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Electricity generation and *in situ* phosphate recovery from enhanced biological phosphorus removal sludge by electrodialysis membrane bioreactor

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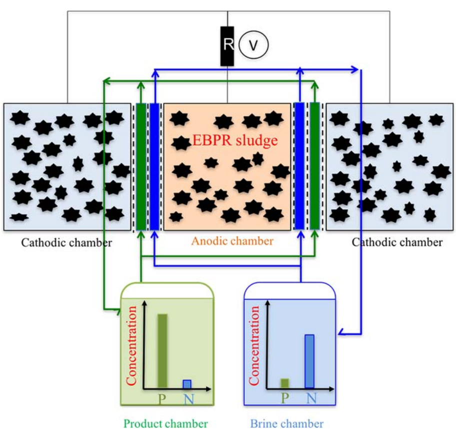
GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a novel electrodialysis membrane bioreactor was used for EBPR sludge treatment for energy and phosphorus resource recovery simultaneously. After 30 days stable voltage outputting, the maximum power density reached 0.32 W/m^3. Over 90% of phosphorus in EBPR sludge was released while about 50% of phosphorus was concentrated to 4 mmol/L as relatively pure phosphate solution. Nitrogen could be removed from EBPR sludge by desalination and denitrification processes. This study provides an optimized way treating sludge for energy production and *in situ* phosphorus recovery.

1. Introduction

Phosphorus is non-renewable nature resource and there is a fact that the reserving phosphorus is depleting, and the remaining phosphorus rock is of lower grade and more difficult to access than ever before (Cordell et al., 2009; Elser and Bennett, 2011). At the same time, there is a large quantity of phosphorus in wastewater, and it will cause eutrophication if excess phosphorus is poured out to environment water body without phosphorus removal (Neyens and Baeyens, 2003). Thus, the removal and recovery of phosphorus from wastewater has the benefits of not only minimizing pollution risk to receiving water but also contributing to sustainable resource management.

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Biological phosphorus removal is widely used in wastewater treatment plant (WWTP) for the removal of phosphate, especially enhanced biological phosphorus removal (EBPR) process. EBPR process is effective for phosphate removing, especially for low concentration phosphate wastewater. Phosphate accumulation organisms can uptake much more phosphate at the end of aerobic stage than release it at anaerobic stage, which mean EBPR could effectively remove phosphorus (Mino et al., 1998). By discharging the phosphorus-rich EBPR sludge at the end of aerobic stage, phosphate was removed from wastewater. Phosphorus content in the discharged EBPR sludge could be as high as 5–7% (Wang et al., 2013a). There was no maturely specific way for EBPR sludge management now. If EBPR sludge is treated in traditional way to dehydrate sludge as a soil amendment or to dispose it in a landfill, high content of phosphorus in EBPR sludge may release to environment water body again, which should be avoided. Alternatively, phosphorus-rich EBPR sludge could be regarded as a kind of phosphorus resource. To achieve maximum phosphorus recovery, pre-treatment of sludge should be used to release phosphorus from solid fraction intracellular (Wang et al., 2016a; Kataki et al., 2016). Separation of phosphorus from bio-solids requires conversion of organic phosphorus to inorganic phosphate (Rittman et al., 2011).

Microbial fuel cells (MFC) use microorganisms as catalysts to convert chemical energy of biomass into electricity directly (Logan et al., 2006; Bullen et al., 2006; Davis and Higson, 2007). Sewage sludge or waste activated sludge, as a kind of biomass, can also be used as substrate of MFC for electricity generation (Zhang et al., 2011; Chen et al., 2013; Abourached et al., 2014). Also, pre-treatment of sewage sludge by ultrasound, sterilization, etc. were used to enhance sludge degradation and chemical oxygen demand (COD) removal (Jiang et al., 2011; Xiao et al., 2011; More and Ghangrekar, 2010). The performance of MFC can also be enhanced by controlling methanogenesis (Rajesh et al., 2015). However, phosphorus could not be removed by MFC due to that it did not be involved in the reduction-oxidation reaction for electron transfer in MFC (Kelly and He, 2014). Thus few articles focused on phosphorus recovery from sewage sludge using MFC. Almatouq and Babatunde (2016) recovered phosphate exclusively by adding enough magnesium and ammonium for struvite generation. Other ways, like precipitation, adsorption, electrodialysis (Huang et al., 2015; Okano et al., 2013; Zhang et al., 2013), might be promising phosphorus recovery in sewage sludge exclusively after treatment in MFC.

