Analysis of phosphorus removal and anaerobic selector performance in a full-scale activated sludge process in Singapore

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Abstract This paper analyses the performance of the anaerobic selector (A/O process) in a full-scale activated sludge process receiving mostly industrial sewage discharge (>60%) in Singapore. In addition to the sludge settleability, enhanced biological phosphorus removal (EBPR) was studied. The sludge volume index (SVI) reduced from 200 to 80 ml g^{-1} and foaming was suppressed significantly, indicating the effectiveness of the anaerobic selector in improving sludge settleability. The phosphorus removal efficiency was 66%, and 7.5 mg HAc-COD was consumed per mg PO_4^{3-}-P removed. In the anaerobic compartment, 31% of the SCOD and 73% of the acetic acid in the settled sewage were removed with PO_4^{3-}-P release of 14.1 mg PO_4^{3-}-P l^{-1}. The linear correlation between PO_4^{3-}-P release in the anaerobic compartment and PO_4^{3-}-P uptake in the aerobic compartment indicates that there is about 0.8 mg PO_4^{3-}-P release in the anaerobic compartment per mg PO_4^{3-}-P uptake in the aerobic compartment. The fates of volatile fatty acids (VFAs) and its short chain acids (SCAs) in the process were studied and discussed.

Keywords Anaerobic selector; biological phosphorus removal; sludge settleability; upgrading wastewater treatment plant

Introduction

Sludge settlability is an issue in wastewater treatment process in Singapore, and the anoxic selctor technology has been applied and successfully verified (Cao *et al.*, 2005a). However, energy consumption by nitrification can be an economic drawback especially when nitrogen removal is not a high priority. The anaerobic selector technology (A/O process), which has been applied in Europe and the United States since the 1970s, is effective in improving sludge settability (Parker *et al.*, 2004), and is capable of saving aeration energy through enhanced biological phosphorus removal (EBPR) due to Anaerobic Stabilization (AnS) (Wable and Randall, 1994; Barker and Dold, 1996). However, there are limited reports on the application of the anaerobic selector technology focusing on phosphorus removal in full-scale municipal wastewater treatment (Lie *et al.*, 1997; Parker *et al.*, 2004), and little information is available especially on the activated sludge process receiving heavy industrial sewage discharges.

A study on the application of the anaerobic selector technology in a full-scale activated sludge wastewater treatment process receiving mostly industrial sewage discharges (>60%) in Singapore has been conducted. The aims are to: (1) improve sludge settleability and suppress *Nocardia* foaming; (2) study enhanced biological phosphorus removal including the functions of volatile fatty acids (VFA) and its components; and (3) explore the feasibility of saving aeration energy. The work on (3) is still on going due to

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the dispersed solids issue in the final effluent. This paper introduces the results on sludge settleability improvement and enhanced biological phosphorus removal.

Site conditions and laboratory study

Jurong Water Reclamation Plant (WRP), one of six sewage treatment plants in Singapore, is located in the southwestern part of Singapore and is in close proximity with many industrial estates in Jurong. Its current influent flow is 140,000 $m^3\,d^{-1}$ on average and more than 60% of its sewage received is generated from the industrial estates.

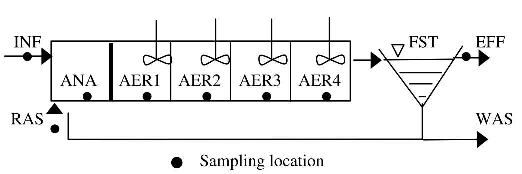
There are eight conventional activated sludge process units with seven units in operation in Jurong WRP. The effective volume of each unit is 10,000 m^3 and consists of five equal volume compartments with a volume of 2,000 m^3 for each. A physical partition is available only between the first and second compartments. The aeration and mixing are achieved with surface aerators. However, the activated sludge process of Jurong WRP suffers from *Nocardia* foaming with the SVI more than 200 $ml\,g^{-1}$ throughout the year and this affects the operation and performance. Activated Sludge Units 7 and 8 (AU7 and 8), which share common influent flow and RAS channels and sedimentation tanks, were chosen for the site investigation of the application of the anaerobic selector technology (A/O process). The operational parameters of the two units are: HRT, 8.25 h; RAS, 35% of average influent flow; and SRT, between 3 and 6 days.

