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Comparison of four enhancement strategies for aerobic granulation in sequencing batch reactors

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ABSTRACT

Aerobic granules were developed in four identical sequencing batch reactors (SBRs) with synthetic wastewater to compare different strategies for the enhancement of granulation. The SBRs were operated by (a) increasing organic loading rate in R1; (b) reducing settling time in R2; (c) extending starvation period in R3; and (d) increasing shear force in R4. The results showed that four operational strategies were able to enhance aerobic granulation successfully in SBR, but that also showed different effect on the granulation process and characteristics of mature aerobic granules. The rapidest granulation was observed by using short settling time (R2) and the granules had higher extracellular polymeric substance (EPS) than other reactors. Extended starvation period (R3) and high shear force (R4) resulted in longer granulation period and the granules with higher integrity and smaller size. Higher organic loading rate (R1) resulted in the granules with larger size and higher K value. The maximum specific COD removal rates (q_{max}) of the granules in all SBRs were at a similar level (0.13–0.16 g COD/h-g VSS) but the granules in R1 and R2 had higher apparent half rate constant (K) of 18 and 16 mg/L, than those in R3 and R4 (2.8 and 3.3 mg/L).

1. Introduction

Aerobic granulation technology is proposed as a new and promising alternative approach of activated sludge process [1,2]. Compared to flocculent sludge, aerobic granules have good settling ability, high biomass retention, ability to withstand high-strength wastewater and shock load, and simultaneous nitrification–denitrification [3–5]. These advantages indicate that aerobic granular technology has great potential for the treatment of various municipal and industrial wastewaters.

Aerobic granulation has been mainly achieved in SBR and strongly related to operating conditions, which should be favorable for microorganisms to form aggregates and/or granular particles [6]. To date, published results indicate that four operational factors have significant influence on granulation process in SBR, including (a) control of organic loading rate, (b) settling time, (c) starvation period, and (d) shear force by aeration [7–10]. Control of organic loading rate to certain levels could be favorable for granulation, and the rate could be adjusted between famine and feast status in substrate to provide a driving force for aggregation or granulation [5,11]. In SBR the settling time is likely to exert a selection pressure to control the biomass remained in reactor based on settling ability. Granulation can be enhanced by reducing settling time to select sludge with good settling ability and wash-out of light flocculent biomass [12,13]. It was reported that aerobic starvation selected microorganisms which secrete more extracellular polymeric substances (EPS), and a longer starvation period had a significant impact on hydrophobicity and zeta potential of biomass [14,15]. Increasing shear force caused by aeration has been tested to select heavy sludge particles, and high shear force has a positive effect on the production of polysaccharides which impact on aerobic granulation and stability of granules formed [16]. Other factors (e.g. divalent metal ions, dissolved oxygen (DO), substrate composition) than above four could also influence the granulation but may not be essential in general because some factors are wastewater-specific except for DO concentration [6,17]. Research results have proved that supplementation of Ca^{2+} and Mg^{2+} enhanced granulation and improved the settling property but aerobic granules can be formed in reactors without metal ions addition [18–20]. The impact of DO on aerobic granulation has been controversial. One research group reported that a high DO concentration enhanced granulation because even when a high shear force was supplied, aerobic granules were not formed at DO below 5 mg/L [21]. But Peng et al. reported that aerobic granules were formed at DO concentration as low as 0.7–1.0 mg/L in a SBR [22]. In addition, the granules

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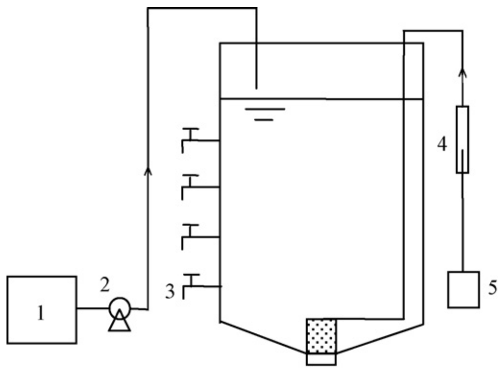

Fig. 1. The schematic diagram of SBR. (The operation procedure of four reactors was shown in Table 1.)

also could be cultivated with a wide variety of substrates including glucose, acetate, ethanol, phenol, and municipal wastewater [6].

A brief review of aerobic granulation showed that different operational strategies would lead to different characteristics of sludge, thereby affecting the performance of reactor and the cost of sludge treatment. However, to date, no research has been done to compare above four factors together to verify the extent of their influence on aerobic granulation. Thus, the purpose of this study was to find the better granulation-enhancement strategies leading to good granulation, and investigate the physical and chemical characteristics of the granules with different operational strategies. It is expected that the results derived from this study would be useful for the cultivation of aerobic granules in SBR.

