

Pilot-scale test of industrial wastewater treatment by UASB and MBR using a ceramic flat sheet membrane for water reuse

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ABSTRACT

A pilot plant was studied to investigate a new method for reclaiming wastewater from the industrial area of Jurong, producing high quality water from it for industrial reuse. The new process used an up-flow anaerobic sludge blanket (UASB) and a membrane bioreactor (MBR) with a submerged ceramic flat sheet membrane. The feedwater from the chamber with the industrial wastewater was high in chemical oxygen demand (COD), which varied between 644 and 2,380 mg L⁻¹ and had a pH range of 6.7–7.1. The MBR process was operated in series at a flux of 18–25 Lm⁻² h⁻¹ for 100 days. The average COD and the biological oxygen demand of products of the above system were 155 and 9 mg L⁻¹, respectively. The results of this study indicated that a UASB-ceramic MBR process was capable of stably producing high quality water for industrial reuse from industrial wastewater.

Key words | ceramic membrane, industrial wastewater, MBR, UASB, wastewater recycling

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INTRODUCTION

Typical industrial wastewater is only minimally treated to reduce the release of pollutants into the environment before it is released to the municipal wastewater treatment stream. The Jurong Water Reclamation Plant (JWRP) in Singapore currently discharges water after using a conventional activated sludge process on the industrial wastewater it receives. A membrane bioreactor (MBR) process, which

can produce high quality water from municipal wastewater, has been in development for over 15 years (van der Roest *et al.* 2002; Tao *et al.* 2005) and some large-scale MBR systems have been operated by the Public Utilities Board (PUB) of Singapore since optimization was completed (Tao *et al.* 2009). A ceramic membrane was used in an MBR to treat municipal wastewater with high flux during a pilot scale study (Noguchi *et al.* 2010). The implementation pilot study of industrial wastewater using an aerobic MBR was carried out by PUB at JWRP with mixed sewage mostly from industrial sources, and it indicated that producing suitable water with a minimum

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aerobic hydraulic retention time (HRT) of 15 h with 17 LMH of flux was possible (Qin *et al.* 2007).

However, the reclamation of industrial wastewater was still a challenge because of the effect of high strength contaminants. Researchers investigated and compared different reclamation methods (Chan *et al.* 2009), some of which were then applied to industrial wastewater treatment such as anaerobic MBR (Lin *et al.* 2013), aerobic MBR (Mutamim *et al.* 2012), and UASB + MBR (Buntner *et al.* 2013). A majority of high strength wastewater has been successfully treated by an MBR, but fouling was a concern because of the sensitive nature of polymer membranes (Mutamim *et al.* 2012). Then, ceramic membranes were used to treat industrial wastewater because they perform well during filtration due to their high chemical resistance, inert nature and ease of cleaning, unlike the polymer membranes (Jin *et al.* 2010).

The industrial wastewater consisted of water discharged from over 300 factories including food, beverage, and pharmaceutical varieties. In the Jurong area, this mixture produces high strength waste containing solvents, oil, and chemicals, resulting in high chemical oxygen demand (COD). The up-flow anaerobic sludge blanket (UASB) process was effective in treating typical industrial wastewater and when used in combination with an aerobic MBR was capable of producing water of high enough quality for industrial reuse (Chen *et al.* 1994, 2008). Anaerobic processes, such as UASB, work well to produce methane gas by reducing the biological oxygen demand (BOD) and COD in the feedwater and emitting excess sludge for volume reduction as well as anaerobic digestion. The subtropical weather in Singapore encourages the activity of the anaerobic bacteria in a UASB reactor without any additional heating. However, treatment was still required after the UASB process to reclaim the water for industrial reuse. Pilot test results for MBR systems with a ceramic membrane submerged in the membrane tank treating the effluent from the UASB process showed that these two systems worked well together to treat industrial wastewater (Farajzadehha *et al.* 2011).

