Treatment of UASB-treated Recycled Paper Wastewater Using SBR and SBBR: A Comparison

Jun Han, Lirong Lei,* Fangrui Cai, and Youming Li

Anaerobic-oxic (AO) systems have been extensively adopted for the biological treatment of wastewater from recycled paper mills, which is characterized by high chemical oxygen demand (COD) concentrations and contains hundreds of organic compounds. In this study, an up-flow anaerobic sludge blanket (UASB) served as the anaerobic treatment of recycled paper mill wastewater. Then, either a sequential batch reactor (SBR) or a sequential batch biofilm reactor (SBBR) were adopted as aerobic treatment to treat the UASB effluent respectively. Parameters such as COD, BOD5, and TSS were measured to compare the treatment performance of SBR and the SBBR. After 80 days' operation, COD removal efficiency of SBR and SBBR were 21.79 ± 3.4% and 38.38 ± 2.69% respectively; TSS removal efficiencies were 20.84 ± 5.15% and 47.02 ± 5.84% respectively. The results indicated that SBR was effective for removing residual organic matter in UASB effluent. However, SBBR showed significant advantages for the removal of COD and total suspended solids (TSS), which are ascribed to the effective biomass retention and biofiltration of SBBR.

Keywords: Biological treatment; Biofilm reactor; SBBR; SBR

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INTRODUCTION

The pulp and paper (P&P) industry has become one of the largest global industries and the most intensive water consumer (Toczyłowska-Mamińska 2017). Untreated wastewater from the pulp and paper industry is generally highly polluted, containing hundreds of organic compounds including lignin, stilbenes, phenols, dioxins, chlorides, furans, phenols, and sulphur compounds (Muna and Sreekrishnan 2001).

The wastewater treatment methods commonly used in the P&P industry are based on anaerobic or aerobic methods (Buyukkamaci and Koken 2010; López-López *et al.* 2010). Anaerobic reactors such as anaerobic fixed film reactors (AFFR) (Rao *et al.* 2005), up-flow anaerobic sludge blankets (UASB) (Chen *et al.* 2011), and up-flow anaerobic stage reactors (UASR) (Chelliapan *et al.* 2011) are often used as the basic biological treatment process for high organic strength wastewater. However, anaerobic treatment alone generally cannot guarantee that the effluent meets discharge requirements, so subsequent treatment is particularly important (Chen *et al.* 2008). The aerobic system has a better treatment effect on wastewater with lower chemical oxygen demand (COD) concentrations, achieves a good removal efficiency on soluble biodegradable organic matters in wastewater, and the biomass produced is usually well settled, which leads to a higher quality of the effluent (Fang 2000; Chong *et al.* 2012). Therefore, anaerobic-aerobic systems have been widely used in industrial wastewater treatment, especially for high strength wastewater (Supaka *et al.* 2004; Kapdan and Oztekin 2006).

Conventional aerobic reactors such as the sequencing batch reactor (SBR) and aerated lagoon are widely used because of the small area covered, strong impact resistance, the ability to treat toxic or high strength organic wastewater, and convenient maintenance and operation (Pokhrel and Viraraghavan 2004; Ashrafi *et al.* 2015). In recent years, biofilm reactors have become more and more popular in the wastewater treatment field, with one of the reasons being that microorganisms are adsorbed on the filler surface with a large specific surface area, so the reactor retains a high concentration of biomass; thereby, effective removal of organic matters can be achieved (Wilderer and McSwain 2004; Guo *et al.* 2009; Bo *et al.* 2010). In addition, biofilm reactors are also characterized by a significant reduction in residual sludge content and excellent settling performance (Iaconi *et al.* 2010; Osman *et al.* 2013). Moreover, biofilm reactors have the advantages of a small footprint, energy savings, easy operation, and large load capacity (Rodgers and Zhan 2003).

