Comparison of aerobic and anoxic phosphorus uptake in NDBEPR systems (UCT and ENBNRAS)


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Abstract Two Nitrification-Denitrification Biological Excess Phosphorus Removal (NDBEPR) systems have been operated for 8.5 months in order to compare their Biological Excess Phosphorus Removal (BEPR) performance. One of these systems, i.e. the University of Cape Town (UCT) system, exhibits mainly aerobic P uptake while the External Nitrification Biological Nutrient Removal Activated Sludge (ENBNRAS) system is characterised by high anoxic P uptake. It was observed that when operating with predominantly aerobic P uptake, the UCT system released more P than the ENBNRAS system, even though it had a lower anaerobic mass fraction. However, when the influent TKN/COD was high, i.e. > 0.1, anoxic P uptake also occurred in the UCT system and P release dropped to lower levels than in the ENBNRAS. Accordingly, P uptake of the UCT system was 5 mg P/l influent higher than that of the ENBNRAS system, when it was predominantly aerobic, but 9 mg P/l influent lower when anoxic P uptake occurred. As a result, the UCT system achieved superior P removal when aerobic P uptake was predominant (23% higher), but when high influent TKN/COD promoted anoxic P uptake the P removal of the UCT system was poorer than that of the ENBNRAS system. This study clearly showed that anoxic P uptake is not beneficial to NDBEPR systems.

Keywords Anoxic P removal; biological nutrient removal; external nitrification

Introduction Anoxic P uptake has been observed by a number of researchers both at laboratory (Kerrn-Jespersen and Henze, 1993; Kuba et al., 1993) and at full scale systems (Kuba et al., 1997a; Østgaard et al., 1997). With anoxic P uptake, the polyhydroxyalkanoates (PHA) stored intracellularly by phosphorus accumulating organisms (PAOs) is utilised with nitrate as electron acceptor in the anoxic zone of biological nutrient removal activated sludge (BNRAS) systems for growth and P uptake, so that P removal and denitrification are achieved simultaneously. Although recent studies (Artan et al., 1997; Kuba et al., 1997a; Kuba et al., 1997b; Østgaard et al., 1997; Simelane, 1999) have improved our knowledge about this biological process, full characterisation of the behaviour and the conditions promoting the growth of DPAOs (denitrifying phosphorus accumulating organisms) and anoxic P uptake is still required.

The objective of this study was to contribute to this characterisation by comparing the performance of two different Nitrification-Denitrification Biological Excess Phosphorus Removal Activated Sludge (NDBEPRAS) systems: i) a conventional system, the University of Cape Town (UCT) process, characterised by purely aerobic P uptake; and (ii) the External Nitrification Biological Nutrient Removal Activated Sludge system (ENBNRAS), characterised by high anoxic P uptake.

In the ENBNRAS system, the nitrification process is removed from the main suspended medium and transferred to an external fixed or suspended media system, so that the slow growing nitrifiers no longer have to be sustained in the main suspended medium activated sludge part of the system. This allows the sludge age of the main activated sludge system to
be reduced to 8 to 10 days and its anoxic zone to be significantly enlarged at the expense of the aerobic zone, stimulating DPAO growth (Hu et al., 2000). Very high anoxic P uptake (> 50%) has been observed in such external nitrification systems (Hu et al., 2000; Moodley et al., 1999 and Sotemann et al., 2000) implicating PAOs in the denitrification.

Materials and methods

Characteristics of the NDBEPRAS systems

A laboratory-scale BNRAS system with a UCT process configuration was run in parallel with a laboratory-scale ENBNRAS system (see Figure 1 and Figure 2). In this study the external nitrification system, usually a trickling filter, was replaced by an independent aerobic suspended activated sludge system for practical reasons.

Table 1 lists the design and operating parameters for both the ENBNRAS and UCT systems. In order to compare their performance these systems were fed with the same influent sewage during 8.5 months (254 days).

The sewage fed to both systems was prepared by diluting raw sewage collected in 18 batches from the Mitchell’s Plain wastewater treatment plant (Cape Town, South Africa) each of which lasted about 14 days. NaHCO₃ was added to keep the pH between 7.2 and 8.2, KH₂PO₄ was also added to keep the treated effluent total P concentration > 5 mg P/l preventing any P limitation in the systems. The average composition of the inlet sewage was: 750 mg COD/l, TKN/COD = 0.10–0.11, 26 mg P/l.

Analytical measurements

To monitor the performance of the two processes samples were drawn virtually daily from the NDBEPRAS units and the following parameters were measured: COD, TKN, FSA, NO₃-N, NO₂-N, TP, OUR, DSVI, TSS, VSS, pH which were averaged for each sewage batch. To confirm the presence of DPAOs and to quantify their contribution to
denitrification, aerobic and anoxic-aerobic batch tests were conducted with the anaerobic reactor sludge from both systems.