The study commenced in March 2005. The aeration in the first compartment was turned off and the mixer turned on from 31 March 2005 to enable anaerobic selector operation. The aeration energy consumption in each train reduced by 8.5% due to the stoppage of air supply to the first compartment. The DO concentrations in the aerobic compartments were maintained in the range between 0.4 and 1.0 $mg\,l^{-1}$. The sewage temperature was 30 ± 2 °C and the pH values in the activated sludge tanks were in the range between 6.5 and 7.1.

Regular monitoring and sampling were made twice weekly from 26 April 2005. Most of the samples were taken from AU8 at the inlet, first and final compartments, RAS and the final effluent between 09:00 and 10:00. Samples from the other unit without anaerobic selector operation were taken for comparison purposes. Due to the phosphorus release and uptake, the activated sludge samples were centrifuged immediately after the sampling on site, and the supernatant samples were used for the laboratory analysis. Figure 1 shows the activated sludge process configuration and the sampling locations. The parameters analyzed include COD, SCOD, TSS, TP, PO_4^{3-}-P, NH_4^+-N, VFA, pH and alkalinity.

Analytical methods

The analyses of COD and SCOD were made using the Hach COD reactor (Model 45600) following the reactor digestion method (Hach Method 8000) while the analysis of TP was made using the Hach COD reactor following the PhosVer®3 with acid persulfate digestion method (Hach Method 8190). PO_4^{3-}-P, NH_4^+-N and SO_4^{2-}-S were measured using the amino acid method (Hach Method 8178), Nessler method (Hach Method 8038) and



Reactor volume:	10,000 m^3
Influent flow:	29,060 m^3d^{-1}
RAS:	10,171 m^3d^{-1}
WAS:	600 m^3d^{-1}
SRT:	3 – 6 d
HRT:	8.25 h

Figure 1 Activated sludge process configuration, sampling locations and operational parameters of AU8 of Phase III of Jurong WRP

SulfaVer 4 method (Hach Method 8051), respectively. The Hach Odyssey DR/2500 colorimeter was used for all the above methods, which are USEPA approved (Federal Register, 1980) except Hach Method 8178, which is adapted from *Standard Methods* (APHA, 1998). Parameter analyses of TSS, VSS and alkalinity were also made according to *Standard Methods*. VFA and SCA analyses were made by gas chromatograph (Shimadzu GC 2010) equipped with a capillary column (ramped-up operation temperature from 30–250 °C) and a FID operating under 250 °C. Sludge morphology was observed with light microscope coupled with a CCD camera (Olympus IX70).

Results and discussion

Characterization of hydraulic flow, conventional parameters and VFAs

The diurnal flow rate profile of the settled sewage in Jurong WRP (Figure 2) is different from those of the other WRPs in Singapore (Raajeevan, 2003; Cao *et al.*, 2005b). The flow during the day is relatively even without much drastic fluctuation, which is most likely due to the continuous industrial activities during the day.

Detailed characterization of the conventional parameters and VFA and the SCA components of the settled sewage are presented in Table 1. The COD and SCOD concentrations were, respectively, twice those of the concentrated municipal sewage reported, which are 530 and 250 mg l^{-1} (Henze *et al.*, 1997), while $CBOD_5$ was in the same range as the concentrated sewage. The large standard deviation indicated strong variation of both COD and SCOD. Nitrogenous and phosphorus components and TSS were in the normal range of the municipal sewages while alkalinity was higher than those in other sewage treatment plants.

Acetic acid, the major source of carbon in biological phosphorus removal, was 37.3 mg l^{-1} on average followed by propanoic acid at 28.8 mg l^{-1}. The average VFA concentration was 78.0 mg l^{-1}. Both acetic acid and VFA concentration were higher than those of the concentrated sewage (Henze *et al.*, 1995). As with the conventional parameters, the standard deviations were large for the VFAs and SCAs concentrations.