Nevertheless, biofilm reactors have not been extensively adopted for paper mill wastewater treatment in spite of these potential advantages. In this study, a UASB was used for the pre-treatment of the recycled paper mill wastewater. Then a SBR and a SBBR were adopted to treat the UASB effluent. The treatment performance of SBBR was evaluated by comparing it with SBR in terms of COD, biochemical oxygen demand (BOD), and total suspended solid (TSS).

EXPERIMENTAL

Materials

Wastewater and Sludge

Wastewater from a recycled paper mill located in Guangdong Province, southern China, which produced testliner board with 100% old corrugated containerboard (OCC) pulp, was treated by coagulation and a lab-scale UASB. Details of the treatment can be found in the supplementary materials. The UASB effluent served as the influent for the SBR and SBBR. The main characteristics of the UASB effluent are shown in Table 1. Activated sludge from the aerobic lagoon in a paper mill of Guangdong served as the inoculum.

Table 1. Main Characteristics of the UASB Effluent

Parameter	Concentration	Parameter	Concentration
COD (mg/L)	440.1 to 550.9	BOD_5 (mg/L)	110 to 170
pH	7.17 to 7.42	B/C	0.25 to 0.3
Color (C.U.)	102 to 138	TSS (mg/L)	48 to 55

Lab-scale SBR and SBBR

Reactor description and operation

The scheme of the SBR is shown in Fig. 1. The main body of the reactor consisted of a cylindrical Plexiglas reactor with diameter 60 mm and height 500 mm, with an aerator (ACO-9601, Hailea Group Co., Ltd., Guangdong, China) being put into the reactor. An operation cycle of the SBR was 12 h, with 5 min of influent addition, 700 min for continuous aeration, 10 min for settling, and 5 min for discharging.

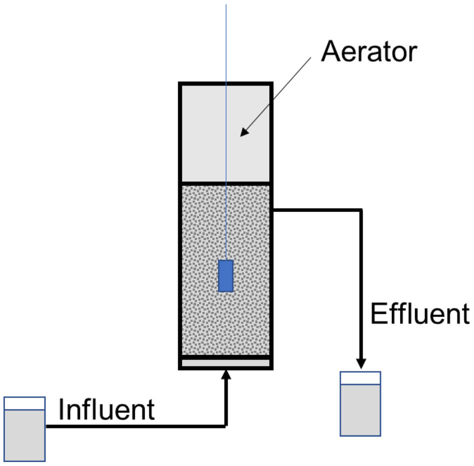

Fig. 1. Scheme of SBR

Figure 2 shows the lab-scale SBBR. The main body of the reactor was the same as the SBR, except that the inside of the reactor was partially filled with biomass support material (10 mm high wheel-shaped plastic elements with 10 mm diameter, effective specific surface area 500 m^2/m^3, specific gravity 960 Kg/m^3, and porosity of 95%). An operation cycle of the SBBR was 6 h. A cycle was further divided into two consecutive phases: the filling and withdrawing phase and the reaction phase. During the filling and withdrawing phase (length: 4 min), 200 mL wastewater was pumped into the reactor from the bottom and 200 effluent was discharged from the top of the reactor. During the reaction phase, a peristaltic pump (BT100-1J, Baoding Longer Peristaltic Pump Co., Ltd., Baoding, China, flow rate of 100 mL/min) was adopted to form the circulation of wastewater within the reactor.

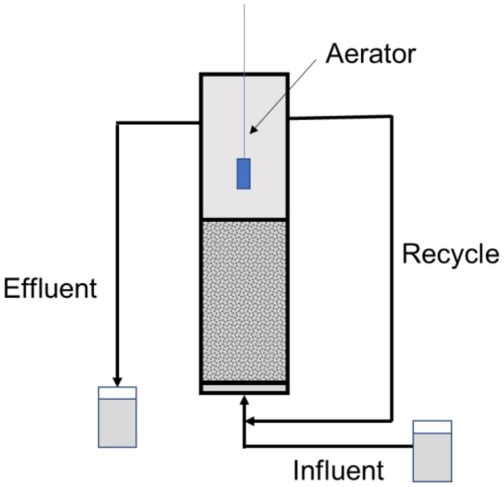

Fig. 2. Scheme of SBBR

Both reactors were placed in a water bath tank (HH-4, Changzhou Aohua Instrument Co., Ltd, Changzhou, China) to maintain a constant temperature of 33 °C. The HRT of both reactors was 12 h. The start-up of both reactors is shown in the supplementary materials. After the start-up, both reactors were operated for 80 days.

