Photocatalytic membrane reactors for high throughput virus removal and inactivation

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Abstract

Photocatalytic membrane reactors (PMRs) combine membrane separation and photocatalysis in one hybrid process. PMR is a highly versatile technology due to the range of engineering designs it affords and many possible applications. Photocatalytic treatment can be highly effective with respect to viruses (e.g. [1–4]). Most of the work on the application of PMRs to water treatment, however, has focused on chemical pollutants. To our knowledge, there have been only five reports on the application of photocatalytic membranes to water disinfection [5–9]. All five studies were on *E. coli* control and three of the five [7–9] also used silver, a known bactericide, as a component of photocatalytic membranes.

In the proposed hybrid process the permeate surface a ceramic membrane (d_{pore} = 0.8 μm) is coated with photocatalytic nanoparticles (TiO_2, anatase) and exposed to UV irradiation (Figure 1) to inactivate viruses during microfiltration [10]. The membrane is operated in the in-out flow geometry to eliminate turbidity and improve efficiency of UV disinfection (Table 1). The membrane-supported photocatalyst ensures generation of reactive oxygen species that act on the pollutants that break through the membrane. Two coating methodologies – dip coating and layer-by-layer self-assembly were employed to render the highly porous permeate side of the membrane photocatalytic. The layer-by-layer self-assembly method produced sub-monolayers of photocatalyst and minimized coating-induced reduction of membrane permeability (Figure 2). Methylene Blue, bacteriophage P22, and human adenovirus 40 were used to evaluate the efficiency of the membrane reactor. Batch UV disinfection and crossflow filtration tests showed that the hybrid photocatalytic UV-microfiltration process is considerably more effective in inactivating viruses (e.g. for P22, LRV_{P22} = 5.0 ± 0.7) than the constituent processes - UV disinfection and microfiltration - applied in series (aggregate LRV_{P22} = 2.0 ± 0.5) (Figure 3).

To our knowledge, this is the first application of photocatalytic membrane reactors to virus removal or inactivation. Potential applications of the proposed treatment process include disinfection of turbid, high fouling, and high flow rate streams.

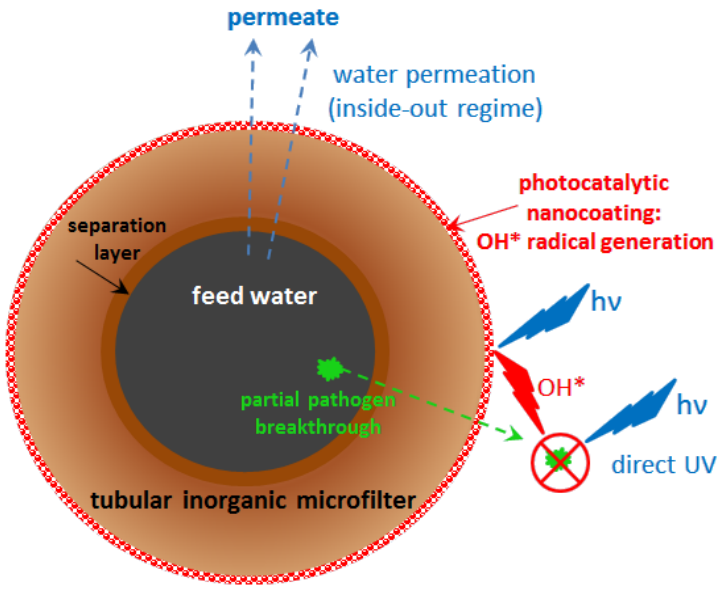


Figure 1: Conceptual illustration of the hybrid membrane filtration-UV disinfection process [10].

Table 1. Synergistic benefits of combing membrane filtration and photocatalytic UV disinfection into a hybrid process.

Technology and its benefits		Challenges	How the challenge is addressed in the proposed PMR
Photocatalytic UV disinfection	Photocatalytic UV is effective against a wide range of microbial pathogens. UV disinfection is catalytically enhanced	Some pathogens are resistant to UV or can repair UV-induced damage	Catalytic oxidation at the membrane surface by ROS complements the physical effect of the direct UV
		Catalyst needs to be recovered	Membrane-supported catalyst is immobilized and does not need to be recovered
		Efficiency is limited when turbidity is present	Turbidity is removed by the microfilter “upstream” from the UV reactor
Membrane filtration	Membranes provide absolute barrier to pathogens	Lower pore size for removal of smaller pathogens results in lower permeate fluxes	Redundancy introduced with catalytic UV disinfection enables trade-offs in pore sizes and product water fluxes