However, reclaiming mixed industrial wastewater by using a UASB in conjunction with a ceramic MBR is implemented infrequently because ceramic membrane technology is still relatively new. Few papers and implementation projects applying this process for reclaiming industrial wastewater exist. Thus, the spread of this combined technology for

use in industrial areas was hindered, and therefore we decided to carry out this study.

The objective of this study was to determine the feasibility of reclaiming industrial wastewater for industrial reuse by UASB and aerobic ceramic MBR processes in series, while reducing energy consumption, sludge production, and the HRT of the entire process. The pilot plant employed a combined method of a UASB and ceramic MBR. The feedwater for the pilot plant was taken only from the industrial wastewater (Phase 3) at JWRP. This raw water is industrial wastewater, its COD is high and varies more than that of domestic wastewater. The ceramic MBR improved the quality of the MBR product because ceramic membranes remove suspended materials without incurring any damages from chemicals or emulsion oil. To maximize these effects, we aimed to determine the operation parameters of this process in a pilot plant.

MATERIALS AND METHODS

Equipment

The experiments were conducted on a pilot scale by using a UASB in conjunction with a ceramic MBR. A schematic flow diagram of the pilot plant is shown in Figure 1. The configuration of the anaerobic bioreactor was a UASB with a gas and liquid separator in the upper section of the reactor to prevent biomass washout. The UASB had a working volume of approximately 2.0 m³ with an internal diameter of 0.75 m and a height of 4.5 m. The equalization tank (EQT) had a working volume of approximately 1.0 m³ and was installed upstream of the UASB to stabilize certain fluctuations in the feedwater. Effluent from the UASB reactor was fed to the ceramic MBR.

A progressive cavity pump provided the up-flow velocity from the EQT to the UASB. The ceramic MBR had two parts: the aeration tank with a working volume of approximately 0.3 m³ and the membrane tank with a working volume of approximately 0.15 m³. A ceramic, flat sheet membrane test unit with a working surface area of approximately 2.3 m² was installed in the membrane tank. The specifications of the ceramic, flat sheet membrane used

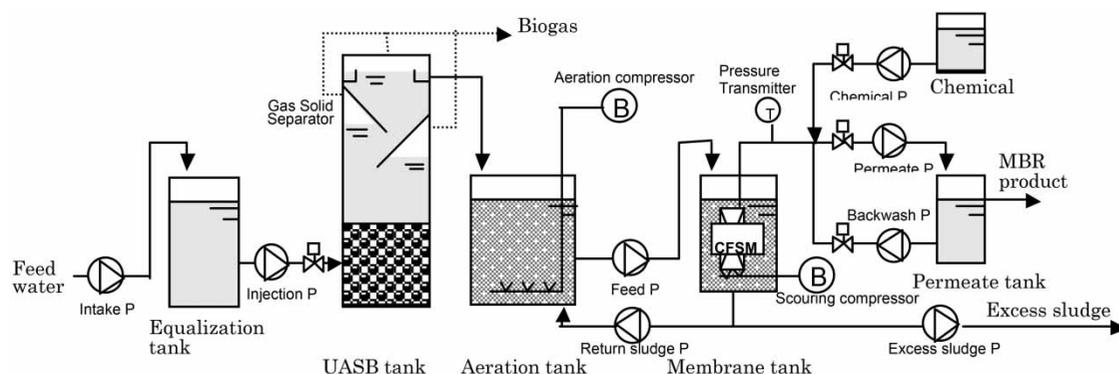


Figure 1 | Processing flow of demonstration plant.

throughout this study are shown in Table 1. The UASB granules used were industrial food grade.

The filtration flow of the ceramic MBR was controlled by a progressive cavity pump and measured by a flow meter. The backwash pump was installed on a separate line of the permeate tank. Two compressors were installed, one to aerate the aerobic biological process and one to scour the ceramic membrane unit with air. The flux of the ceramic MBR was controlled by a variable speed drive with a progressive cavity pump located on the permeate side.

