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An integrated membrane bioreactor system with iron-dosing and side-stream co-fermentation for enhanced nutrient removal and recovery: System performance and microbial community analysis

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ABSTRACT

An integrated membrane bioreactor (MBR) system was developed for enhanced nutrient (N and P) removal and effective P recovery in wastewater treatment. The system consisted of an iron-dosing MBR and side-stream fermentation for P removal and recovery and side-stream denitrification for N removal. Around 98.1% of the total phosphorus (TP) in wastewater was removed by ferric iron-induced precipitation and membrane filtration in the aerobic MBR, and nearly 53.4% of the TP could be recovered via anaerobic fermentation from the MBR sludge. In addition, the fermenter that allowed acidogenic co-fermentation with food waste provided sufficient soluble organics for biological denitrification, and an overall 91.8% total N removal was achieved through the side-stream denitrification. High-throughput sequencing was applied to analyse the microbial communities in the integrated system, and important functional bacteria were identified for nitrification, denitrification, acidogenic fermentation and dissimilatory iron reduction through the different components of the system.

1. Introduction

Membrane bioreactor (MBR) systems can be used for high-performance wastewater treatment and have thus been increasingly applied in recent years. Due to membrane filtration and a high level of biomass concentration retained in the MBR with a long sludge retention time (SRT), removal of organic pollutants can be reliably achieved (Judd, 2010; Li et al., 2018). However, the conventional aerobic MBR system is known for its low nutrient removal capabilities (Fleischer et al., 2005). As phosphorus (P) and nitrogen (N) in wastewater mainly exist as soluble phosphate and ammonia, it is difficult to remove these nutrient pollutants by simple biological degradation and solid-liquid separation. Therefore, it is necessary to improve MBR systems with effective chemical and biological methods for enhanced N and P removal in wastewater treatment.

Many studies have combined MBR with the chemical phosphorus removal (CPR) process to achieve reliable and efficient P removal from wastewater (Donnert and Salecker, 1999; Li et al., 2018). With the addition of metal salts such as $FeCl_3$ and $AlCl_3$, MBR can decrease the effluent TP concentration to lower than 0.5 mg/L (Zhang et al., 2015). Moreover, chemical precipitation offers further possibilities for recovering valuable P resources from P-rich sludge (Wilfert et al., 2015). Wet chemical P dissolution by strong acidic or alkaline treatment has been applied to extract P from sludge with P precipitates (Petzet et al., 2012); however, effective methods of P recovery from P-rich sludge still need to be developed for MBR systems.

N removal is usually achieved by two biological steps, nitrification and denitrification, which refer respectively to the oxidation of ammonia to nitrate under an aerobic condition and the reduction of nitrate to nitrogen gas under the anoxic condition. Many studies introduce an anoxic unit into MBR systems for enhanced N removal. There are two main types: pre-denitrification (A/O) and post-denitrification (O/A) (Metcalf, 2003). The A/O process utilises organic carbon in the influent to denitrify nitrate in the recirculated aerobic effluent. The N removal performance of the A/O configuration depends greatly on the recirculation ratio and the available organic carbon content in the influent (Yuan et al., 2002). However, the decreasing C/N ratio in municipal wastewater in recent years has significantly impacted N removal performance (Sun et al., 2010). The O/A process adds an anoxic unit after the aerobic unit and uses external carbon sources, such as volatile fatty acids (VFAs) and methanol, for denitrification. Post-denitrification is more stable than A/O due to the addition of a sufficient carbon source. Problems with post-denitrification include the need for an external carbon source and the possibility of a high organic concentration

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in the final effluent in the case of organic overdosing after the aerobic MBR (Acharya et al., 2006). There is still a need of new N removal strategies for the MBR in connection with the P removal and recovery process.

In this study, an innovative wastewater treatment system was developed to integrate MBR with CPR and side-stream co-fermentation and denitrification for enhanced N removal together with P recovery. The side-stream fermentation process utilised food waste as an additional carbon source to produce VFAs and facilitate P release and recovery. The side-stream denitrification process utilised the VFAs from the fermentation process to N removal. Use of the fermented effluent from sewage sludge and food waste as the external carbon source provides a more sustainable and economical approach for N removal than using methanol and commercial VFAs (Guo et al., 2015; Kim et al., 2016). During the experimental study, the performance of the integrated system for advanced wastewater treatment was evaluated. The microbial communities were also analysed by high-throughput sequencing to investigate the changes in the microbial population structure and functional microbial groups involved in the iron-dosing aerobic MBR, acidogenic fermentation and denitrification processes.

