Anaerobically induced cell internal storage of unknown carbon compound used for enhanced post-denitrification

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Abstract

Two membrane bioreactor (MBR) plants were operated with a process which combines enhanced biological phosphorus removal (EBPR) and post-denitrification without external carbon dosing. An enhanced post-denitrification with denitrification rates (DNR) twice as high as the expected endogenous rate was observed. Batch tests revealed a linear correlation between the anaerobic acetate loading and the post-DNR which is remarkable since the aerobic phase is located in-between the anaerobic and anoxic phase. An anaerobic build up of a carbon storage compound which can outlast the aerobic phase is postulated. Measurements showed that neither polyhydroxyalkanoates (PHAs) nor glycogen are used as carbon source for the enhanced post-denitrification. A carbon mass balance in the anaerobic phase strongly indicates the formation of a different so far unknown storage compound. This assumption is supported by literature data which show carbon recovery ratios of known storage compounds (PHAs and glycogen) in the anaerobic phase of EBPR systems often below 1 down to 0.3, in particular for trials performed with real wastewater. The potential of enhanced post-denitrification in conventional UCT systems is also demonstrated in full-scale non-MBR wastewater plants.

Keywords: post-denitrification, endogenous denitrification, EBPR, storage compounds, PHA, glycogen, MBR
1 Nomenclature

COD Chemical oxygen demand (mg O$_2$/L) calculated to (mgC/L) for C-mass balance by factor 0.375 assuming only CO$_2$ production

DNR Denitrification rate (mgN h$^{-1}$ gVSS$^{-1}$)

EBPR Enhanced biological phosphorus removal

F/M Feed to micro-organism, here (gAcetate/gTS)

MBR Membrane activated sludge system, commonly referred to as membrane bioreactor

PHB Poly-β-hydroxybutyrate (mg/L or mgC/L)

PHA Polyhydroxyalkanoates (mgC/L) values given in this study exclude PHB

SRT Solid retention time

TS Total solids (g/L) equals mixed liquor suspended solids (MLSS) plus app.1 g/L of salts

WWTP Wastewater Treatment Plant

2

3 Introduction

Increasingly stringent requirements for the effluent of waste water treatment plants result in the necessity of innovative processes for nutrients removal. With commonly used nutrients removal systems where pre-denitrification is implemented nitrogen removal is limited by the recirculation ratio. In post-denitrification systems theoretically 100% nitrate removal can be achieved but an external carbon source is dosed in general and causes additional effort and costs. A process which combines EBPR and post-denitrification without external carbon dosing in an MBR was presented by Lesjean et al. (2003) and Gnirss et al. (2003). The EBPR and post-denitrification process showed excellent results and encouraged further investigations. Vocks et al. (2005) showed that denitrification rates of 1 to 1.5 mgN h$^{-1}$ gVSS$^{-1}$ in post-
denitrification systems are possible without external carbon dosing. These rates are clearly above endogenous denitrification rates which are reported between 0.2 and 0.6 \( \text{gN h}^{-1} \text{gVSS}^{-1} \) (Kujawa and Klapwijk (1999)). Own measurements of the endogenous denitrification rate after 24h of aeration showed DNR values in a similar range. The question of the carbon source used for the observed enhanced post-denitrification aroused and was firstly discussed by Vocks et al. (2005). It was revealed that lysis and hydrolyses are unlikely to represent a significant source of carbon. It was also shown that the anaerobic zone plays an important role in this process of enhanced post-denitrification. A plant operated without an upstream anaerobic zone showed post-DNRs half as high as a system operated with upstream anaerobic reactor. Tests with washed sludge showed similar DNRs as with unwashed sludge. Hence, the use of an internal carbon source was concluded. A hypothesis was formulated which explained the observed effects with internally stored glycogen resulting from the EPBR process as carbon source. This paper presents the further investigations made to identify the carbon source for enhanced post-denitrification.

