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Comparison of Treatment Capacities of Swim-bed and Activated Sludge Processes for Domestic Wastewater

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Abstract

Some operational problems remain unsolved for the conventional activated sludge (CAS) process, such as the large space requirement, high operational cost and large excessive sludge production. Swim-bed technology using a novel acrylic-fiber material biofringe (BF) material for biomass attachment is considered as a solution to some of these problems. In lab-scale tests, the CAS and BF processes were operated in parallel while contaminant removal efficiencies and sludge productions were compared. The study was conducted in two runs with BOD volumetric loading rates of 0.5 kg-BOD/m^3/d for the Run I and 1.0 kg-BOD/m^3/d for the Run II, corresponding to hydraulic retention times of 7.2 h and 3.6 h, respectively. Overall, superior contaminant removal efficiencies were demonstrated for the BF process. Average COD removal efficiencies for the BF and CAS processes in Run I were 92% and 86%, respectively, and in Run II, 90% and 83%, respectively. High nitrification efficiencies were obtained for both processes throughout the study; however, during Run II, the BF process had a significantly improved nitrogen removal efficiency of 44% versus 34% for the CAS process. After increasing the volumetric loading rates in Run II, sludge washout occurred in the CAS process, while high biomass levels were maintained in the BF process, demonstrating the retention capacity of the BF carrier. Sludge yields were calculated to be 0.12 kg-MLSS/kg-COD$_{removed}$ for the CAS process versus 0.081 kg-MLSS/kg-COD$_{removed}$ for the BF process in Run I and 0.22 kg-MLSS/kg-COD$_{removed}$ versus 0.12 kg-MLSS/kg-COD$_{removed}$, in Run II, respectively. A large amount of protozoa and metazoa were found in the BF process, which could have contributed to the observed reduction of excess sludge.

Keyword: swim-bed, attached growth, biofringe, sludge production

INTRODUCTION

For aerobic wastewater treatment, some problems remain unsolved for the conventional activated- sludge process such as large space requirement, complicated system operation and large excess sludge production. The expense for excess sludge treatment has been estimated to be half of the total cost of wastewater treatment plant operation[1)]. Fixed-bed attached-growth processes offer some advantages over suspended-growth processes due to reduced sensitivity to toxicity, co-existence of aerobic and anoxic metabolic activities and compactness. While newly developed fluidized-bed (or moving-bed) attached-growth processes have further demonstrated elimination of head losses with absence of clogging and channeling, improved mass transfer and the potential for upgrading existing treatment plants without constructing new tanks[2, 3]. Fluidized-bed reactors have thus been of considerable interest for the removal of organic compounds from wastewater in recent years[4, 5]. In addition, Lazarova and Manem[6], using gas-lift technology, introduced the circulating floating-bed reactor, which demonstrated a synergy between hydrodynamic characteristics and biological treatment performance countering the negative influence of solid media hold-up that can occur in fluidized-bed processes.

Swim-bed technology involving the novel acryl-fiber material, biofringe,is a new concept for the treatment of organic wastewater. The biofringe (BF) material allows for attachment of large amounts of biomass on a flexible matrix in a fixed position. By this approach, flexing of the matrix induced by wastewater flow creates a "swimming" motion that enhances mass transfer of nutrients to the attached growth (*i.e.*, biofilm). Thus, all the potential benefits of fixed-bed and fluidized-bed reactors stated above are retained.

Application of metozoa and protozoa predators is one strategy considered for excess sludge reduction. During carbon transfer from low to high trophic levels, energy is lost during biomass conversion. Under optimal conditions, the total loss of energy will be maximal and the total biomass production will thus be minimal[7]. It was our hypothesis that excess sludge production will be reduced using a swim-bed process because there are always many metazoa and protozoa in proximity with the attached-growth sludge[8].

