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Insights into the operational characteristics of a multi-habitat membrane bioreactor: Internal variation and membrane fouling

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ABSTRACT

This work investigated the operational characteristics of a multi-habitat membrane bioreactor to reveal its internal variation and membrane fouling. During the 100d operating period, a combined anaerobic and aerobic zone gradually formed in a single membrane bioreactor. In the anaerobic zone, DO decreased to nearly zero, while in the aerobic zone, DO value still remained at above 3.1 mg/L, which created beneficial conditions for the removal of nitrogen (TN removal = 87.1%) and phosphorus (TP removal = 90.2%), although the phosphorus removal efficiency decreased in the later stage of operation (TP removal = 44.6%). The increase of torque in the bioreactor accorded with the Boltzmann model (r^2 = 0.97891), and the growth trend between torque and apparent viscosity of the fluid was highly consistent, which implied that an on-line torque approach may play an important role in the timely detection of rheological information about the mixed liquor suspended solids. As operational time increased, the size of sludge particles in the aeration zone tended to decrease, and the permanent membrane resistance gradually increased. These relationships revealed the reason for accelerated membrane fouling. Scanning electron microscopy revealed that the membrane fouling was mainly caused by a compact fouling layer that formed on the surface of membrane module.

1. Introduction

In the past decade, membrane bioreactor (MBR) process has aroused intense and extensive scholarly interests in the fields of industrial, municipal wastewater treatment and ground water purification [1–7]. The dominant merit of an MBR is the complete retention of biomass by membrane modules, which enables the control of sludge retention time (SRT) independently from hydraulic retention time (HRT), and makes it possible to operate the bioreactor at very high microbial biomass and to produce high-quality effluent for reuse [8]. Compared to a conventional activated sludge (CAS) process, the biomass concentration accumulated in an MBR may be about 10 times higher than that in conventional wastewater treatment plants (WWTP) [9]. At such a biomass concentration, the fluid within the reactor exhibits rather obvious non-Newtonian properties, which heavily influence the transfer of mass and momentum, fluid flow, energy consumption, and bioreactor performance. A "bottleneck" that still limits the successful operation of an MBR is the fouling of membrane modules [10–12], which has a close relationship with the biomass characteristics [13–15]. Therefore, a full understanding of the internal mechanism of an MBR during its operational period is especially important [16–19].

Recently, a hybrid MBR system, comprised of sequential or alternating anoxic–oxic (A/O) zones, has been operated very successfully [13,20–25]. In this system, biodiversity and activity of the sludge is supported by diverse environmental conditions, resulting in effective degradation of complex organic pollutants [26] and removal of nutrients. Many studies [27–29] have verified the importance of multi-environment conditions in supporting the biodiversity and dynamic performance of the biomass, whether in a natural ecosystem or an artificial bioreactor. For this reason, in our previous study, a multi-habitat MBR (MHMBR) was successfully established [30]. Interestingly, with the proliferation of biomass, an obvious difference in dissolved oxygen (DO) concentration gradually emerged in different zones of the bioreactor, which markedly improved the biodiversity of the system.

Previous investigations have proved that concentration and bioactivity are the two most important aspects of the biomass in a bioreactor [31]. From an ecological viewpoint, each bioreactor may be regarded as an artificial ecosystem [32], which needs a constant input and output of mass and energy. Due to the fact that an MBR is generally operated at a high concentration of biomass, effective operation is particularly dependent on the rapid mass transfer of nutrients, DO, and metabolites. However, to a large extent, the success and operating efficiency of the system are determined by

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Table 1
Operating conditions.

Parameter	Value	Parameter	Value
Operating time (d)	100	HRT (h)	3.6
Temperature (°C)[a]	26.5 (23.1–32.0)	SRT (d)	100
pH[a]	7.5 (7.1–8.0)	Flux (LMH, L/m^2 h)	21.7
Aeration rate (L/min)	1.0	Rotate speed (rmp)	65

[a] Numbers are means (minimum and maximum values).

the effectiveness of transfer processes within the MBR. Therefore, the internal hydrodynamic properties of the bioreactor are imperative factors that must be fully understood [19,33]. In this regard, accurate and timely understanding of the internal hydrodynamic properties is essential for optimizing and monitoring the operation of a bioreactor.

The conventional approach used to detect the characteristics of activated sludge is generally based on sequential sampling, namely, sampling sludge from a bioreactor and measuring its characteristics according to a pre-set schedule. This is an *off-line* approach, and although information can be obtained, the data are discrete. However, the proliferation of biomass in an MBR is a continuous process that is highly time-dependent. Thus, it is of prime importance to obtain timely information on the characteristics of the activated sludge within the reactor. An *on-line* method of data collection could retrieve timely data for the convenience of controlling and monitoring the operation of the bioreactor. Seyssiecq et al. [34] have emphasized the importance of adopting an *in-situ* measurement technique to characterize the complex rheological properties of the sludge suspensions in a bioreactor, and they successfully established such an *on-line* torque-based method to detect the triphasic flow properties of the sludge suspensions in an aerated bioreactor. Other reports [35–39] also verified the useful applications of *on-line* torque measurement in sludge conditioning and dewatering, anaerobic digestion, and solid-liquid mixing.