2. Materials and methods

2.1. SBR system

Four identical SBRs with a working volume of 12 L were operated for aerobic granulation (Fig. 1). The temperature of the reactors was maintained at $24 \pm 1\,^{\circ}C$ using a temperature controller. The reactor pH was maintained at 7.3–7.8 during operation. Air was introduced through a diffuser at reactor bottom using an air pump. The upflow shear force was adjusted by changing air flow rate.

Synthetic wastewater prepared with tapwater was used in this study with glucose as a carbon source. The tapwater contained low concentrations of temporary hardness (5.7 mg/L as $CaCO_3$) and ammonium-N (0.52 mg/L). The chemicals added in the synthetic wastewater (per liter) were: NH_4Cl, 125 mg; $NaHCO_3$, 250 mg; and KH_2PO_4, 25 mg; trace element solution, 0.1 mL. The trace element solution contained (mg/L): $MgSO_4{\cdot}7H_2O$, 20; $FeCl_3$, 15; $CuSO_4$, 30; $MnSO_4{\cdot}H_2O$, 50; $CoCl_2{\cdot}6H_2O$, 50; KCl, 18; and $AlCl_3$, 15.

Activated sludge from an aeration tank of Wenchang Municipal Wastewater Treatment Plant, Harbin, China was used as inoculum. The activated sludge was aerated with air for 3 days and then inoculated to each SBR to achieve an initial concentration of approximately 3500 mg SS/L.

2.2. Operational strategy for granulation

The granulation process was investigated using four different strategies in each SBR. The reactors were operated for two sequential cycles and then maintained under resting condition till next day. The filling time (1 min) and discharging time (5 min) were the same for all reactors. The detailed operational strategies for individual SBR are described as below (Table 1).

Table 1
Operational conditions of four SBRs.

	Reactor			
	R1	R2	R3	R4
Influent COD (mg/L)	300–1000	500	500	500
COD load (g/(L-d))	0.45–1.5	0.75	0.75	0.75
Added Ca^{2+} (mg/L)	50	0	0	0
Settling time (min)	15	15 and then 1	15	15
Aeration time (min)	280	280	445	280
Total cycle time (min)	300	300	465	300
SRT (days)	15	Various	15	15
Air flow (m^3/h)	0.3	0.3	0.3	0.6

2.2.1. COD loading rate and Ca addition (R1)

The influent COD concentration of R1 was increased from 300 to 1000 mg/L over a 90-day period. In R1, Ca^{2+} (50 mg/L) was supplemented in order to enhance granulation [18,19].

2.2.2. Settling time (R2)

The settling time of R2 was 15 min at the beginning and then reduced gradually from 15 to 5 min from day 1 to day 11. Afterwards, the settling time was further shortened to 4 min on day 20, 3 min on day 28, and 2 min on day 37. The settling time was reduced to 1 min on day 45 and then maintained throughout remaining period.

2.2.3. Aerobic starvation (R3)

A long starvation time was considered to help aerobic granulation [14,15]. The total cycle time of 465 min was maintained in reactor R3 (1 min filling, 445 min aeration, 15 min settling, and 4 min discharging) and much longer than other SBR (about 300 min).

2.2.4. Shear force and DO (R4)

An air flow of 0.6 m^3/h (or an upflow velocity of 3.9 cm/s) was used in R4 and was 2 times of that in other SBRs. The DO concentration in R4 was above 5.0 mg/L and was higher than those (2.0–4.0 mg/L) in other reactors.

2.3. Analytical methods

Measurement of COD, ammonium-N, nitrate-N, nitrite-N, total phosphorus, suspended solids (SS), volatile solids (VS), and sludge volume index (SVI) were performed in accordance with Standard Methods for the Examination of Water and Wastewater [23]. The extraction of EPS from granules was performed using heating-centrifugation extraction method and the phenol-sulfuric acid method was used to quantify polysaccharides in EPS [24,25]. The concentration of protein in the extracted EPS was determined using the modified Lowry method [26]. The granule samples were taken for size distribution analysis which was conducted based on the dry weight of the granules passed through different sized wet sieves [20]. The settling velocity of sludge was measured as reported by Zheng et al. [27]. The integrity coefficient (%) was measured based on the ratio of the weight of residual granules after shaking at 300 rpm for 5 min on a platform shaker versus the weight of test sample [28].