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Performance Evaluation of Anaerobic Bioreactors and Effects of Ammonia on Anaerobic Digestion in Treating Swine Wastewaters

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ABSTRACT: The operational characteristics of anaerobic bioreactors in treating swine wastewater were evaluated upto hydraulic retention time (HRT) of 1 day and organic loading rate (OLR) of 5.1 kg-COD/m^3·d for 200 days. The bioreactors were effective in treating swine wastewaters with COD removal efficiency of 78.9~81.5% and biogas generation of 0.39~0.59 m^3/kg-COD_r at OLR of 1.1~2.2 kg-COD/m^3·d. The two-stage ASBF anaerobic bioreactors was effective in treating different characteristics of swine wastewaters since they showed high and stable COD removal efficiency at high OLR due to effective retention of biomass by media and staging. The effects of ammonia on anaerobic digestion were investigated by operating two-stage ASBF reactors using swine wastewaters as influent without and with ammonia removal at HRT of 1~2 days and OLR of 2.2~9.6 kg-COD/m^3·d for 250 days. The COD removal efficiency and biogas generation of two-stage ASBF reactors was decreased by increasing influent ammonia concentrations to 1,580 mg (T-N)/L with increasing OLR to 6.3 kg-COD/m^3·d, while those were increased by maintaining influent ammonia concentrations below 340 mg (T-N)/L by MAP precipitation with increasing OLR to 9.6 kg-COD/m^3·d. Initial inhibition of ammonia on anaerobic processes was observed at a concentration of 760 mg (T-N)/L and the COD removal efficiency and biogas generation dropped to 1/2 at ammonia concentration ranges of 1,540~1,870 mg (T-N)/L. It is essential to remove ammonia in swine wastewaters to an initial inhibition level before anaerobic processes for the effective removal of COD.

Key Words: swine wastewater, anaerobic bioreactor, biogas, COD, ammonia

INTRODUCTION

Anaerobic digestion is known to be effective in treating high strength organic industrial wastewaters. It produces methane (biogas) as a by-product and less sludge production while stabilizing organic materials. However, the process has major disadvantages due to unstable nature as well as its large facility requirement due to the diversity and slow growth of the microbial communities involved in the process. Recent advancements in anaerobic biotechnology make it possible to maintain high concentrations of biomass in bioreactors leading to the development of high-rate processes, such as upflow anaerobic sludge blanket (UASB)[1], anaerobic filter (AF)[2], anaerobic sludge blanket filter (ASBF) which is a hybrid of UASB and AF[3], and phase separation[4] that have been operated at stable conditions and at high organic loading rates in full-scale industrial installations[5]. The process performance and operation conditions of bioreactors depend on the relative concentrations of soluble and suspended organics in substrates since the bioreactors maintain high biomass concentrations.

Swine wastewaters in Korea have been a major source of contamination in rural areas and have proved to be difficult tasks for environmental engineers because they contain high concentrations of soluble as well as suspended organic materials and T-N and T-P as nutrients, depending on the types of pig raising facilities and the seasons[3]. Therefore it is necessary to

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perform a comparative study for each high-rate anaerobic process using swine wastewaters.

Ammonia is known to exert inhibition or toxic effects to anaerobic bacteria. T-N in swine wastewaters which is consisted of 90% as NH_4^+-N and 10% as org-N, ranged 120~4,500 mg/L. Ammonia in water exists in the form of NH_3 or as NH_4^+ depending on pH (pKa = 9 at 35℃) and NH3 is reported responsible for ammonia inhibition. Ammonia inhibition to anaerobic bacteria has been reported by many authors in the literature[6-8]. Threshold inhibition occurred at 1,700~1,800 mg/L as NH_4^+-N, fatal inhibition at 1,500~3,000 mg/L as NH_4^+-N, and complete inhibition at >3,000 mg/L as NH_4^+-N. However long-term experimental study[9] at a pilot scale revealed that the activity of anaerobic bacteria was recovered at NH_4^+-N concentration of above 4,000 mg/L from a fatal inhibition.