Materials and Methods

Activated sludge

Activated sludge out of two MBR units operated for more than one year with the identical process was used for the conducted tests. The process combines EPBR with post-denitrification without external carbon dosing (Figure 1).

MBR pilot plant:

The TS concentration ranged in the pilot scale unit (140L) between 6g/L and 14g/L for a solid retention time (SRT) of 28d in average. The influent consisted of domestic waste water devoid of storm and industrial water. Average influent concentrations were: COD 1200 mg/L, TN 120 mg/L, TP 18 mg/L. More details on the pilot plant operation can be found in Vocks et al. (2007a).
MBR demonstration plant:
The second plant had a total volume of 10 m³. The TS concentration ranged between 6 g/L and 14 g/L for SRT varying between 20 and 50d. The influent consisted of domestic waste water devoid of storm and industrial water. Average influent concentrations were: COD 1300 mg/L, TN 155 mg/L, TP 21 mg/L. More details on the demonstration plant operation can be found in G nirss et al. (2007) and Vocks et al. (2007b).

Analyses
Anions (NO$_3$-N, NO$_2$-N, PO$_4$-P) were measured on a Dionex DX 100 ion chromatograph with an IonPac AS 4a column. NH$_4$-N was determined on a Dionex DX 100 ion chromatograph with an IonPac CS12a column.

Glycogen determination was made according to the method presented in Brdjanovic et al. (1998) with a slight modifications: the glucose was determined with a colorimetric enzyme test kit Glucose Liquicolor (Human GmbH, Germany).

PHB and total PHA determination were made with the enzymatical method presented in Hesselmann et al. (1999). Enzyme test kits (nr. 0907979) from Boehringer-Mannheim were used for the colorimetric measurement.

TS and VSS were measured according to German standard methods (DIN 38409-1).

CO$_2$ off gas analyses were done with a Malhak Modular System S710.

Batch tests
For the determination of P-release, P-uptake, nitrification and denitrification rates, as well as for monitoring the evolution of storage compounds, batch tests were conducted at 20°C. Activated sludge from the second anoxic zone was filled in a 1L stirred and tempered batch reactor, spiked with 250mg/L sodium acetate and flushed with N$_2$ for 1h to simulate the anaerobic zone. Subsequently ammonium chloride was dosed and the sludge was aerated until P uptake was almost completed (60-90min). In order to avoid nitrate limitation sodium nitrate was
spiked at the start of the anoxic phase during which the reactor was flushed with \( \text{N}_2 \). The pH was kept below 8 by dosage of 1N sulphuric acid if necessary.

Long term DNR measurements were conducted similar to the test described above but with an anoxic phase lasting for 20h. Sodium nitrate was spiked several times to maximum concentrations of 70 mg/L \( \text{NO}_3^-\text{-N} \).

To determine the endogenous denitrification rate, the sludge was first aerated for 24h and then spiked with sodium nitrate and kept under anoxic conditions for 2h monitoring the DNR.

**Results**

**Correlation of post-denitrification rate to anaerobic organic loading in batch test**

Numerous batch tests with activated sludge from the pilot plant were performed, from which DNRs between 1 and 4 \( \text{mgN h}^{-1} \text{gVSS}^{-1} \) could be derived in the final anoxic phase, all of them above reported rates of endogenous denitrification. From these tests a linear correlation between the post-denitrification rate and the anaerobic acetate loading was revealed (Figure 2). This is remarkable since the anaerobic phase was followed by 90 min of aeration before the anoxic phase occurred and the DNR was determined. This shows the importance of the anaerobic phase for the whole process. The extrapolation of the correlation down to a F/M ratio of 0 g/g gives a DNR of 0.4 \( \text{mgN h}^{-1} \text{gVSS}^{-1} \) which is in the range of the endogenous rates. A similar correlation was also found in the demonstration plant. Figure 3 reveals a linear correlation between the COD sludge load and the post-DNR. Although the anoxic zone is located after the aerobic treatment, were all COD is degraded, a higher sludge load leads to higher denitrification rates. Hence, the used organic substrate for the denitrification must be stored beforehand.

