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Nitrogen and phosphorus removal from tertiary wastewater in an osmotic membrane photobioreactor

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HIGHLIGHTS

- Osmotic membrane photobioreactor (OMPBR) used for tertiary wastewater treatment.
- Excellent N and P removal through microalgal assimilation and membrane rejection.
- Removal efficiencies of 93% NH_4^+-N, 53% NO_3^--N and 89% PO_4^{3-}-P at 3 days HRT.
- High biomass accumulation (>5 g/L) in OMPBR and changes in biomass composition.
- OMPBR operation sustained for 162 days through periodic backwashing.

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ABSTRACT

An osmotic membrane photobioreactor (OMPBR) was designed and operated for 162 days for nitrogen and phosphorus removal from wastewater using *Chlorella vulgaris*. The removal efficiency for NH_4^+-N, NO_3^--N and PO_4^{3-}-P reached as high as 95%, 53% and 89%, whereas the maximum removal rates were 3.41 mg/L-day, 0.20 mg/L-day and 0.8 mg/L-day, respectively. The microalgae exhibited high tendency to aggregate and attached to the bioreactor and membrane surfaces, and total biomass accumulation in the OMPBR was over 5 g/L. Salt accumulation and biofouling had adverse effects on membrane filtration, but the performance could be recovered through periodic backwashing of the membranes. Extracellular polymeric substances characterization indicated higher fraction of polysaccharides as compared to proteins. The biomass in the OMPBR accumulated higher levels of carbohydrates and chlorophyll. These results indicate the suitability of OMPBR in wastewater treatment and in high-density microalgae cultivation.

1. Introduction

One of the many consequences of rapid industrialization and urbanization has been the generation and discharge of large volumes of wastewater from municipal, industrial and agricultural sources. While the presence of aromatics and heavy metals in wastewater have adverse effects on the environment and living beings (Praveen et al., 2015), the presence of excessive amounts of innocuous nutrients, such as nitrogen (N) and phosphorus (P), can also upset the balance of aquatic ecosystem through eutrophication (Cai et al., 2013). Eutrophication is a process of rapid plant/algae growth in natural water bodies due to nutrient overloading; this leads to oxygen depletion resulting in deterioration of water quality and endangering of aquatic life (Ruiz et al., 2014).

Conventional techniques for N and P removal from wastewater are based on physical and chemical methods. These techniques are not economical and do not facilitate nutrients recycle and reuse (Shi et al., 2014). Since algal bloom is one of the natural consequences of eutrophication, one approach to remove N and P from wastewater is through bioremediation using autotrophic microalgae. Microalgae exhibit high N and P uptake rates (Wang et al., 2014), and the nutrients can be recovered as microalgal biomass, which is a coveted feedstock for the production of a variety of useful chemicals including biofuels (Guo et al., 2015). The use of microalgae in wastewater treatment also prevents any sludge handling problems, and generates oxygenated effluents. In addition, this process also has the potential for concomitant wastewater treatment and carbon capture, as flue gases from industries can be used for photosynthesis (Pires et al., 2012).

The use of microalgae in wastewater treatment, especially in N and P removal, has been widely investigated in the last few years.

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Batch and fed-batch studies have been performed with *Nannochloropsis*, *Scenedesmus* and *Chlorella* species demonstrating excellent removal performance (Ji et al., 2013; Kim et al., 2013; Shi et al., 2014; Sulzacova et al., 2015; Xu et al., 2014). Some studies have also been performed in continuous mode using membrane bioreactors (MBR) (Low et al., 2014; Singh and Thomas, 2012). Due to the independence of hydraulic retention time (HRT) from sludge retention time (SRT), MBRs mitigate the risk of biomass washout and allow bioreactor operation at low HRTs. The MBRs also have the advantages of relatively smaller footprint, process flexibility and high volumetric loadings (Huang and Lee, 2015).

While conventional MBRs, based on microfiltration or ultrafiltration, exhibit high biomass retention and large removal rates, the removal of pollutants in these bioreactors is mainly through microbial assimilation. Membrane filtration in these MBRs plays little role in enhancing effluent quality, especially when the pollutants are of small size, such as N and P salts. Recently, osmotic membrane bioreactors (OMBR) have emerged as an alternative to conventional MBRs. The OMBRs are based on forward osmosis (FO), wherein water flows across a selectively permeable membrane under an osmotic pressure gradient (Praveen et al., 2015). While the low pore size of the FO membranes imparts them high solute rejection properties, the absence of any hydraulic pressure makes FO energy-efficient and less susceptible to membrane fouling (Achilli et al., 2009). Consequently, OMBRs combine microbial metabolic potential and membrane rejection to generate high quality effluent.