The specific objectives of this study were to evaluate the performance of three different types of lab-scale anaerobic bioreactors, UASB, AF and ASBF, in treating swine wastewaters. The application of these high-rate bioreactors depends on the characteristics of substrates to be anaerobically digested, specially the relative concentration of soluble and suspended organics in wastes. Therefore the process performance and operation conditions of these high-rate bioreactors have to be evaluated for biogasfication of organic fraction of agricultural wastes. The effects of ammonia on anaerobic bacteria for effective biogasification were also evaluated using the two-stage ASBF bioreactor. In the ammonia effects study the two-stage ASBF was used since it maintained high concentrations of active biomass in the form of suspended and attached growth and showed as an effective bioreactor for the treatment of swine wastewaters at high organic loading rate (OLR) and short hydraulic retention time (HRT). The influent of the two-stage ASBF for the ammonia effects study was swine wastewater that ammonia has been removed by MAP (magnesium ammonium phosphate, $MgNH_4PO_4$) precipitation method[10].

METERIALS AND METHODS

Performance Evaluation of Anaerobic Bioreactors

Three lab-scale anaerobic bioreactors, UASB, AF packed with pall rings, and two-stage ASBF, were setup for performance evaluation in treating swine wastewaters as shown in Fig. 1. The bioreactors were made up of acrylic cylinders with a cross-section area of 63.6 cm^2. The UASB and AF were 120-cm long with an effective volume of 6.8 L, and the two-stage ASBF were made up two cylinders, a 30-cm for acid

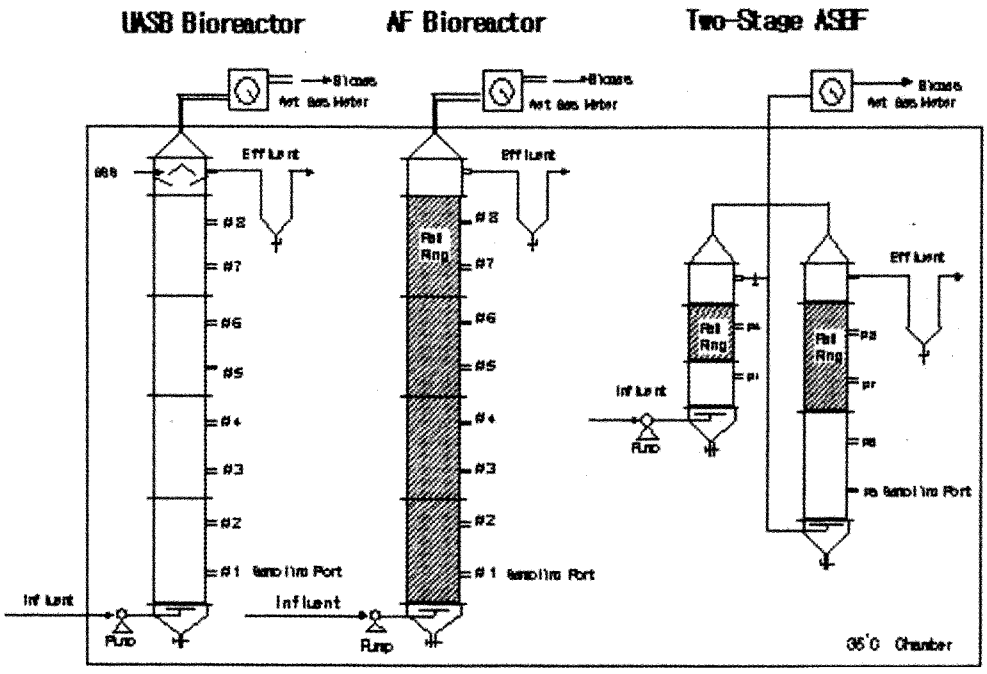

Fig. 1. Schematics of high-rate anaerobic bioreactors for performance evaluation.