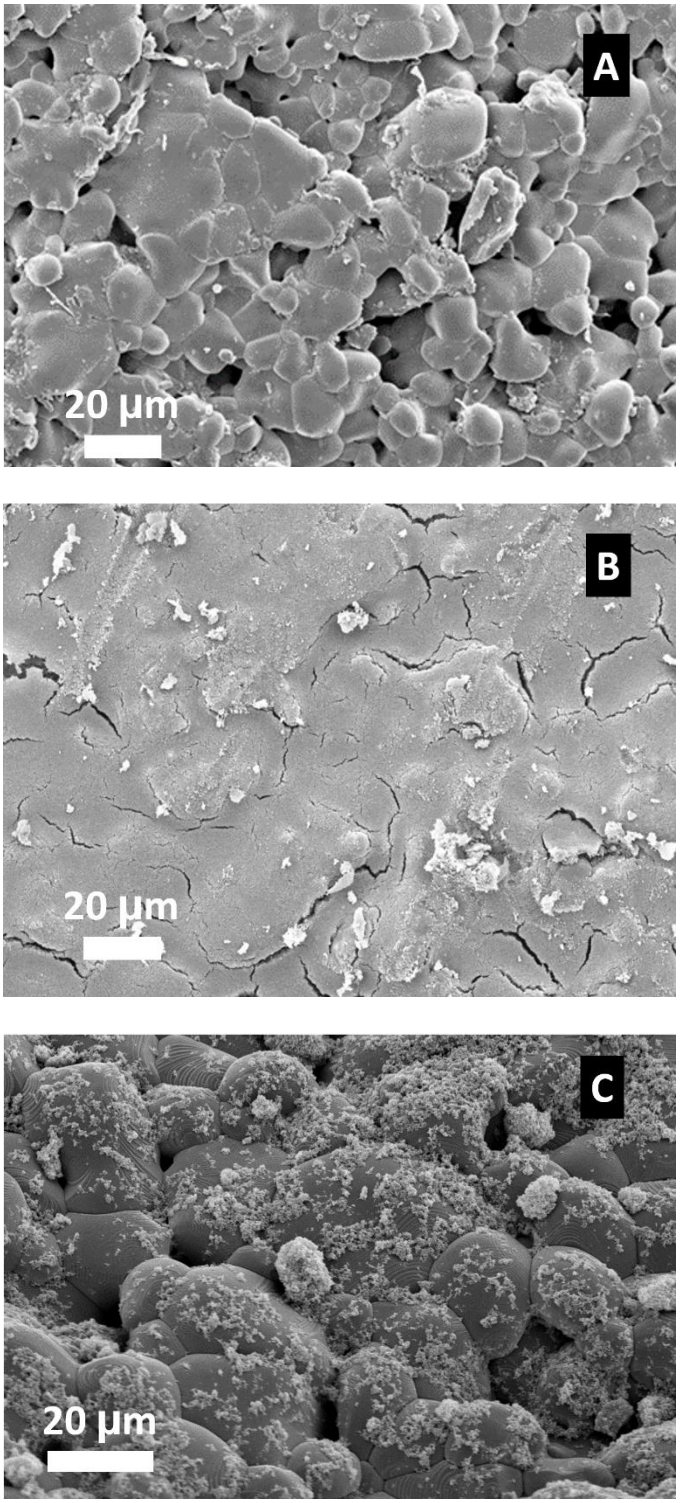


Figure 2: SEM images of outer surface of a ceramic 0.8 m nominal pore size membrane: A) uncoated, B) dip-coated by 10 coats of TiO_2, C) coated by1 layer of TiO_2 using the L-b-L method with PDADMAC and PAA as binder polyelectrolytes [10, 11].