SVI and sludge morphology changes

Since the commissioning of the anaerobic selector (end of March) the SVI of the activated sludge of AU7 and AU8 has reduced continuously from more than 200 to

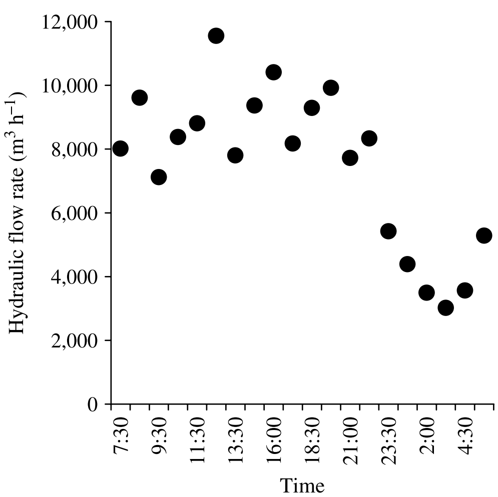


Figure 2 Typical diurnal hydraulic flow rate profile of the settled sewage of Jurong WRP (18 July 2005)

Table 1 Conventional parameters and SCAs concentrations of the settled sewage of Jurong WRP (26 April–11 August 2005) (mg l^{-1})

Conventional parameter	Range	Average	Short chain acids	Range	Average
COD	403–2 644	1189 ± 572 (28)	Acetic acid	ND–131.9	37.3 ± 43.2 (11)
SCOD	227–2 384	958 ± 537 (28)	Propanoic acid	ND–122.1	28.8 ± 15.1 (11)
TSS	112–212	133 ± 27 (28)	Isobutyric acid	ND–4.4	0.6 ± 1.5 (11)
$CBOD_5$	79–599	255 ± 30(5)	Butyric acid	ND–0.9	0.1 ± 0.3 (11)
NH_4^+-N	32.3–75.0	48.4 ± 17.5 (4)	Isovaleric acid	ND–0.4	0.04 ± 0.13 (11)
TP	6.6–31.0	15.5 ± 5.2 (28)	Valeric acid	ND–39.5	8.7 ± 14.0 (11)
PO_4^{3-}-P	5.0–19.2	10.5 ± 3.5 (28)	Isocaproic acid	ND–2.3	0.2 ± 0.7 (11)
SO_4^{2-}-S	60–240	133 ± 49 (11)	Caproic acid	ND–3.6	0.3 ± 1.1 (11)
Alkalinity	155.0–293.3	225.9 ± 41.4 (10)	Heptanoic acid	ND–5.0	2.0 ± 1.9 (11)
pH	6.19–8.33	7.02 ± 0.42 (28)			

ND–Non detectable (detection limit at 0.1 mg l^{-1})

80 ml g^{-1} in three months as depicted in Figure 3. This shows the significant effect of the anaerobic selector in improving sludge settleability and is consistent with the reported data in the United States and Europe (Parker *et al.*, 2004).

Signs of foaming suppression were also observed on site. The thickness of the foams on the surface of the activated sludge tanks and that of the central chamber of the secondary clarifier has reduced markedly. Microscopic observations of the micro-community of the activated sludge with and without anaerobic selector operation were made and are shown in Figures 4(a) and (b). The micro-community of the sludge taken from the unit without the operation of the anaerobic selector was dominated by filamentous bacteria, which resembled *Nocardia*, while the micro-community of the sludge taken from AU8 was dominated by cocci bacteria with the filamentous bacteria almost totally disappeared. All these observations are consistent with those reported in the literature (Kim and Pagilla, 2000) indicating that the anaerobic selector is effective in improving sludge settleability through the metabolic selection mechanism.

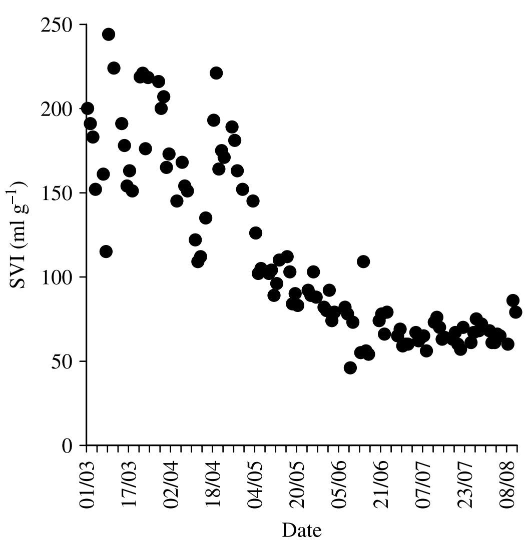


Figure 3 SVI profile of the activated sludge of the aerobic compartment of AU8 of Jurong WRP (01 March–11 August 2005)

