Use of nanomaterials in water purification

The recent earthquake in Haiti has focused worldwide attention on the need for improved water purification materials and systems. Numerous individuals, religious charities, non-governmental organizations, and private companies have sent water purifications systems to Haiti in recent months in order to stem the spread of waterborne diseases. This recent tragedy has placed a spotlight on the ongoing problem of inadequate access to safe water in developing countries. The United Nations estimates that 1.1 billion people, or eighteen per cent of the world population, cannot obtain safe water at this time[1]. In developing countries, waterborne diseases such as cholera, dysentery, enteric fever, and hepatitis A are quite common[2]. Endemic diarrheal diseases place individuals, particularly children, at risk of arrested growth, malnutrition, and neurological conditions. The World Health Organization states that 1.6 million individuals, mostly young children, die from diarrheal diseases each year[1].

Roger Narayan
Joint Department of Biomedical Engineering, NC State University and UNC Chapel Hill
E-mail: roger_narayan@msn.com

Improving water quality provides social and economic benefits to developing countries. For example, chlorination, filtration, solar disinfection, or combined flocculation and chlorination can yield benefits of $5 to $140 for each $1 that is invested[1]. In developing countries, large-scale municipal water treatment systems face problems such as inadequate maintenance, intermittent delivery, contamination with microorganisms, and lack of chlorination[3-6]. The high cost of water transportation and the high cost of constructing centralized water systems also have limited the use of centralized water purification[4,5].

Disinfecting water after collection, which is commonly referred to as point-of-use disinfection, enables individuals to improve water obtained from unsafe sources[6-9]. Low-cost point-of-use technologies are being developed to convert water from untreated sources such as springs, wells, community taps, and rivers[7]. At this time, chlorination, flocculation, boiling, and filtration are the most commonly used point-

ISSN:1369 7021 © Elsevier Ltd 2010

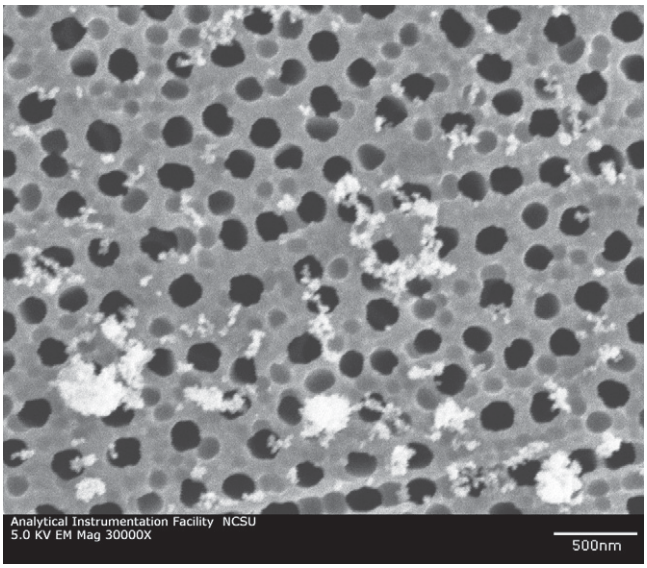

Fig.1 Plan-view scanning electron micrograph obtained from the large pore side of a zinc oxide-coated 20 nm pore size nanoporous alumina membrane.

of-use water purification technologies. 30–40% reductions in diarrheal disease have been attributed to point-of-use treatments[10]. In addition, point-of-use water treatment involves lower energy costs and provides more straightforward control over water treatment than conventional methods.

In recent years, the use of nanostructured materials in point-of-use water purification devices has been considered[11]. Nanostructured materials exhibit several advantages over conventional microstructured materials for water purification, including larger relative surface areas[12]. These chlorine-free water purification methods are of particular interest since carcinogenic disinfection byproducts may be formed when components of natural water interact with chloramines or chlorine[13].

For example, Van de Bruggen *et al.* have described using nanoporous membranes for removal of arsenic, bacteria, organic material, nitrates, salinity, and viruses from groundwater and surface water[14]. Srivastava *et al.* demonstrated the use of membranes containing radially aligned carbon nanotube walls for removal of viruses and bacteria, including *Poliovirus sabin 1, Escherichia coli,* and *Staphylococcus aureus*[15]. Thermal processes may be used to regenerate carbon nanotube membranes[16].

