The significance of denitrifying polyphosphate accumulating organisms in biological nutrient removal activated sludge systems

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Abstract In this paper the advantages and disadvantages of denitrifying PAOs (polyphosphate accumulating organisms) in conventional BNRAS (biological nutrient removal activated sludge) and external nitrification BNRAS (ENBNRAS) systems are evaluated, with experimental data exhibiting a range of anoxic P uptake from low (<10%) to very high (>60%). The results indicate that the specific denitrification rate of the PAOs on internally stored PHB COD is about 1/5th of that of the "ordinary" heterotrophic organisms on SBCOD, and the PAOs contribute little (maximum 20%) to the denitrification in BNRAS systems even when the anoxic P uptake is high (60% of the total P uptake). Considering the unpredictable nature of anoxic P uptake and the reduction in BEPR it causes compared with aerobic P uptake BEPR, it is concluded that anoxic P uptake does not add a significant advantage to the BNR system.

Keywords Activated sludge; biological nutrient removal; denitrification; kinetic rates; models

Introduction

In nitrification-denitrification activated sludge (NDAS) systems, the influent readily biodegradable (RB)COD usually enters the primary anoxic zone where it is utilized for denitrification by “ordinary” (non P removal) heterotrophic organisms (OHOs), contributing significantly (30–40%) to the N removal (WRC, 1984). In contrast, in biological nutrient (N + P) removal activated sludge (BNRAS) systems the influent RBCOD enters the anaerobic zone where the fermentable fraction of RBCOD (F-RBCOD) is acid fermented by OHOs to short chain fatty acid (SCFA) RBCOD. The resultant SCFA are sequestered (together with any SCFA RBCOD in the influent) and stored as polyhydroxyalkanoates (PHAs) by polyphosphate accumulating organisms (PAOs) (Wentzel et al., 1986). If the PAO stored PHA is used aerobically (with associated aerobic P uptake), then the influent RBCOD is lost for denitrification in the subsequent anoxic reactor (Clayton et al., 1991), so that the only available substrate for denitrification is the influent slowly biodegradable (SB)COD. Predominantly aerobic P uptake biological excess P removal (BEPR) (>90%) calculated as the mass of P taken up in the aerobic zone as a % of the total P uptake in the anoxic and aerobic zones and a % anoxic P uptake = 100 – % aerobic P uptake) has been observed in a number of systems (e.g. Wentzel et al., 1989, 1990; Clayton et al., 1991). Since the earlier activated sludge kinetic models that include BEPR, such as UCTPHO (Wentzel et al., 1992) and IAWQ ASM No2 (Henze et al., 1995), drew information from these systems, only aerobic P uptake PAOs were included in these models.

However, since 1990 significant anoxic P uptake has been observed more frequently in laboratory-scale (Kerrn-Jespersen and Henze, 1993; Kuba et al., 1993) and full-scale (Kuba et al., 1997) systems. With anoxic P uptake BEPR, the PHA stored intracellularly by PAOs is utilized with nitrate as electron acceptor in the anoxic zone for growth and P uptake, so that it accomplishes both BEPR and denitrification. Consequently, research attention has been focussed on the behaviour of denitrifying PAOs (DPAOs), with an objective to recover the influent RBCOD for denitrification in BNRAS systems.
To maximize anoxic P uptake, and hence utilize as much “influent RBCOD” for denitrification as possible, Bortone et al. (1996) and Sorm et al. (1996) developed the DEPHANOX system. This system removes the nitrification process from the suspended medium and transfers it to an external fixed media system, so that the slow growing nitrifiers no longer have to be sustained in the suspended medium activated sludge part of the system. This allows the anoxic zone to be significantly enlarged at the expense of the aerobic zone, stimulating DPAOs (Hu et al., 2000). Very high anoxic P uptake (>50%) has been observed in such external nitrification systems (Hu et al., 2000; Moodley, 1999 and Sotemann et al., 2000), implicating PAOs in the denitrification.

In determining denitrification kinetics in BNRAS systems, Ekama and Wentzel (1999) noted that with anoxic P uptake, the P removal was significantly reduced, with an observed P removal of about 2/3rds to 3/4th of that with predominantly aerobic P uptake BEPR. This indicates the denitrification by PAOs comes at a cost to BEPR. Thus, it would be useful to quantify PAO denitrification, to assess whether this denitrification is advantageous, and outweighs the associated reduction in BEPR.

