Bioresource Technology 198 (2015) 418–423

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Forward osmosis membrane bioreactor for wastewater treatment with phosphorus recovery

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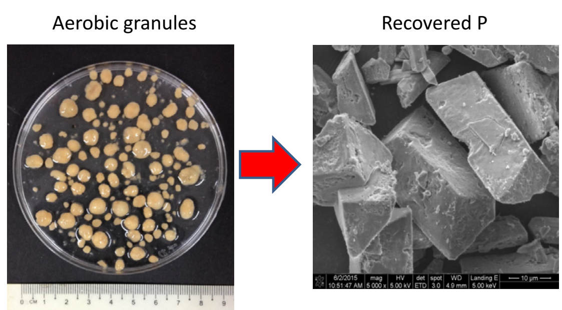
HIGHLIGHTS

- A forward osmosis membrane bioreactor (OMBR) was tested with TFC membrane.
- Flocculated sludge and aerobic granules were the seeds to OMBR.
- The OMBR showed 96%, 43% and 100% removals of PO_4^{3-}-P, NH_4^+-N, TOC.
- Phosphorus in supernatant was recovered by pH adjustment.
- At pH 8.5 with 2.65–2.71 g 3 M NaOH/g-P, 814–817 mg-P/L was recovered.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 July 2015
Received in revised form 3 September 2015
Accepted 5 September 2015
Available online 21 September 2015

Keywords:
Phosphorus recovery
Aerobic granule
Forward osmosis
Membrane bioreactor
Thin-film composite membrane

ABSTRACT

A forward osmosis membrane bioreactor (OMBR) with a thin film composite membrane was seeded with flocculated sludge and aerobic granules to treat a synthetic wastewater with 1 M NaCl as draw solution. The tested OMBR showed 96%, 43% and 100% removal of PO_4^{3-}-P, NH_4^+-N, and total organic carbon. Salinity was accumulated in OMBR principally owing to membrane rejection and salt leakage from draw solution. At high salinity level membrane fouling could be induced. Intermittent withdrawal and replenishment of supernatant from OMBR maintained its operation stability, while phosphorus in withdrawn supernatant was recovered by pH adjustment. The OMBR enriched phosphorus concentration from 156 mg/L in feed solution to 890–990 mg/L. At pH 8.5 with 2.65–2.71 g 3 M NaOH/g-P, 814–817 mg-P/L was recovered in the form of sodium hydrogen phosphite hydrate. The OMBR is a volatile wastewater treatment unit with capability for enrichment and recovery of phosphorus at reduced chemical costs.

1. Introduction

Phosphorus is an essential, nonrenewable nutrient necessary to feed increasing population, but must be largely removed form waste streams to avoid eutrophication of receiving waters (Sørensen et al., 2015). Phosphate can be recovered from the liquid phase, sludge phase and mono-incinerated sludge ash (Cornel and Schaum, 2009). Most techniques recovering phosphorus from the wastewater incorporate precipitation/crystallization processes. With addition of calcium or magnesium salts and other necessary compounds phosphorus can be collected as phosphate salts (Desmidt et al., 2015). The increase of the solution pH and Ca/P ratio are both effective to enhance precipitation of phosphorus from waters (Driver et al., 1999).

Membrane bioreactor (MBR) has been studied extensively (Huang and Lee, in press). Relevant review articles with >400 citations are listed (Le-Clech et al., 2006; Kim et al., 2006; Meng et al.,

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http://dx.doi.org/10.1016/j.biortech.2015.09.045
0960-8524/

2009). By the action of membrane screening, particulates including specific functional strains can be retained in the broth so the effluent yielded is of satisfactory quality for reuse (Skouteris et al., 2015; Luo et al., 2014; Yuan and He, 2015). Aerobic granules (AG) are compact aggregates of microorganisms, extracellular polymeric substances (EPS) and other organic and inorganic particulates that can efficiently treated high-strength wastewaters with supreme solid-liquid separation performances (Adav et al., 2008). The aerobic granules membrane bioreactor (AGMBR) combined the AG and MBR processes into a unique unit that exhibits the benefits for both (Yu et al., 2009).

The forward osmosis membrane bioreactor (OMBR) is an emerging MBR technology with water being spontaneously drawn by a solution with high salt concentration and with most microbes and impurities being retained in the mixed liquor (Wang et al., 2014). The OMBR has a few advantages over traditional MBR technologies, including its low fouling propensity, low energy consumption, and the effluents quality in highly polluted waters (Qiu and Ting, 2014b). However, since the driving force of high salt concentration to the suspended liquor leads to salinity accumulation in the OMBR, nitrification activity by nitrifiers would be deteriorated (Qiu and Ting, 2013). Qiu and Ting (2014b) noted that elevated salinity in mixed liquor could alter surface hydrophobicity of sludge particles and increase the amounts of extracellular polymeric substances being produced so membrane was severely fouled.

The accumulated salinity in OMBR may be applied for resource recovery. Qiu and Ting (2014a) enriched the concentrations of salinity in their OMBR and then precipitate the salts in the form of amorphous calcium phosphate (ACP) from PO_4^{3-}, Ca^{2+}, Mg^{2+} and NH_4^+ by adjust solution pH to 8.0–9.5. Qiu et al. (2015) continuously withdrew the suspended liquor from OMBR and recovered the phosphorus in filtrate of the liquor through a microfiltration membrane. These reports have revealed a novel way of recovering phosphorus from wastewater using OMBR. Most studies applied cellulose triacetate (CTA) membranes in their FO/OMBR studies (Huang and Lee, 2015); while only a few considered the use of thin film composite (TFC)-type membranes (Zhang et al., 2012; Lay et al., 2012; Alturki et al., 2012) although the latter dominants the commercial market (Wang et al., 2015).

