

**Effect of algae growth on aerobic granulation and nutrients removal from  
synthetic wastewater by using sequencing batch reactors**

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## **Abstract**

The effect of algae growth on aerobic granulation and nutrients removal was studied in two identical sequencing batch reactors (SBRs). Sunlight exposure promoted the growth of algae in the SBR (Rs), forming an algal-bacterial symbiosis in aerobic granules. Compared to the control SBR (Rc), Rs had a slower granulation process with granules of loose structure and smaller particle size. Moreover, the specific oxygen uptake rate was significantly decreased for the granules from Rs with secretion of 25.7% and 22.5% less proteins and polysaccharides respectively in the extracellular polymeric substances. Although little impact was observed on chemical oxygen demand (COD) removal, algal-bacterial symbiosis deteriorated N and P removals, about 40.7-45.4% of total N and 44% of total P in Rs in contrast to 52.9-58.3% of TN and 90% of TP in Rc, respectively. In addition, the growth of algae altered the microbial community in Rs, especially unfavorable for Nitrospiraceae and Nitrosomonadaceae.

**Keywords:** Aerobic granules; Sunlight; Algae; Nitrification; Phosphorus removal

1

## 2 **1. Introduction**

3       Twenty years ago aerobic granular sludge was first reported by Mishima and  
4 Nakamura (1991) in a continuous upflow aerobic sludge blanket bioreactor. Up to  
5 now much effort has been put on this promising biotechnology which possesses many  
6 incomparable advantages like excellent settleability, high biomass and ability to  
7 withstand toxicity and organic loading (Adav et al., 2008a; Huang et al., 2014) in  
8 comparison to conventional activated sludge processes. So far, research works on  
9 aerobic granular sludge are mainly focused on pollutants removal efficiency and  
10 granulation mechanism in lab-scale sequencing batch reactors (SBRs), from which the  
11 results can be utilized as guidance for its practical engineering applications (Lee et al.,  
12 2010; Maszenan et al., 2011). Moreover, aerobic granular sludge with good  
13 performance for pollutants removal has been successfully cultivated in pilot-scale  
14 SBRs (Ni et al., 2009; Long et al., 2014). Therefore, in the near future, it is expected  
15 that the aerobic granular sludge technology can be applied as one of major processing  
16 units in wastewater treatment plants.

17       On the other hand, natural water bodies worldwide have suffered for a long time  
18 from frequent algae blooms. Algae are also attracting researchers' attention in the field  
19 of wastewater treatment, partially because of their high capacity of nutrients uptake  
20 and oxygen production thus facilitating aeration in wastewater (Abdel-Raouf et al.,  
21 2012). Recently, the microalgal-bacterial symbiosis has been tested in ponds and  
22 photo-bioreactors, achieving cost-effective wastewater treatment (Boelee et al., 2014;

1 Marcilhac et al., 2014). De Godos et al. (2009) used a tubular biofilm-based  
2 photobioreactor to treat pretreated swine slurry, and found that the microalgal–  
3 bacterial symbiosis could achieve nitrogen (N), phosphorus (P) and chemical oxygen  
4 demand (COD) removal efficiencies up to 100%, 90% and 75%, respectively with no  
5 external O<sub>2</sub> supply. Still, some researchers pointed out that the microalgal-bacterial  
6 symbiosis had some impact on the metabolism and biodiversity of microorganisms.  
7 The activity of ammonia oxidizing bacteria (AOB) was decreased by 20% with the  
8 co-existence of algae due to algae were superior competitors for N uptake compared  
9 with AOB (Risgaard-Petersen et al., 2004). In addition, Su et al. (2012) found that the  
10 bacterial communities varied with different ratios of algae to sludge inoculation in the  
11 algal-bacterial system for wastewater treatment. Up to now, however, little  
12 information can be found in the literature about the effect of algae growth on aerobic  
13 granules.

14 This work aimed to investigate the effect of algae growth on aerobic granulation  
15 and nutrients (COD, N and P) removal. The influences of algae on COD, N and P  
16 removal performance, and bioactivity of aerobic granules were determined. The  
17 components of extracellular polymeric substances (EPS) in addition to the changes in  
18 microbial diversity of the granules were also analyzed in order to shed light on the  
19 mechanism involved in the influence of algae growth on the aerobic granules. It is  
20 expected that this work will be useful for the cultivation and application of aerobic  
21 granules in practice.

22

## **2. Materials and methods**

### ***2.1. Reactor set-up and operation strategy***

Aerobic granules were cultivated in two identical sequencing batch reactors (SBRs) made of acrylic transparent plastic, 6 cm in diameter with a height of 60 cm. The working volume of each SBR was 1.4 L. One of the two SBRs, Rs, was placed near the window in the laboratory and irradiated around 4 hours per day (from 9:00 to 13:00 due to the location of Rs) by natural sunlight from March to June, 2014. During the 100 days' operation, 61 days were sunny and the average visible light and UV-light intensity were 42 and 3 mW/cm<sup>2</sup>, respectively during the irradiation period. Another SBR (Rc), without sunlight irradiation, was used as control.