In this paper the advantages and disadvantages of anoxic P uptake BEPR in conventional BNRAS and external nitrification BNRAS (ENBNRAS) systems are evaluated, with experimental data exhibiting a range of anoxic P uptake from low (<10%) to very high (>60%).

**Relative contribution of PAOs to denitrification**

It is possible to estimate the relative contribution of the PAOs to denitrification with the aid of the steady state BEPR model of Wentzel et al. (1990). This model essentially divides the influent biodegradable substrate between the OHOs and PAOs. Thus, from the Wentzel et al. model, the concentration of influent RBCOD obtained by the PAOs is known, with the balance of the influent RBCOD and all of the influent slowly biodegradable (SB)COD available to the OHOs. With the substrate available to each organism group known, the mixed liquor VSS is fractionated into OHO and PAO active masses (X_{BH} and X_{BG}), OHO and PAO endogenous masses (X_{EH} and X_{EG}) and inert unbiodegradable organic mass from the influent (X_I). Now, to determine the contribution of the PAOs to the denitrification in the anoxic reactor, it was assumed that the total P uptake in the anoxic and aerobic zones results in the utilization of all of the RBCOD obtained by the PAOs anaerobically, which has been determined above from the steady state model of Wentzel et al. (1990). Simulations with the kinetic models of Wentzel et al. (1992) show that this assumption is reasonable. Further, it was accepted that the % P uptake in the anoxic and aerobic zones reflects the % PAO RBCOD utilized in these respective zones. Thus, with say 40% anoxic P uptake, 40% of the influent RBCOD obtained by PAOs is utilized in the anoxic zone and 60% in the aerobic zone. It was recognized that this assumption is not strictly correct, in that equal anoxic and aerobic P uptake, 50/50 do not result from equal substrate consumption because anoxic metabolism is energetically less favourable than aerobic metabolism (see later). However, the relative effect of this in the calculation procedure is small (data not shown)]. The % anoxic P uptake can be calculated from total P balances around each reactor using experimental data measured on BNRAS systems. With the COD concentration utilized by the PAOs in the anoxic reactor known, the nitrate denitrified with this COD in the PAO anoxic growth process can be calculated via the PAO anoxic growth yield coefficient (Y_{Ganoxic}) and the oxygen equivalent of nitrate, i.e. 2.86 mgO/mgNO_3-N denitrified. In this calculation, it was accepted that Y_{Ganoxic} is lower than the equivalent aerobic value (Y_{Gaerobic}) because under anoxic conditions ideally only 2 moles ATP are formed per pair of electrons transferred, whereas under aerobic conditions 3 moles of ATP are formed (Payne, 1981; Casey et al., 1999). From bioenergetic calculations, this reduces Y_{Gaerobic} = 0.666 to Y_{Ganoxic} = 0.54 (Orhon et al., 1997), with experimental data confirming this reduction (Sperandio et al.,...
With the nitrate concentration denitrified by the PAOs calculated, the nitrate concentration denitrified by the OHOs is the difference between the observed nitrate concentration denitrified in the anoxic reactor and the nitrate concentration denitrified by the PAOs. In this manner the observed nitrate denitrified can be divided between the PAOs and OHOs. The detailed calculation procedures for this are given by Hu (2001).

The calculation procedure above was applied to the experimental data set collected in the UCT laboratory over the past decade on BNRAS and more recently on ENBNRAS systems respectively (see below).

**BNRAS systems**

For BNRAS systems, the calculation procedure was applied to the steady state data sets of Wentzel et al. (1990), Clayton et al. (1991), Musvoto et al. (1992), Pilson et al. (1995), Sneyders et al. (1997) and Mellin et al. (1998) (for some details of the respective investigations see Wentzel et al., 1990 and Ekama and Wentzel, 1999). In this application it is necessary to determine a value for the unbiodegradable particulate COD fraction \( f_{S,up} \) of the influent. All the investigations received raw (unsettled) municipal wastewater from the same source, i.e. Mitchell’s Plain Wastewater Treatment Plant (Cape Town, South Africa). Thus, since \( f_{S,up} \) is a wastewater characteristic, there is a reasonable expectation that \( f_{S,up} \) should be constant. This was the case for 4 long term parallel investigations on aerobic and NDAS systems receiving the same wastewater, \( f_{S,up} = 0.10 \) to 0.16 (Warburton et al., 1991; Mbewe et al., 1995; Ubisi et al., 1997; Mellin et al., 1998). Accordingly, a constant \( f_{S,up} \) of 0.12 was accepted for the Mitchell’s Plain wastewater (see below).