The objectives of this research are to test and compare the performances of the conventional activated-sludge (CAS) and BF processes for domestic wastewater treatment. To achieve these objectives, contaminant removal efficiencies, sludge productions and biomass characteristics were evaluated experimentally. The study was conducted during two testing periods with volumetric loading rates (VLRs) of 0.5 kg-BOD/m^3/d and 1.0 kg-BOD/m^3/d, corresponding to hydraulic retention times (HRTs) of 7.2 h and 3.6 h, respectively. The influent BOD concentrations for both processes were maintained at 150 mg/*l* throughout the test.

MATERIALS AND METHODS

Reactors and operating conditions The CAS and BF processes were compared in parallel under the same operational conditions. Two identical acryl resin reactors with the same working volume of 10.8 *l* were used, one with the BF material and one without. The filling ratio of biofringe was 50%. Downdraft and updraft sections existed in each reactor due to a parallel upright arrangement as shown in Fig. 1. Below and above the biofringe, there were clear zones of approximately 70 mm and 30 mm, respectively. Influent was introduced deeply into the updraft section using a peristaltic pump. Air was also introduced near the base of the updraft section, serving to mix and oxygenate the wastewater while circulating it through the reactor.

The settling tanks were also made of acryl resin with 2.5-*l* working volumes and 0.017-m^2 water surface areas. The effluents from the bioreactors were fed into the settling tanks by gravity. The settled sludges were drawn from the central-bottom part of the settlers and returned to the bioreactors with 100% recycle rates.

Corn-steep liquor was used to make the synthetic wastewater. The original solution contained about 667 g-COD/*l* and the 5-day biochemical oxygen demand (BOD) was 72% of the chemical oxygen demand (COD) for influent solutions. The corn-steep liquor was diluted with the tap water to make up of the influent. A summary of the characteristics of the feed water is shown in Table 1. To maintain the operational temperature at 25℃, heaters and air-conditioners were used as necessary under relatively dark conditions. Samples were taken every two days.

The study was divided into two runs based on BOD VLR. Table 2 shows an overview of the main operational characteristics of the whole test. The air-flow rates were initially fixed at 10 *l*/min. For reducing the shear stress in the reactors to keep the biomass

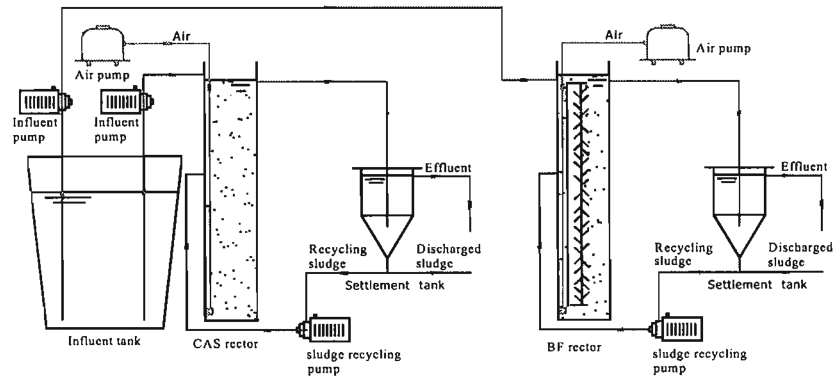


Fig. 1 Schematic diagram of experimental apparatus

attached on the BF, the air-flow rates were reduced to 8 *l*/min on day 71. Since the decrease in the air-flow rate caused effluent SS concentrations increase in the BF reactor, the air-flow rates were re-increased to 10 *l*/min on day 84. In order to estimate sludge production, total sludge was measured at the end of each run. For the CAS process, total sludge was determined from both the reactor and settling tank; while for the BF process, it also included the sludge attached on the support material. After sludge quantification, the two reactors were re-started immediately, using the sludge taken from previous run of each reactor. VLRs were then increased to a higher level after allowing several days for acclamation. Effluents of both processes were collected every day and the sludge discharges in the effluents were quantified.