The two reactors, namely Rs and Rc, were operated sequentially in a 4-h cycle at room temperature (25 ± 2°C): 2 min of influent filling, 28 min of non-aeration period, 185-200 min of aeration, 5-20 min of settling, and 5 min of effluent discharge. The settling time was gradually decreased from 20 min to 5 min due to the increase in settleability of the sludge. The volumetric exchange ratio was kept at 50%, leading to a hydraulic retention time of 8 h. The airflow rate was 2.0 cm/s and controlled via a gas-flow controller to keep the dissolved oxygen (DO) level between 7-9 mg/L in each aeration cycle.

### ***2.2. Seed sludge and synthetic wastewater***

Each reactor was inoculated with 0.5 L of seed sludge sampled from a sedimentation tank of the Shimodate Sewage Treatment Plant, Ibaraki Prefecture,

1 Japan. On the sampling day the concentrations of chemical oxygen demand (COD),  
2 ammonia nitrogen ( $\text{NH}_4\text{-N}$ ), and orthophosphate phosphorus ( $\text{PO}_4\text{-P}$ ) were about 200,  
3 30, and 3 mg/L in the plant influent, respectively. The treatment plant was under  
4 normal operation with high efficient COD,  $\text{NH}_4\text{-N}$ , and  $\text{PO}_4\text{-P}$  removals of 89%-95%.  
5 The seed sludge was dark brown in color before the start-up of granulation. The initial  
6 mixed liquor suspended solids (MLSS) concentration was 3.8 g/L with sludge volume  
7 index (SVI) of 87 ml/g and MLVSS/MLSS of 0.8 in the two reactors. After aerobic  
8 granules appeared, the mixed liquor was withdrawn daily from the reactors in order to  
9 keep their solids retention time (SRT) around 20 days.

10 Synthetic wastewater was used in this study, and its composition was as follows:  
11 COD 600 mg/L (50% of which was contributed by glucose and sodium acetate,  
12 respectively); 10 mg  $\text{PO}_4\text{-P/L}$  ( $\text{KH}_2\text{PO}_4$ ); 100 mg  $\text{NH}_4\text{-N/L}$  ( $\text{NH}_4\text{Cl}$ ); 10 mg  $\text{Ca}^{2+}/\text{L}$   
13 ( $\text{CaCl}_2$ ); 5 mg  $\text{Mg}^{2+}/\text{L}$  ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ); 5 mg  $\text{Fe}^{2+}/\text{L}$  ( $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ ); and 1ml/L of  
14 trace element solution. The trace element solution contained (in mg/L)  $\text{H}_3\text{BO}_3$  (50),  
15  $\text{ZnCl}_2$  (50),  $\text{CuCl}_2$  (30),  $\text{MnSO}_4 \cdot \text{H}_2\text{O}$  (50),  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$  (50),  $\text{AlCl}_3$  (50),  
16  $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$  (50), and  $\text{NiCl}_2$  (50) (Adav et al., 2008b). The pH in the reactors was  
17 adjusted with sodium bicarbonate to be within 7.0-8.3.

18

### 19 **2.3. Analytical methods**

20 Mixed liquor (volatile) suspended solids (ML(V)SS), sludge volume index (SVI),  
21 COD,  $\text{NH}_4\text{-N}$ , nitrite nitrogen ( $\text{NO}_2\text{-N}$ ), nitrate nitrogen ( $\text{NO}_3\text{-N}$ ), and phosphorus  
22 ( $\text{PO}_4\text{-P}$ ) were measured in accordance with the standard methods (APHA,1998). Total

1 concentration of phosphorus in the liquid was determined with molybdenum blue  
2 method after digestion by potassium persulfate at 120°C. Dissolved oxygen (DO)  
3 concentration in the bulk liquor was measured with a DO meter (HQ40d, HACH,  
4 USA). pH was determined by a pH meter (Mettler Toledo FE20, Switzerland).

5 The microbial activity of activated sludge was indicated by specific oxygen  
6 uptake rate (SOUR), in terms of milligrams of oxygen consumed by per gram of  
7 sludge per hour. In this study, SOUR was determined at 25°C in a 100-ml volumetric  
8 flask, which was filled with 20 ml of the mixed liquor taken from the SBR at the end  
9 of the operational cycle and 80 ml synthetic wastewater, and then sealed after  
10 insertion of a DO electrode (HQ40d, HACH, USA). The mixed liquor was agitated  
11 using a magnetic stirrer. DO level in the bulk liquor of the volumetric flask was  
12 continuously recorded by the DO meter. SOUR value was obtained by linear  
13 regression of the DO concentrations over time divided by the constant concentration  
14 of MLSS.