With the procedure above, the calculated PAO contribution to denitrification (as a % of the total observed denitrification) versus % anoxic P uptake is shown plotted in Figure 1. From Figure 1, as expected the % denitrification by PAOs is linearly related to the % anoxic P uptake. For the data sets under consideration, the % anoxic P uptake varies from 0 to 56%, while the % contribution of the PAOs to denitrification varies from 0 to about 20%. Thus, for this data, even though there was substantial anoxic P uptake, the contribution of the PAOs to denitrification never exceeded 25%. This would indicate that, in conventional BNRAS systems, the contribution by the PAOs to denitrification is small. Since this comes at a cost to BEPR (see below), this would suggest that anoxic P uptake should be discouraged in these systems.

**ENBNRAS systems**

For ENBNRAS systems, the calculation procedure was applied to the steady state data sets of Hu et al. (2000), Moodley et al. (1999) and Sotemann et al. (2000). Again, since these sys-
tems received the same Mitchell’s Plain wastewater as the BNRAS systems above, a constant $f_{\text{Sup}}$ of 0.12 was accepted. The calculated PAO contribution to denitrification (as a % of the total observed denitrification) versus % anoxic P uptake is shown plotted in Figure 2. From Figure 2, again as expected the % denitrification by PAOs is linearly related to the % anoxic P uptake. For the data sets under consideration, the % anoxic P uptake varies from 37 to 62%, while the % contribution of the PAOs to denitrification varies from 18 to 25%. Thus, for this data also the contribution of the PAOs to denitrification was small. As concluded above, since this comes at a cost to BEPR (see later), this would suggest that anoxic P uptake should be discouraged even in the ENBNRAS system, and aerobic P uptake promoted.

Calculation of the PAO and OHO specific denitrification rates

For the purposes of design of BNRAS and ENBNRAS systems, it is essential to have an estimate of the specific denitrification rates for OHOs and PAOs in these systems. Data from experimental systems can be used to determine specific denitrification rates. To calculate specific denitrification rates from this data, the relevant denitrification process needs to be correctly ascribed to the organism group performing it, and the organism group needs to be quantitatively determined. For NDAS systems, this calculation is relatively simple, since only one organism group mediating denitrification is present, namely OHOs, and procedures to quantify OHOs in NDAS systems are reasonably well established (Van Haandel et al., 1981; Ekama and Wentzel, 1999). Accordingly, specific denitrification rates for these systems are available (e.g. WRC, 1984). However, in BNRAS and ENBNRAS systems both OHOs and PAOs are present, with the PAOs making a variable (see above) contribution to denitrification. Accordingly, to develop specific denitrification rates for these systems, the denitrification by each of the organism groups needs to be determined from the experimental data, and the organism group concentration quantified in some manner.

In defining their denitrification rates in BNRAS systems, Clayton et al. (1991) accepted from experimental observations that in their systems the PAOs did not contribute to the denitrification. Accordingly, the denitrification was correctly assigned to the OHOs only. However, in quantifying the OHO mass, Clayton et al. neglected that some of the influent substrate would be used by PAOs (albeit under aerobic conditions), and ascribed all the influent biodegradable substrate to the OHOs, thereby overestimating the OHO mass. Ekama and Wentzel (1999) recognized this oversight, and developed a calculation procedure to remedy it. Applying the steady state BEPR model of Wentzel et al. (1990), with the measured wastewater characteristics (including influent RBCOD) and system parameters, the influent unbiodegradable particulate COD fraction ($f_{\text{Sup}}$) was varied until the calculated VSS matched that measured. As noted above, this essentially fractionates the measured VSS mass in the experimental system into OHO and PAO active masses ($X_{\text{BH}}$ and $X_{\text{BG}}$), OHO and PAO endogenous masses ($X_{\text{EH}}$ and $X_{\text{EG}}$) and inert unbiodegradable organic mass from the influent ($X_{\text{I}}$). From such a VSS fractionation calculation, the concentration of influent RBCOD obtained by the PAOs is known, with the balance of the influent RBCOD and all of the influent slowly biodegradable (SB)COD available to the OHOs. With the VSS fractionated, the calculated P removal was matched to that measured by varying the active PAO P content ($f_{X_{\text{BG}},P}$) from the standard value of 0.38 mgP/mg active PAO VSS. In determining specific denitrification rates, Ekama and Wentzel were unable to divide the observed denitrification between OHOs and PAOs in batch tests, because the batch tests were not run long enough to know the final total P uptake. Accordingly, they incorrectly ascribed the entire observed denitrification to OHOs only, to derive a specific denitrification rate for the OHOs [$K'_2\text{OHO} = \text{mgNO}_3^-/\text{N/mg OHO active VSS d)}$. Clearly, this $K'_2\text{OHO}$ will be in error for systems with observed anoxic P uptake, i.e. with PAO denitrification. Despite this source of error, Ekama and Wentzel applied the procedure to 5 long term inves-
tigations on conventional BNRAS systems in which denitrification rates were measured in anoxic batch tests on mixed liquor drawn from the steady state system (for system details, see Ekama and Wentzel, 1999). The determined $f_{S,up}$, OHO active fraction of the VSS ($f_{av,OHO}$) and $K_2'OHO$ and their interrelationships are shown plotted in Figure 3a and b.