The superior performance of OMBRs has been demonstrated in several studies (Achilli et al., 2009; Huang and Lee, 2015; Praveen and Loh, 2016). However, these studies were based on the use of activated sludge or other bacteria. To the best of our knowledge, the OMBRs have never been used in microalgae cultivation, and all FO application in microalgae research has been focused on dewatering of microalgae suspension. In this research, the objective was to design and operate an osmotic membrane photobioreactor (OMPBR) for continuous removal of N and P from wastewater using autotrophic microalgae. The OMPBR performance and biomass accumulation trends have been observed for over five months at different operating conditions. Membrane biofouling by the microalgae has been investigated and changes in the microalgal biomass composition have been examined.

2. Methods

2.1. Microorganisms, culture conditions, and chemicals

All the chemicals used in this research were of analytical grade and purchased either from Sigma–Aldrich (St. Louis, United States) or Merck (Darmstadt, Germany). A 5 M stock solution of sodium chloride was prepared and the stock was diluted to be used as the draw solution (DS) during osmotic filtration.

Chlorella vulgaris ATCC 13482 was used throughout this study. The microalgae were cultivated in Bold's Basal Medium (BBM) supplemented with 5% CO_2 enriched air at a rate of 0.2 gas volumes per reactor volume per minute (VVM), and provided with 2000 lux light intensity (control experiment). All media, pipette tips, and Erlenmeyer flasks fitted with cotton plugs were autoclaved before use. Activated cells in late exponential growth phase were used as inoculum for all the experiments.

2.2. OMPBR

2.2.1. Experimental setup

Fig. 1 shows the laboratory scale OMPBR setup. The bioreactor tank (20 cm length × 12.5 cm width × 21 cm height) had an effective volume of 5.5 L. A plate-and-frame membrane module was prepared using commercial thin film composite (TFC) FO membranes (HTI, USA) and the module was immersed in the bioreactor tank for osmotic filtration. Two pieces of membranes (15 cm length × 12 cm width) were used in the module, resulting in an effective filtration area of 0.036 m^2. The membrane module was designed in such a way that the active layer of the TFC membranes faced the wastewater, whereas the support layer faced the DS. A continuous stream of humidified 5% CO_2-enriched air was sparged in the OMPBR at the rate of 0.4 VVM to provide inorganic carbon to the microalgae. The OMPBR was illuminated from all four sides and the top using fluorescent lights of 1000–1500 lux intensity. A 2 L beaker designed with an overflow outlet at 1.5 L was used as the DS reservoir. The beaker was stirrer on a magnetic stirrer and the DS was recirculated in the membrane module using a peristaltic pump (Masterflex, USA). DS concentration in the reservoir was kept constant using a feedback control system (eChem, Singapore) based on conductivity measurements, and any dilution of the DS was compensated through pumping of concentrated DS stock

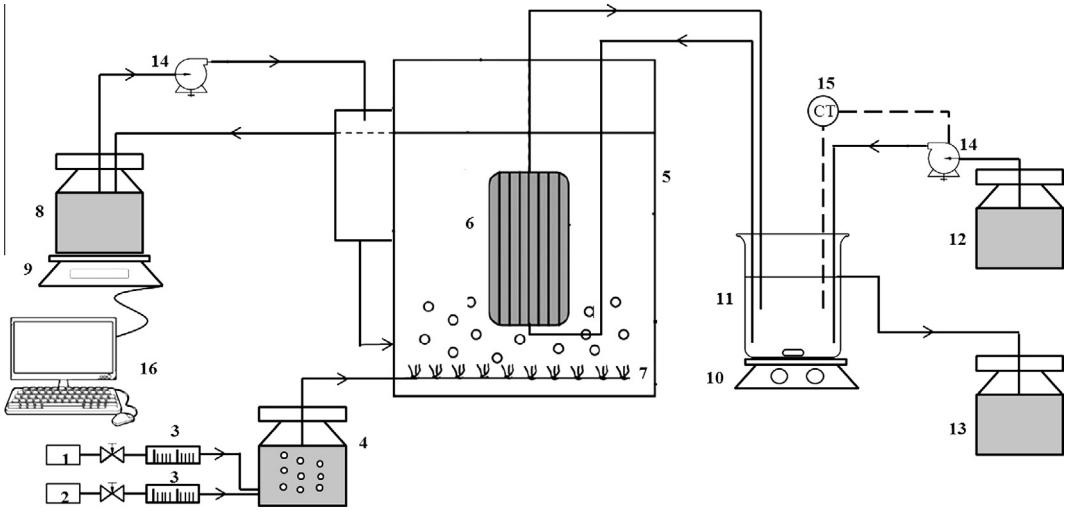

Fig. 1. Schematic diagram of the OMPBR setup: (1) compressed air; (2) compressed CO_2; (3) flow meter; (4) humidification tank; (5) MBR tank; (6) membrane module; (7) air diffuser; (8) feed tank; (9) weighing scale; (10) stirring plate; (11) DS; (12) concentrated DS stock; (13) effluent; (14) peristaltic pump; (15) conductivity meter, and; (16) data logger.