15 Batch tests were performed under  $DO \geq 8.0$  mg/L at 25°C in order to obtain the  
16 maximum specific ammonium uptake rate (SAUR) and specific ammonium nitrite  
17 uptake rate (SNUR). Before testing, granules were taken from the two reactors  
18 respectively at the end of the operational cycle and aerated for 1 h to ensure that all  
19 ammonium ions were completely consumed and converted. Subsequently, the  
20 granules were washed with tap water, and then divided into three aliquots based on  
21 wet weight. Each aliquot was dosed into one 250 ml flask filled with the same  
22 synthetic wastewater used in this study (except for ammonium or nitrite

1 concentration). A pulse of concentrated stock solution of ammonium or nitrite was  
2 added at the beginning of test in order to achieve an initial concentration of 50 or 20  
3 mg-N/L, respectively. Samples were collected at an interval of 20 min and then  
4 measured. Granular SAUR or SNUR was obtained by linear regression of the  $\text{NH}_4\text{-N}$   
5 or  $\text{NO}_2\text{-N}$  concentrations over time divided by the constant concentration of MLSS.

6 Extracellular polymeric substances (EPS) were extracted from the sludge by  
7 using ultrasound-formaldehyde-sodium hydroxide method (Adav and Lee, 2008).  
8 Extracellular proteins (PN) in the extracted EPS were determined by Bradford method  
9 with bovine serum albumin (BSA) as standard (Bradford, 1976). Extracellular  
10 polysaccharides (PS) were measured by using phenol-sulfuric acid method with  
11 glucose as standard (Dubios et al., 1956).

12 The mean granular size was measured by a stereo microscope (STZ-40TBa,  
13 SHIMADZU, Japan) with a program Motic Images Plus 2.3S (Version 2.3.0).  
14 Morphology characteristics of the granules were observed using a scanning electron  
15 microscope (JSM6330F, Japan).

16

#### 17 ***2.4. High-throughput sequencing***

18 The total DNA (100  $\mu\text{l}$ ) of granular sludge samples harvested on day 80 from Rs  
19 and Rc were extracted by using Mo Bio PowerSoil DNA Isolation Kit (MoBio  
20 Laboratories, Inc., USA) according to the manufacturer's protocol. The  
21 electrophoresis of genomic DNA was then performed in 0.8% agarose gels and  
22 quantified by spectrometry (NanoDropetry-1000).



1 The hypervariable region (~200 bp) of the bacterial 16S rRNA gene was  
2 amplified. The primer set composed of a forward primer V4F,  
3 5'-AYTGGGYDTAAAGNG-3' and an equimolar mixture of four reverse primers, i.e.  
4 V4R1 5'-TACCRGGGTHCTAATCC-3', V4R2 5'-TACCAGAGTATCTAATTC-3',  
5 V4R3 5'-CTACDSRGGTMTCTAATC-3', and V4R4  
6 5'-TACNVGGGTATCTAATCC-3' based on the RDP pyrosequencing pipeline  
7 (<http://pyro.cme.msu.edu/pyro/help.jsp>). The PCR conditions were as follows: 95°C  
8 for 7 min, followed by 32 cycles at of 95°C for 1 min, 55°C for 1 min, 72°C for 1  
9 min and a final extension step at 72°C for 10 min. After quantification using Qubit  
10 2.0 kit, the PCR products of all samples were taken for high-throughput sequencing  
11 on Ion Torrent PGM System (Life Technology, USA). Mothur (version: 1.31.2) was  
12 used for analyzing microbial biodiversity in the granules.

13

## 14 **2.5. Calculations**

15 Free nitrous acid nitrogen (FNA-N) concentration was calculated according to  
16 Eq. (1) after total nitrite nitrogen (TNO<sub>2</sub>-N) and solution pH being measured  
17 (Anthonisen et al., 1976).

$$18 \quad [\text{FNA-N}](\text{mg/L})/[\text{TNO}_2\text{-N}](\text{mg/L})=1/(1 + e^{-2300(273+T)} \cdot 10^{\text{pH}}) \quad (1)$$

19 where T is the room temperature in 25°C.

20

## 21 **3. Results and discussion**

### 22 **3.1. Formation and characterization of granules in the reactors**

1       The initial seed sludge had irregular and loose structure with a mean floc size of  
2   0.14 mm. After 15 days' cultivation, yellowish granules with clear boundary were  
3   observed in the two reactors and grew gradually. Interestingly, the surface of granules  
4   in Rs gradually turned into green from day 19 on, due to the growth of algae resulted  
5   from sunlight exposure (Figs. S1a and S1b). SEM observation on day 90 clearly  
6   shows that bacteria prevailed all over the granules with compact and dense structure  
7   in Rc (Fig. S1c). The granules in Rs, however, with symbiotic growth of bacteria and  
8   algae had rough surface and loose structure (Fig. S1d). This phenomenon implies that  
9   the community structure of microorganisms in Rs should be different due to the  
10  growth of algae, which was further investigated in this study.

11       The physical characteristics such as MLSS, SVI and particle size of the sludge in  
12  the two reactors were monitored (Table 1). After 40 days' operation, the MLSS in Rs  
13  kept around 7.5 g/L, higher than that in Rc (about 6.4 g/L), probably brought about by  
14  the rapid growth of algae due to sunlight irradiation. It is worth noting that the SVI<sub>30</sub>  
15  value of granular sludge decreased from initial 87 ml/g to 38 ml/g in Rs while to 25  
16  ml/g in Rc at the end of experiment, suggesting the growth of algae in Rs has some  
17  negative effect on the settleability of granules. This observation is to some extent in  
18  agreement with previous findings that the settleability of bacterial sludge is much  
19  better than algae (Choi et al., 2010; Su et al., 2012). In addition, different increase in  
20  granular diameter was noticed between the granules in Rs and Rc along with the  
21  operation. After 100 days' cultivation, the average diameter of granules in Rs was  
22  about 0.78 mm, much smaller than that of granules in Rc (1.21 mm). Therefore, it

could be inferred that the growth of algae in Rs affected the settleability of granular sludge, slowing down the growth of granules to a certain extent.