Micro-organisms may form biofilms on the surfaces of water purification membranes. These biofilms decrease membrane permeability and increase water purification costs[17-19]. In addition, some microorganisms may release substances that degrade water quality, such as metabolic products and biological toxins[20,21]. Conventional methods for preventing the formation of microbial biofilms involve treating membranes with biocidal agents; however, biocidal agents may not be effective in eliminating rapidly growing

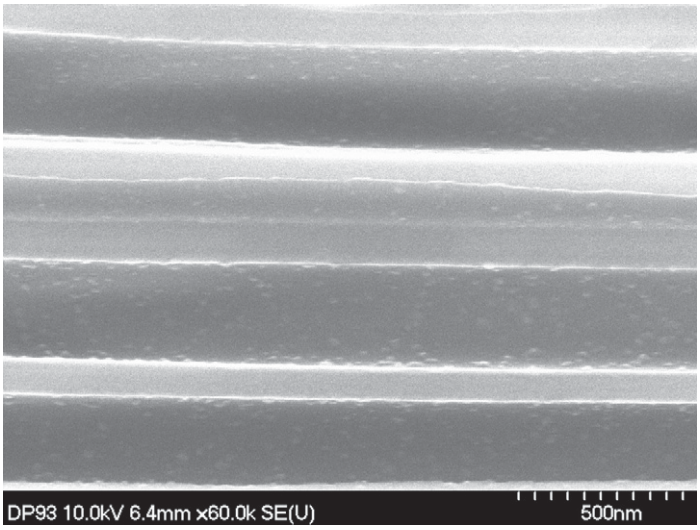

Fig. 2 Cross-sectional scanning electron micrograph obtained after fracturing a 60 μm thick nanoporous alumina membrane.

bacteria[22,23]. In addition, biocidal agents may destroy the surfaces of water purification membranes[23]. Several investigators have described fabrication of nanostructured ceramic membranes containing zinc oxide and the anatase phase of titania[24-26]. Zinc oxide and the anatase phase of titania have been shown to photocatalytically degrade pollutants as well as prevent growth of microorganisms[24-28]. Unlike conventional polymeric membranes, ceramic membranes do not undergo degradation when exposed to heat or ultraviolet light[25].

Functionalization of nanoporous membranes with photocatalytic titania coatings has attracted significant interest over the past few years. When irradiated by an ultraviolet A light source (e.g., solar energy), titania is able to degrade organic contaminants as well as destroy microorganisms[24,29]. For example, Zhang *et al.* demonstrated that silica/titania nanotube composite membranes on porous alumina support membranes removed Direct Black 168 dye by means of membrane separation and photocatalysis[25]. In another study, Ma *et al.* used a sol-gel method in order to coat silicon-doped titania layers on commercial alumina membranes[11]. These membranes demonstrated removal and photocatalytic degradation of a model pollutant (Reactive Red ED-2B). Zhang *et al.* grafted anatase titania nanotubes within the channels of alumina microfiltration membranes by means of a liquid-phase deposition method[30]. Membranes with titania nanotube inner diameters between 5 nm and 100 nm were obtained using this technique. These titania nanotube membranes demonstrated photocatalytic degradation of humic acid as well as reductions in membrane biofouling. Antimicrobial coatings and photocatalytic coatings have also been deposited on nanoporous membranes using atomic layer deposition[26,31]. For example, atomic layer deposition was used to deposit anatase titania coatings on nanoporous alumina membranes, which exhibit straight pores, high pore densities, and small pore sizes. Scanning electron microscopy of cross-sectional samples revealed that titania nanocrystals extended to the middle of the 60 mm thick nanopores. Titania-coated 20 nm pore size nanoporous alumina membranes that were exposed to ultraviolet light demonstrated activity against *Escherichia coli* and *Staphylococus aureus* bacteria. Atomic layer deposition may be useful in creating membranes with extremely small pore sizes for preventing penetration of viruses.

