OH)] is a robust abrasion-resistant adsorbent with a huge specific surface area that enables adsorption of arsenic from waste and drinking water.23.

Nanosilver and nano-titanium dioxide

Nanosilver exhibits a strong and broad-spectrum antimicrobial activity, it has hardly any harmful effects in humans. It is already applied to point-of-use water disinfection systems and antibiofouling surfaces.24 Nano-titanium dioxide (TiO_2), featuring high chemical stability and low human toxicity at a cheap price, is utilizable in disinfection and decontamination processes.25,26 Further information is provided in the section on photocatalysis. The main advantage of nano-TiO_2 over nanosilver is the nearly endless life time of such coatings, since TiO_2 as a catalyst remains unchanged during the degradation process of organic compounds and micro-organisms. The antimicrobial effect of nanosilver is based on the continuous release of silver ions. A disadvantage of bactericidal nanoparticles in general except for nano-TiO_2 is that no bactericidal substances such as hydroxyl radicals remain in the water past the contact time that could ensure the water quality in storage and distribution devices (depot effect).

Magnetic nanoparticles

The use of magnetic nanoparticles (magnetite Fe_3O_4) for separation of water pollutants has already been established in ground water remediation, in particular for the removal of arsenic.28 The conventionally applied "pump-and-treat" technology for groundwater treatment comprises pumping up the groundwater to the surface and further treatment, usually by activated carbon for final purification. The considerably extended operating hours and higher environmental clean-up costs can be reduced by applying in situ technologies. Magnetic nanoparticles can be injected directly into the contaminated ground, and loaded particles can be removed simply through a magnetic field.22 Besides ground water remediation, magnetic recovery makes such nanoparticles an ideal compound to increase the osmotic pressure of draw solutions used in forward osmosis. Forward osmosis as contrary process to reverse osmosis draws water from a low osmotic pressure to one with a higher osmotic pressure (draw solution) using the osmotic gradient.29

Nano-zero valent iron

As an alternative, nano-zero valent iron can be used for remediation of groundwater contaminated with chlorinated hydrocarbon fluids and perchlorates. A suspension of nano-zero valent iron can be injected into the groundwater, allowing in situ treatment of the ground water. On the one hand, due to its high specific surface, nano-zero valent iron is much more reactive in comparison with conventional granular iron; on the other, as a result of its high reactivity, the life time of nano-zero valent iron is very low, so that further research work, for example, on surface modifications, is necessary for stabilization of these nanoparticles.23,30,31

Properties, applications, and innovative approaches for nanometals and nanometal oxides

Photocatalytic TiO_2 benefits from its low price, high availability, inertness, and broad-spectrum effect on the chemical degradation of the majority of organic contaminants and micro-organisms. This makes it an ideal, robust, durable, and effective nanomaterial for chemical-free water and wastewater treatment processes in both large-scale and small-scale treatment plants. However, up until now, the efficacy of ultraviolet-visible photocatalytic TiO_2 in particular has been relatively low compared with similar oxidation processes like ozonation. Nanosilver benefits from its low toxicity, high availability, and well proven bactericidal effect. However, since it is dissolved during the duration of the process, its application is restricted to low feed volumes where a maximum life time can be achieved, for example, with point-of-use devices.

Limitations of nanobased materials and processes for water applications

Commercialization of nanoengineered materials for water and wastewater technology strongly depends on their impact on the aqueous environment. Numerous studies including toxicity tests, life cycle analysis, technology assessment, and pathways and dispersal of nanoparticles in water bodies have been carried out in order to evaluate the health risks of nanomaterials. The results of these studies have led to a better understanding of the behavior of nanoparticles such as CNTs, TiO_2, and silver nanoparticles in aqueous systems; thus, stakeholders from administration, politics, and industry are supported to create new laws and regulations or modify present ones.

Conclusion and future prospects

There is a significant need for novel advanced water technologies, in particular to ensure a high quality of drinking water, eliminate micropollutants, and intensify industrial production processes by the use of flexibly adjustable water treatment systems. Nanoengineered materials, such as nanoadsorbents, nanometals, nanomembranes, and photocatalysts, offer the potential for novel water technologies that can be easily adapted to customer-specific applications. Most of them are compatible with existing treatment technologies and can be integrated simply in conventional modules. One of the most important advantages of nanomaterials when compared with conventional water technologies is their ability to integrate various properties, resulting in multifunctional systems such as nanocomposite membranes that enable both particle retention and elimination of contaminants. Further, nanomaterials enable higher process efficiency due to their unique characteristics, such as a high reaction rate.

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