### **3.2. Performance of Rs and Rc**

#### **3.2.1. COD and TP removals**

As shown in Fig. 1a, COD removal was lower than 90% for both reactors during the initial 10 days, most probably due to low MLSS in the reactors and some adaptation period was necessary for the seed sludge (used to treat domestic wastewater) to effectively treat the synthetic wastewater prepared in this study. From day 12 on, however, the COD removal efficiencies in Rc and Rs were averagely 96.1% and 95.2%, respectively with effluent COD < 30 mg/L till the end of experiment, suggesting the granular sludges in both reactors have good potential for organics removal.

On the other hand, from day 5 on, a different trend in TP removal was detected between the two reactors. The effluent TP from Rc was always below 1.0 mg/L after 20 days' operation with P removal rate > 90%. The granular P release rate in Rc during non-aeration stage was around 4.6 mg-P/(g-MLSS·h), signaling the presence and high activity of polyphosphate accumulating organisms (PAOs) in Rc. However, only a small amount of P release was monitored during non-aeration period and the effluent TP concentration was averagely 5.6 mg/L in Rs, possibly attributable to the inhibited activity of PAOs by free nitrous acid (FNA) (Fig. 1b). Pijuan et al. (2010) detected 50% inhibition on PAOs growth, phosphate uptake and glycogen production

1 at FNA concentration of approximately  $0.5 \times 10^{-3}$  mg HNO<sub>2</sub>-N/L and pH 7.0, while  
2 complete inhibition occurred at FNA concentration of about  $6 \times 10^{-3}$  mg HNO<sub>2</sub>-N/L.  
3 In this study, the FNA concentration in Rs was about  $6.3\text{-}9.8 \times 10^{-3}$  mg HNO<sub>2</sub>-N/L  
4 from day 10 on, most probably brought about by the inhibited nitrataion process (the  
5 conversion of produced NO<sub>2</sub>-N into NO<sub>3</sub>-N) due to algae growth thus resulted in  
6 NO<sub>2</sub>-N accumulation (Fig.1b). This observation implies that algae growth might  
7 affect the activity of NOB (nitrataion process), resulting in FNA accumulation and  
8 subsequent inhibition on PAOs.

9

### 10 3.2.2. Nitrogen profiles

11 Fig. 1b shows the changes of N species and N removal performance in Rs and Rc  
12 during the 100 days' operation. The granules in Rc exhibited excellent performance in  
13 removing NH<sub>4</sub>-N, with removal ratio > 99% from day 10 on to the end of experiment.  
14 However, it took about 40 days for the NH<sub>4</sub>-N removal rate in Rs to increase from 43%  
15 to 98%. Moreover, an obvious difference in the effluent NO<sub>2</sub>-N concentration was  
16 noticed between Rc and Rs. NO<sub>2</sub>-N was observed to rapidly accumulate in Rs and  
17 reached the maximum 43.6 mg/L on day 20. Although decreased to some extent from  
18 day 20 to the end of experiment, the NO<sub>2</sub>-N concentration in Rs was still at high level  
19 (> 28 mg/L). In contrast, only transient NO<sub>2</sub>-N accumulation was detected in Rc  
20 during the first 10 days, and the effluent NO<sub>2</sub>-N concentration maintained below 0.3  
21 mg/L from day 20 on.

22 In addition, much higher granular SAUR and SNUR were detected in the

1 granules taken from Rc in the batch experiments, especially SNUR ( $\text{NO}_2\text{-N}$  uptake  
2 rate, Table S1). These results confirm that algae growth inhibited the activity of  
3 nitrifying bacteria in Rs, especially nitrite oxidizing bacteria (NOB). Stated, the TN  
4 removal efficiency in Rs varied between 40.7 % - 45.4% after mature granules formed,  
5 lower than that in Rc (52.9 % - 58.3%), indicating that the denitrification process in  
6 the granules from Rs was also impacted to some extent by algae growth.

7

### 8 ***3.3. EPS and SOUR of granules***

9 Extracellular polymeric substances (EPS), sticky metabolic products secreted by  
10 bacteria, are mainly composed of proteins (PN), polysaccharides (PS), humic acids  
11 and lipids. Adav et al. (2008b) pointed out that EPS were beneficial for aerobic  
12 granulation and granular stability, especially PN and PS, and the latter formed the  
13 backbone of the granules. The contents of PN and PS extracted from granules at  
14 different stages are presented in Fig. 2a. Both compounds from the granular sludge in  
15 the two reactors increased a lot when compared with the seed sludge (day 0). In  
16 addition, PN/PS ratio was about 3.3 for the granules in Rc and 3.1 for those in Rs,  
17 increasing more than 2 times compared to the seed sludge. This observation is in  
18 agreement with Zhang et al. (2007) who found that the protein content was  
19 significantly high in aerobic granules with PN/PS ratios ranging between 2.3 and 4.9.  
20 A meaningful finding is that the PN and PS contents in the granules from Rs were  
21 determined to be 49.6 and 15.9 mg/g-VSS on day 100, i.e. decreased by 25.7% and  
22 22.5% respectively in comparison to Rc, leading to the significant decrease in EPS

1 production and further slowing down the growth of aerobic granules.

