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# Performance evaluation of the sulfur-redox-reaction–activated up-flow anaerobic sludge blanket and down-flow hanging sponge anaerobic/anoxic sequencing batch reactor system for municipal sewage treatment

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## HIGHLIGHTS

- $A_2SBR$ could be applicable for sulfur-redox-cycle–activated UASB–DHS systems.
- The UASB–DHS–$A_2SBR$ system consistently produced effluent with a total BOD of 8 mg $L^{-1}$.
- The UASB–DHS–$A_2SBR$ system consistently produced effluent with a TP of 0.8 mg-P $L^{-1}$ and TN of 9 mg-N $L^{-1}$.
- Anaerobic sulfur oxidation phenomena was confirmed in the UASB reactor.

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## ABSTRACT

A sulfur-redox-reaction–activated up-flow anaerobic sludge blanket (UASB) and down-flow hanging sponge (DHS) system, combined with an anaerobic/anoxic sequencing batch reactor ($A_2SBR$), has been used for municipal sewage treatment for over 2 years. The present system achieved a removal rate of 95 ± 14% for BOD, 74 ± 22% for total nitrogen, and 78 ± 25% for total phosphorus, including low water temperature conditions. Sludge conversion rates during the operational period were 0.016 and 0.218 g-VSS g-COD-removed$^{-1}$ for the UASB, and DHS, respectively, which are similar to a conventional UASB–DHS system, which is not used of sulfur-redox-reaction, for sewage treatment. Using the sulfur-redox reaction made advanced treatment of municipal wastewater with minimal sludge generation possible, even in winter. Furthermore, the occurrence of a unique phenomenon, known as the anaerobic sulfur oxidation reaction, was confirmed in the UASB reactor under the winter season.



## 1. Introduction

Conventional activated sludge treatment, commonly used to treat municipal wastewater, causes problems such as excessive generation of sludge and involves consumption of a large amount of energy. In contrast, the anaerobic biological treatment process, used mainly to treat wastewaters with medium-to-high chemical oxygen demand (COD) concentrations has a number of advantages such as low sludge production, low power consumption, and energy recovery as methane gas (Narihiro and Sekiguchi, 2007; van Lier et al., 2008). In particular, the up-flow anaerobic sludge blanket (UASB) based method has been successfully used for the treatment of industrial wastewater in medium-to-high temperature ranges (Frankin, 2001; Onodera et al., 2013b; Pattananuwat et al., 2013). In recent years, the UASB method has been applied to the treatment of sewage in tropical and subtropical countries such as India, Brazil, Colombia, Egypt, and Mexico (Alaerts et al., 1993; Seghezzo et al., 1998). However, only the anaerobic biological treatment method has been applied to sewage treatment, and thus, removal of organics, suspended solids (SS), and nutrient salts remains inadequate. Therefore, application of a post-treatment process is necessary to improve the treated water to a quality acceptable for discharge.

Several post-treatment units have been developed and applied to the UASB process (Kassab et al., 2010; Khan et al., 2011). One

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of the more promising post-treatment units is the down-flow hanging sponge (DHS) process, which is similar to a conventional trickling filter, except for the sponge media (Machdar et al., 1997; Okubo et al., 2015; Onodera et al., 2014; Tawfik et al., 2006). Recently, our research group developed an advanced wastewater treatment system comprising a UASB–DHS–anaerobic/anoxic sequencing batch reactor ($A_2$SBR) system in which the DHS method and the $A_2$SBR are combined and then applied after implementation of the UASB method (Hatamoto et al., 2015; Maharjan et al., 2014). This system achieves the basic removal of organics and SS during the initial UASB process; this is then followed by decomposition of the organics and nitrification by the DHS method, nitrogen and phosphorus are finally removed by the $A_2$SBR, in which including use of denitrifying polyphosphate-accumulating organisms (DPAOs). Thus, this system improves the treated water to a level that meets or even exceeds the quality standards of discharge water.

Treatment of sewage by the UASB method in low-temperature environments creates problems such as reduction in the removal rate of organics and SS. The cause of such problems is the decrease in activities of the methanogenic archaea, which are the final decomposer of organics during the anaerobic treatment, associated with reduction in the water temperature. The reduced performance of treatment by the UASB method leads to decline in the performance of the DHS method in terms of removal of organics and nitrification, causing a system-wide decline in treatment performance. In an attempt to overcome these problems, the implementation of a sulfur-redox-reaction–activated UASB and aerobic post-treatment system has been reported (Sumino et al., 2007; Takahashi et al., 2011b). Such a system focuses on using sulfate-reducing bacteria as an alternative to the methanogenic archaea for the removal of the organics. The results of continuous treatment of sewage using the sulfur-redox reaction–activated UASB–DHS system showed that removal rates of 95 ± 1%, 79 ± 7%, and 38 ± 8% were achieved for biochemical oxygen demand (BOD), SS, and for total nitrogen, respectively, under the following conditions: hydraulic retention time (HRT) of 12 h, treatment water temperature of 7.0 ± 2.8 °C, and influent sulfate concentration of 140 mg-S $L^{-1}$ (Takahashi et al., 2011b).