fermentation and a 60-cm for methane fermentation. The AF was packed full with pall rings but only the top half of the ASBF was filled. The swine wastewater had the following characteristics: COD 18,400 (8,000~44,000) mg/L, SS 5.900 (1,870~11,200) mg/L, TN 3,000 (650~5,400) mg/L and TP 350 (150~610) mg/L. The swine wastewaters were used as an influent into the three bioreactors after dilution according to operating conditions, i.e., given OLR and HRT. All bioreactors were seeded with 2 L of anaerobic digester sludge (MLSS, 24,400 mg/L) from a sewage treatment plant. The bioreactors were operated at increasing OLR up to 5.1 kg/m^3·d as shown in Table 1 while achieving steady-state at each phase.

Ammonia Effects on Anaerobic Bioreactors

Two sets of two-stage ASBF bioreactors were formulated for the effects of ammonia as shown Fig. 2. The bioreactors were made up of glass cylinders with a cross section area of 268 cm^2. The 1st-stage bioreactor was 65-cm long and the 2nd-stage 130-cm long with an effective volume of 10 L and 20 L, respectively. The two-stage ASBF bioreactors were also filled with pall ring. Removal of ammonia in swine wastewater was achieved by adding $MgCl_2$ as a Mg source and H_3PO_4 as a P source to obtain Mg:NH_4^+-N:P molar ratio of 1.2:1:1 at pH 8.5[10]. After precipitation of MAP for 30 min, the supernatant was adjusted to pH 8.5 with NaOH. Analysis of the

Table 1. Operational condition of anaerobic bioreactors in treating swine wastewaters

Period	Operating Period (days)	OLR (kgCOD/m^3·d)	HRT (days)	Influent Concentrations (mg/L)			
				COD	VFAs	T-N	T-P
Phase I	41-55	1.1	2	2,200 (1,900~2,260)	1,040 (900~1,100)	390 (370~400)	300 (140~310)
Phase II	56-84	2.2	2	4,390 (2,100~4,820)	1,460 (400~2,370)	800 (480~950)	290 (190~330)
Phase III	85-137	3.8	1	3,780 (2,100~4,820)	1,300 (390~2,390)	760 (670~840)	270 (220~460)
Phase IV	138-200	5.1	1	5,130 (4,430~9,070)	1,620 (60~2,350)	1,310 (890~1,870)	350 (290~360)