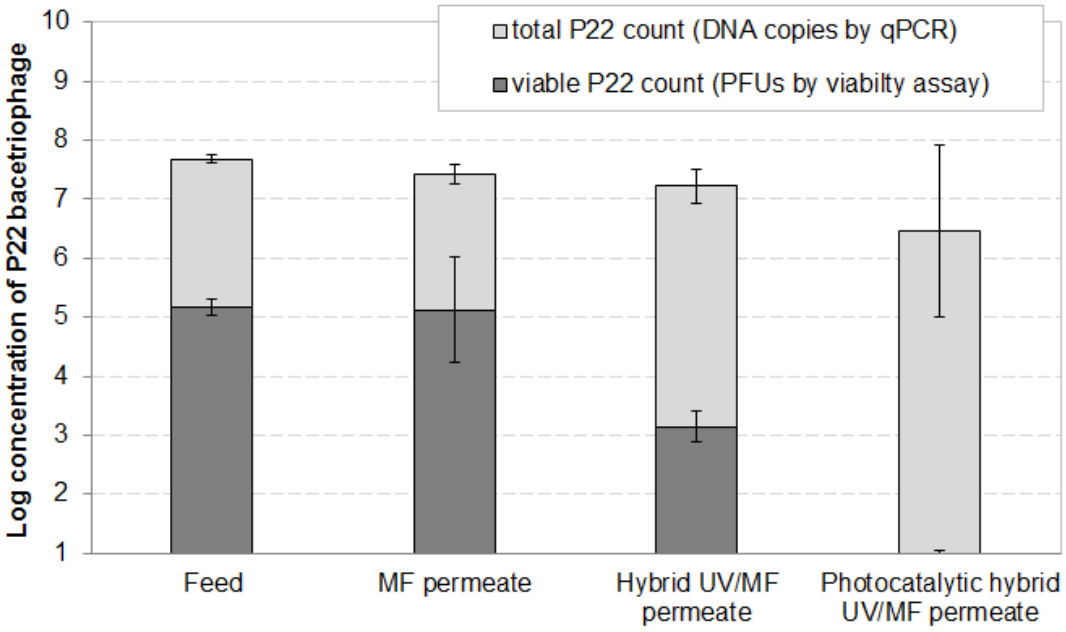


Figure 3. Log concentration of viable and total bacteriophage P22 in the feed solution and in the permeate 30 min into the filtration process. Error bars correspond to standard deviations [10].

References

1. J.C. Sjorgen, R.A. Sierka, Inactivation of phage MS2 by iron-aided titanium dioxide photocatalysis, Appl. Environ. Microbiol. 60 (1994) 344–347.
2. Q. Li, M.A. Page, B.J. Marinas, J.K. Shang, Treatment of coliphage MS2 with palladium-modified nitrogen-doped titanium oxide photocatalyst illuminated by visible light, Environ. Sci. Technol. 42 (2008) 6148–6153.
3. J. Lee, K. Zoh, G. Ko, Inactivation and UV disinfection of murine norovirus with TiO_2 under various environmental conditions, Appl. Environ. Microbiol. 74 (2008) 2111–2117.
4. D. Gerrity, H. Ryu, J. Crittenden, M. Abbaszadegan, Photocatalytic inactivation of viruses using titanium dioxide nanoparticles and low-pressure UV light, J. Environ. Sci. Health A 43 (2008) 1261–1270.
5. H. Choi, M.G. Antoniou, A.A. de la Cruz, E. Stathatos, D.D. Dionysiou, Photocatalytic TiO2 films and membranes for the development of efficient wastewater treatment and reuse systems, Desalination 202 (2007) 199–206.
6. H. Zhang, H. Zhao, P. Liu, S. Zhang, G. Li, Direct growth of hierarchically structured titanate nanotube filtration membrane for removal of waterborne pathogens, J. Membr. Sci. 343 (2009) 212–218.

7. N. Ma, X. Fan, X. Quan, Y. Zhang, Ag–TiO2/HAP/Al2O3 bioceramic composite membrane: fabrication, characterization and bactericidal activity, J. Membr. Sci. 336 (2009) 109–117.
8. L. Liu, Z.Y. Liu, H.W. Bai, D.D. Sun, Concurrent filtration and solar photocatalytic disinfection/degradation using high-performance Ag/TiO2 nanofiber membrane, Water Res. 46 (2012) 1101–1112.
9. R. Goei, T.-T. Lim, Ag-decorated TiO2 photocatalytic membrane with hierarchical architecture: photocatalytic and antibacterial activities, Water Res. 59 (2014) 207–218.
10. Guo, B.; Pasco, E. V.; Xagoraraki, I.; Tarabara, V. V. Virus removal and inactivation in a hybrid microfiltration-UV process with a photocatalytic membrane. Separ. Purif. Technol. 2015, 149, 245–254.
11. Starr, B. J. Photocatalytic membranes for virus inactivation. MS Thesis, Michigan State University, East Lansing, MI. 2015