From Figure 3a and b, it is evident that $f_{S,up}$ and $f_{av,OHO}$ varied considerably, with $f_{av,OHO}$ varying almost linearly with $f_{S,up}$. As a consequence, the $K_2'OHO$ also varied, changing almost linearly with $f_{av,OHO}$. From a sensitivity analysis, it was concluded that the variability in $f_{S,up}$, $f_{av,OHO}$ and $K_2'OHO$ was caused by the calculation procedure which is based on a 100% COD mass balance, and determines $f_{S,up}$ as the value which matches the calculated VSS to the measured VSS. However, the measured VSS is from systems which only gave 80 – 90% COD mass balances. Furthermore, all 5 systems examined received as influent raw (unsettled) municipal wastewater from the same source, i.e. Mitchell’s Plain Wastewater Treatment Plant (Cape Town, South Africa). As noted above, since $f_{S,up}$ is a wastewater characteristic, this wastewater should have a consistent $f_{S,up}$. From 4 long term parallel investigations on aerobic and NDAS systems receiving the same wastewater, $f_{S,up}=0.12$ was obtained (see above).

Accordingly, the calculations of Ekama and Wentzel were repeated, but with a constant $f_{S,up}$ of 0.12 accepted for the Mitchell’s Plain wastewater. With a constant $f_{S,up}$, $f_{av,OHO}$ and $K_2'OHO$ and their interrelationships are shown plotted in Figure 4a and b. Comparing Figures 3 and 4, it is evident that accepting a constant $f_{S,up}$ has brought greater consistency to the data. The variation in calculated $K_2'OHO$ is considerably reduced, and no
longer related to $f_{\text{av, OHO}}$. This would suggest that accepting a constant $f_{\text{S, up}}$ is reasonable for this data set. However, the constant $f_{\text{S, up}}$ will impact on the predicted VSS, since this is no longer matched to that measured by changing $f_{\text{up}}$, to determine the effect of a constant $f_{\text{S, up}}$ on predicted VSS, predicted VSS against measured VSS is shown plotted in Figure 5. From Figure 5, the calculated VSS do not deviate unduly from the measured values. This further supports the proposed constant $f_{\text{S, up}}$.

In the calculations above, as noted earlier, all the denitrification is ascribed to the OHOs, and the calculated $K_{2}'_{\text{OHO}}$ are based on this premise. It was recognized that the observed denitrification in the BNRAS systems which exhibit anoxic P uptake is in fact the combined contribution of the OHOs and PAOs, as described in the section above. Accordingly, it was decided to separate the OHO denitrification from the PAO denitrification, by following the procedure set out in the section above. This enabled the nitrate denitrified by each of the PAOs and OHOs to be quantified. The specific denitrification rate of the PAOs and OHOs, viz $K_{2}'_{\text{PAO}}$ and $K_{2}'_{\text{OHO}}$, were then obtained by dividing the calculated nitrate denitrification of the PAOs and OHOs by the active PAO and OHO VSS concentrations respectively determined from the VSS fractionation calculation ($f_{\text{S, up}}$). In this way the observed denitrification rate is apportioned and expressed in terms of the specific organism group mediating denitrification. This calculation procedure was applied to the BNRAS and ENBNRAS systems.