Feedwater characteristics

The industrial wastewater contained solvents, oil, and chemicals and was obtained from the existing distribution chamber (DBC) of Phase 3 at JWRP. The industrial wastewater came from factory discharge waste including food, beverage, and pharmaceutical facilities located in the industrial area of Jurong. The typical characteristics of the feedwater flowing into the UASB are listed in Table 2. Because the feedwater has a large variation in water quality that was more homogenized in the EQT, located upstream of the UASB, it is more homogenized than that in the existing DBC.

Table 1 | Ceramic membrane specifications

Membrane type	Meiden CFMS Appearance: Flat sheet Filtration: Submerge type, Out-In filtration Material: Ceramics (α alumina)
Specifications	Nominal Pore size: 0.1 μm

During this study, the raw feed flowing into the UASB had concentration ranges of total COD and BOD of 664–2,380 and 265–1,035 mg L^{-1} , respectively; temperatures of 26–32 $^{\circ}\text{C}$; and pH of 6.6–7.8. The BOD/COD ratio in the feedwater varied from 0.28 to 0.84, indicating a large fluctuation in the concentrations of non-biodegradable chemicals and biodegradable biomass.

Pilot plant operation

The pilot trials were carried out over three months, from February 27 to May 31, 2012, after steady UASB and ceramic MBR operation.

The UASB was operated at a fixed flow rate of 0.25 $\text{m}^3 \text{h}^{-1}$ and maintained most of the biomass with a mixed liquor suspended solids (MLSS) concentration of 39,000–52,000 mg L^{-1} . The ceramic MBR as a ceramic membrane test module is characterized by an effective surface area of 2.35 m^2 with a stable sludge MLSS concentration range of 4,500–12,000 mg L^{-1} . Dissolved oxygen (DO) concentration of the MBR was maintained at 0.1–2.9 mg L^{-1} . A level control sensor controlled the liquid levels in each reactor. The flux of the ceramic membrane was maintained between 18.0 and 25.0 LMH, and the scouring aeration was carried out continuously at a flow rate of 110 L min^{-1} . Specific aeration demand (SAD) for the membrane at this flow rate was 16 $\text{m}^3 \text{air/m}^3 \text{permeate}$ when the ceramic flat sheet membrane was applied with a height of 5 m for the scaled-up treatment plant. A 10-min backwash cycle consisted of 9.5 min of permeate period and 0.5 min backwash period and backwash was applied with a flow rate twice the filtration rate (2Q). Chemical cleaning was conducted online twice a

Table 2 | Water quality data

	Raw feed		UASB effluent		MBR product		Target quality
	Average \pm SD	Minimum–maximum	Average \pm SD	Minimum–maximum	Average \pm SD	Minimum–maximum	
Total COD _{Cr} (mg L ⁻¹)	1,152 \pm 461	644–2,380	632 \pm 313	252–1,470	155 \pm 103	66–439	<150
Soluble COD _{Cr} (mg L ⁻¹)	764 \pm 454	384–2,056	438 \pm 259	178–1,165	155 \pm 103	66–439	NA
BOD ₅ (mg L ⁻¹)	554 \pm 230	265–1,035	258 \pm 124	133–583	9 \pm 21	<1–78	<10
TSS (mg L ⁻¹)	294 \pm 139	186–703	158 \pm 97	55–402	<1	<5.0	
Total nitrogen (mg L ⁻¹)	83 \pm 32	37–145	76 \pm 37	18–145	43 \pm 33	3–110	NA
Total phosphorus (mg L ⁻¹)	56 \pm 14	33–76	52 \pm 10	38–71	36 \pm 20	5–65	NA
Sulfate as S (mg L ⁻¹)	164 \pm 60	27–280	21 \pm 17	2–55	136 \pm 44	23–220	NA
pH (-)	7.10 \pm 0.23	6.68–7.69	7.27 \pm 0.22	6.57–7.80	7.37 \pm 0.49	5.70–7.90	6.5–8.5
BOD/COD (%)	51 \pm 23	28–98	46 \pm 23	18–98	6 \pm 11	2–39	NA

SD, standard deviation; NA, not available.

week with 200 mg L⁻¹ sodium hypochlorite during continuous operation.

