A proposed sustainable BNR plant with the emphasis on recovery of COD and phosphate

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Abstract Water problems have to be solved in an integrated way, and sustainability has become a major issue. For this reason, developing more sustainable wastewater treatment processes is needed. New discoveries and good understanding on microbial conversions of nitrogen and phosphorus make more sustainable processes possible. New options for decentralized sustainable sanitation are generally compared to conventional sewage systems, we think that for a proper comparison also innovative centralized treatment schemes should be evaluated. In this article, a more sustainable WWTP is proposed for municipal wastewater treatment, mainly based on the principles of denitrifying dephosphatation and anaerobic ammonium oxidation (ANAMMOX). The proposed system consists of a first stage of the A/B process in which maximal sludge production is achieved. In this way, COD is regained as sludge for methanation. The following BCFS® and CANON processes can remove N and P with minimal or no COD need. As a potential fertiliser, struvite can easily be removed from the sludge water by adding magnesium compounds. A case study is done on the basis of the mass balance over the proposed plant. The effluent from the system has a good quality to be recycled. This could also make a contribution to meeting the world’s water needs and lessening the impact on the world’s water environment. Since all the separate units are already applied or tested on pilot-scale, no problems for technical implementation are foreseen.

Keywords ANAMMOX; BCFS®; CANON; denitrifying dephosphatation; methanation; struvite

Introduction Nowadays, wastewater treatment deals with the main polluting components such as COD, ammonium and phosphate. Traditionally, COD and ammonium are eliminated by biological oxidation and nitrification coupled with denitrification. Phosphate is removed either by biological accumulation in the sludge or by chemical precipitation. The main problems of conventional processes include:

- energy consumption due to aeration for COD oxidation and nitrification, which actually results in considerable loss of chemical energy from COD oxidation (about 14 MJ/kg COD);
- COD requirement for denitrification and biological phosphate removal;
- sludge production;
- no recovery of nutrients;
- emissions of CO₂ into the atmosphere.

Wastewater treatment plants (WWTPs) have to cope with increasingly stricter effluent standards. The general EC effluent standards for nutrient discharge have been tightened; the total effluent nitrogen and phosphorus have to be below 10 g N/m³ and 1 g P/m³, respectively. In other continents of the globe, eutrophication is also a major problem in the water environment. For example, China has tightened its effluent standards for nutrient discharge (N_{tot} ≤ 15 g N/m³ and P_{tot} ≤ 0.5 g P/m³) in the last decade, even though the development of its WWTPs is still in the early stages. Complying with these stricter effluent standards will cause even more energy consumption (thus higher CO₂ emissions), more organic carbon
consumption (even including additional COD for denitrification and/or dephosphatation) and larger sludge production if conventional processes have to be used. Therefore, improved effluent quality by conventional processes may easily lead to overall adverse effects on the environment (van Loosdrecht et al., 1997). From the point of view of an integrated approach to environmental aspects, conventional processes somehow seem to have an unsustainable feature in fighting eutrophication.

It is really needed to develop sustainable wastewater treatment processes. Sustainable processes can be characterised by a minimum of COD oxidation, a maximum of methanation (by COD conversion), a minimum of energy consumption, a minimum of CO₂ emissions, a minimum of sludge production, and recovery of phosphate. On the other hand, increasing attention has to be paid to recycling of purified effluent, especially in regions with water shortage, such as in large parts of China. Purified effluent is a valuable resource. Instead of being thrown away, this water after appropriate treatment can be reused to reduce the demand on the fresh water sources. Therefore, water recycling can make a sustainable contribution to meeting the world’s water needs and lessening the impact on the world’s water environment. A move, from the old “use once and throw away” approach to a new “conserve, use wisely and recycle” water economy, will benefit the whole world.

Effluents resulting from full biological treatment and nutrient removal (tertiary treatment) have a good quality to be recycled. By applying advanced treatment processes such as flocculating filtration, membrane filtration, UV and activated carbon to remove the remaining inert COD and bacteria, effluents from tertiary treatment can be further improved and reused for various purposes such as process water, household water, urban water, agricultural irrigation, groundwater supplement and so on (van der Graaf, 2001). Therefore, constructing sustainable WWTPs can simultaneously contribute to two key water problems: i) deterioration in quality, and ii) shortage in quantity. This is like killing two birds with one stone.