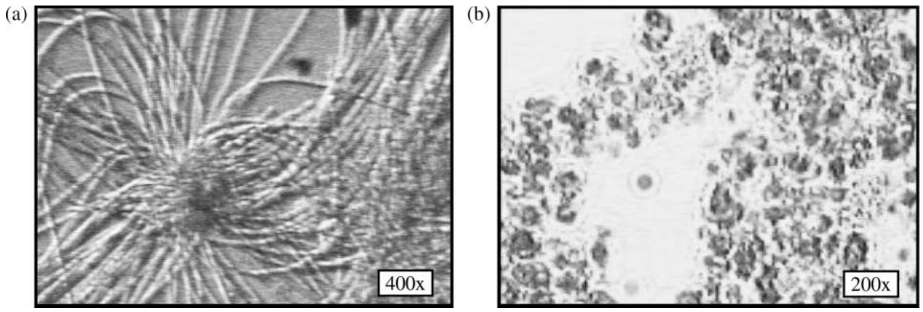


Figure 4 (a) Microscopic image of the sludge taken from the activated sludge unit of Jurong WRP without anaerobic selector operation (26 June 2005); (b) Microscopic image of the sludge taken from AU8 of Jurong WRP (26 June 2005)

Enhanced biological phosphorus removal (EBPR)

Removal Efficiency. Figure 5 shows the PO_4^{3-}-P concentration profiles of the settled sewage and final effluent of AU7 and 8. The PO_4^{3-}-P concentration in the final effluent varied between 1.2 and 7.6 mg PO_4^{3-}-P l^{-1} corresponding to a removal efficiency of between 41 and 91%. The final effluent average PO_4^{3-}-P concentration is 3.5 mg PO_4^{3-}-P l^{-1} and the average removal efficiency is 66% corresponding to an average concentration of 10.5 mg PO_4^{3-}-P l^{-1} in the influent. The efficiency may be further improved despite the strong variations of sewage characteristics and operating conditions during the site study period. Taking 2 mg PO_4^{3-}-P removed due to growth, 7.5 mg HAc-COD is needed per mg PO_4^{3-}-P removal, which is much less than 20 mg HAc-COD per mg PO_4^{3-}-P removal (Lie *et al.*, 1997) but still within the range of between 7 and 10 mg HAc-COD per mg PO_4^{3-}-P removal (Wable and Randall, 1994).

Concentration Profiles of Full-Scale System. Figures 6(a) and (b) present the SCOD, PO_4^{3-}-P, acetic and propanoic acids concentration profiles in the settled sewage, five compartments, RAS and the final effluent. The SCOD and acetic acid concentration reduction occurred mainly in the anaerobic compartment: SCOD reduced from 926 to

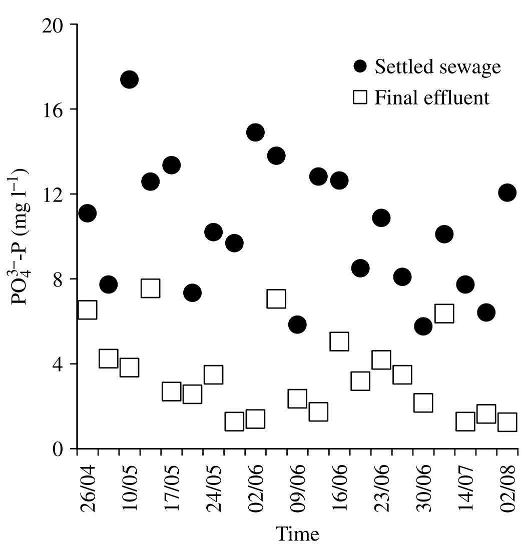


Figure 5 PO_4^{3-}-P concentration profile of the settled sewage and final effluent of AU8 of Jurong WRP 26 April–11 August 2005)

