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Research review paper

# Recent advances in membrane bio-technologies for sludge reduction and treatment

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ABSTRACT

This paper is designed to critically review the recent developments of membrane bio-technologies for sludge reduction and treatment by covering process fundamentals, performances (sludge reduction efficiency, membrane fouling, pollutant removal, etc.) and key operational parameters. The future perspectives of the hybrid membrane processes for sludge reduction and treatment are also discussed. For sludge reduction using membrane bioreactors (MBRs), literature review shows that biological maintenance metabolism, predation on bacteria, and uncoupling metabolism through using oxic-settling-anaerobic (OSA) process are promising ways that can be employed in full-scale applications. Development of control methods for worm proliferation is in great need of, and a good sludge reduction and MBR performance can be expected if worm growth is properly controlled. For lysis-cryptic sludge reduction method, improvement of oxidant dispersion and increase of the interaction with sludge cells can enhance the lysis efficiency. Green uncoupler development might be another research direction for uncoupling metabolism in MBRs. Aerobic hybrid membrane system can perform well for sludge thickening and digestion in small- and medium-sized wastewater treatment plants (WWTPs), and pilot-scale/full-scale applications have been reported. Anaerobic membrane digestion (AMD) process is a very competitive technology for sludge stabilization and digestion. Use of biogas recirculation for fouling control can be a powerful way to decrease the energy requirements for AMD process. Future research efforts should be dedicated to membrane preparation for high biomass applications, process optimization, and pilot-scale/full-scale tracking research in order to push forward the real and wide applications of the hybrid membrane systems for sludge minimization and treatment.



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## 1. Introduction

The biological treatment process is widely used for wastewater treatment. However, during the degradation of organic pollutants by microorganisms, a huge amount of waste activated sludge (WAS) is produced that is difficult and expensive to handle and dispose of. According to statistics, the USA currently generates about 8.2 million tons of dry WAS per year, and the EU annually produces over 10 million tons (Wang et al., 2012). In China, the total amount of dry sludge is about 4.4 million tons in 2010 and is estimated to increase to about 6.0 million tons in 2015 (ChinaWater.net, 2011). Sludge treatment and management have aroused much attention worldwide (Liu, 2003; Rai et al., 2004; Wang et al., 2008c; Zhao and Kugel, 1996).

There are two phases to cope with sludge-associated problems, i.e., minimizing sludge production during the wastewater treatment, and the post-treatment of the sludge produced. With the rapid development of membrane technology in the past two decades, membrane separation has been used in not only sludge minimization but sludge post-treatment. A large number of peer-reviewed journal papers have been published regarding the topics. Successful sludge minimization efficiencies have been achieved in membrane bioreactors (MBRs) based on the mechanisms of predation on bacteria (Luxmy et al., 2000, 2001; Wang et al., 2011; Wei et al., 2003a), lysis-cryptic growth (Do et al., 2012; Ventura et al., 2011; Wang et al., 2008b), biological maintenance metabolism (Pollice et al., 2008b; Sun et al., 2007; Teck et al., 2009), and uncoupling metabolism (Saby et al., 2003; Song et al., 2010). In addition, membranes have also been used for sludge thickening and aerobic or anaerobic digestion in recent years. The applications of microfiltration (MF) and ultrafiltration (UF) membranes for sludge thickening and aerobic digestion have been reported (Eusebio et al., 2011; Schaller et al., 2012; Wang et al., 2008c). Anaerobic membrane digesters for concurrent thickening and digestion of WAS were also successfully carried out (Martha et al., 2010; Xu et al., 2011). More recently, the feasibility of applying forward osmosis (FO) to the simultaneous thickening, digestion, and direct dewatering of waste activated sludge has been tested as well (Nguyen et al., 2013; Zhu et al., 2012). The progress of membrane technology for sludge minimization and treatment may offer an applicable and novel way to solve sludge-related problems.

However, to date, a comprehensive review on the application of membrane bio-technology to sludge reduction and treatment is lacking though there are several reviews related to sludge minimization (Khursheed and Kazmi, 2011; Liu and Tay, 2001; Wei et al., 2003b). This paper aims to critically review the recent developments in the use of membranes for sludge minimization and post-treatment by covering: (1) the process fundamentals, (2) the performances in terms of sludge reduction rate, thickening efficiency, membrane fouling (filtration performance), and pollutant removal, (3) key parameters influencing the performances (key factors for operation and design), and (4) the future perspectives. With the increasing research efforts in the field, a detailed analysis and characterization of past academic research achievements can contribute to establish a general understanding of the processes. Furthermore, synthesis of the knowledge can also be of interest not only to individuals involved in membrane technology but in sludge treatment and management. It may also be conducive to filling the gap between fundamental researches and engineering applications.

## 2. Process fundamentals

### 2.1. Sludge minimization in MBRs

Four mechanisms for sludge minimization in MBRs, i.e., biological maintenance metabolism, lysis-cryptic growth, predation on bacteria, and uncoupling metabolism, are schematically shown in Fig. 1. The energy obtained in the form of ATP during biological oxidation is used by the microbes for their maintenance followed by synthesis (Khursheed and Kazmi, 2011). Therefore, by increasing energy consumption for maintenance, new cell synthesis will be reduced due to the lowered energy that can be used for. Maintenance metabolism for sludge minimization (Fig. 1(a)) can be readily realized in MBRs because MBRs are usually operated under long sludge retention time (SRT) resulting in high mixed liquor suspended solids (MLSS) concentration and low food/microorganisms (F/M) ratio. At a low F/M ratio, the microbes tend to use a portion of feed substrate for maintenance purpose (as indicated by the bold arrow in Fig. 1(a)) and consequently decrease the quantity of substrate for growth (Van Loosdrecht and Henze, 1999).

Lysis-cryptic growth pathway for sludge minimization is a more widely used method in MBRs among academic researches. Cell contents are released into bulk solution during cell lysis, providing an autochthonous substrate for microbes. This autochthonous substrate is reused during microbial metabolism (cryptic growth), liberating a portion of the carbon as products of respiration, which results in a reduced overall biomass production. The use of membrane for solid–liquid separation can ensure that the released cellular substances are well utilized by microbes during cryptic growth, at the same time preventing the deterioration of effluent water quality. Lysis is always a rate-limiting stage (Wei et al., 2003b). In order to enhance lysis efficiency, a series of measures have been employed in MBRs for sludge minimization, such as ozonation (He et al., 2003, 2006; Huang et al., 2010; Jiang et al., 2007; Wang et al., 2008b), ultrasonication (Yoon, 2003; Yoon et al., 2004a), Fenton oxidation (He and Wei, 2010), alkaline treatment (Lee and Yeom, 2007; Oh et al., 2007), and thermo-chemical disintegration (Banu et al., 2009; Do et al., 2009; Ventura et al., 2011). In addition, it has to be pointed out that high oxygen concentration in MBRs may also induce cell lysis and consequently result in sludge minimization.

The mechanism of using predation on bacteria to achieve sludge reduction is to exploit higher organisms, such as protozoa and metazoan, to predate microorganisms (bacteria) existing in bulk solution. Energy is lost during the transfer from low (microbes) to high trophic levels (organisms), and thus sludge production can be minimized. In MBRs, protozoa and metazoan have been found, such as *sessile ciliates* and *free-swimming ciliates* (Luxmy et al., 2000), *Aeolosoma hemprichi* (Wang et al., 2011), *Tubificidae* (Wang et al., 2011), and *Oligochaete* (Wei et al., 2003a), which demonstrate relatively good sludge reduction efficiency. It has to be pointed out that protozoa and metazoan

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