2       The stimulated EPS excretion in aerobic granules can be associated with the  
3 bioactivity of bacteria. The granular SOUR of Rc was 76.4 mg-O<sub>2</sub>/g-VSS·h on day 20  
4 and slightly decreased to 67.8 mg-O<sub>2</sub>/g-VSS·h on day 100, much higher than the  
5 granular SOUR of Rs during the whole process (Fig. 2b). Results from Yang et al.  
6 (2004) showed that the PN/PS ratio had a negatively linear relationship with the  
7 SOUR of bacteria in the granules under varied influent FA conditions. In this study,  
8 the PN/PS ratio was also found to be negatively correlated with the granular SOUR  
9 during operation ( $R^2=0.99$  and  $0.92$  for the granules in Rs and Rc, respectively),  
10 implying that high metabolic activity of bacterial cells favors the production of PS  
11 rather than PN. Moreover, the following two aspects may have some contribution to  
12 the difference in SOUR values: (1) The growth of algae may decrease the quantity of  
13 co-existing bacteria in granules. Algae are photoautotrophic microorganisms and have  
14 lower bioactivity than bacteria under no sunlight condition (during the testing of  
15 SOUR), while most bacteria in granules belong to heterotrophic and have high  
16 bioactivity on organics degradation. (2) Algae may influence the activity of bacteria  
17 and thus the distribution of bacterial community in the granules, which needs further  
18 investigation.

### 20 ***3.4. Changes in microbial biodiversity in granules***

21       The difference in nutrients removal and physical and biochemical properties  
22 between the granules from Rs and Rc is probably attributable to the difference in

1 microbial diversity in the aerobic granules from the two reactors. As shown in Fig. 3,  
2 the predominant bacteria cover Actinobacteria, Bacteroidetes (Flavobacteria and  
3 Sphingobacteria), Nitrospira, Proteobacteria (Alphaproteobacteria, Betaproteobacteria,  
4 Gammaproteobacteria, and Deltaproteobacteria) and Firmicutes, accounting for 92.1%  
5 and 90.4% respectively in the granules of Rs and Rc. Significant difference in the  
6 proportion of dominant bacteria has also been found in the granules from the two  
7 reactors. The family of Chitinophagaceae from class Sphingobacteria is about 27.9%,  
8 occupying the largest portion of the bacteria in Rs, while Rhodocyclaceae from class  
9 Betaproteobacteria is about 30.8% dominating the granules in Rc. Moreover, the  
10 bacteria from families Rhodobacteraceae and Comamonadaceae, are about 15.6% and  
11 10.5%, respectively in the granules in Rc, much higher than those in Rs (10.1% and  
12 4.4%, respectively), indicating that algae growth inhibits the growth of these bacteria.  
13 Three genera from family Rhodocyclaceae, i.e. *Thauera*, *Zoogloea*, and *Rhodocyclus*  
14 are reported to closely associate with EPS excretion, the formation of activated sludge  
15 flocs and P removal, respectively (Allen et al., 2004; Shao et al., 2009; Wong et al.,  
16 2005). The genus *Lamproedia* from family Comamonadaceae has been identified as  
17 the major PAOs responsible for P removal in wastewater treatment (Stante et al.,  
18 1997). In addition, genera *Paracoccus denitrificans* and *Comamonas*, from families of  
19 Rhodobacteraceae and Comamonadaceae respectively, can oxidize  $\text{NH}_4\text{-N}$  to nitrite or  
20 nitrate under aerobic condition and reduce nitrate and nitrite to  $\text{N}_2$  under anoxic  
21 condition (Baumann et al., 1996; Crossman et al., 1997; Gumaelius et al., 2001).  
22 Therefore, it was deduced that because of the algal-bacterial symbiosis Rs became