Developing novel biological processes for wastewater treatment has to depend on new discoveries and a good knowledge of microbiology and biochemistry. In the last decade, the discoveries of denitrifying dephosphatation (Vlekke et al., 1988; van Loosdrecht et al., 1992; Kerrn-Jespersen et al., 1994; Kuba et al., 1996) and anaerobic ammonium oxidation – ANAMMOX (Mulder, 1992) have made sustainable WWTPs possible. As a practical technique for denitrifying dephosphatation, the BCFS® process has been successfully applied in several Dutch WWTPs (Brandse and van Loosdrecht, 2002). Although still under research, ANAMMOX coupled with partial nitrification has been tested in experiments (Strous et al., 1997; Dijkman and Strous, 1999) and observed in several on-site applications (Hippen et al., 1997; Siegrist et al., 1998; Helmer and Kunst, 1998; Helmer et al., 1999).

It has been quantitatively evaluated that minimising use of COD in WWTPs can significantly contribute to the total environmental quality (Hao et al., 2001a). Moreover, recovery of phosphate will make WWTPs more sustainable. In consideration of these key aspects for sustainability, a sustainable WWTP is proposed for biological nutrient removal (BNR), based on the BCFS® process for denitrifying dephosphatation evaluated by Hao et al. (2001b), the CANON process for completely autotrophic ammonium removal in biofilm evaluated by Hao et al. (2001c and 2001d), the A/B process for COD recovery developed by Boehnke (1978), and potential struvite formation for recovery of phosphate tested by Battistoni et al. (1998), Li et al. (1999). Jaffer et al. (2001) and Battistoni et al. (2001).

Principles of the BCFS® and CANON processes
The BCFS® processes
The BCFS® (biological and chemical phosphorus and nitrogen removal) process is based on the modified UCT process, with the emphasis on developing denitrifying phosphorus-
removing bacteria (DPB). The BCFS® process was developed and has been applied in The Netherlands (van Loosdrecht et al., 1998; Brandse and van Loosdrecht, 2002). Unlike the standard UCT process, the BCFS® process is extended to five compartments, three internal recirculation flows and an integrated P-stripper in the first compartment (Figure 1).

A contact tank (DO = 0) is added as a second selector, to remove soluble hydrolyses products coming from the anaerobic tank with nitrate from return sludge. In this way, growth of filaments is strongly repressed. A mixed tank (DO = 0.5 mg/l) is specially designed for simultaneous nitrification and denitrification and to ensure a low nitrogen concentration in the effluent. This added tank is only aerated when necessary. When influent COD is not enough for bio-P removal or sludge age is too long to biologically accumulate phosphate, released phosphate can be easily extracted from the anaerobic stage. This option can also be used in order to recover phosphate.

Denitrifying phosphorus-removing bacteria (DPB) use nitrate as electron acceptor instead of oxygen. DPB can contribute towards a significant reduction in the need of COD for integrated nitrogen and phosphorus removal. Up to 50% less COD is required, compared to conventional aerobic P-uptake processes (Kuba et al., 1996; Hao et al., 2001a). Moreover, oxygen requirement and sludge production can be decreased up to about 30% and 50%, respectively (Kuba et al., 1996). Because of the reduced COD need, the saved COD can be used for methanation (energy production) in a digestion reactor. Both energy savings from aeration and energy production from methanation can finally contribute to a significant reduction of CO₂ emissions into the atmosphere.

The CANON process
A one-stage ammonium removal process is possible to be achieved in a biofilm reactor with simultaneous nitrification and ANAMMOX (Figure 2), which was tested and observed in experiments (Strous et al., 1997; Dijkman and Strous, 1999) and in practical applications (Hippen et al., 1997; Siegrist et al., 1998; Helmer and Kunst, 1998; Helmer et al., 1999). This process has been entitled “CANON” (completely autotrophic N-removal over nitrite, Strous, 2000).

In a biofilm supporting nitrification and ANAMMOX, there can generally be three autotrophic organisms: ammonium oxidisers, nitrite oxidisers and ANAMMOX organisms. They compete with one another for oxygen, ammonium and nitrite. Due to different affinity constants for oxygen between ammonium and nitrite oxidisers as well as the mass transfer limitation, accumulation of nitrite is completely possible. Under this condition, ANAMMOX could occur with ammonium and accumulated nitrite. The overall stoichiometry of the CANON process can be represented by Eq. (1).

\[
\text{NH}_4^+ + \frac{3}{4} \text{O}_2 \rightarrow \frac{1}{2} \text{N}_2 + \frac{3}{2} \text{H}_2\text{O} + \text{H}^+ \tag{1}
\]
Proposed concept for a sustainable BNR plant

The regularly applied A/B process (Boehnke, 1978) was specially designed for recovery of COD from wastewater. The A-stage of the A/B process has a short solids retention time (SRT = 8–25 h), and a large part (up to 70–80%) of both suspended and soluble COD can be converted into biomass sludge. The sludge produced in this stage can be concentrated and used for methanation. This also maximises the assimilation of nitrogen and phosphorus in the sludge thereby concentrating them for potential recovery. The sludge produced in the A-stage has better digestion characteristics than normal secondary sludge, which results in a lower overall sludge production (Boehnke, 1978). The B-stage of the A/B process was designed for oxidation of the remaining ammonium.