Analytical methods

During this study, representative samples of raw feedwater, EQT water, UASB effluent, and MBR permeate were collected from fixed sampling sites between 9 and 10 a.m. daily for the COD analysis. DO, pH, and ORP were measured at the same sites daily. Transmembrane pressure (TMP) was measured by a digital pressure sensor (Azbil, JTD930A), and the flow rates of feed, permeate, and backwash water were measured by an electromagnetic flow sensor (Azbil, MTG11A). MLSS was measured for the mixed liquor of the activated sludge from the membrane tank. The EQT, UASB effluent, and MBR permeate samples were analyzed for COD and BOD. All the water quality analysis was performed according to standard methods (APHA 2005).

RESULTS AND DISCUSSION

UASB performance

The COD and BOD concentration of the UASB influent varied from 644–2,380 to 265–1,035 mg L⁻¹, respectively, during the 100 days of operation (Table 2), resulting in

COD loading rates in the range of 1.0–3.3 kg m⁻³ d⁻¹. During this study, the temperature of the feedwater was in the range of 26–32 °C and feedwater pH ranged from 6.6 to 7.8. The BOD/COD ratio in the feedwater varied from 0.28 to 0.98, indicating high fluctuation in the concentrations of non-biodegradable chemicals and biodegradable biomass. The concentrations of COD and BOD are given in Figure 2. During the startup period, effluent water quality was stable and the UASB produced gas as expected. The concentration of COD and BOD in the UASB effluents were in the range of 252–1,470 mg L⁻¹ and 133–583 mg L⁻¹, respectively, corresponding to COD and BOD removal rates of 15–73 and 9–75%, respectively. The pH of the UASB effluent ranged from 6.6 to 7.8. Gas generation in the UASB was observed for several days after the raw water was supplied to it. The average biogas production rate was 484 L/d⁻¹. The generated gas was analyzed and found to be 68% (average) methane after passing through the desulfurizer, which indicated decomposition of organic matter by methane fermentation. The profiling data of the granular sludge in the UASB tank during the startup period is shown in Figure 3. After two months of operation, the sludge volume index increased slightly, yet appropriate granular sludge was maintained in the UASB reactor. The UASB biodegraded properly during this operation, meaning no prohibitive materials were present in the UASB feed. Thus, a UASB reactor could be applicable for the treatment of industrial