1 unfavorable for the growth of these bacteria related with N and P removal, leading to  
2 the deterioration in nutrients (N and P) removal and the physicochemical properties of  
3 the granules. Also, it is noticeable that the percentage of Nitrospiraceae and  
4 Nitrosomonadaceae in Rc are about 2.2% and 1.5% respectively, much higher than  
5 that in Rs ( $<0.1\%$ ), signaling that nitrifying bacteria(AOB and NOB) were  
6 significantly inhibited under the symbiotic growth of bacteria and algae in Rs,  
7 resulting in decreased nitrification performance (Fig. 1b). On the other hand, the  
8 bacteria from families Chitinophagaceae, Flavobacteriaceae and Bdellovibrionaceae,  
9 are about 27.9%, 9.0% and 16.5% respectively in Rs, much higher than those in Rc  
10 (9.7%, 5.1% and 5.6%, respectively), suggesting that the growth of these bacteria was  
11 favored due to the co-existence of algae. Except some genera from family  
12 Flavobacteriaceae could remove N or P (Bernardet and Nakagawa, 2006), little  
13 information could be found about the correlation of Chitinophagaceae and  
14 Bdellovibrionaceae with nutrients removal. In addition, the Bdellovibrionaceae, a  
15 family of Proteobacteria, have many genera which are bacterial parasites: they can  
16 enter into the periplasmic space of other bacteria and feed on the biopolymers like  
17 proteins and nucleic acids of the host bacteria (Strauch et al., 2006). From this study,  
18 the Bdellovibrionaceae are considered to have negative effect on the growth of  
19 microorganisms in the granules. The above preliminary results clearly demonstrate  
20 that the symbiotic growth of algae and bacteria greatly influence the biodiversity of  
21 microbial community in the aerobic granules. Some specific species might also be  
22 responsible for the different performance of the granules in two reactors, which is still



under followed-up investigation.

### ***3.5. Preliminary analysis of mechanisms involved in this study***

The current study investigated the effect of algae growth on aerobic granulation, nutrients removal and biodiversity of the microbial community in aerobic granules.

Fig.4 illustrates the possible influences of algae growth on aerobic granules. High

effluent NO<sub>2</sub>-N concentration with lower TN removal was always detected in Rs

during the 100 days' operation (Fig. 1b), clearly indicating that the co-existence of

algae suppressed the nitrification and denitrification processes in the granules under the

tested conditions. Guerrero and Jones (1996) and Kaplan et al. (2000) noticed that the

activity of nitrifying bacteria exposed to sunlight was significantly inhibited, and

NOB was more sensitive to sunlight than AOB. Previous studies attributed this greater

sensitivity of NOB to the relatively low cytochrome c content of Nitrobacter

compared to Nitrosomonas (Philips et al., 2002). As a possible mechanism, Barak et

al. (1998) suggested that light may destroy the electron transfer from cytochrome c to

nitrite reductase. However, in this study it is still not clear whether and to what extent

the sunlight impacted NOB in the granules, due to the fact that a temporary inhibited

nitrification was also detected in Rc during the first 10 days' operation (Fig. 1b).

After 19 days' operation, algae were clearly observed, forming algal-bacterial

symbiosis in Rs. The impact of algae growth on the granular performance is

complicated. Previous work shows that a proper algae/sludge inoculation ratio (1:5)

could yield the maximum N and P removal efficiencies along with better settleability

of the sludge in an algal-bacterial culture (Su et al., 2012). Most recently, Marcilhac et

1 al. (2014) found that the activity and abundance of AOB decreased with algae growth  
2 leading to a decreased nitrification in a microalgal-bacterial ecosystem, which is  
3 attributable to that algae is a better competitor for N compared with AOB. In this  
4 study the growth of algae in aerobic granules deteriorated nutrients removal,  
5 especially P, which might be resulted from accumulated  $\text{NO}_2\text{-N}$  due to an inhibited  
6 nitrification process. As can be seen from Fig. 1b, averagely high concentration of  
7  $\text{NO}_2\text{-N}$  ( $>28 \text{ mg NO}_2\text{-N/L}$  since day 10) was detected in Rs and FNA was estimated to  
8 be  $6.3\text{-}9.8 \times 10^{-3} \text{ mg HNO}_2\text{-N/L}$ ), greatly inhibiting the activity of PAOs (Fig. 1a).  
9 Besides,  $\text{O}_2$  possibly generated by algae may affect P release by PAOs during  
10 non-aeration phase. On the other hand, the microbial biodiversity and distribution in  
11 the aerobic granules was altered due to the symbiotic growth of bacteria and algae,  
12 leading to the suppression of functional bacteria in the granules to some extent with  
13 resultant decreased bioactivity, such as *Thauera* and *Zoogloea*, further slowing down  
14 the granulation process.

15

#### 16 **4. Conclusion**

17 The symbiotic growth of algae greatly decreased the bioactivity of granules with  
18 less EPS production in the granules. The results demonstrated that the activity and  
19 growth of nitrifying bacteria (especially Nitrospiraceae and Nitrosomonadaceae),  
20 denitrifying bacteria and PAOs were inhibited in algal-bacterial symbiosis to a great  
21 extent, resulting in lower TN and TP removal efficiencies of the granules. Further  
22 research will be related with how to ameliorate these inhibition effects brought about

by algae growth. And quantification and classification of the algae in the granules will also be done, which will help to further disclose the mechanisms involved.

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1 **Tables**

2

3 Table 1- Physical characteristics of granules in the reactors during 100 days'

4 operation

Operation duration (day)	MLSS (g/L)		SVI <sub>30</sub> (ml/g)		Average diameter (mm)	
	Rc	Rs	Rc	Rs	Rs	Rc
0	3.4	3.3	87	87	0.14	0.14
20	4.7	4.8	41	56	0.35	0.31
40	6.1	7.2	28	40	0.61	0.53
60	6.4	7.5	26	37	0.97	0.69
80	6.5	7.3	27	39	1.13	0.74
100	6.3	7.7	25	38	1.21	0.78

5



**Figure captions**

Fig. 1. Variations of COD removal and effluent TP concentration (a), and effluent  $\text{NO}_3\text{-N}$  and  $\text{NO}_2\text{-N}$  concentrations, and  $\text{NH}_4\text{-N}$  and TN removals (b) during the operation of the two reactors.