Startup For startup of the two reactors, 12.4 g of activated sludge from a lab-scale fill-and-draw batch reactor were placed into each reactor with tap water, corresponding to an initial MLSS concentration of 1,150 mg/*l* in the mixed liquor. Influent feeding started after allowing 30 hours for sludge attachment on biofringe[8].

In the BF reactor, the biomass retention matrix was composed of fringe yarns (diameter, *ca.* 3 mm) attached to a support filament as shown in Fig. 2. The staple fiber of the fringe yarns was a hydrophilic acrylic composite. The material had a rough texture formed by bonding three threads with different heat resistances in a sinoidal pattern using a partial-melting process.

Table 1 Influent characteristics

Component	Concentration (mg/*l*)	Component	Concentration (mg/*l*)
Na^+	19	COD	200
K^+	6	T-N	11
Mg^+	7	T-P	4
Ca^+	20	Alkalinity	70
NO_3^-	3		
SO_4^{2-}	24		

Table 2 Operational conditions

	Run I			Run II	
VLR (kg-BOD/m³/d)	0.5			0.5	1
Operational days (d)	1-71	71-84	84-91	91-104	104-148
Air flow rate (*l*/min)	10	8	10	10	
HRT (h)	7.2			7.2	3.6

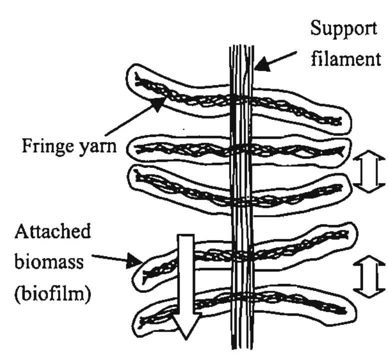


Fig. 2 Configuration of biomass carrier

ANALYTICAL METHODS

COD was measured by the closed reflux colorimetric method according to *Standard Methods*[9], with prior filtration of samples using filter paper (No.5B) to remove undissolved components. BOD was measured using a respirometer (BOD Track; Hach Co., Ltd., Loveland, CO). The pH was measured using a pH meter (IM-22P; TOA Electronics, Ltd., Tokyo, Japan). Dissolved oxygen (DO) was determined with a DO meter (OM-51; Horiba, Ltd., Kyoto, Japan). Ammonium (NH_4^+) was quantified by the phenate method as described by Kanda[10], with prior filtration of samples using filter paper (No.5B). Nitrite (NO_2^-) and nitrate (NO_3^-) ions were measured using an ion analyzer (IA-100 system; TOA Electronics, Ltd., Tokyo, Japan), with sample injection through a 0.45μm syringe filter. Total nitrogen (T-N) was determined by the persulfate method according to *Standard Methods*[9] (4500-N_{org} D; APHA *et al.*, 1995). MLSS, SS and SVI were all determined according to *Standard Methods*[9]. Activated sludge flocs were examined by light microscopy (Nikon, ECLIPSE E600) and the images were captured using a digital camera (Nikon CooLpix 4500). The sludge particle size distribution was measured using a laser scattering particle size distribution analyzer (LA920, HORIBA, Japan).

RESULTS AND DISCUSSION

General treatment performance The degradations of organic constituents in the two processes were evaluated by COD removals as shown in Fig.3. Although satisfactory and stable effluent COD levels were achieved in the CAS process during Run I with an average COD removal efficiency of 86%, the BF process demonstrated better performance with an average removal efficiency of 92%. However, the COD removal performance in the CAS process became unstable in Run II. First, the removal efficiencies dropped sharply below 80% after the BOD VLR was increased to 1.0 kg-BOD/m³/d on day 104. Although the COD removal increased to 90% on day 114, the performance was not stable during the following operational periods. The average removal efficiency for the CAS process was calculated to be 83% in Run II. In contrast, higher and more stable COD removal efficiencies were achieved in the BF process in Run II with an average of 90%.