Nanoporous membranes with biocidal properties as well as other nanostructured materials may be useful in the development of point-of-use water purification systems for developing countries and emergency situations. It should be noted that nanostructured material-based water purification technologies are also being incorporated within centralized water systems in developed countries[32]. For example, use of nanofiltration in a large distribution system was shown to reduce the amount of microorganisms and organic material[33]. In addition, fouling-resistant membranes may be used in distributed optimal technology networks; these networks are being considered as an alternative to centralized water treatment facilities[34]. Efforts are also underway to develop nanostructured materials for water purification with other functionalities, including removal of radionuclides and desalination[35,36]. For these efforts to have a significant impact, it will be necessary to reduce the processing costs for nanostructured water purification materials so that they are similar to those for conventional ceramic and polymeric water purification materials. In addition, comparisons between nanostructured water purification materials and their conventional counterparts with regard to effectiveness over extended periods of time are also needed. mt

REFERENCES

1. WHO/UNICEF *Joint Monitoring Programme for Water Supply and Sanitation*. Water for Life: Making It Happen. WHO Press, Geneva, 2005.
2. Sobsey, M. D., *et al., Environ Sci Technol* (2008) **42**, 4261.
3. Varghese, A., *A comparative risk approach to assessing point-of-use water treatment systems in developing countries*. In Comparative Risk Assessment and Environmental Decision Making, Linkov, I., Ramadan A. B., (eds.), NATO Science Series IV Earth and Environmental Sciences, Rome, (2004), **38**, 99.
4. Gleick, P. H., *Science* (2003) **302**,1524.
5. Haas, C. N., *J Am Water Works Assoc* (2000) **92**, 72.
6. Mintz, E., *et al., J Amer Med Assoc* (1995) **273**, 948.
7. Colindres, R. E., *et al., J Water Health* (2007) **5**, 367.
8. Elimelech, M., *J Water Supply Res Technol* (2006) **55**, 3.
9. Quick, R. E., *et al., Epidemiol Infect* (1999) **122**, 83.
10. Sobsey, M. D., *et al., Environ Sci Technol* (1008) **42**, 4261.
11. Ma, N., et al., *J Membr Sci* (2009) **335**, 58.
12. Savage, N., and Diallo, M. S., *J Nanopart Res* (2005) **7**, 331.
13. Krasner, S. W., *et al., Environ Sci Technol* (2006) **40**, 7175.
14. Van der Bruggen, B., *et al., Environ Poll* (2003) **122**, 435.
15. Srivastava, A., *et al., Nature Mater* (2004) **3**, 610.
16. Brady-Estevez, S., *et al., Small* (2008) **4**, 481.
17. Hilal, N., *et al., Desalin* (2004) **167**, 293.
18. Kochkodan, V., *et al., Desalin* (2008) **220**, 380.
19. Liu, C. X., *et al., J Membr Sci* (2010) **346**, 121.
20. Park, N., *et al., J Membr Sci* (2005) **258**, 43.
21. Upadhyayula, V. K. K., *et al., Sci Total Environ* (2009) **408**, 1.
22. Flemming, H. C., *et al., Desalin* (1997) **113**, 215.
23. Kim, D., *et al., Desalin* (2009) **238**, 43.
24. Li, Q., *et al., Water Res* (2008) **42**, 4591.
25. Zhang, H. M., *et al., Environ Sci Technol* (2006) **40**, 6104.
26. Narayan, R. J., *et al.,* Phil Trans Royal Soc A (2010) **368**, in press.
27. Aal, A. A., *et al., Mater Sci Eng C* (2009) **29**, 831.
28. Gittard, S. D., *et al., Appl Surf Sci* (200) **255**, 5806.
29. Danion, A., *et al., Appl Catal B* (2004) **52**, 213.
30. Zhang, X. W., *et al., Appl Catal B* (2008) **84**, 262.
31. Narayan, R. J., *et al., JOM* (2009) **61**, 12.
32. Smith, A., *Filtr Sep* (2006) **43**, 32.
33. Peltier, S., *et al., Water Sci Technol Water Supply* (2003) **3**,193.
34. Weber Jr., W. J., *Water Sci Technol* (2002) **46**, 241.
35. Favre-Reguillon, A., *et al., Ind Eng Chem Res* (2003) **42**, 5900.
36. Mohsen, M. S., *et al., Desalin* (2003) **157**, 167.