### BNRAS systems

The investigations on BNRAS systems listed by Ekama and Wentzel (1999) determined denitrification rates from batch tests on mixed liquor drawn from the steady state continuous system. However, the calculation procedure only can be applied to determine denitrification rates from steady state system data, and requires that the anoxic reactors are overloaded with nitrate, i.e. have significant nitrate concentrations in their outflow to ensure that the biological OHO and PAO denitrification potential is exceeded. Wentzel et al. (1990) list many steady state data on BNRAS systems. Accordingly, the calculation procedure was applied to the steady state data of Wentzel et al. (1990) and Ekama and Wentzel (1999) in which the anoxic reactor nitrate concentration $> 1 \text{ mgN/l}$. This provided estimates for the OHO and PAO specific denitrification rates, $K_{2}'_{\text{OHO}}$ and $K_{2}'_{\text{PAO}}$ respectively. These rates are shown plotted statistically in Figure 6a and b respectively. From Figure 6a, in the BNRAS systems $K_{2}'_{\text{OHO}}$ varied from 0.05 to 0.32 mgN/(mg active OHO VSS.d), with a mean of 0.14 and sample standard deviation of 0.02. From Figure 6b, $K_{2}'_{\text{PAO}}$ varied from 0.005 to 0.071 mgN/(mg active PAO VSS.d), with a mean of 0.028 and sample standard deviation of 0.003. Comparing the specific denitrification rates of the two population groups, the PAO rates on “RBCOD” are only 20% of the OHO rates on SBCOD, and this confirms the conclusions earlier that PAO contribution to denitrification is small.

**Figure 5** Measured versus calculated VSS concentrations with the steady state BEPR of Wentzel et al. (1990) with a constant of $f_{\text{S, up}}$ of 0.12 for BNRAS systems

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ENBNRAS systems

Similar to the above, the PAO and OHO specific denitrification rates were determined for the ENBNRAS systems of Hu et al. (2000), Moodley et al. (1999) and Sotemann et al. (2000) and shown plotted in Figure 7a and b. From Figure 7a, the $K'_2\text{OHO}$ varied from 0.122 to 0.176 mgN/(mg active OHO VSS.d), with a mean of 0.15 and sample standard deviation of 0.03. From Figure 7b, the $K'_2\text{PAO}$ varied from 0.029 to 0.071 mgN/(mg active PAO VSS.d), with a mean of 0.051 and sample standard deviation of 0.002. Comparing the specific denitrification rates of the two population groups, even in the ENBNRAS system with high % anoxic P uptake, the PAO rates on “RBCOD” are only 34% of the OHO rates SBCOD, and this further confirms the conclusions earlier that PAO contribution to denitrification is small.

BEPR behaviour in systems with anoxic P uptake

As noted above, two types of BEPR behaviour have been observed in BNRAS systems, viz. (1) P uptake is confined exclusively (>90%) to the aerobic reactor, and (2) P uptake takes place in both the anoxic and aerobic reactors. However, Ekama and Wentzel (1999) observed that in conventional BNRAS systems there appears to be significant differences in P removal performance between the two types of BEPR behaviour: (1) With only aerobic P uptake (e.g. Clayton et al., 1991; Sneyders et al., 1997), the P release/P removal, P removal/influent RBCOD and the P removal/influent COD ratios are around 3.0 mgP/mgP, 0.11 mgP/mgCOD and 0.21 mgP/mgCOD respectively, and are in conformity with the steady state (Wentzel et al., 1990) and dynamic state (Wentzel et al., 1992; Henze et al., 1995) BEPR models; (2) With anoxic P uptake (Musvoto et al., 1992; Pilson et al., 1995; Mellin et al., 1998), these ratios decrease to 1.5–2.0, 0.06–0.08 and 0.012–0.015 respectively and the BEPR is depressed to around 60% of that with only aerobic P uptake. Furthermore, in these latter systems in order to match the theoretical P removal calculated by the model of Wentzel et al. (1990) to that observed (see above), the P content of the PAOs in the system $(f_{XBG,P})$ needs to be decreased from 0.38 mgP/mgPAO active VSS for aerobic P uptake to only 0.10–0.28 for anoxic/aerobic P uptake. In ENBNRAS systems, significant anoxic P uptake was observed (> 37%) with similar reductions in the ratios above, 1.1–2.8, 0.06–0.08 and 0.012–0.017 respectively, with $f_{XBG,P}$ in the range of 0.1–0.28 (Hu, 2001). By operating a UCT (conventional internal nitrification) BNRAS system in parallel with the external nitrification BNRAS system of Sotemann et al. (2000), Vermande et al. (2000) confirmed the reduced BEPR with significant anoxic/aerobic P uptake compared with that with predominantly aerobic P uptake.