Electrodialysis membrane bioreactor (EDMBR) is a novel reactor, which had been demonstrated successfully for electricity generation and *in situ* phosphate recovery by using urine as substrate (Wang et al., 2017). EBPR sludge is rich in organics and phosphorus, and traditional treatment of EBPR sludge by landfill or incineration was environmentally unfriendly and costly, it might be suitable for electricity generation and phosphorus recovery. But there are still some challenges to use EBPR sludge as substrate and phosphorus resource in EDMBR. First, organics in EBPR sludge was in the form of macromolecular which was difficult to be used directly by electricigens to maintain high and stable electricity generation. Secondly, phosphorus in EBPR sludge was mainly presence intercellular in the form of organic phosphorus and polyphosphate, which could not be easily recovered. So, before using EDMBR process to recover resources from EBPR sludge, all these challenges should be overcome.

Thus, the aim of this work was to recover phosphate from phosphorus-rich EBPR sludge using EDMBR system. Electricity generation by using EBPR sludge as substrate is evaluated, and *in situ* phosphate accumulation and recovery performance were investigated. Also, mechanisms of phosphate and nitrogen removal in EDMBR were explored. This study provides a specific method for phosphorus-rich EBPR sludge treatment together with phosphorus resource recovery, which could be in favor of remitting the crisis of energy and phosphorus.

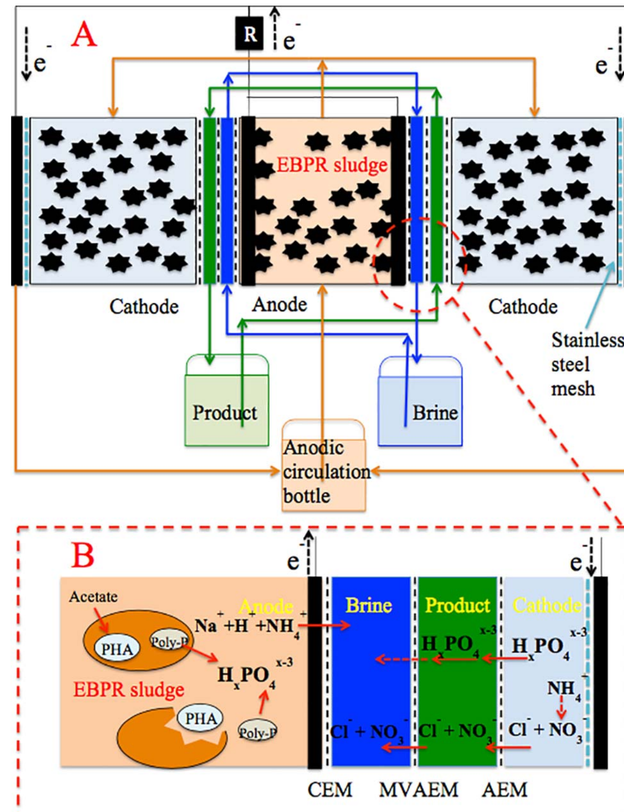

Fig. 1. Construction of EDMBR (A), and mitigation of phosphate in different chambers (B).

2. Materials and methods

2.1. EBPR sludge

The phosphorus-rich EBPR sludge was collected from a laboratory scale EBPR reactor. The reactor was operated at controlled room temperature (20 ± 2 °C) with a cycle time of 6 h, consisting of a 130-min anaerobic period, 160-min aerobic period followed by 60-min settling and 10-min decant. During the aerobic period, air was provided by an aerator using an on/off control system to keep the dissolved oxygen level at between 1.5 and 2.5 mg/L, and sludge was collected at the end of aerobic phase (Xia et al., 2014). The collected sludge was then concentrated by gravity, stored in refrigerator at 4 °C, analyzed and used within 1 week.

2.2. EDMBR reactor construction and operation

The structure of reactor used in this article had been described in our previous work (Wang et al., 2017). For better understanding of the structure, schematic diagram of the reactor was shown in Fig. 1A. In brief, the main body of the reactor was constructed by three cubic plexiglass blocks, which was filled with granular graphite (3–5 mm diameter Sanye Carbon Co., China). The middle one was used as anodic chamber while the stride two were used as cathodic chambers. Anode and cathode were connected by titanium wires. And a 1000 Ω resistance was used as load. Two ion exchange membranes (IEM) stacks were sandwiched by three blocks. IEM stacks composed of 3 ion exchange membranes, namely cation exchange membrane (CEM), monovalent selective anion exchange membrane (MVAEM) and anion exchange membrane (AEM) (NEOSEPTA CMX, AMX and ACS, respectively; ASTOM Co., Japan). Chambers between AEM and MVAEM were named as product chamber while chambers between MVAEM and CEM were named as brine chamber. Two coupons of carbon felts (3 mm