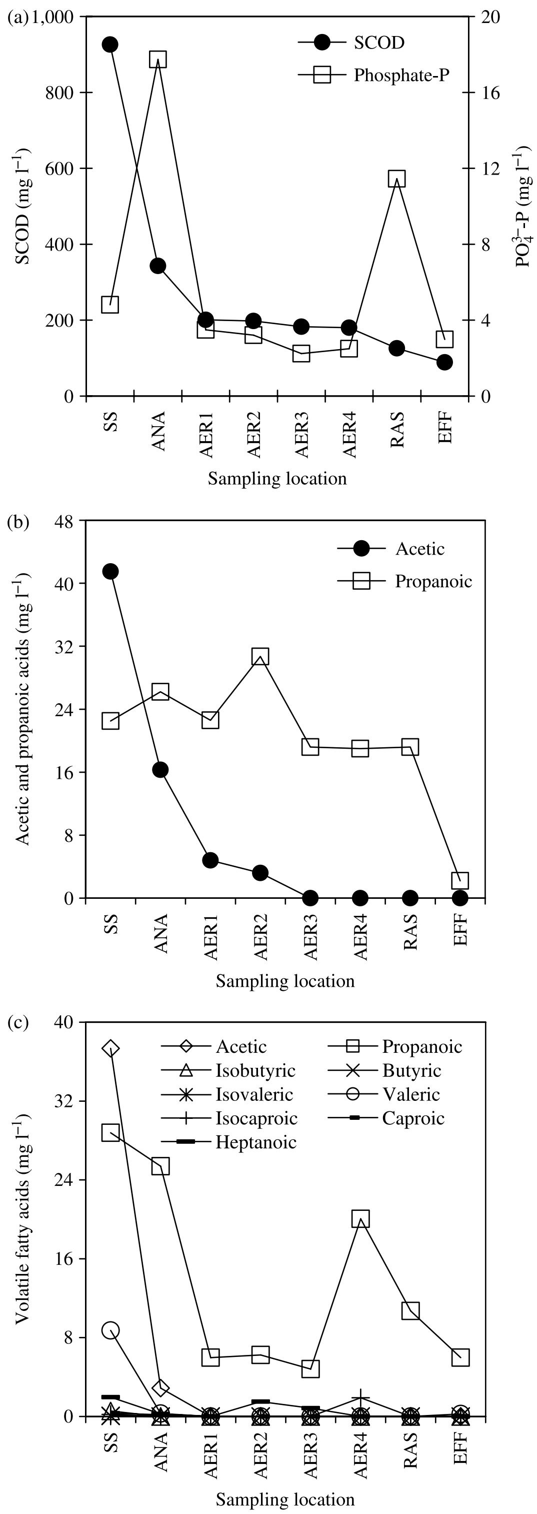


Figure 6 (a) SCOD and PO_4^{3-}-P concentration profiles at different sampling locations of AU8 of Jurong WRP (20 September 2005); (b) Acetic and propanoic acids concentration profiles at different sampling locations of AU8 of Jurong WRP (20 September 2005); (c) Volatile fatty acids concentration profiles at different sampling locations of AU8 of Jurong WRP (20 September 2005)

343 mg COD l^{-1}, acetic acid concentration reduced from 41.5 to 16.3 mg l^{-1}, while PO_4^{3-}-P release resulted in a concentration increase from 4.8 mg PO_4^{3-}-P l^{-1} in the settled sewage to 17.7 mg PO_4^{3-}-P l^{-1} in the anaerobic compartment. Further reductions of the SCOD and acetic acid concentration occurred in the first aerobic compartment, and the reduction was smaller in the subsequent compartments. PO_4^{3-}-P uptake occurred in the first two aerobic compartments. However, there was not much reduction in the propanoic acid concentration in the activated sludge tank, but a significant reduction was observed in the secondary clarifier instead, which coincided with another PO_4^{3-}-P release. This was likely the cause of a higher PO_4^{3-}-P concentration in the RAS and a lower SCOD in the final effluent compared with that in the final aerobic compartment.

Figure 6(c) shows the SCA concentrations profiles in the activated sludge process. Acetic acid, valeric acid and other SCAs were biodegraded in the anaerobic compartment except for propanoic acid. All the SCAs except propanoic acid were then totally biodegraded by the final compartment. A laboratory-scale sequencing batch reactor (SBR) test was conducted to simulate the site operation and concentration profiles obtained were similar to those on site (data not shown).

PO_4-P release and SCOD/HAc-COD uptake. Calculations for PO_4^{3-}-P release, HAc-COD and SCOD uptake in the anaerobic compartment were made based on mass balance by using relevant measured data of the analyzed parameters, influent hydraulic flow rate and the RAS. There were no standard correlations between PO_4^{3-}-P release and acetic acid concentration in the settled sewage and between PO_4^{3-}-P release and HAc-COD uptake in the anaerobic compartment as shown in Figures 7 and 8. This is in contrast to what was observed for municipal sewage treatment (Lie *et al.*, 1997). The PO_4^{3-}-P release increased with increase in SCOD removal until a SCOD removal of 400 mg COD l^{-1} was reached. The PO_4^{3-}-P release then reduced when the SCOD removal reached 500 mg COD l^{-1} in the anaerobic compartment (data not shown). The underlying reason for this phenomenon was not known.