Dynamic simulation models

Denitrification by PAOs was included into the UCTPHO activated sludge kinetic simulation model (Wentzel et al., 1992) by Hu (2001). This required resolution of three problems...
(i) determination of the concentration of DPAOs, (ii) reduced OHO and PAO yields under anoxic conditions compared with aerobic conditions, and (iii) anoxic P uptake per mg internally stored PHB COD utilized by DPAOs compared with aerobic P uptake. The first problem was resolved as for denitrifying OHOs, i.e. by introducing an $\eta_G$ factor, which is the reduction factor for PAO anoxic growth rate on internally stored PHB COD compared to the aerobic rate (Mino et al., 1995), similar to $\eta_H$ for OHOs. The second problem was resolved by setting $Y_{G\text{anoxic}} = 0.54 \text{ mgCOD PAO cells grown per mg PHB COD utilized}$. This value was determined from the literature (see above). The same reduction in yield under anoxic conditions was also applied to the denitrifying OHOs viz $Y_{H\text{anoxic}} = 0.54 \text{ mgCOD OHO cells grown per mg COD utilized}$. The third problem was resolved by reducing the P uptake/mgPHB utilized ($f_{P,\text{upt}2}$) from the aerobic value of 0.75 to 0.61 for anoxic P uptake; this value was also calculated from literature information (see Hu, 2001). The model was implemented in AQUASIM (Reichert, 1994).

The kinetic model was applied to the experimental data sets on BNRAS and ENBNRAS systems described above. The default values for the model constants from UCTPHO (Wentzel et al., 1992) were accepted, with the values for the OHO and PAO anoxic yield coefficients and the PAO anoxic P uptake/PHB utilized ratio ($f_{P,\text{upt}}$) from above. Only the values of $\eta_G$ and $\eta_H$ in the model were varied. Taking the experimental data of Wentzel et al. (1990), Kashula et al. (1993), Musvoto et al. (1992), Pilsen et al. (1995), Sneyders et al. (1997) for conventional BNRAS systems demonstrating variable anoxic P uptake and Hu et al. (2000), Moodley (1999) and Sotemann et al. (2000) for ENBNRAS systems exhibiting high anoxic P uptake, the $\eta_G$ and $\eta_H$ values were calibrated as follows. First $\eta_H$ was varied until the predicted and measured effluent nitrate concentrations matched, then $\eta_G$ was varied until the predicted and measured anoxic P uptake matched, and finally $\eta_H$ was refined until the effluent nitrate concentrations matched again. No other model constants were changed. The measured wastewater characteristics, in particular the measured influent RBCOD concentrations for the particular experiments, were given as input to the model, except in the case of the unbiodegradable particulate COD fraction ($f_{S,\text{up}}$) which was fixed at 0.12 as described above.

For the data sets, the measured % anoxic P uptake varied from 0 to 62%. The $\eta_G$ and $\eta_H$ values varied from 0 to 0.6 and 0.22 to 0.34 respectively. This variability in $\eta_G$ reflected the variable and uncertain anoxic P uptake in the system. In examining the experimental data, it appeared that the anoxic P uptake, and hence $\eta_G$ was related to the anoxic mass fraction and the nitrate load to the anoxic reactor. However, a quantitative relationship could not be established. The $\eta_H$ values also exhibited some variability, but not as large as $\eta_G$. A comparison of the predicted and measured P removal, P release, anoxic P uptake, aerobic P uptake, total P uptake, effluent P concentration and % anoxic P uptake gave reasonable correlation for most data sets. Also the correlation between the predicted and measured nitrate denitrified, OUR, VSS concentration and effluent nitrate concentration was reasonable (Hu, 2001).
This kinetic model application confirmed the observations above that the contribution of PAOs to denitrification was low. From a sensitivity analysis with the kinetic model for $\eta_G = 0$ (100% aerobic P uptake) and $\eta_G = 1$ (maximal anoxic P uptake), it is concluded that the PAOs contribute little (maximum 20%) to the denitrification in conventional (internal nitrification) and external nitrification BNRAS systems.

Conclusions

The specific denitrification rate of the PAOs on internally stored PHB COD is about 1/5th of that of the OHOs on SBCOD. From a sensitivity analysis with the kinetic model for $\eta_G = 0$ (100% aerobic P uptake) and $\eta_G = 1$ (maximal anoxic P uptake), it is concluded that the PAOs contribute little (maximum 20%) to the denitrification in BNRAS systems even when the anoxic P uptake is high (~60% of the total P uptake). Considering the unpredictable nature of anoxic P uptake and the reduction in BEPR it causes compared with aerobic P uptake BEPR, it is concluded that anoxic P uptake does not add a significant advantage to the BNR system.

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