Analytical methods

The COD, TSS, and BOD were determined according to standard methods (APHA 2005). COD was measured using a spectrophotometer (DR2800, HACH, Loveland, USA), BOD was measured using a respirometric BOD apparatus (BODTrak™II, HACH, Loveland, USA) and pH was measured using a pH meter (PB-10, Sartorius, Gottingen, Germany).

RESULTS AND DISCUSSION

Figure 3a shows the performance of the SBR and SBBR with respect to COD removal efficiency. During 80 days of operation, the COD concentrations of SBR and SBBR effluent were decreased from 473.57 ± 14.64 to 370.20 ± 15.88 mg/L and 281.51 ± 7.87 mg/L, respectively. The COD removal efficiency and organic removal rate (ORR) were 21.79 ± 3.4% and 206.74 g COD/m^3/d, respectively for SBR; 38.38 ± 2.69% and 384.12 g COD/m^3/d respectively for SBBR.

The treatment results on COD confirmed the presence of residual organic matter in the UASB effluent. SBBR and SBR was were both effective for removing these residual organic compounds. However, the treatment performance of SBBR on COD was evidently superior than SBR. The superior treatment performance of SBBR on COD removal can be firstly ascribed to carriers in the reactor which enabled the development of biofilm, leading to more biomass being effectively retained in the reactor (Iaconi *et al.* 2005; Wimpenny *et al.* 2006; Wu *et al.* 2009; Sytek-Szmeichel *et al.* 2016). As the biodegradation of pollutants generally depends on the functional bacteria in bioreactors, the effective biomass retention of biofilm reactors can cause relatively higher pollutants removal efficiency than flocculent sludge reactors. The adsorption-desorption theory provided a good explanation for the results. A part of the compounds in the wastewater were adsorbed onto the SBBR biofilm so that the reactor rapidly removes the degradable compounds and some recalcitrant compounds. As the compounds which in the liquid phase in the reactor were gradually consumed, the desorption process began, providing substrates for microbial growth and metabolism. Therefore, SBBR can use internal equalization to control fluctuations in biomass load and provides a stable living environment for microorganisms maintain the biological activity of microorganisms (Gieseke *et al.* 2002; Ding *et al.* 2011; Jin *et al.* 2012; Wilderer and McSwain 2004).

The treatment results of this study were consistent with many previous studies. For instance, Sirianuntapiboon *et al.* (2005) used SBBR and SBR to treat dairy wastewater, turning out that COD removal efficiency of SBR and SBR was 81.8% and 63.5%, respectively. Ozturk *et al.* (2019) confirmed that, compared to SBR, the biomass support materials in SBBR can improve the quality of effluent and under the same organic load, the efficiency of SBBR in removing COD was about 8% higher than SBR. Actually, the great potential of biofilm reactors for industrial effluent treatment has been extensively reported. For instance, Farabegoli *et al.* (2008) used a lab-scale biofilm reactor to remove COD and AOX from recycled paper wastewater and an average removal efficiency of more than 90% was obtained. Jucherski *et al.* (2019) indicated in his research that SBBRs can achieve 97% COD removal efficiency in domestic sewage treatment. In addition, biofilms also show a good potential in the treatment of dairy wastewater, with a COD removal efficiency between 89.7% and 97% (Abdulgader *et al.* 2010).