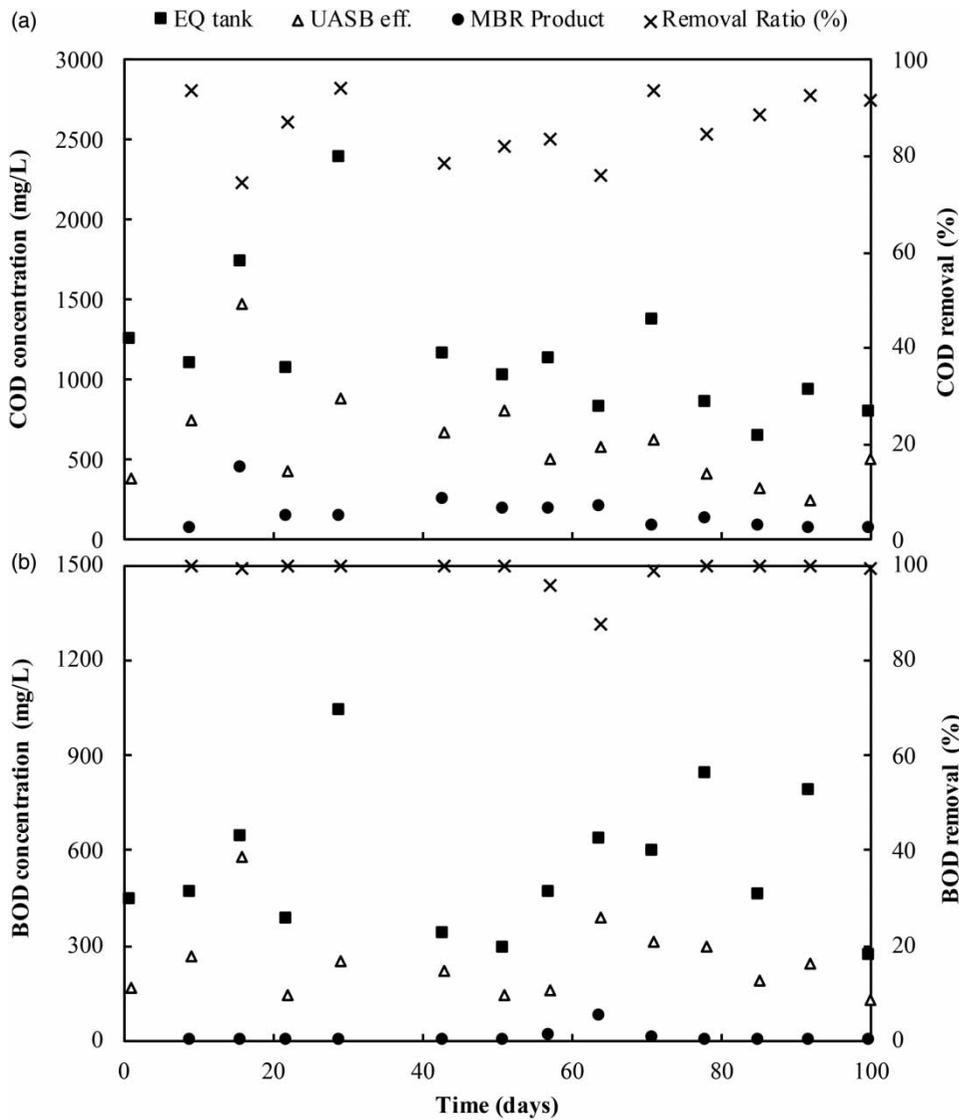


Figure 2 | Variation in concentrations and removal ratios of COD (a) and BOD (b).

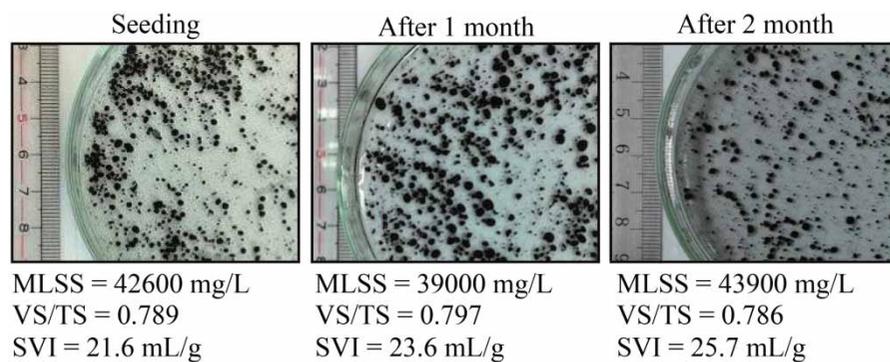


Figure 3 | Granular sludge profiles from the UASB tank.

wastewater. The COD mass balance is shown in Figure 4. Sixty percent of the removed COD was converted to methane.

MBR performance

The range of the COD of the MBR influent (the UASB effluent) and MBR product fluctuated between 252–1,470 and

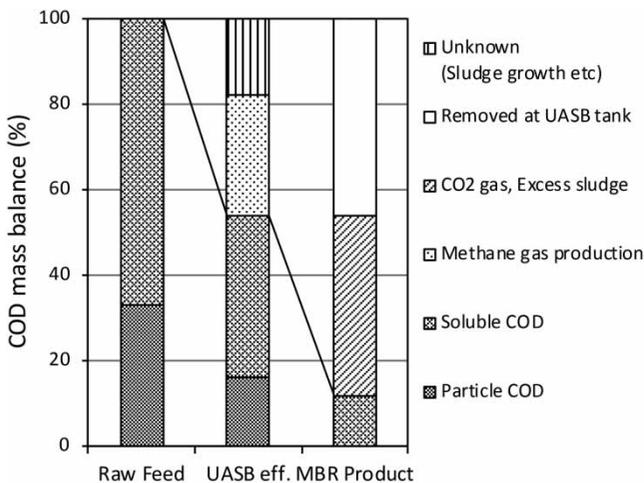


Figure 4 | COD mass balance analysis.