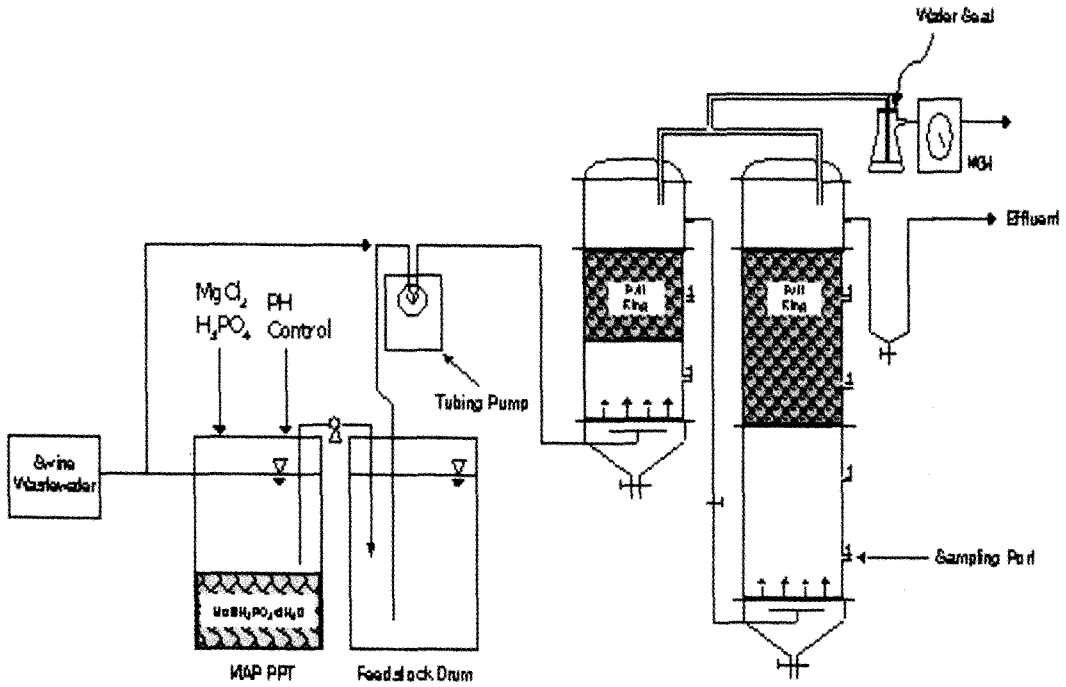

Fig. 2. Schematics of two-stage ASBF for ammonia effects using influent without (ASBF-SW) and with removal of ammonia (ASBF-SWAR) from swine wastewaters.

Table 2. Operational condition of two-stage ASBF in treating swine wastewater with (ASBF-SW) and without removal of ammonia (ASBF-SWAR)

Reactors	Periods	Operation Period (days)	OLR (kg-COD/m^3·d)	HRT (days)	Influent Concentrations (mg/L)			
					COD	VFAs	T-N	T-P
ASBF-SW	Acclimation	0-55	1.1	2	2,200	1,040	400	310
	period I	56-84	2.2	2	4,490	1,460	480	290
	period II	85-137	4.1	1	4,100	1,340	760	270
	period III	138-253	6.3	1	6,310	1,580	1,310	350
ASBF-SWAR	Acclimation	0-56	4.8	2	9,600	2,700	530	400
	period I	57-128	2.4	2	4,800	1,930	340	90
	period II	129-156	4.8	1	4,800	2,660	160	82
	period III	157-250	9.6	1	9,600	2,850	320	60

supernatant showed that 90% of T-N, 80% of T-P and 80% of SS were removed; however, the concentration of soluble COD was not affected by MAP precipitation.

The seeding and acclimation of the bioreactors were performed as described performance evaluation section. The swine wastewater used in performance evaluation section was also used in the ammonium effects study. The one set of the two-stage ASBF received swine wastewater as an influent (ASBF-SW) and the other set received swine wastewater that ammonia was removed (ASBF-SWAR). The two-stage ASBF bioreactors were operated at increasing OLRs up to 9.6 kg/m^3·d for 250 days as shown in Table 2 while achieving steady-state at each phase.

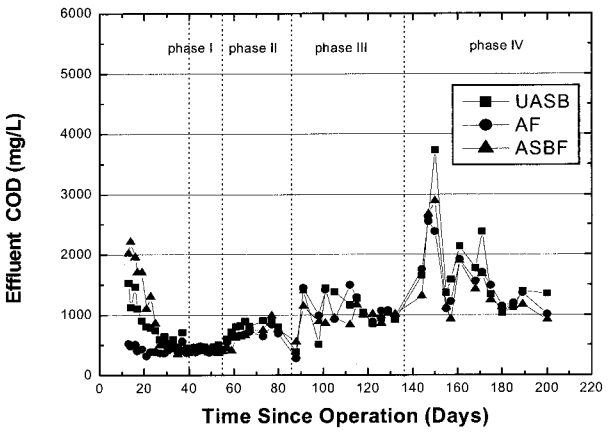

Fig. 3. Effluent COD of high-rate anaerobic bioreactors in treating swine wastewaters.

Performance Evaluation of Bioreactors

The operational characteristics and performance evaluation of anaerobic bioreactors were evaluated by taking influent and effluent samples from the bioreactors at 2~4 day-intervals. The samples were analyzed for COD, SS, VSS, T-N, T-P, VFAs (Volatile Fatty Acids as Acetate), alkalinity and pH according to the method recommended by APHA[11]. The biogas production rate and composition was monitored everyday using wet gas meter (W-NK-0.5A, Shinagawa) and GC-FID (14B, Shimazu) equipped with Hayesep Q stainless steel column, respectively.