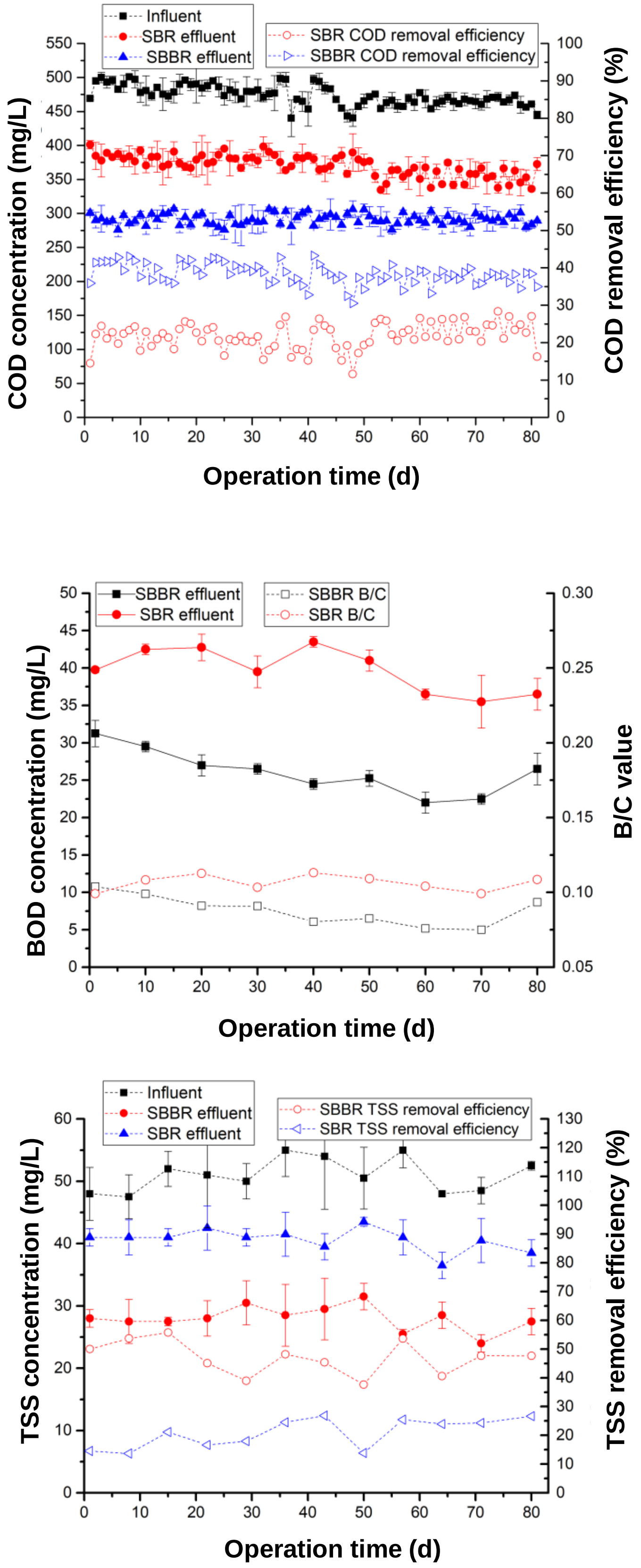

Fig. 3. Treatment performance of SBBR: (a) COD, (b) BOD and B/C, (c) TSS

Figure 3b shows the BOD concentration and B/C values of the SBBR and SBR effluents. The BOD concentrations of the SBBR and SBR effluents were 26.5 mg/L and 37 mg/L, with the B/C value being 0.093 and 0.108, respectively. The lower BOD concentration and B/C value of effluent was obtained by the SBBR. Comparing the BOD concentrations of the SBBR effluent and influent, it can be speculated that the recalcitrant compounds were removed progressively in the reactor. Associated with the COD removal, the removal of recalcitrant compounds may be also responsible for the higher COD removal efficiency of the SBBR than the SBR. As a matter of fact, many studies have indicated that recalcitrant compounds such as benzene derivatives and phenolic compounds can be effectively removed in biofilm reactors. Moreover, Cai *et al.* (2019) detected that a SBBR could even be effective for treating secondary effluent from a recycled paper mill as the recalcitrant compounds can be removed in biofilm reactors.