Fig. 2. Changes in extracellular polymeric substances (EPS) extracted from the sludge in Rs and Rc (a) and specific oxygen utilization rate (SOUR) of the granules (b) during the operation, respectively.

Fig. 3. Abundance of families in the granules of Rc and Rs on day 90

Fig. 4. Schematic diagram of algae growth and its effect on aerobic granules. FNA, free nitrous acid; PAOs, polyphosphate accumulating organisms.

1 **Figures**  
2

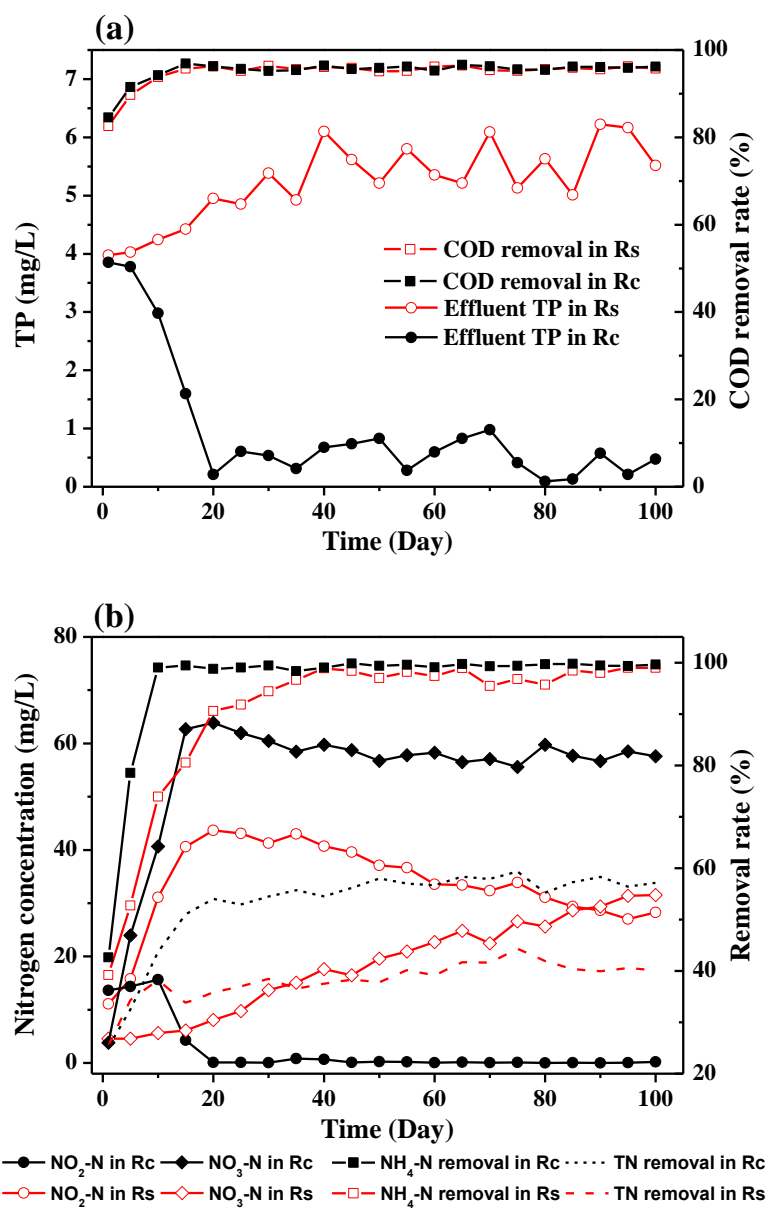


Fig. 1 Huang *et al.*

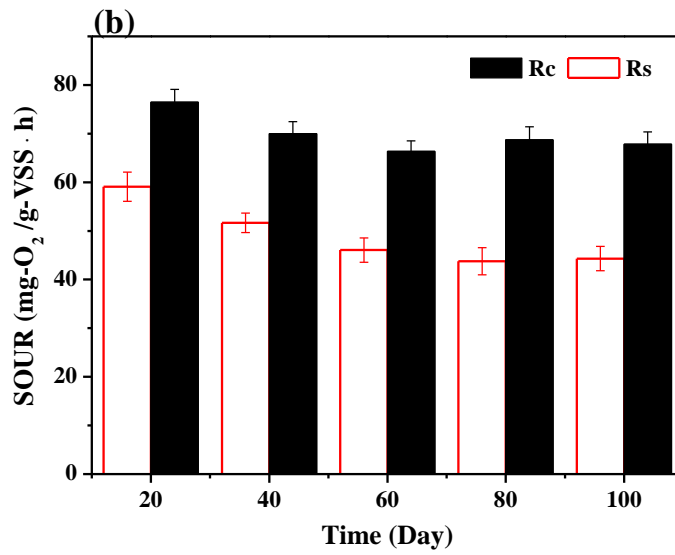
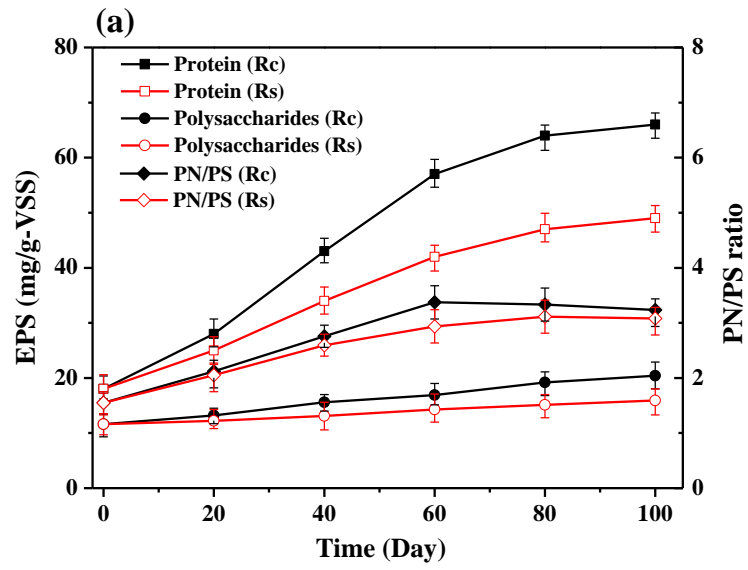


Fig. 2 Huang *et al.*

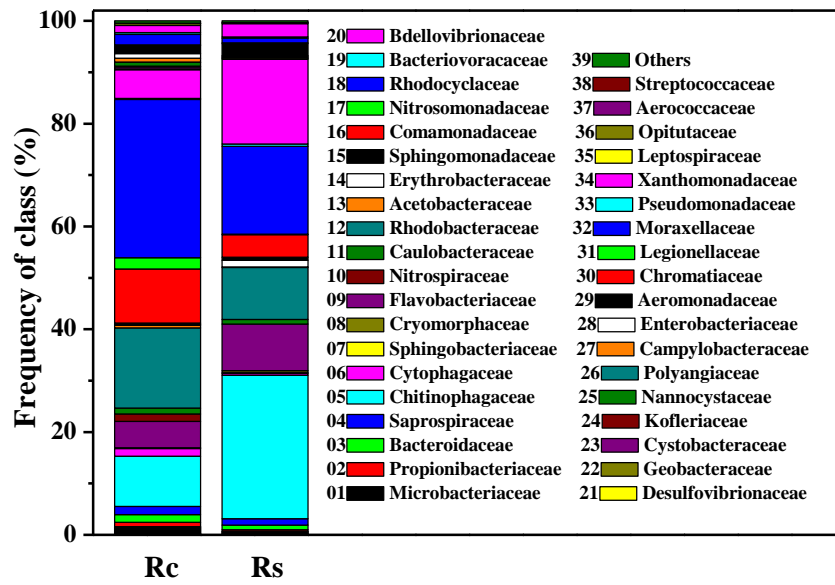
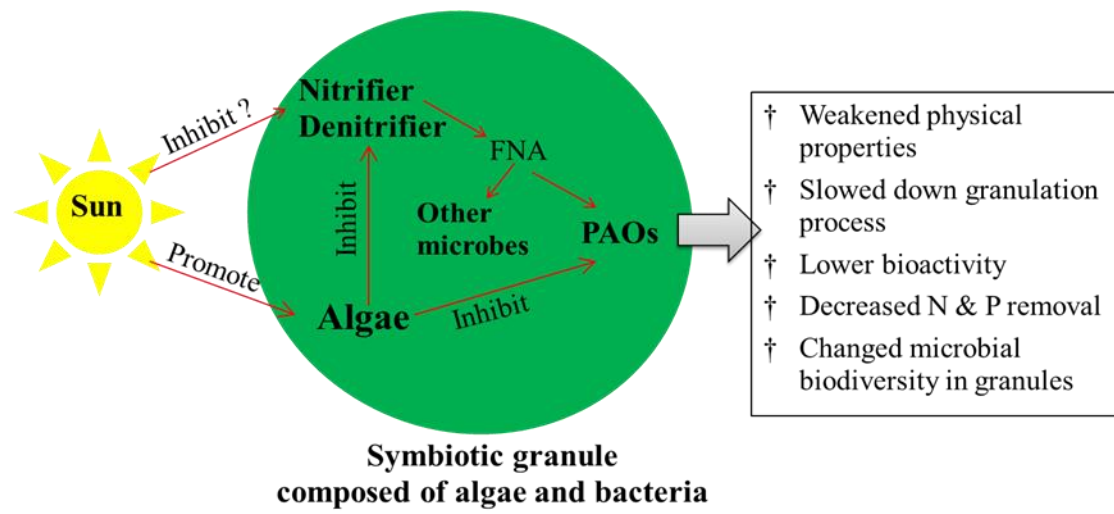


Fig. 3 Huang *et al.*

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Fig. 4 Huang *et al.*