The average HAc-COD uptake and SCOD removal in the anaerobic compartment were 27.4 and 299 mg COD l^{-1}, respectively. These amounts corresponded to 73% of the

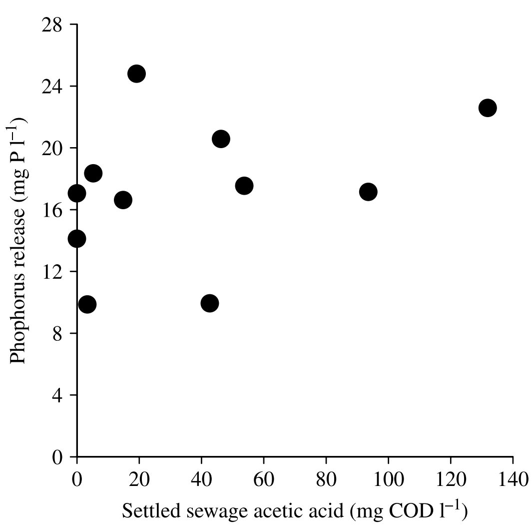


Figure 7 Phosphorus release of the activated sludge of the anaerobic compartment of AU8 versus acetic acid concentration of the settled sewage of Jurong WRP (26 April–11 August 2005)

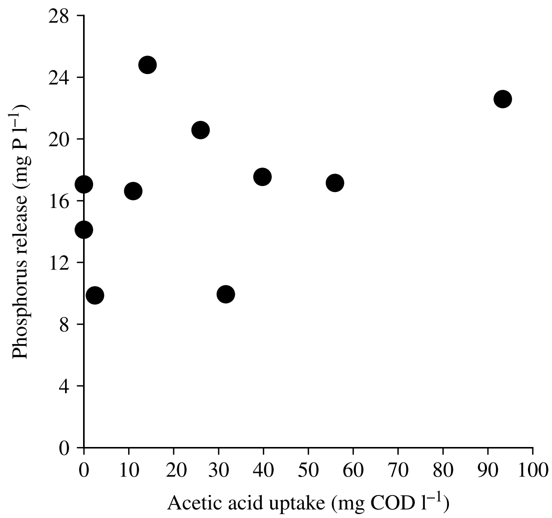


Figure 8 Phosphorus release versus acetic acid uptake of the activated sludge of the anaerobic compartment of AU8 of Jurong WRP (26 April–11 August 2005)

acetic acid and 31% of the SCOD in the settled sewage, which were removed without any oxygen consumption. The average PO_4^{3-}-$P_{release}$/HAc–COD_{uptake} ratio was 1.17 mg PO_4^{3-}-P (mg COD)$^{-1}$, which is much higher than that (0.23–0.73 mg PO_4^{3-}-P (mg COD)$^{-1}$) (Smolders, 1995) and (0.46 mg PO_4^{3-}-P (mg COD)$^{-1}$) (Lie *et al.*, 1997) reported for municipal sewage treatment and the average PO_4^{3-}-$P_{release}$/$SCOD_{removed}$ ratio was 0.08 mg PO_4^{3-}-P (mg COD)$^{-1}$. These ratios indicated that approximately 0.85 mg HAc-COD and 12.5 mg COD were removed, respectively, per mg PO_4^{3-}-P release in the anaerobic compartment. The mechanisms for such high SCOD removal and the fate of the end products in the anaerobic environment are unknown. The average COD uptake per mg MLSS was 0.1 mg COD (mg MLSS-COD)$^{-1}$.

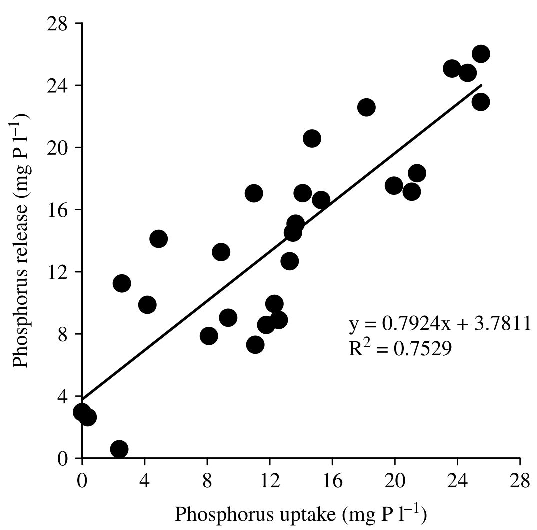


Figure 9 Phosphorus release versus phosphorus uptake profile of the activated sludge of AU8 of Jurong WRP (26 April–11 August 2005)