The treatment performances of the SBBR and SBR on TSS removal are shown in Fig. 3c. Similar to COD removal, the treatment performances of the two reactors differed. The TSS removal efficiencies for SBBR and SBR were 47.02 ± 5.84% and 20.84 ± 5.15% respectively, which was attributed to the insoluble organic matters in the wastewater that could be adsorbed onto the biofilm. The biofiltration provided by biofilm enables massive insoluble pollutants to be removed, as they can be adsorbed in the surface of carriers or biofilms and then be degraded. Therefore, considerable TSS removal can be achieved in biofilm reactors and this feature has been extensively reported. For example, El-Shafai *et al.* (2013) used a submerged biofilm reactor in the treatment of municipal wastewater and a TSS removal efficiency of 95% was obtained. Rodriguez-Sanchez *et al.* (2020) also confirmed the excellent performance of biofilm reactors in TSS removal efficiency in his research. Therefore, in comparison with traditional biological reactors, SBBR has a great potential for wastewater treatment.

CONCLUSIONS

1. The removal efficiency for chemical oxygen demand (COD) of the sequential batch biofilm reactor (SBBR) was higher than that of the sequential batch reactor (SBR). The SBBR owes its superior performance to effective biomass retention, leading to a high activity of microorganisms and high organic removal rate (ORR). Additionally, the recalcitrant organic matter might be partly removed by the SBBR.
2. The total suspended solids (TSS) removal by the SBBR was evidently superior than that of the SBR, which can be attributed to the biofiltration as insoluble pollutants can be adsorbed and degraded by the biofilm

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SUPPLEMENTARY

Treatment Process of Wastewater

The main characteristics of raw wastewater from a recycled paper mill are shown in Table S1. After being taken to our lab, the wastewater was firstly treated by coagulation and UASB, then the UASB effluent was treated by SBR and SBBR separately (Fig. S1).

Table S1. Main Characteristics of Raw Wastewater

Parameter	Concentration	Parameter	Concentration
COD (mg/L)	4452.68 -5221.45	BOD_5 (mg/L)	2500-3000
PH	6.3-6.8	B/C	0.5-0.7
Color (C.U.)	730-800	TSS (mg/L)	245-300

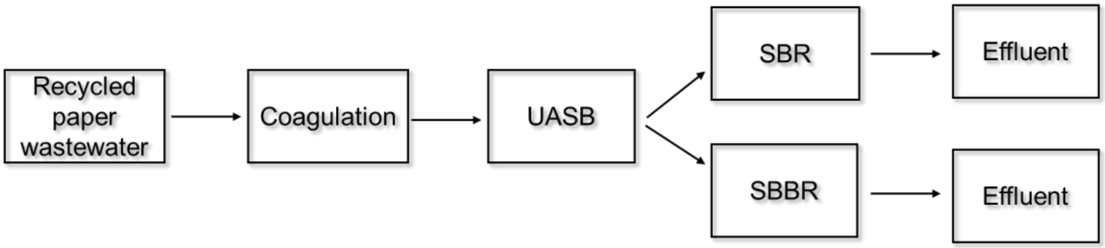


Fig. S1. Scheme of two treatment systems

Coagulation

Coagulation has been used as pre-treatment prior to biological treatment. Firstly, 6 mg/L polyferric sulfate (PFS) was added to wastewater and stirred rapidly at 240 r/min for 2 min. Then 6 mg/L cationic polyacrylamides (CPAM) was added and stirred for 30 s, followed by slow stirring at 60 r/min for 20 min. After 30 min of precipitation, the supernatant was collected, and COD and TSS concentrations were decreased to about 4292 mg/L and 135 mg/L, respectively.