Satisfactory effluent SS concentrations (Showed in Fig. 4) were achieved in both processes during Run I except the result of the CAS process on day 40 that was as high as 205 mg/*l*. This high SS concentration was thought to be related to a pronounced change in the sludge particle size distribution in the CAS process. The particle size distribution measured on day 37 ranged from 0.67 μm to 8.82 μm, while on day 41 they ranged from 2.98 μm to 394 μm. It was observed on day 40 that some small particles floated on the surface of the CAS settling tank. Apart from the formation of the large size flocs, the smaller particles should have washed out with the effluent, which caused the high effluent SS levels.

Reducing airflow rate from 10 *l*/min to 8 *l*/min caused an obvious increase in effluent SS concentrations for the BF process, which became higher than those of the CAS process. There were also pronounced changes in the particle size distribution for the BF process. It was considered that the reduction of air-flow rate caused this change due to an increase in non-flocculating microorganisms concentrations[11], which resulted in higher effluent SS levels.

For Run II, effluent SS concentrations in the CAS process sharply increased with an average value of 49 mg/*l*. On the contrary, lower effluent SS concentrations were achieved in the BF process with an average value of 18 mg/*l*.

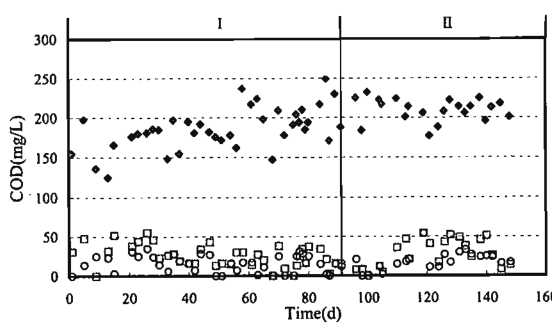


Fig. 3 Time courses of COD concentrations
◆ Influent, □ CAS effluent, ○ BF effluent

Nitrogen transformations Influent nitrogen mainly consisted of organic nitrogen at about 13 mg/*l*. Figure 5 shows the daily changes in ammonium, nitrite and nitrate concen-trations, respectively. The two processes showed good nitrification performances during both runs. Effluent ammonia decreased to lower than 1 mg/*l* in both the CAS and BF processes. Almost similar nitrogen removals were obtained for both processes in Run I as shown in Fig. 6. A higher average total nitrogen removal efficiency of 44% was obtained for the BF process in Run II. On the other hand, average T-N removal efficiency for the CAS process was only about 34%. These higher T-N removal efficiencies for the BF process can be explained by the creation of an anoxic denitrification zone inside the attached biofilm of the BF biomass carrier.

Sludge production The observed sludge production (Y_{obs}) was calculated according to the following equations:

$$Y_{obs} = \frac{g\text{-}SS_{end} - g\text{-}SS_{start}}{g\text{-}COD_{removed}} \qquad (1)$$

$$g\text{-}SS_{end} = SS_{ST} + SS_{R} + SS_{E} \qquad (2)$$

Where the term $g\text{-}SS_{start}$ is the total amount of seed sludge present at the initial stage of each run. The term $g\text{-}SS_{end}$ is the sum of the sludge at the end of every run. This includes the sludge in the reactor (SS_R, which is the sum of the suspended solids and the sludge attached on biofringe), the sludge in the settling tank (SS_{ST}) and the sludge in the effluent (SS_E). The term $g\text{-}COD_{removed}$ refers to the total COD removed in each run. The sludge productions were calculated to be 0.12 kg-MLSS/kg-$COD_{removed}$ for the CAS process and 0.081 kg-MLSS/kg-$COD_{removed}$ for the BF process in Run I, 0.22 kg-MLSS/kg-$COD_{removed}$ for the CAS process and 0.12 kg-MLSS/kg-$COD_{removed}$ for the BF process in Run II. Although increased sludge productions were obtained for both processes after increasing the VLR, sludge production of the BF process was only half that of the CAS process.