**Parallel batch tests**

To avoid other influences than the F/M ratio such as mixed liquor concentration, SRT or operational conditions in the plant, parallel batch tests were conducted. One batch was per-
formed with the standard procedure and a second batch test was operated in parallel with the
same activated sludge, whereby only half of the ordinary amount of acetate was dosed. Figure
4 demonstrates that this led to a 50% reduction of the DNR. Similar results were obtained
with other substrates such as lactate (data not shown). Hence, it can be concluded that a higher
anaerobic load yields higher post-denitrification rates. This alludes to the use of a storage
compound which is formed under anaerobic conditions. The absorption of acetate to the cell
surface instead of an uptake and cell internal storage is unlikely due to its easy availability for
the micro-organisms, as demonstrated by Bracklow et al. (2007). Furthermore, absorbed readily degradable carbon substances would be rapidly degraded under aerobic condition and
would therefore not be available anymore in the following anoxic zone.

On the other hand the storage compound is not used exclusively under anoxic conditions. In
batch tests, where the sludge was aerated for 24h instead of 90min before implementing an-
oxic conditions the measured DNR was between 0 mgN h\(^{-1}\) gVSS\(^{-1}\) and 0.58 mgN h\(^{-1}\) gVSS\(^{-1}\).
This is in the range of endogenous rates. It can be concluded that the storage compound was
completely used in the aerobic phase. However, the aerobic degradation of the compound is
slow enough that a significant amount of carbon remains for the anoxic phase under normal
process conditions. Usually less than 90min of contact time within the aerobic zone were im-
plemented. A second explanation can also be provided. In a continuous process, the aerobic
zone receives continuously a loading of slowly biodegradable substrate which is used by the
denitrifyers if they are facultative aerobes. In a batch experiments with long term aeration
they ultimately have to attack the internal carbon pool.

Enhanced post-denitrification in conventional EBPR systems

The question if there is a potential for enhanced post-denitrification in common EBPR sys-
tems was raised. Therefore stirred batch test with sludge from three different WWTP operat-
ing with EBPR and pre-denitrification (Berlin-Ruhleben, Berlin-Schönerlinde) were per-
formed, showing post-DNRs between 1 and 2 mgN h\(^{-1}\) gVSS\(^{-1}\) (see Table 1). Batch tests with
sludge from a non EBPR plant (Berlin-Münchehofe) showed DNR rates around 0.6 mgN h\(^{-1}\) gVSS\(^{-1}\), hence in the range of the endogenous rate. This shows also that there is a potential for enhanced post-denitrification also in conventional EBPR plants and it strengthens again the importance of the anaerobic zone.

However, if there was a potential for enhanced post-denitrification in conventional EBPR systems one could assume more severe scum sludge in secondary clarifiers of these systems compared to non-EBPR systems, due to wild denitrification in the sludge blanket. But this is not observed in the full-scale plants of Berlin. Non-stirred batch tests, in which the sludge could settle, were conducted. They revealed that the sludge was bulking after 30 minutes. Samples from the clear water phase and the sludge blanked were taken and it was observed that the denitrification rate in the sludge layer was at least two times higher than in the clear water phase. This will be probably caused by transport limitations since nitrate has to be transported mainly by diffusion. Convection was only inducted by rising nitrogen gas bubbles and sludge particles. It can be then concluded that due to the optimized hydraulics of a clarifier and nitrate transport limitations no amplified sludge bulking is observed in conventional EBPR systems.