RESULTS AND DISCUSSION

Performance of Anaerobic Bioreactors

The effluent COD of the UASB, AF and ASBF bioreactors at various OLR is illustrated in Fig. 3. During the 40-days of start-up period, AF was acclimated first followed by ASBF and UASB. This result can be explained by the biomass holding capability of the packing media. The effluent COD of the three bioreactors did not show significant differences in efficiency and maintained stable values of 370~500 mg/L during phase I and 410~990 mg/L during phase II with corresponding high COD removals of 77~83% and 79~91%, respectively. The effluent COD at phases III and IV ranged widely 280~640 mg/L and 940~3,740 mg/L with corresponding COD removals of 53~94% and 24~94%, respectively. The low efficiency at phases III and IV may result from the fact that the bioreactors were operated under lower HRT and higher OLR compared with those of phases I and II. The negative effects of HRT and OLR on the performance were high in UASB but low in AF and ASBF suggesting that both AF and ASBF are relatively reliable at higher OLR than UASB.

The effluent T-N of the UASB, AF and ASBF bioreactors at various OLR are illustrated in Fig. 4. The T-N in the effluent of the bioreactors showed similar

concentrations with those in the influent. The COD removal efficiency was higher and stable during phase I~II with T-N range of 370~800 mg/L. However, the efficiency was decreased as T-N increased to 760~1,310 mg/L during phase III~IV. The T-N is equivalent to 70~120 mg/L as ammonia at pH 8 and 35℃, which is an enough concentration range for exerting inhibition to anaerobic bacteria. When the influent T-N increased to 1,570 mg/L at 144-days operation, the COD removal efficiency decreased sharply to less than 50%. The results strongly suggest that the T-N in swine wastewater be enough to exert inhibition to anaerobic bacteria, resulting in a decrease of COD removal efficiency as well as biogas production.

The COD removal efficiency was approximately 60% within the bottom 10 cm and increased to 75% at the top (effluent) of the bioreactors as shown in Fig. 5. The large extent of COD removal at the bottom of the bioreactors is due to high concentrations of biomass. Tay *et al.*[12] observed similar results with packed-bed bioreactors. ASBF with similar biomass concentration at bottom showed high COD removal efficiency and large CH_4 production at relatively high OLR as shown in Table 3. The biomass at bottom of the 2nd bioreactor of ASBF can be used as a buffer in case of organic shock load and/or toxic influent. The COD removal efficiency of the bioreactors at steady state operation were similar to each other but decreased slightly with increasing OLR as summarized in Table 3.

The COD removal efficiency and biogas production of the UASB, AF and ASBF at steady state were presented in Table 3. High levels of the COD removal efficiency were observed for all the bioreactors during the entire operational periods. The increase of influent COD to the bioreactors by decreasing HRT or increasing OLR resulted in decrease in the COD removal efficiency. CH_4 production per COD removed in UASB was 0.26, 0.25 and 0.29 m^3/COD_r at phases I, II and III, respectively, showing higher levels than those of AF and ASBF. At the high OLR of phase IV, UASB showed 0.32 $m^3/CODr$, lower than both AF and ASBF of 0.37 $m^3/CODr$. The results strongly suggest that UASB can be efficient at low OLR operation while both AF and ASBF can be efficient at high OLR operation for the treatment of swine wastewaters as well as for production of biogas from the organic materials in swine wastewaters.

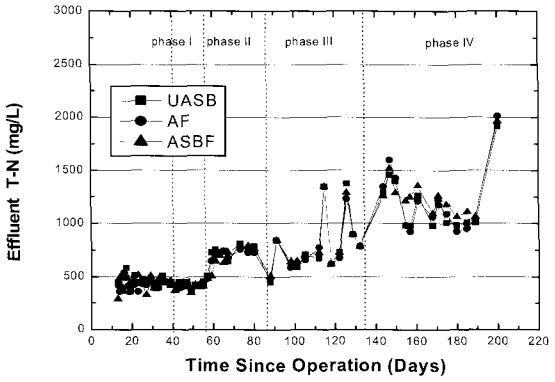

Fig. 4. Effluent T-N of high-rate anaerobic bioreactors in treating swine wastewaters.