Sludge morphology Figure 7 shows the time courses of reactor MLSS and SVI value. Accumulated biomass in the settling tank of the CAS process affected the MLSS levels in reactor during Run I with reactor MLSS levels increasing from 1,150 to 3,560 mg/*l*. As soon as BOD VLR was increased from 0.5 to 1.0 kg-BOD/m³/d in Run II, about 10 g TSS sludge washed out of the CAS reactor, corresponding to a drop in MLSS from 3,630

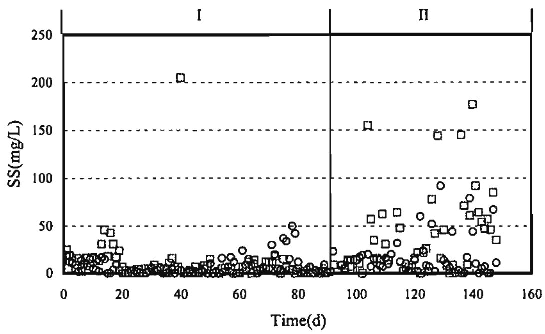


Fig. 4 Time courses of effluent SS concentrations
□ CAS effluent, ○ BF effluent

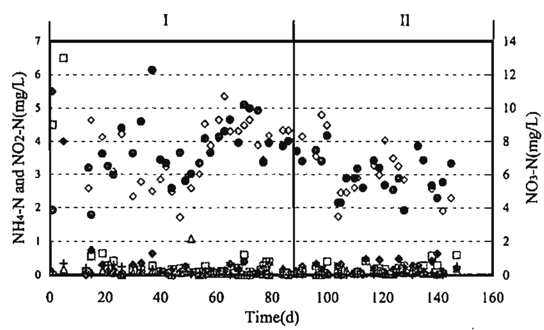


Fig. 5 Time courses of effluent ammonium, nitrite and nitrate concentrations
◆ CAS-NH_4-N, □ BF-NH_4-N, △ CAS-NO_2-N, + BF-NO_2-N, ◇ CAS-NO_3-N, ● BF-NO_3-N

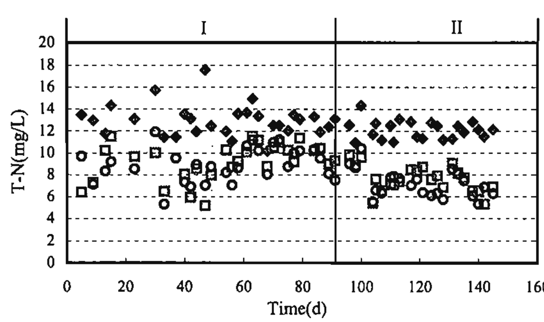


Fig. 6 Time courses of T-N concentrations
◆ Influent, □ CAS effluent, ○ BF effluent

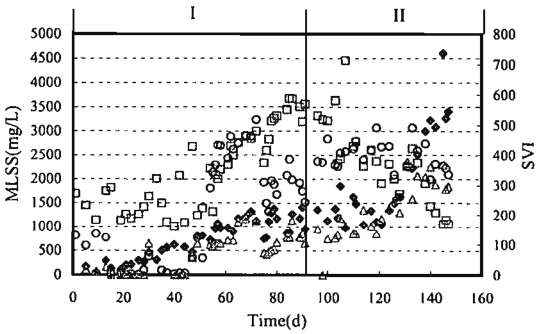


Fig. 7 Time courses of MLSS concentrations and SVI values
□ CAS-MLSS, ○ BF-MLSS,
◆ CAS-SVI, △ BF-SVI