**Evolution of known storage compounds in batch tests**

It was assumed that the carbon storage compounds known for their contribution in the EBPR process (PHA and glycogen) could be a carbon source in the anoxic phase for enhanced post-denitrification (Vocks *et al.* (2005)). 10 batch tests were conducted in which the evolution of the storage compounds was measured. Since acetate was used as carbon source in the anaerobic zone which is mainly metabolised to PHB (Maurer *et al.* (1997), PHB and glycogen were measured. Figure 4 presents one representative test, which contradicted the assumption that PHB or glycogen serve as carbon source for the post-denitrification. In the anaerobic and aerobic phases glycogen and PHB show the typical EBPR metabolism. PHB is build up in the anaerobic phase accompanied with glycogen depletion and P-release. In the aerobic phase the
glycogen storage is regenerated by PHB reduction and P-uptake. In the anoxic phase the PHB concentration is low and relatively constant. Hence, PHB cannot be the carbon source for enhanced post-denitrification. Glycogen is on a high level and shows some dynamics, but this random behaviour cannot explain the enhanced post-denitrification.

In addition, the evolution of the denitrification can be divided into three parts. In the first five hours the DNR is around 0.95 mgN h\(^{-1}\) gVSS\(^{-1}\) which is above endogenous rates. Afterwards the DNR stays for ten hours at 0.6 mgN h\(^{-1}\) gVSS\(^{-1}\). Finally the DNR declines down to 0.3 mgN h\(^{-1}\) gVSS\(^{-1}\). These rates are in the range of endogenous rates and a shift to a different carbon source compared to the first part of the anoxic phase can be concluded.

The unsteady dynamic of glycogen with sudden raise and fall of the concentration during the first hours of the anoxic phase was a very typical behaviour in many batch tests. It was also typical that after a long period of time of at least 15h the glycogen concentration was definitely lower than at the beginning of the anoxic zone, showing no sudden changes anymore.

This may indicate an involvement of glycogen in the metabolism for the enhanced post-denitrification, but it is not the major source of carbon. In long starvation periods glycogen might be used for other endogenous processes.

Considering the first part of the anoxic phase where the enhanced post-denitrification takes place 33.2 mgNO\(_3\)-N or 147 mgNO\(_3\) were denitrified. The stoichiometric correlation for denitrification with sugar states the need of 0.208 mol C\(_6\)H\(_{12}\)O\(_6\) per mol NO\(_3\) (Halling-Sørensen and Jørgensen (1993)). This leads to a theoretical need of 35.5 mgC/L but only a decline of 20 mg/L glucose which equals 8 mgC/L was measured during the entire anoxic phase. Therefore, if glycogene took part as carbon source in the enhanced post-denitrification process, it could explain maximum 20% of the carbon demand.

To be also noted that the phosphate is taken up completely in the aerobic phase and no further uptake occurs in the anoxic phase, hence the enhanced post-denitrification observed in the batch test can not be linked to DNPAOs, as already postulated by Vocks et al, (2005).
Since neither PHB nor glycogen can be the main carbon source and all indications point on a storage compound which is formed due to the anaerobic conditions, a carbon mass balance for the anaerobic phase was set up. The known cell internal carbon storage compounds such as glycogen, PHB and total PHA, as well as cell external COD and CO₂ production were measured.

The outcomes of this experiment are presented in Figure 5 and demonstrate that the carbon mass balance is far from being closed. Acetate was taken up completely (80 mgC/L), but this lost is not compensated by an increase of another compound. The dissolved COD was relatively constant showing only a slight rise of about 15 mgC/L, which might be due to fermentation products formed during the anaerobic phase. The glycogen concentration declined by 19.1 mgC/L and the PHB concentration raised by 5 mgC/L. The concentration of the remaining PHAs were relatively constant showing only a slight increase of 1.2 mgC/L, and the CO₂ production was negligibly small with 0.7 mgC/L. However, this small CO₂ production matches with data in Smolders et al. (1994) where 1 molC CO₂ was produced by the build up of 7 molC PHB. This ratio is at 7.14 in the present study. A slightly increasing pH was always observed during the anaerobic phase. Hence, it is unlikely that produced CO₂ is dissolved and not measured in the off-gas. The disappearance of acetate carbon mass in the mass balance is a strong indication of the build up of a different so far unknown storage compound.