UASB Treatment

The investigation was carried out using a lab scale UASB reactor as primary biological treatment. The working volume of UASB was 750 mL and HRT 24 h. Approximate 90% COD and TSS removal efficiency were obtained by UASB. The COD and TSS concentration of wastewater was decreased from 4292.41±58.99 mg/L to 473.57±14.64 mg/L and 135 ±10.13mg/L to 51±2.7303 mg/L, respectively.

Start-up of SBR and SBBR

The start-up of SBR and SBBR are referenced in the same way; 200 mL inoculated sludge and 200 mL synthetic wastewater were added into the reactor to cultivate sludge. COD concentration of synthetic wastewater during the cultivation phase (400 mg/L, 600 mg/L, 800 mg/L, 1000 mg/L) was gradually increased. The main composition of synthetic wastewater was glucose, ammonium nitrate, and potassium dihydrogen phosphate; the C:

N: P ratio was according to 100: 5: 1. Coagulated wastewater was added to the synthetic wastewater in a certain proportion after the cultivation stage to achieve acclimation of sludge and the treatment system entered the operational phase. The effluent of UASB was served as influent of SBR and SBBR. The detail of the start-up was presented in Table S2.

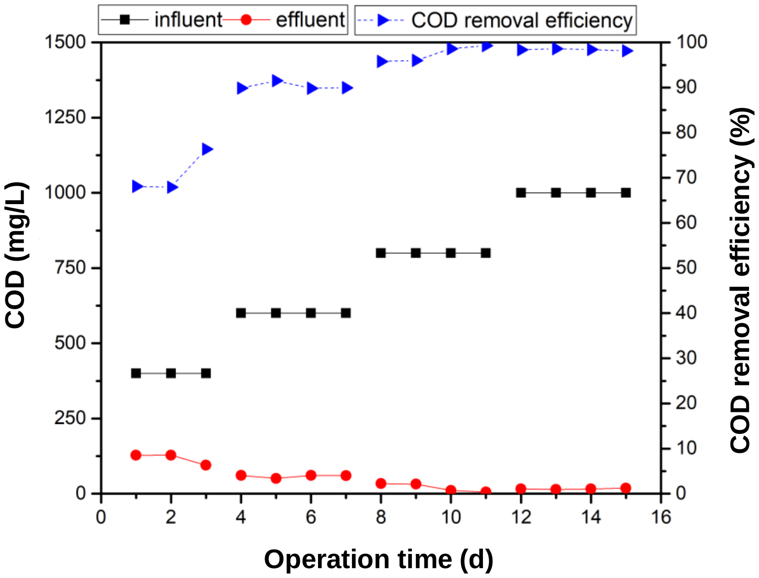
Table.S2 Operative Condition of Cultivation Stage

Stage	Time (d)	COD (mg/L)	Stage	Time (d)	COD (mg/L)
Cultivation	1-3	400	Acclimation	1-6	1241.25-1291.81
	4-7	600		7-17	1644.48-1651.20
	8-11	800		18-30	2280.42-2286.94
	12-15	1000	Operation	1-69	2415.2-441.10

During the start-up stage, the HRT was set as 12 h. The operation cycle of SBR and SBBR were set as 12 h and 6 h, respectively.

RESULTS

Figure S2 showed the cultivation condition of SBR. The COD removal efficiency of SBR and SBBR was about 98%, indicating that activated sludge had a certain ability to remove organic matter. Therefore, the coagulated water was mixed with synthetic wastewater to achieve acclimation of the sludge.



