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Review

The roles of bacteriophages in membrane-based water and wastewater treatment processes: A review

Bing Wu [a,*], Rong Wang [a,b,**], Anthony G. Fane [a,b]

[a] Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, 1 Cleantech Loop, CleanTech One #06-08, 637141, Singapore
[b] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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ABSTRACT

Membrane filtration processes have been widely applied in water and wastewater treatment for many decades. Concerns related to membrane treatment effectiveness, membrane lifespan, and membrane fouling control have been paid great attention. To achieve sustainable membrane operation with regards to low energy and maintenance cost, monitoring membrane performance and applying suitable membrane control strategies are required. As the most abundant species in water and wastewater, bacteriophages have shown great potential to be employed in membrane processes as (1) indicators to assess membrane performance considering their similar properties to human pathogenic waterborne viruses; (2) surrogate particles to monitor membrane integrity due to their nano-sized nature; and (3) biological agents to alleviate membrane fouling because of their antimicrobial properties. This study aims to provide a comprehensive review on the roles of bacteriophages in membrane-based water and wastewater treatment processes, with focuses on their uses for membrane performance examination, membrane integrity monitoring, and membrane biofouling control. The advantages, limitations, and influencing factors for bacteriophage-based applications are reported. Finally, the challenges and prospects of bacteriophage-based applications in membrane processes for water treatment are highlighted.

Contents

* Corresponding author.
** Corresponding author. Singapore Membrane Technology Centre, Nanyang Environment and Water Research Institute, Nanyang Technological University, 1 Cleantech Loop, CleanTech One #06-08, 637141, Singapore.
E-mail addresses: wubing@ntu.edu.sg (B. Wu), rwang@ntu.edu.sg (R. Wang).

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1. Introduction

Bacteriophages (also known as phages) are virus that have a capability only to infect and kill bacteria (Duckworth and Gulig, 2002; Haq et al., 2012). Bacteriophages perform antimicrobial roles either by directly causing lysis of bacteria or by extruding and replicating its genome inside of bacterial cells before undergoing lysis of bacteria under deteriorated conditions (Campbell, 2003; Nobrega et al., 2015). After bacteriophages were first discovered by Frederick Twort in 1915 and Félix D'Hérelle in 1917, bacteriophages were initially applied to treat pathogenic bacterial infections in the medical field, i.e., bacteriophage therapy (Campbell, 2003; Duckworth and Gulig, 2002; Nobrega et al., 2015). Recently, other potential applications of bacteriophages have received enormous attention, for example, as an additive in food products for conservation, as predators against plant pests/bacteria, and as vehicles for vaccines delivery etc. (Campbell, 2003; Haq et al., 2012).

Bacteriophages are the most abundant life forms on earth, especially in the ocean and in fresh water sources (Hanlon, 2007; Wommack and Colwell, 2000). It is therefore not at all surprising that the application of bacteriophages has been extended to the environmental field. An early study emphasized that bacteriophages were useful alternatives to other microbiological and chemical tracers in modelling surface water due to their non-toxic nature (Martin, 1988). With the development of membrane filtration technology such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and forward osmosis (FO) in the water and wastewater treatment processes, the roles of bacteriophages in membrane processes have been paid much attention. In this regard, due to their viral nature and similar properties to human enteric virus, monitoring indigenous bacteriophages have been conducted in the pilot and full-scale water treatment plants in order to evaluate human enteric virus removal in membrane processes. Also, several types of bacteriophages are used as model tracers to assess the effectiveness of membrane separation processes. Because of their nano-sized property, bacteriophages could be applied as surrogate particles in the membrane processes to examine membrane integrity. In addition, bacteriophages display antimicrobial properties, thus they could also be considered as biological agents for membrane biofouling control.

This review summarizes the recently reported literature on the roles of bacteriophages in membrane-based water treatment processes, with a focus on membrane performance examination, and membrane integrity monitoring, and membrane fouling control (Fig. 1). Noticeably, the uses of bacteriophages, especially as tracers or antimicrobial agents, in membrane processes are mainly performed in the bench-scale or lab-scale systems till now. Thus, the advantages and limitations of bacteriophage-associated techniques are critically reviewed. In particular, the influences of operating conditions of membrane processes on the performance of bacteriophages are highlighted. The technological challenges are carefully evaluated and the breakthroughs required for the further development of the bacteriophage-associated techniques are suggested. Finally, the prospects and research directions for bacteriophage-associated techniques in membrane processes are proposed.

2. The role of bacteriophages in evaluating membrane performance

2.1. Examination of membrane performance by monitoring indigenous bacteriophages

In the membrane process for drinking water production and wastewater treatment, the removal of human pathogenic waterborne viruses (especially human enteric viruses) is a critical parameter to evaluate the membrane treatment efficiency (Kopecka et al., 1993). To directly detect human enteric viruses, either the fecal indicator bacteria methods or molecular methods (such as reverse transcription, polymerase chain reaction, and hybridisation etc.) are typically used. Compared to conventional fecal indicator bacteria methods, molecular techniques are more sensitive, specific, and rapid, but more expensive and cumbersome (Ebdon et al., 2012; Francy et al., 2012; Havelaar et al., 1991).

An alternative approach is to use indigenous bacteriophages as indicators to determine the presence of human enteric viruses considering the properties of bacteriophage. Specifically, the structure, composition, size, and replication features of indigenous bacteriophages are comparable to human enteric viruses. For example, FRNA bacteriophages have sizes of 25 nm and isoelectric point (IEP, i.e., the pH value at which the electrophoretic mobility of the particle equates zero) of 3.9, which are similar to those of human enterovirus (22–30 nm, IEP 4.0–6.4) and hepatitis A (27–28 nm, IEP 2.8) (Branch et al., 2016; Michen and Graule, 2010). At neutral pH (typical operation conditions for membrane-based water and wastewater treatment processes), the low IEP of typically-used indigenous bacteriophages appears to avoid membrane adsorption due to their negatively-charged surfaces. Moreover, indigenous bacteriophages are either positively correlated with the presence of enteric viruses in water and wastewater or more conservatively removed by membranes than the enteric viruses (Cromeans et al., 2005; Leclerc et al., 2000; Otaki et al., 1998). Importantly, bacteriophage assay technique is much simpler and cheaper than any of the human enteric virus detection methods (Leclerc et al., 2000).

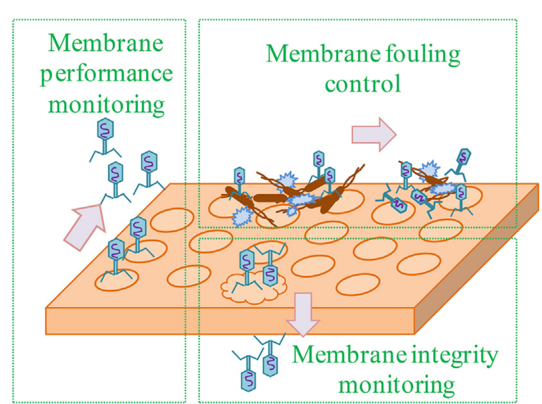

Fig. 1. A diagram illustrating the roles of bacteriophages in membrane-based water and wastewater treatment processes.