Instead of the B-stage, the BCFS® process is proposed here to remove the remaining N and P with the remaining COD in the main stream (a large diluted cold stream). The CANON process is proposed to treat the sludge liquor (reject-water from sludge digestion, a small warm concentrated side stream). The relatively constant flow-rate with a constant warm temperature will be favourable for the CANON process.

Figure 3 depicts the proposed flow scheme of a sustainable BNR plant. In the proposed BNR plant, recovery of COD and phosphate is emphasised. The A-stage of the A/B process is only used to concentrate both suspended and soluble COD and no chemical P-removal is involved. After the separation and digestion of the sludge from the A-stage, two streams remain: (i) a main stream: the wastewater itself and (ii) a side stream: the sludge liquor. Parts of COD, N and P remain in the main stream, and the BCFS® process is designated to treat this stream.

The main components of the side stream are enriched ammonium and phosphate. Recovery of phosphate from this stream could be achieved by formation of struvite by adding magnesium compounds when the molar ratio of $\text{Mg}^{2+}$:$\text{NH}_4^+$:$\text{PO}_4^{3-}$ is greater than 1:1:1. The chemical composition of struvite is magnesium ammonium phosphate (MAP: $\text{MgNH}_4\text{PO}_4\cdot6\text{H}_2\text{O}$). Struvite is a hard crystalline deposit and has a commercial value. The most suitable stream for formation of struvite in WWTPs was identified as the sludge liquor separated from digested sludge (Momberg and Oellermann, 1992; Battistonni et al., 1998, 2001; Jaffer et al., 2001). Experiments indicated that the solubility of struvite decreased.
with increasing pH and reached its minimum at pH = 8.5–9.0 (Li et al., 1999; Jaffer et al., 2001).

Following formation of struvite, the CANON process would be suited to remove the ammonium remaining in the side stream.

**Case study of the proposed BNR plant**

To demonstrate the proposed BNR plant, an assumed inflow (Q = 8,500 m³/d, COD = 625 g/m³, TKN = 60 g N/m³ and P = 9.5 g P/m³) is used here as a case study. According to the proposed flow scheme (Figure 3) and some experimental data, it can be assumed that 40% of N-load in the influent can be bound into biomass sludge in the A-stage. It is assumed that sludge thickening is performed by centrifugation. Therefore, 1,200 g NH₄⁺ – N/m³ can be expected in the side stream (Mulder et al., 2001). Before making a mass balance, it is further assumed that ordinary biomass sludge contains 8% N and 2% P (maximal 7–8% for P-bacteria sludge) and that about 50% of the sludge-COD can be converted into methane (CH₄). This means that maximum 300 g P/m³ could exist in the side stream, leading to a necessity and possibility of phosphate recovery by formation of struvite.

Based on the above assumptions and a temperature of 15°C, the mass balance of COD, N and P in the proposed BNR plant can be calculated, which is shown in Figure 4. Practical removal efficiencies in every treatment unit have been considered in calculating the mass balance. If 74% of the influent COD-load is removed in the A-stage, 40% of the influent N-load and 63% of the influent P-load will be assimilated, and 26% of the influent COD-load (based on a sludge yield of 0.65 g biomass-COD/g substrate COD) will be oxidised. This actually results in a total COD removal efficiency of 74% in the A-stage.

The remaining COD (26%) is introduced in the BCFS® process to remove the remaining nitrogen (60%) down to 8 g N/m³ in the effluent and the remaining phosphorus (37%) down to 0.5 g P/m³ in the effluent. The conversions are based on a full dynamic simulation model (Hao et al., 2001b). A SRT of 20 days is set for the BCFS® process, leading to a small part of excess secondary sludge (6.6% of the influent COD load). This sludge will be combined with the sludge from the A-stage for digestion.

![Figure 3 Flow scheme of a proposed sustainable BNR plant](https://iwaponline.com/wst/article-pdf/48/1/77/423044/77.pdf)
During digestion, roughly 50% of biomass-COD is converted into methane (CH₄). As a result, the corresponding amounts of nitrogen and phosphorus bound in the sludge are released into the liquid, which will appear in the digester effluent. The other half of biomass-COD remains as excess sludge to be incinerated.