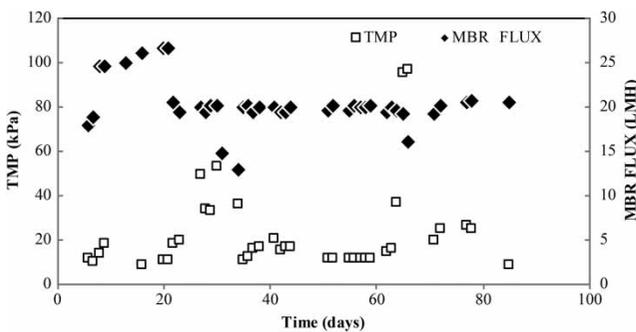


Figure 5 | Variation of TMP and flux.

66–439 mg L⁻¹, respectively, in the 100-day test period (Table 2). The COD removal rate by the UASB combined with a ceramic MBR was calculated from the COD of the EQT and MBR permeate and found to be 69–94%. The quality of the effluent was high enough for it to be reused as industrial water. During continuous operation for 100 days, MLSS in the membrane tank was maintained between 6,000 and 12,000 mg L⁻¹ by purging of excess sludge, and the pH ranged from 5.7 to 8.5 in this study. These results indicated that a ceramic membrane flux of 21–25 LMH, which was higher than values previously observed in an aerobic MBR (17 LMH), was sustainable downstream of the UASB (Buntner et al. 2013).

The TMP of the MBR was stable at 2–10 kPa when the MBR was operated at a membrane flux of 18–25 LMH during the first 30 days of operation (Figure 5). However, the TMP increased rapidly after the granule sludge flushed out from UASB reactor and MLSS of aeration tank increased too high. The MBR was restarted with 21 LMH flux after a clean in place (CIP) was performed on day 34. Filtration stabilized after day 40. Sodium hypochlorite was used for the CIP. The TMP results were in the range of 2–10 kPa during operation and a weekly CIP was conducted online. During the ceramic membrane filtration process, 10 min cleaning cycles with 9.5 min of filtration followed by 0.5 min of backwash without chemicals were carried out periodically.

UASB + MBR or MBR systems treating high strength municipal wastewater or industrial wastewater were reported previously. Table 3 shows a comparison of this system and other systems.

The application of UASB with ceramic MBR is comparable with other similar process to treat industrial wastewater. The UASB contributed to reduce energy and

Table 3 | UASB and MBR application in industrial wastewater and high strength municipal wastewater

Water source	Process (HRT)	COD removal (UASB) (%)	MBR flux	Reference
Various industries	UASB + MBR (14)	94 (69)	21–25 LMH	This study
Various industries	MBR (15)	68–89 (NA)	17 LMH	Tao et al. (2009)
High strength municipal	UASB + MBR (4–6)	98 (73–85)	–	Farajzadehha et al. (2011)
Dairy wastewater	UASB + MBR (20)	99 (66–85)	13–19 LMH	Buntner et al. (2013)
Petrochemical wastewater	MBR (13)	94–96 (NA)	12.5 LMH	Jian-Jun et al. (2007)

sludge production compared with an aerobic MBR process theoretically, and this implementation determined that UASB with a ceramic MBR system using the above operation parameters is suitable to treat mixed industrial wastewater to produce good quality water as industrial water.

CONCLUSIONS

The conclusions from this pilot study are summarized as follows:

- (1) No prohibitive materials to the UASB were observed in this study.
- (2) The EQT and UASB adsorbed a majority of the fluctuation of the COD of the influent water.
- (3) The membrane flux of 21–25 LMH was sustainable in this MBR process.
- (4) The combined UASB and ceramic MBR process achieved target water quality from industrial wastewater.

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