**Results and discussion**

**Carbon removal**

The analytical procedures and the accuracy of the experimental data were checked by means of mass balances, i.e. the closer the mass balances are to 100%, the more reliable the data is. In the COD balance, the COD leaving the systems via: i) final effluent flow, ii) oxygen utilized, iii) sludge wasted, iv) nitrite and nitrate denitrified, and for the ENBNRAS system only v) the COD utilized in the external nitrification system was reconciled with the COD mass entering the system with the influent flow.

The average COD balance achieved for the UCT system was 78.3% and that for the ENBNRAS system was 76.8%. After excluding analytical and measurement errors, these equally low COD recoveries indicate that the same unidentified and unaccounted for biological processes occurred in both systems and consumed a fraction of the influent COD. Since similar low COD recoveries have been observed in previous investigations (Moodley, 1999; Kaschula et al., 1993), it seems that low COD balances are not a characteristic of ENBNRAS systems, but a characteristic of BNRAS systems in general.

Concerning the COD removal performance, the UCT removed an average of 92.8% of the influent COD, while the ENBNRAS removed 93.5%. BNRAS systems generally remove COD virtually completely irrespective of their configuration and this was clearly demonstrated here. It was observed that by nitrifying externally the ENBNRAS system required about 76% less oxygen than the UCT system required with nitrification taking place internally.

A further interesting comparison regards the VSS concentration of the two systems. The ENBNRAS system had a VSS concentration 16.8% lower, due to the fact that a fraction of the influent COD (18.3%) was removed in the external nitrification system and hence was not available to the microorganisms in the BNRAS system.
N removal
For the N balance, the N mass leaving the systems via: i) final effluent flow; ii) sludge wasted; iii) nitrite and nitrate denitrified; and for the ENBNRAS system only, iv) the N removed in the external nitrification system was reconciled with the TKN mass entering the system with the influent flow.

The average N mass balance over the investigation period for the UCT and the ENBNRAS systems was of 86.1% and 87.0% respectively. As for the case of the COD balances, the results are very close to each other, albeit considerably higher.

Concerning the TKN removal efficiencies the ENBNRAS had a slightly lower performance with an average TKN reduction of 93.8% compared with 94.7% for the UCT system. This is due to the fact that some ammonia bypasses the external nitrification system in the sludge bypass and since almost no nitrification occurs in the main aerobic reactor this ammonia flows out in the effluent.

On average the ENBNRAS system removed 87.8% of the total influent N, while the UCT system removed 78.2% of the total influent N. Thus, the ENBNRAS system produced a better effluent quality, only 12.2% (33% of TKN and 67% of NO₃⁻) of the influent N was present in the effluent of the ENBNRAS system compared to 21.8% for the conventional system (25% of TKN and 75% of NO₃⁻). The main reason for this difference is the potential of the ENBNRAS system to denitrify completely with its larger anoxic mass fraction and its low nitrification in the aerobic reactor. The UCT system cannot denitrify completely because all nitrification takes place in the aerobic reactor.

Biological excess phosphorus removal (BEPR)
The ENBNRAS system favours anoxic/aerobic P uptake, while the UCT system favours aerobic P uptake. However, when the UCT system is fed with sewage with a high TKN/COD ratio, which results in high nitrate load on the main anoxic reactor, anoxic P uptake in the UCT system does occur. In the ENBNRAS system the low aerobic and the large anoxic mass fractions seemed to promote anoxic P uptake even at low NO₃⁻ loads. So, in order to compare the BEPR of the ENBNRAS system to the BEPR performance of the UCT system with anoxic P uptake as well as with predominantly aerobic P uptake, two experimental periods were conducted (see Table 1): period I (sewage batches 1 to 9) only aerobic P uptake occurred in the UCT system (low TKN/COD); period II (sewage batches 10 to 15) aerobic and anoxic P uptake occurred in the UCT system (high TKN/COD > 0.1). For batches 16 to 18 the ammonia dosing to the influent was stopped and the TKN/COD diminished to its original level.

During the whole investigation considerable anoxic P uptake (40 to 70%) occurred in the ENBNRAS system with an overall average of ~ 60%. As expected, in the UCT system negligible anoxic P uptake took place during period I, but in period II when the influent TKN/COD was kept consistently above 0.100 (by dosing ammonia to the influent), appreciable anoxic P uptake occurred in the UCT system (10–30%). However, the anoxic P uptake in the UCT system never reached the magnitude observed in the ENBNRAS system, and an overall average of only 20% anoxic P uptake occurred.