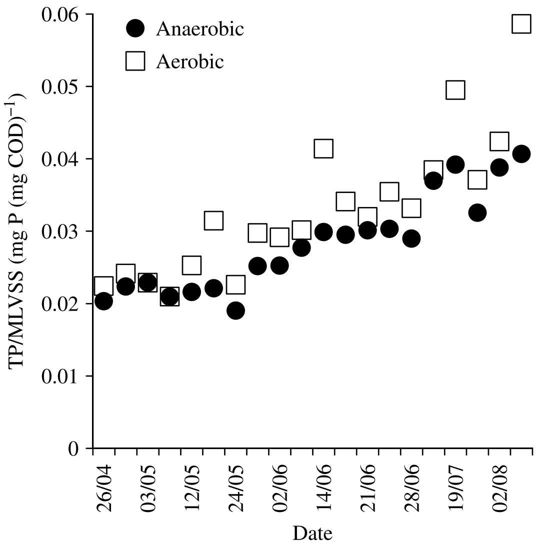


Figure 10 TP/MLVSS ratio profiles of the activated sludge of the anaerobic and final aerobic compartments of AU8 of Jurong WRP (26 April–11 August 2005)

PO_4^{3-}-P uptake in the aerobic compartment. Calculations for PO_4^{3-}-P uptake in the aerobic compartment (from the 2nd to the 5th compartment) were made based on mass balance by using relevant measured data of the analyzed parameters, influent hydraulic flow rate and the RAS. Figure 9 shows the apparent linear relationship between PO_4^{3-}-P release in the anaerobic compartment and PO_4^{3-}-P uptake in the aerobic compartment. The correlation indicated that there was about 0.8 mg PO_4^{3-}-P release in the anaerobic compartment per mg PO_4^{3-}-P uptake in the aerobic compartment.

Phosphate accumulating organisms (PAOs) development. To characterize the PAOs, the TP/MLVSS ratios of the sludge taken from the anaerobic and final aerobic compartments were calculated and compared as shown in Figure 10. The sludge taken from the aerobic compartment gave a higher ratio in general, which is consistent with the phosphorus uptake there. The average TP/MLVSS ratios of the activated sludge of the anaerobic and final aerobic compartments were 2.8 and 3.3%, respectively. Compared with literature data, which are 5% in the anaerobic and 6.2% in the aerobic compartments for municipal sewage treatment (Lie *et al.*, 1997), it seems that both phosphorus release in the anaerobic compartment and uptake in the aerobic compartment in the current study were weaker than those reported for municipal sewage treatment.

Conclusions

- The SVI reduced from more than 200 ml g^{-1} to 80 ml g^{-1} and filamentous bacteria almost disappeared with significant foaming suppression indicating the effectiveness of the anaerobic selector in improving sludge settleability under the site conditions.
- Enhanced biological phosphorus removal capacity was developed with an average PO_4^{3-}-P concentration of 3.5 mg PO_4^{3-}-P l^{-1} in the final effluent corresponding to a removal efficiency of 66%. About 7.5 mg HAc-COD was required per mg PO_4^{3-}-P removed. The average PO_4^{3-}-$P_{release}$/HAc–COD_{uptake} in the anaerobic compartment was 1.17 mg PO_4^{3-}-P (mg COD)$^{-1}$. This value was much higher than those of

municipal sewage treatment. The average TP/MLVSS ratios of the activated sludge of the anaerobic and final aerobic compartments were 2.8 and 3.3%, respectively.

- There were no standard correlations between PO_4^{3-}-P release in the anaerobic compartment and acetic acid concentration in the settled sewage, and between PO_4^{3-}-P release and HAc-COD uptake in the anaerobic compartment. The linear correlation between PO_4^{3-}-P release in the anaerobic compartment and PO_4^{3-}-P uptake in the aerobic compartment was apparent with about 0.8 mg PO_4^{3-}-P release in the anaerobic compartment per mg PO_4^{3-}-P uptake in the aerobic compartment.
- About 31% of the SCOD and 73% of the acetic acid in the settled sewage were removed in the anaerobic selector without oxygen supply. The energy saving due to anaerobic stabilization seems feasible.

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