This study seeded flocculated sludge and aerobic granules cultivated from the same inoculum into OMBR and tested its performances on wastewater treatment and salinity enrichment in the reactor. The P in the enriched liquor was recovered at 7-d intervals using pH adjustment method. This study is the first report on the use of AGOMBR for wastewater treatment and P-recovery.

2. Methods

2.1. Experimental setup and OMBR tests

The OMBR is composed of three parts: the MBR, the feed solution tank, and the draw solution tank. A schematic similar to our setup was available (Huang and Lee, 2015). The working volume of the MBR is 4.85 L (200 mm length × 125 mm width × 250 mm height). The plate-and-frame FO module submerged in the reactor held two pieces of TFC flat-sheet FO membranes (Hydration Technologies Inc., Albany, OR, USA). Each of the membranes, with its active layer facing the mixed liquor, has an effective membrane area of 0.018 m^2 (12 × 15 cm). The flow rate of the 1 M NaCl draw solution was 0.2 L/min. The concentration of the draw solution was maintained by a conductivity controller (Thermo, Pittsburgh, PA, USA) connected to a concentrated DS reservoir.

Synthetic wastewaters were of the following compositions (in mg/L): 400, sodium propionate; 400, peptone 250, meat extract; 200, NH_4Cl; 660, KH_2PO_4; 40, $CaCl_2$; 25, $MgSO_4{\cdot}7H_2O$; 20, $FeSO_4{\cdot}5H_2O$; 1330, $(NH_4)_2SO_4$; 13, $NaHCO_3$. Restated, the synthetic wastewater had a chemical oxygen demand (COD) of 1500 mg/L. The feed to OMBR was continuously fed to balance the flow drawn by the DS so the liquid level in the OMBR was maintained. But at 7-d internal, 2.5 L of mixed liquor was withdrawn from the bottom pipe of OMBR for P-recovery (discussed in Section 2.2). The system was aerated through three perforated pipes at the bottom to supply air at 8 L/min to minimize membrane fouling. The dissolved oxygen (DO) was monitored by IDS sensors (WTW, White Plains, NY, USA) and was maintained at 7.2 ± 0.3 mg/L in all tests. The reactors were maintained at 27 °C by water bath.

Seed sludges for OMBR were obtained from two sequential batch reactors (SBRs), RC and RS, with the former one providing aerobic granules and the latter, flocculated sludge. The details of the SBR operations are available in Supplementary Materials. The alternating strategy proposed by Yang et al. (2014) was applied to enhance aerobic granulation. The flocculated sludge from RC was used in the OMBR for the first stage (1–30 d) and the aerobic granules from RS were fed to replace all sludge for the second stage test (31–75 d).

2.2. Cross-membrane flux measurements

To quantify the cross-membrane fluxes of cations and anions through the studied TFC membrane, the present OMBR without biomass was applied with 1 M NaCl draw solution to filter inductively coupled plasma (ICP) standard solution (containing 10 mg/L of Li^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, B^{3+}, Al^{3+}, Ga^{3+}, Cr^{3+}, Mn^{2+}, Fe^{3+}, Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+} and Pb^{2+}) or a stock anion solution (containing 10 mg/L of NO_3^-, SO_4^{2-}, PO_4^{3-}) as feed solution. The cross-membrane fluxes were estimated in 24-h filtration tests with samples collected from effluent from OMBR and in draw solutions. The mass balances of individual ions are calculated so the cross-membrane fluxes can be estimated. Based on the concentrations of ions and their correlation to osmotic pressure at feed solution and draw solution, the reduction of net osmotic pressure difference can be obtained.

2.3. Phosphorus recovery

During d 1–58 at 7-d intervals, the 2.5 L liquor from OMBR was recovered with its phosphorous after 60 min settling. This sampling was stopped after d 58 to observe the adverse effects of accumulated salinity on fouling propensity of the FO membranes.

The collected 2.5 L sample was separated to five equal parts (each with 500 mL) and were added with $MgCl_2{\cdot}6H_2O$ at P:Mg = 1:1.3 (mol/mol) and 1 M NaOH to adjust solution pH to 8.0 ± 0.02, 8.50 ± 0.02, 9.00 ± 0.02, 9.50 ± 0.02, or 10.0 ± 0.02, individually. The samples were stirrer at 600 rpm at room temperature. 4.0 mL sample solution from each reactor was taken and filtered with 0.2 μm membrane for analysis. The precipitated solids were collected and then dried at 55 °C for 24 h. The solid samples were stored in a dry cabinet for analysis.

2.4. Other measurements

The concentrations of PO_4^{3-}-P and NH_4^+-N in solution were determined according to Standard Methods (APHA, 1998; Chen et al., 1997). The electrical conductivity in mixed liquor was measured by IDS sensors (WTW, NY, USA). Total organic carbon (TOC) content was determined using a TOC analyzer (OI Analytical, College Station, Texas, USA). The total suspended solid and volatile suspended solids (VSS) were measured based on Standard Methods