Figure 3 and Figure 4 show the P release and P uptake respectively for the UCT and the ENBNRAS systems over the 18 sewage batches. It can be seen that when operating with predominantly aerobic P uptake (batches 1 to 9), the UCT system releases more P than the ENBNRAS system does, even though it has lower anaerobic mass fraction. However, when anoxic P uptake takes place in the UCT system (batches 10 to 15), the P release dropped to lower levels than in the ENBNRAS system. This shows that with anoxic P uptake in the UCT system: (i) less P is released per unit RBCOD (readily biodegradable COD) than under aerobic P uptake, and (ii) P release decreases also
due to the high nitrate load on the anoxic reactor and nitrate recycling to the anaerobic reactor.

P release occurred mainly in the anaerobic reactor, > 90% for the UCT system and 61.4% for the ENBNRAS system. These results contradict the theoretical expectation that the ENBNRAS system with a higher anaerobic mass fraction should have a higher anaerobic P release. This may be explained by: i) metabolic differences between the PAOs and the DPAOs, ii) a lower concentration of OHOs (ordinary heterotrophic organisms) in the ENBNRAS system and consequently lower production of short-chain fatty acids.

From Figure 4 it can be observed that the P uptake followed exactly the same trend as the P release. For sewage batches 1 to 9 the UCT system P uptake (predominantly aerobic) was about 5 mg P/l influent higher than that of the ENBNRAS system; for sewage batches 10 to 15, when anoxic/aerobic P uptake occurred in the UCT system (20% anoxic P uptake), the P uptake was about 9 mg P/l influent less than that of the ENBNRAS system (64% anoxic uptake). On average over the 18 sewage batches, the UCT system uptake was 34.0 mg P/l influent and that of the ENBNRAS system was 32.8 mg/l.
The P removal achieved by the UCT and the ENBNRAS systems is presented in Figure 5. In essence the P removal reflects the combination of those tendencies found for the P release and the P uptake. When the UCT system operates with predominantly aerobic P uptake, on average it removes ~ 4 mg P/l influent more than the ENBNRAS system. Under conditions where the UCT system does show anoxic P uptake, the ENBNRAS system removes ~ 2 mg P/l influent more than the UCT system. On average over the 18 sewage batches, the UCT system removed 12.7 mg P/l influent, while the ENBNRAS system removed 9.8 mg P/l influent. This shows that under normal circumstances the UCT system with predominantly aerobic P uptake removes ~ 23% more P than the ENBNRAS system with anoxic P uptake. If, however, the UCT system receives an influent that causes a consistently high nitrate load on its anoxic reactor, anoxic P uptake occurs (to a lesser extent than in the ENBNRAS system), resulting in poorer P removal performance than the ENBNRAS system can achieve when receiving the same effluent.

The fact that P removal diminishes when anoxic P uptake occurs is probably a consequence of the reduced energy capture by the DPAOs when NOx serves as electron acceptor compared to oxygen (2 moles ATP/pair of electrons transferred compared to 3 moles ATP/pair of electrons transferred). Consequently P removal performance was lower for the ENBNRAS system.

Sludge settleability

The overall average DSVI of the UCT system over the 18 sewage batches was 138 ml/g and that for the ENBNRAS system was 102 ml/g. The DSVI of the UCT system fluctuated with the % anoxic P uptake and as anoxic P uptake increased in the UCT system the abundance of filamentous organisms increased and the DSVI rose from 115 ml/g to 200 ml/g. This can be explained by the fact that as the nitrate load on the anoxic reactor of the UCT system increased, the nitrate concentration flowing to the anoxic reactor also increased, causing the DSVI to increase (see Casey et al., 1994). This phenomenon did not occur in the ENBNRAS system.

Conclusions

This study has shown that in terms of COD removal, the UCT and the ENBNRAS system achieved almost identical results. For the nitrogenous material removal, the ENBNRAS system produced on average an effluent of better quality with a TN concentration of nearly
half that of the UCT system. The ENBNRAS system was capable of producing an effluent with TN content < 10 mg/l, while the UCT system did not achieve this for any sewage batch. The UCT system, which exhibited predominantly aerobic P uptake, removed about 3 mg P/l influent more than the ENBNRAS system with anoxic/aerobic P uptake. P removal is the only process where the UCT system achieved superior results to that of the ENBNRAS system. The ENBNRAS system required approximately 75% less oxygen than the UCT system to perform the same BNR. The ENBNRAS system produced a better settling sludge than the UCT system did, and the ENBNRAS system DSVI did not produce a bulking sludge when high nitrate concentrations flowed from the anoxic reactor as was observed in the UCT system.

References