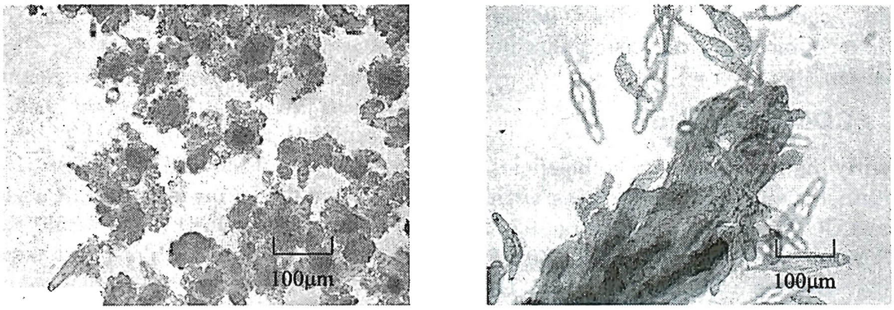
mg/*l* to 2,330 mg/*l*, while sludge filled the settling tank of the CAS process. In order to maintain enough effective biomass for treatment in the CAS process, most of the sludge in settling tank was returned to CAS reactor by hand on day 107, resulting in a MLSS increase to 4,460 mg/*l*. However, the biomass could not be effectively retained in CAS reactor due to the diminished settling characteristic (SVI values varied about 200 g/m*l*). MLSS levels reduced thus dropped to 2,690 mg/*l* again on day 110. Sludge bulking in the CAS process could account for the frequent sludge washout events following day 126. The MLSS levels in CAS reactor had dropped to 1,060 mg/*l* by the end of Run II.

Large activated sludge flocs developed in the BF process during the initial 46 days of operation when the average reactor MLSS concentration was as low as 100 mg/*l*. On day 47 reactor MLSS level increased suddenly, which was related to the detachment of immobilized activated sludge on the BF material. The reason for this sludge detachment was the decrease in flow velocity caused by the excess accumulation of attached biomass. The increase in suspended biomass enhanced their ability to compete with the attached-growth biomass for nutrients, which caused an increase in suspended biomass and decrease of attached-growth biomass. In order to make the sludge attach on the BF again, the airflow rates were reduced to 8 *l*/min. Subsequently, the decrease in reactor MLSS concentration implied that the biomass re-attached on the BF successfully. Sludge bulking occurred in the BF process after day 134 in Run II as well, but low effluent SS concentrations were still obtained for the BF process.

Samples of mixed liquors from the BF and CAS processes were observed microscopically and numerations of protozoa and metazoa in sludge samples were carried out periodically as shown in Table 3. It is well known that protozoa and metazoa in aerobic wastewater treatment process play an important role in keeping the effluent clear by consuming dispersed bacteria. In the past, protozoa and metazoa were usually used as an indicator of process performance and efficiencies in the biological wastewater treatment. Recently, many researches have focused on sludge reduction induced by grazers[7].

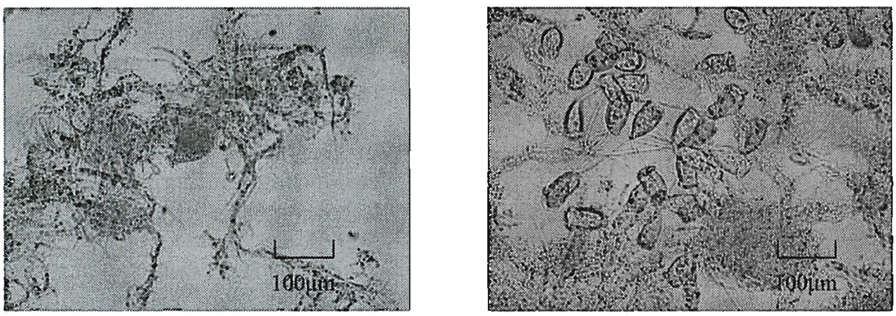
Seed biomass consisted of granular-like flocs containing *Rotatoria*. After few days of operation, the microorganisms changed significantly in the two processes (Fig.8 (a)). Filamentous microorganism were found on day 39 and their numbers increased sharply in the CAS process, while the filamentous microorganisms appeared in the BF process at the end Run I and the numbers increased following day 134. The numbers of filamentous microorganisms in the CAS process were much greater than those in the BF process at the end of Run II (Fig.8 (b)). The filamentous microorganisms were thought to account for the sludge bulking and it was thought that they also had a negative effect on sludge reduction[12].