2. Materials and methods

2.1. Integrated MBR system for enhanced N and P removal

The integrated wastewater treatment system included an aerobic MBR, anaerobic fermenters and an anoxic reactor (Fig. 1) for enhanced N and P removal and P recovery. Different from the A/O and O/A configurations, the fermenters and anoxic reactor were connected in side streams to the aerobic MBR. The main-stream process was an iron-dosing aerobic MBR for municipal wastewater treatment with enhanced P removal. Raw wastewater was collected from Stanley Sewage Treatment Works (STW) in Hong Kong for the experimental study. The wastewater influent was dosed with $FeCl_3$ (20 mg-Fe/L) and pumped (Master FLEX, Cole-Parmer) into the aerobic MBR tank without sedimentation. The $FeCl_3$ was determined to achieve an overall P removal efficiency of 95% based on the previous experimental results (Li et al., 2018). A flat-plate ceramic membrane module (0.0384 m^2, Meidensha) with an average pore size of 100 nm was submerged vertically in the aerobic bioreactor. The aeration was provided through air diffusors at the bottom of the MBR. The seed sludge was collected from the Stanley STW, and the mixed-liquor suspended solids (MLSS) concentration was kept at around 4–5 g/L in the MBR suspension. The effluent was withdrawn through the ceramic membrane in intermittent filtration mode, with 9 min on and 1 min off in each cycle, corresponding to an overall flux of 17.4 L/h-m^2 (LHM) and a hydraulic retention time (HRT) of 12 h. The trans-membrane pressure (TMP) was continuously recorded during the MBR operation.

Activated sludge from the MBR was circulated through the anaerobic reactor in the side stream for fermentation and P extraction and recovery. Two fermenters were used to receive the sludge mixture on alternative days, resulting in a 48-h fermentation period. Every day, 20% of the sludge suspension was withdrawn from the aerobic MBR and added to a fermenter. To facilitate sludge fermentation, food waste was mixed into the sludge for co-fermentation, and cooked rice as a model food waste was added. Together with the 1.6 L MBR sludge, 160 mL seed sludge and 3.3 g cooked rice in a slurry (i.e., 2.0 g-COD/L or ~1.05 g-COD/g-SS/d) were placed in the fermenter. During the 2-d fermentation at room temperature (~25 °C), sludge underwent acidogenesis together with reduction of Fe(III) to Fe(II), leading to the production of VFAs and release of PO_4^{3-}-P into the supernatant. After fermentation, 1.6 L sludge suspension was withdrawn, and the residual 160 mL sludge mixture was left as seed sludge in the fermenter. Following sedimentation, 1.0 L supernatant was collected for subsequent P recovery and denitrification. Of the settled sludge, 500 mL was returned to the MBR tank and 100 mL was discharged, which resulted in an SRT of about 30 d in the aerobic MBR. In the precipitation tank, the sludge liquor was adjusted to pH 8 by adding 2 M NaOH, and P-precipitates were readily formed and separated. The supernatant was then pumped into the anoxic reactor for denitrification and N removal.

The sludge suspension from the MBR was continuously circulated by pumping (Master FLEX, Cole-Parmer) at a predetermined rate through the anoxic reactor for biological denitrification. The VFA-rich sludge liquor from the precipitation tank was also pumped into the anoxic tank at a flowrate of 1 L/d to supply the organic carbon source for biological denitrification. The integrated system was continuously operated to treat raw sewage collected from Stanley STW at room temperature (25 °C) for over 90 d, and the typical system and operating conditions are summarised in Table 1. After start up, the experiment was carried out in three phases. In Phase I, the aerobic MBR was first operated and stabilised for wastewater treatment without iron dosing for 20 d. In Phase II, $FeCl_3$ coagulant was added at 20 mg-Fe/L in the wastewater influent into the MBR, and the fermenters and anoxic tank were connected to the MBR and operated in the side stream, as shown in Fig. 1.

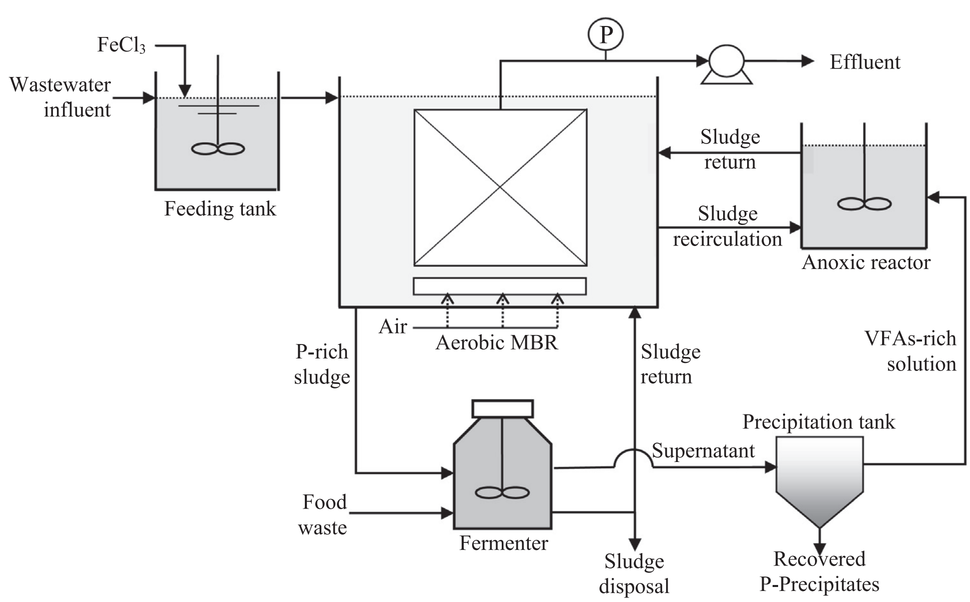

Fig. 1. Schematics of the integrated MBR system with side-stream fermentation and denitrification for enhanced nutrient removal.