**Discussion**

Storage compound candidates and carbon recovery ratio in the literature

Storage compounds different to PHA and glycogen are rarely discussed for biological waste water treatment processes. Jeon et al. (2000) postulated the build up of a lactate polymer in an EBPR system. However, they used glucose as sole carbon source and a direct transfer to the results obtained in this study can not be made. But this shows the possibility for the formation of substances different from the commonly mentioned ones.
It is also possible that the carbon storage which is build up consists of a sugar different to glycogen such as trehalose which is widely used by biological systems (Avonce et al. (2006))

Although anaerobic substrate uptake is the key in the enhanced post-denitrification metabolism, the anaerobically stored carbon might not be used directly in the anoxic phase. A process wherein carbon is taken up under anaerobic conditions and metabolised later into a different polymer, similar to the EBPR process where anaerobically stored PHB is partly transformed to glycogen under aerobic conditions, is also to be considered. This would also explain the fact, that the carbon can outlast the aerobic conditions for a certain time. The consideration that storage compounds others than PHA or glycogen might be formed under anaerobic conditions in EPBR systems is also strengthened by Table 2. The carbon recovery ratio which is calculated by: \[
\frac{\text{PHA accumulated (mgC/L)}}{\text{Substrate taken up (mgC/L)} + \text{Glycogen consumed (mgC/L)}}
\]
is often clearly below 1. In the cases were this ratio could not be calculated due to lack of data the ratio is given. Since glycogen is not included in this ratio the carbon recovery ratio is below that value. Under anaerobic conditions only minor CO₂ production takes place, hence if the carbon recovery ratio is below 1 carbon could be used for a different purpose than PHA build up. Table 2 shows also the broad range in which the data given in literature are scattered. PHA/TS concentrations in activated sludges grown on real waste water vary between 0.95 and 30 mgC/gTS and anaerobic PHA accumulation lies between 0.7 and 30 mgC/gTS. The data obtained from this study fit in that range. The table also shows the difference between data gained from studies with real sewage and studies made with synthetic waste water. Activated sludges originated from a synthetic feed trend to have higher PHA accumulation and concentrations and also higher carbon recovery ratios than sludges fed with real sewage especially when acetate was used as sole carbon source. Most metabolic models in literature are based on experiments with synthetically fed sludge. The more complex feed
in real sewage systems will create different microbiological communities performing other
metabolisms.

It is also apparent that no data for MBR EBPR plants are available. MBR plants contain much
higher TS concentrations and retain all micro-organisms and might therefore also have differ-
ent biological communities.

Considerations on endogeneous denitrification

The definition of “endogenous denitrification” can be also discussed. Denitrification on cell
internal PHB as it happens in the UCT process (e.g. Meinhold et al. (1999)) is not viewed as
endogenous denitrification (Kujawa and Klapwijk (1999)). Hydrolysed cell lysis products are
often declared as the sole carbon source for endogenous denitrification (e.g. van Haandel et
al. (1981)). Lysis as a carbon source for the enhanced post-denitrification was excluded by
Vocks et al. (2005). Furthermore, the fact that bacteria are dying in large amounts, releasing
significant quantity of carbonaceous material, is questioned in literature (van Loosdrecht and
Henze (1999), Rosenberger et al. (2000)). They regard endogenous processes as a process
based on cell internal material leading only to a small decrease in biomass. But it is not clear
which kind of carbon source is used. They also state that predation by protozoa can play a
major role.

In any case, Figure 5 shows that three different DNRs were successively measured. Thus,
several pools of carbon might be used for denitrification. None of them can be clearly speci-
fied at the present state. It shows that there is still significant lack of knowledge on endoge-
rous denitrification processes and the related carbon source.