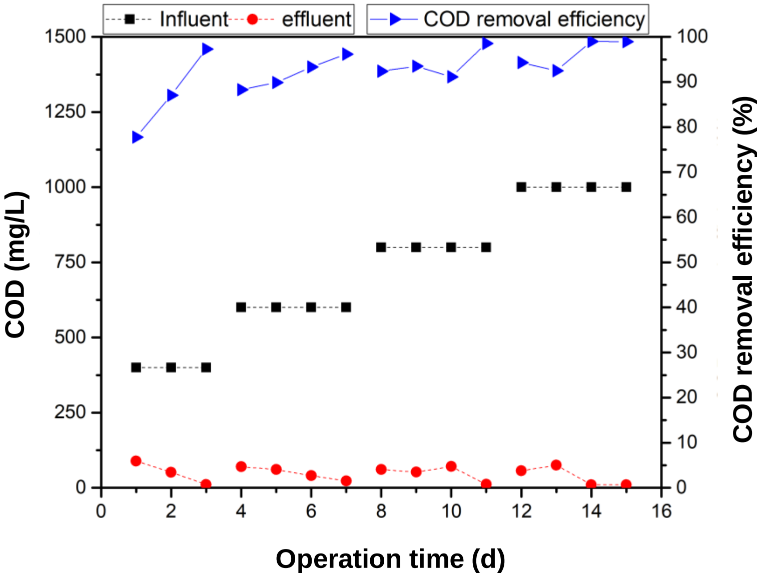
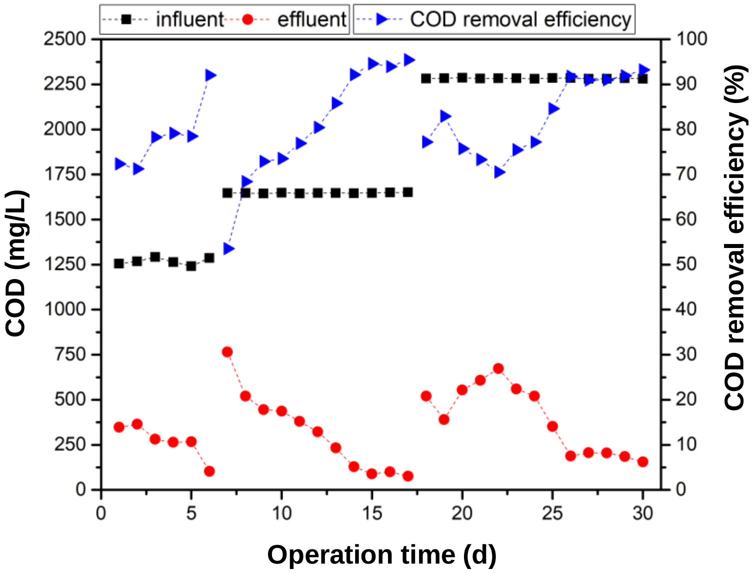


Fig. S2. Treatment results of SBR and SBBR reactor during sludge cultivation stage

After 30 days of acclimation, the influent COD concentration of SBR and SBBR was increased from 1644.48 to 2286.94 mg/L, meeting the requirements for sludge acclimation, and the removal efficiency of COD both reached approximately 93%, which means the completion of acclimation of sludge.