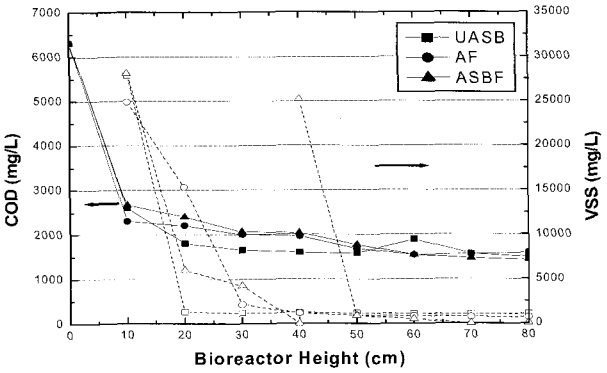

Fig. 5. COD and biomass (VSS) profile throughout bioreactors at HRT 1 day and OLR 5.1 kg/ m^3-d (dotted line for VSS).

Table 3. Performance comparison of anaerobic bioreactors in treating swine wastewaters

	Phase I		Phase II		Phase III		Phase IV	
	COD Removal Efficiency(%)	Biogas Production ($m^3/kgCOD_r$)	COD Removal Efficiency(%)	Biogas Production ($m^3/kgCOD_r$)	COD Removal Efficiency(%)	Biogas Production ($m^3/kgCOD_r$)	COD Removal Efficiency(%)	Biogas Production ($m^3/kgCOD_r$)
UASB	78.9	0.56	81.3	0.62	76.7	0.73	76.2	0.81
AF	81.3	0.59	83.8	0.54	78.6	0.65	74.7	0.93
ASBF	81.5	0.39	82.2	0.37	78.8	0.68	77.2	0.94

Effects of Ammonia Removal from Swine Wastewaters

The effluent COD of the ASBF-SW and ASBF-SWAR (ammonia removal) is illustrated in Fig. 6. A decreasing tendency of the COD removal efficiency was observed while increasing OLR for ASBF-SW. The effluent COD of ASBF-SW at phase III was 2,500 (920~4,910) mg/L with the removal efficiency of 60.4 (37.6~85.9) %. However, ASBF-SWAR showed an increasing COD removal efficiency while increasing OLR. The effluent COD of ASBF-SWAR at phase II was 2,030 (1,740~4,500) mg/L with the removal efficiency of 71.3 (68.0~77.2) %. The results suggest that the removal of T-N in swine wastewater increase the COD removal efficiency as well as biogas production. Therefore, the removal of ammonia in swine wastewater is essential for the effective operation of the two-stage ASBF in treating swine wastewater upto OLR of 10 kg-COD/m^3·d.

The effluent T-N of ASBF-SW and ASBF-SWAR at various OLR is shown in Fig. 7. The T-N in the influent of ASBF-SW increased from 480 mg/L to 1,850 mg/L during phase I to III, respectively. As the T-N concentration increased, the COD removal efficiency decreased and unstable, suggesting the ammonia inhibition has occurred. The T-N concentration of ASBF-SWAR maintained at 160~340 mg/L during the entire operation period and did not present inhibition as evidenced by the COD removal efficiency.

The COD removal efficiency and biogas production of ASBF-SW and ASBF-SWAR at steady state were presented in Fig. 8. In case of ASBF-SW, the COD removal efficiency decreased and the biogas production increased while the OLR increased. However, the ASBF-SWAR showed that the COD removal efficiency as well as biogas production increased when the OLR increased. When the OLR of the two-stage ASBF bioreactors increased, the COD removal efficiency of ASBF-SW deceased but that of ASBF-SWAR increased. The difference between ASBF-SW and ASBF-SWAR is observed in COD removal efficiency while increasing the OLR. This occurred at the T-N concentration of 760 mg/L. The results strongly suggest that the performance of ASBF bioreactor decreased when the concentration of T-N in swine wastewater is above 760 mg/L as shown in Fig. 7. Therefore, efficient operation of anaerobic bioreactors in treating swine wastewater as well as production of biogas requires the T-N concentration below the suggested value of