The enumeration data revealed that the occurrences of protozoa and metazoa in the BF process were much more than that of the CAS process both in Run I and Run II. Especially when the BOD VLRs of the two reactors were raised from 0.5 kg-BOD/m^3/d to 1.0 kg-BOD/m^3/d on day 103, the numbers of protozoa and metazoa in the CAS process dropped sharply and only *Ciliophora* and *Rotatoria* were found at 63 and 10 ml^{-1}, respectively. On the contrary, the increasing numbers of them were observed in the BF process. Moreover, a large number of *Mstigophora* were found in the BF process sludge both in Run I and Run II, while there were no occurrences of them in the CAS



CAS BF

(a) Taken on day 25 in the first run



CAS BF

(b) Taken at the end of the second run

Fig. 8 Microscopic photographs of suspended sludge from both reactors

Table 3 Enumeration of protozoa and metazoa

		Run I		Run II	
		CAS	BF	CAS	BF
Bacteria	*Filamentous microorganism*	+ → ++	+	+++	++
Protozoa	*Mstigophora*	–	0~5.5	–	–
	Ciliophora	2.3~2.8	2.4~3.9	1.8~3.7	4.5~4.9
Metazoa	*Rotatoria*	1.6~2.9	2.8~3.4	1.3~2.7	3.4~3.8
	Chaetonotus	2.4~2.8	2.8~3.2	0~2.1	2.2~2.7
	Arthropoda	–	0~3	–	–

Note: Results are given as log(count/m*l*); + :few, ++ :many, +++ : dominant

process. The growth of *Ciliophora* in a two-stage pure culture chemostat system has been associated with 12–43% sludge reduction[13]. Lee also found that *Ciliophora* and *Mstigophora* contributed to sludge reduction in an aerobic treatment process[14]. J. Lapinski studied the reduction of suspended biomass in municipal wastewater using *Rotatoria*. *Rotatoria* have been shown to remove wastewater particles from suspension, partially by consumption and partially by improving the settling ability. They have a beneficial effect on biomass yield and clarity of treated wastewater effluent[15]. All in all, many more of protozoa and metazoa occurred in the BF process than in the CAS process and should contribute to the better contamination removal and considerable sludge reduction.

CONCLUSIONS

1. Consistently high COD removal efficiencies were obtained using the BF process with an average COD removal efficiency of 92% versus 86% for the CAS process in Run I and 90% versus 83% in Run II, respectively. Moreover, the BF process showed stable COD removal performances under varying COD loading rates.
2. Clear effluents were obtained for both processes during Run I. Elevated effluent SS concentrations for the CAS process were observed after increasing the VLR to 1.0 kg-BOD/m^3/d by shortening the HRT. Due to sludge washout occurring in the CAS process, the average effluent SS concentration for the CAS process was 49 mg/*l*, while that for the BF process was only 18 mg/*l*.
3. Good nitrification performances were obtained for the two processes throughout the two runs. However, enhanced nitrogen removals were achieved for the BF process, especially in Run II with an average removal efficiency of 44% versus 34% for the CAS process.
4. Observed sludge yields were calculated to be 0.12 kg-MLSS/kg-$COD_{removed}$ for the CAS process versus 0.081 kg-MLSS/kg-$COD_{removed}$ for the BF process in Run I and 0.22 kg-MLSS/kg-$COD_{removed}$ versus 0.12 kg-MLSS/kg-$COD_{removed}$ for Run II, respectively. Reductions in sludge yields were related to the relatively large number of protozoa and mentozoa retained in the BF process.

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