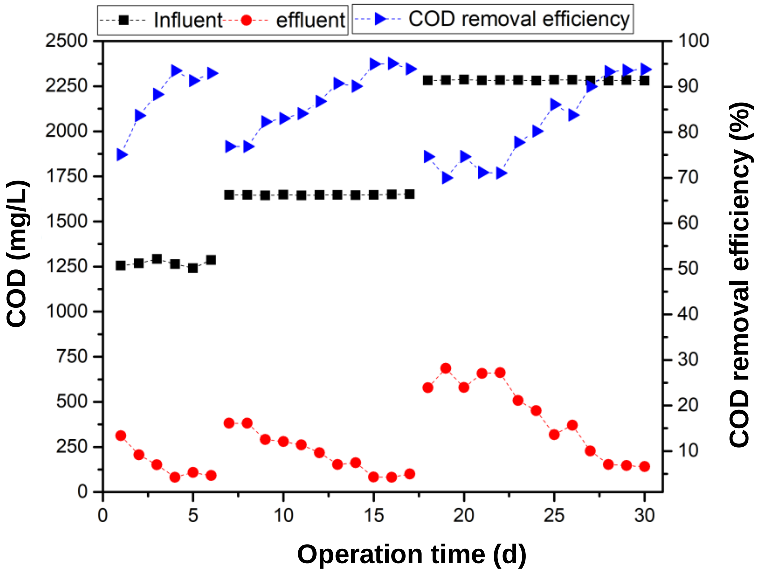
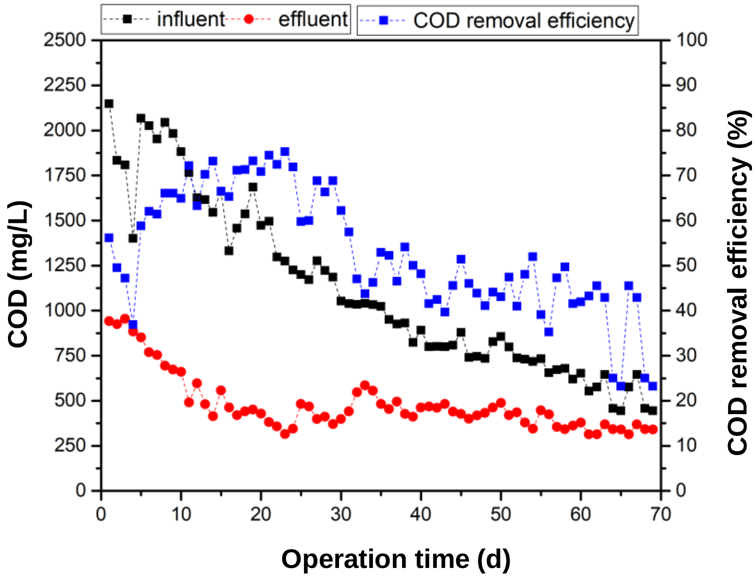


Fig. S3. Treatment results of SBR and SBBR reactor during sludge acclimation stage

The UASB effluent was added to SBR and SBBR reactor separately as the influent in the next 70 days to achieve further adaptation of the sludge. The effluent COD concentration of SBR and SBBR were decreased to 341 mg/L and 248.89 mg/L, and the reactors entered a stable stage.



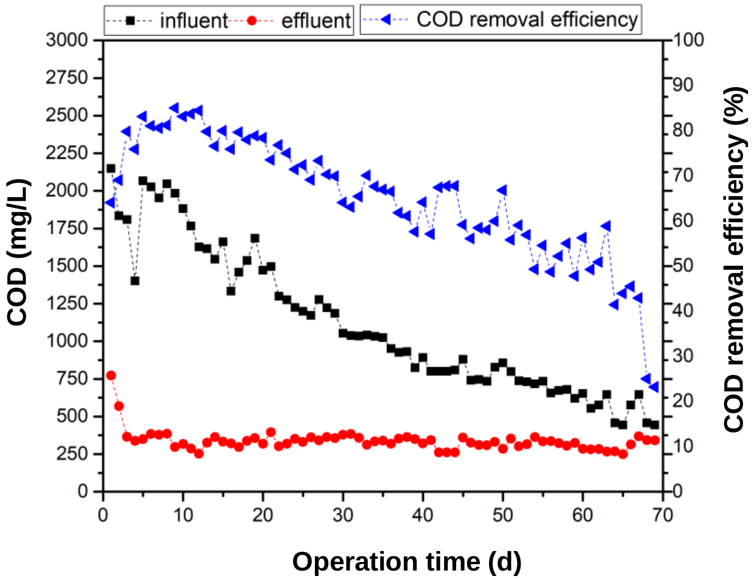


Fig. S4. Treatment results of SBR and SBBR reactor during the operation stage