This study combined the $A_2$SBR with the sulfur-redox reaction–activated UASB–DHS system and examined its performance in continuous treatment of wastewater, based on the amount of sludge generated. In addition, the unique sulfur dynamics of the UASB reactor were also investigated.

## 2. Methods

### 2.1. Reactor setup and operational conditions

The dimensions of the UASB used in this experiment were as follows: height, 4.7 m; inner column diameter, 0.56 m; and total volume, 1178 L. The total volume of the sponge of the DHS was 454 L and its filling rate was 53%. As the sponge carrier for the DHS, cubic sponges (33 mm) were inserted into plastic net rings ($\varphi$33 mm; G 3.2. type) (Tanaka et al., 2012) and loaded into the reactor. Details of the process configuration have been described elsewhere (Onodera et al., 2013a). The $A_2$SBR was 0.86 m in height and 0.5 m in diameter, with a total volume of 200 L. A schematic diagram of UASB–DHS–$A_2$SBR system is shown in Supplementary Fig. S1.

The complete UASB–DHS–$A_2$SBR system was installed in a sewage treatment center and was operated continuously under ambient conditions (influent wastewater temperature: 9–28 °C). For the sewage supply, separated sewage was temporarily stored in a tank after passing through a coarse screen. On the 178th day after the start of the operation, sodium sulfate was added to activate the microorganisms of the sulfur-redox cycle. About 500 L of mesophilic sewage digestion sludge was used for the seed sludge in the UASB and about 50 L of active sludge was used in the $A_2$SBR. Seed was not used for the DHS. The HRTs of the reactors were as follows: 8 h for the UASB, 3.1 h for the DHS, and 12 h for the $A_2$SBR.

For the $A_2$SBR, a period of 6 h was set for one anaerobic/anoxic cycle. Anaerobic conditions were maintained for 90 min from the start of the cycle. Following the period of anaerobic conditions, 50 L of UASB–DHS-treated water was added into the reactor and stirred and mixed for 270 min under anoxic conditions. Then, the mixing was halted and sedimentation of the sludge conducted for 60 min, following which 50 L of supernatant from the reactor was discharged as the $A_2$SBR-treated water. The concentration of sludge in the $A_2$SBR was adjusted to about 2000 mg-SS $L^{-1}$ by continuous removal of excess sludge. A mixed solution of acetic acid and sodium acetate was used as the added organics to the $A_2$SBR at an amount of COD/P ratio against an inflow of phosphorus concentration of 25 g-COD/g-P. The pH of the $A_2$SBR was maintained at 7.4 ± 0.3. Details of the $A_2$SBR configuration and operational conditions have been described elsewhere (Hatamoto et al., 2015).

### 2.2. Analytical method

Samples of the sewage and UASB effluent were obtained by 24-h composite sampling and stored in tanks at 4 °C. Samples of the DHS and $A_2$SBR effluents were obtained by grab sampling. Sampled water that passed through glass-fiber filter paper with 0.4-μm size particle retention (GB-140, ADVANTEC) was used to analyze the soluble components. The analyzed items were SS, volatile suspended solids (VSS), BOD, $COD_{Cr}$, ammonium, nitrate, nitrite, total Kjeldahl nitrogen (TKN), total phosphorus (TP), sulfide, and sulfate. The values of COD, TKN, and TP were analyzed using a water-quality analyzer (DR-2800, HACH). A high-performance liquid chromatograph (LC-20-ADsp, Shimadzu) was used to measure the concentrations of sulfate, ammonium, nitrate, and nitrite. The total nitrogen (TN) concentration was calculated from the individual values measured for each type of nitrogen. Analyses of, both, the water quality in the vertical direction of the UASB reactor and the sludge samples were performed regularly. Each sample was collected from a tube installed in the UASB reactor. Samples for the measurement of sulfide concentration were collected while ensuring that air did not enter the vials, following which the solid and liquid were separated by centrifugation. Each sample was quickly transported to the laboratory, and the appropriate measurements were taken immediately. Other water-quality experiments were performed according to APHA (2005).

## 3. Results and discussion

### 3.1. Treatment performance of the UASB–DHS–$A_2$SBR system

Time courses of COD, BOD, and SS concentrations that reflect the treatment performance of the UASB–DHS–$A_2$SBR system (UASB–DHS operation days 1–980, and $A_2$SBR operation days 700–980) are shown in Fig. 1. A summary of the treatment performance of the UASB–DHS–$A_2$SBR system is also shown in Table 1. The period when the influent sewage temperature was $\geqslant$17 °C was considered summer, and the period when it was <17 °C was considered winter. The mean total BOD concentration in summer was 227 ± 115 mg $L^{-1}$ in the influent sewage, 88 ± 48 mg $L^{-1}$ in the UASB-treated water, 8 ± 8 mg $L^{-1}$ in the DHS-treated water, and 8 ± 10 mg $L^{-1}$ in the $A_2$SBR-treated water (Table 1). In contrast, the mean BOD concentration in winter was 185 ± 107 mg $L^{-1}$ in the