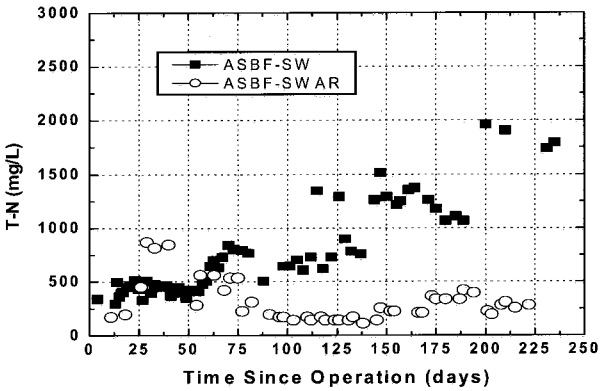

Fig. 7. Effluent T-N of two-stage ASBF bioreactor using swine wastewater as influent without (ASBF-SW) and with (ASBF-SWAR) ammonia removal.

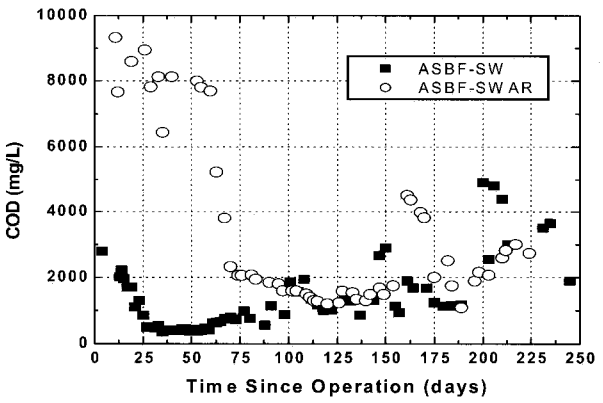

Fig. 6. Effluent COD of two-stage ASBF bioreactor using swine wastewater as influent without (ASBF-SW) and with (ASBF-SWAR) ammonia removal.

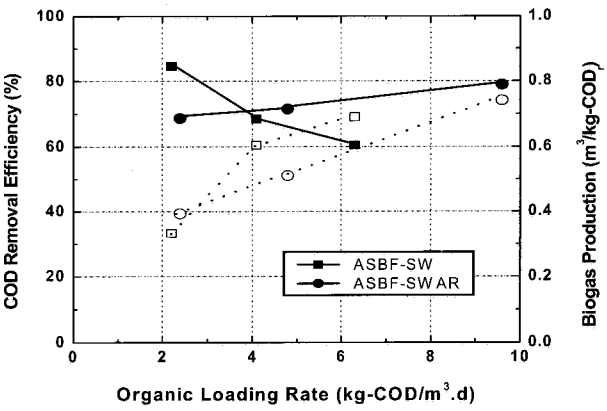

Fig. 8. Performance of two-stage ASBF bioreactor at steady state operation (solid line for COD removal and dotted line for biogas production).

760 mg/L by either dilution or pretreatment for ammonia removal.

CONCLUSION

The operational characteristics of anaerobic bioreactors in treating swine wastewater and the effects of ammonia by operating lab-scale anaerobic bioreactors using swine wastewaters as influent without and with ammonia removal were investigated. The two-stage ASBF anaerobic bioreactor was effective in treating different characteristics of swine wastewaters as compared with UASB and AF since it showed high and stable COD removal efficiency at high OLR due to effective retention of biomass by media and staging. Initial inhibition of ammonia on two-stage ASBF anaerobic bioreactor was observed at a concentration of 760 mg (T-N)/L and the COD removal efficiency and biogas generation dropped to 1/2 at ammonia concentration ranges of 1,540~1,870 mg (T-N)/L. Ammonia in swine wastewater has to be removed to an initial inhibition level for proper treatment and biogas production by anaerobic digestion.

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