To the best of our knowledge, the formation of a multi-habitat ecosystem in a single MBR is a field of research with few studies, and there is very little information available with which to understand the timely operational status of an MBR. On the basis of the above analyses, insights into the operational characteristics of the MHMBR are very necessary. Thus, our investigation mainly focused on a detailed analysis of the operational characteristics of a MHMBR from start-up to steady state, including the MBR operation, the relationship between viscosity and *on-line* torque, and membrane fouling. In the experiments, a combined anaerobic-aerobic MBR was designed with an *on-line* torque sensor, the operational characteristics were tested by considering the parameters as HRT (3.6 h), SRT (100 d), aeration rate (1.0 L/min), flux (21.7 L/m^2 h), MLSS, and pollutants removal et al. We hope the presented results will provide a useful reference in monitoring and optimizing the performance of this kind of MBR.

2. Materials and methods

2.1. Experimental process

The experimental details, including the bioreactor configuration, inoculation and operating conditions of the MHMBR, were all given in Fig. 1 and Table 1, and they are exactly the same with our previous investigation [30]. The bioreactor was operated under the previously stated conditions for 100 d without discharging any excess sludge, except for small amounts (100 mL) removed by sampling for analysis. The daily concentration of MLSS was determined by averaging the values obtained simultaneously from both the "O" and the "A" zones each day. The DO concentrations in both the "A" and the "O" zones were measured automatically by two DO probes. The performance of the MHMBR was evaluated by using several conventional indexes of water quality, including COD_{Cr}, NH_4^+-N, NO_2^--N, NO_3^--N, TN and TP. For the convenience of comparison, the concentrations of COD_{Cr}, NH_4^+-N, and TP in the influents were adjusted to 600 mg/L, 30 mg/L, and 6 mg/L, respectively, on the 47th day of operation; similarly, the influent concentrations of these three parameters were adjusted to 800 mg/L, 40 mg/L, and 8 mg/L, respectively, at the 67th day according to the proliferation of the biomass, respectively. Other nutrients included: 160 mg/L of $NaHCO_3$, 132 mg/L of $MgSO_4$, 12 mg/L of $MnSO_4{\cdot}H_2O$, 8 mg/L of $CaCl_2$, and 0.6 mg/L of $FeSO_4{\cdot}7H_2O$.

2.2. Analytical methods

A variety of parameters including chemical oxygen demand (COD_{Cr}), ammonium nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N), nitrate nitrogen (NO_3^--N), total nitrogen (TN), total phosphorus (TP) and mixed liquor suspended solids (MLSS) were measured according to the standard method [40]. Dissolved oxygen (DO) was automatically measured every 10 s by two DO detectors (JPSJ-605F, INESA, China) installed in the oxic ("O") and the anoxic-anaerobic ("A") zones, respectively. Data were stored by the connected computer for subsequent analysis. The pH was measured by a pH meter (pH2-S, INESA, China).

2.3. Measurement of apparent viscosity and torque

The viscosity of MLSS in the experimental bioreactor was measured with a rotary viscosity meter (NDJ-5S, CHANGJI, China) by sampling the biomass at the same position within the bioreactor at the same time of each day. For the non-Newtonian characteristics of the biomass in the bioreactor, only the apparent viscosity could be obtained. All the torque data were automatically measured every 0.2 s by a torque sensor (NJ-5N, Taide, China) connected with a stirrer mounted vertically in the "A" zone. The obtained torque data were all automatically stored and processed by a computer.

2.4. Analysis of the membrane fouling

Since the exact contribution to the membrane fouling of each individual factor is not fully understood, a commonly-used indirect approach proposed by Patsios [14], was adopted in our experiments to evaluate the degree of membrane fouling. Accordingly, the total fouling resistance (R_t) was comprised of initial membrane resistance (R_m), reversible resistance (R_r), irreversible fouling resistance (R_{ir}), and irrecoverable or permanent resistance (R_p). Each component of resistance was classified based on how its effect could be negated. Thus, R_m referred to the resistance that was the characteristic of the membrane module itself, R_r was resistance that could be eliminated by physical cleaning, R_{ir} was resistance that could be removed only by chemical cleaning, and R_p was the resistance that could not be eliminated by any method, and ultimately determined the lifetime of the membrane module. In the experiments, transfer membrane pressure (TMP) was used to describe quantitatively the resistances caused by the membrane fouling [17,33]; therefore, TMP_t, TMP_m, TMP_r, TMP_{ir}, and TMP_p were the transfer membrane pressures that were surrogates for R_t, R_m, R_r, R_{ir}, and R_p, respectively.

To accurately evaluate the contribution of the above factors to membrane fouling [41], experiments were conducted at the conclusion of each running period using the following procedures. First, in each running period, the membrane module was not cleaned until the TMP reached approximately 30 kPa; thus, TMP_t was approximately 30 kPa. Second, TMP_m (a membrane-specific characteristic) was determined through a permeability experiment using clean water on new membrane modules at 10 L/m^2/h flux; Third, TMP_r