Conclusion

Two MBR units were operated with the same process which combines EBPR with post-
denitrification without external carbon dosing. Post-denitrification rates above the endoge-
rous rates were observed. Batch tests with activated sludge collected in these plants were con-
ducted in order to investigate the used carbon source for the enhanced post-denitrification. It was revealed that:

- A strict linear correlation exists between the anaerobic organic load and the anoxic denitrification rates, despite the presence of the aerobic phase between the aerobic and anoxic conditions;
- The carbon mass balance for the anaerobic phase was incomplete measuring only the known storage polymers;
- Known EBPR storage compounds (PHA, glycogen) are not used as main carbon source for enhanced post-denitrification.

The obtained results provide strong indications of the presence of a so far unknown storage carbon compound in the post-denitrification process. This assumption is strengthened by the fact that also many literature data on EBPR show carbon recovery ratios below 1.

Investigation on conventional UCT-type WWTPs demonstrated also the potential of enhanced post-denitrification in EBPR processes not combined with membrane filtration.
Figure 1 Process scheme for both plants

Figure 2 Correlation between the *anaerobic* acetate loading and the post-denitrification rate from 25 batch tests
Figure 3 Linear correlation between the sludge load and the post-DNR in the demonstration plant
Figure 4 DNR in parallel batch tests with different anaerobic F/M (3 parallel batch tests, sludge from pilot plant)
Figure 5 Long term DNR Batch test with determination of PHB and Glycogen; AN=anaerobic phase, AE=aerobic phase, AX=anoxic phase
Figure 6 Measured carbon compounds at the start and at the end of the anaerobic phase

Table 1 Post-DNR batch test with sludge from conventional WWTP

<table>
<thead>
<tr>
<th>WWTP</th>
<th>System</th>
<th>Post-DNR range (mgN h⁻¹ gVSS⁻¹)</th>
<th>Average post-DNR (mgN h⁻¹ gVSS⁻¹)</th>
<th>Number of batch tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schönerlinde</td>
<td>UCT</td>
<td>0.7-2.7</td>
<td>1.6</td>
<td>10</td>
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<tr>
<td>Ruhleben</td>
<td>UCT</td>
<td>1.2-1.5</td>
<td>1.4</td>
<td>2</td>
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<tr>
<td>Münchehofe</td>
<td>Pre-den, no EBPR</td>
<td>0.4-0.7</td>
<td>0.6</td>
<td>3</td>
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</table>
Table 2: Overview on the details of storage compounds metabolism for EBPR systems provided in literature.

The trial type indicates in which kind of experiment the storage compounds were measured. The sludges grown on real sewage were often used in batch tests with other substrate than sewage which is noted in the substrate column.

* PHA accumulation respectively PHA max. concentration in mgC/L due to lack of TS data

<table>
<thead>
<tr>
<th>Literature</th>
<th>Trial type</th>
<th>Substrate</th>
<th>MLSS or TS (g/L)</th>
<th>PHA accumulation (mgC/gTS)</th>
<th>PHA max. concentration (mgC/gTS)</th>
<th>Glycogen consumption (mgC/L)</th>
<th>Carbon recovery ratio</th>
<th>PHA formed/COD uptake (gCOD/gCOD)</th>
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<tbody>
<tr>
<td>Satoh et al. (1996)</td>
<td>Batch</td>
<td>Acetate</td>
<td>1.65</td>
<td>10.48</td>
<td>18.79</td>
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<td>0.7</td>
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<td>Propionate</td>
<td>1.65</td>
<td>12.9</td>
<td>18.2</td>
<td>7</td>
<td>1.01</td>
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<td>Batch</td>
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<td>8.82</td>
<td>12.94</td>
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<td>0.7</td>
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<td>30</td>
<td>34.83</td>
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<td>3.2</td>
<td>30</td>
<td>30</td>
<td>34.83</td>
<td>1.62</td>
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<td>19.35</td>
<td>19.35</td>
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<td>60</td>
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<td>30</td>
<td>0.88</td>
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<td>Acetate+Propion.+Butyrate</td>
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<td>21.33</td>
<td>43.33</td>
<td>160</td>
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<td>47*</td>
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<td>0.8</td>
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References