By using magnesium chloride (MgCl₂) as a chemical precipitant (Jaffer et al., 2001), 97% of P-removal as struvite can be achieved, which is equivalent to a phosphate recovery of 46.2% of the influent P-load. Under full turbulence and high pH (8.5–9.0), struvite can be formed within 15 min and settle to reach its maximal compact density (2,050 kg/m³) within only 10 min (Li et al., 1999). This means that a very compact chemical precipitation unit can be expected.

As a final step, the CANON process is proposed to further treat the side stream still containing high ammonium concentration at a temperature of 30°C. Based on the previous studies (Hao et al., 2001c and 2001d), it has been ascertained that at 30°C the CANON process could achieve 90% of N-removal in a 1-mm thick biofilm at an ammonium surface load of 1.5 g NH₄⁺-N/m²·d associated with a DO concentration level of about 1 g O₂/m³. If a biofilm has a total surface of 250 m² biofilm/m³·reactor, a biofilm reactor of 265 m³ is needed.

Although higher concentrations of ammonium and phosphate still remain in the treated side stream after formation of struvite and autotrophic N-removal, this treated stream can be mixed with the effluent of the main stream before being discharged. In this way, the large flow-rate of the main stream with lower concentrations of ammonium and phosphate could dilute the treated side stream. It is also possible to recycle the side stream water back to the influent and to get a slightly better effluent. In this case study, the total effluent concentrations of COD, N and P are calculated to be 30 g COD (inert)/m³, 9 g N/m³ and 0.6 g P/m³, respectively.

Figure 4 Mass balance in the proposed BNR plant (%: relative to the influent load), indicating what the different line types mean
Remarks of sustainability for the proposed BRN plant

In the proposed BNR plant, COD oxidation into CO₂ is minimised (26% oxidation in the A-stage), which is needed for the formation of biomass out of soluble COD. 48% of the influent COD-load is converted into biomass sludge in the A-stage. The remaining COD (26%) is used in the second stage for N and P removal in the BCFS® process. Since only 60% of the influent N-load needs to be removed through denitrifying dephosphatation, a corresponding amount of COD saving for denitrification could be expected. Summed over the whole process, 1 mg-N removed needs only 2.6 mg oxygen, which is less than the normal value. As shown in Figure 4, over ¼ (27.3%) of the influent COD load could be converted into CH₄. After formation of struvite, almost half (46.2%) of the influent P-load could be recovered. Compared with a conventional activated sludge WWTP with a low sludge load (0.05 kg BOD₅/kg VSS·d), the main differences are shown in Table 1.

Evaluation of the proposed BNR plant

In the proposed BNR plant, the different technologies such as the A/B process, the BCFS® process, and formation of struvite have been separately applied in practice (Momberg et al., 1992; van Dongen et al., 2001; Brandse and van Loosdrecht, 2001). Digestion is an existing technology for sludge conversion into methane. Although the CANON process is still under research, some co-incidental application cases have been reported (Hippen et al., 1997; Siegrist et al., 1998; Helmer and Kunst, 1998; Helmer et al., 1999). The previous studies of ours (Hao et al., 2001c, 2001d) have given a good qualitative description of this novel concept of autotrophic ammonium removal. This will speed up its deliberate application. Therefore, technological difficulties will not be a problem in application of the proposed BNR plant to practice.

Due to the integration of all the concerned technologies, the infrastructure costs (engineering, construction and materials) of the proposed BNR plant will be relatively high. Attributed to its sustainability, however, the operational costs (mainly consumption of electricity and production of sludge) of the proposed BNR plant will be lower, according to Table 1. Moreover, CO₂ emissions into the atmosphere can be reduced, and recovery of phosphate as struvite can be realised, which could be used as a potential fertiliser in agriculture or horticulture.

In wastewater treatment, increasing sustainability is often associated with decentralized treatment schemes, which are then compared to conventional centralised systems without any recovery. Owing to recovery of COD and phosphate, the proposed centralised plant should be competitive with decentralized treatment schemes.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Main differences between the proposed BNR plant and a conventional WWTP</th>
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</thead>
<tbody>
<tr>
<td><strong>Proposed plant</strong></td>
<td><strong>Conventional WWTP</strong></td>
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<tr>
<td>Oxygen demand</td>
<td></td>
</tr>
<tr>
<td>kg O₂/kg N removed</td>
<td>2.6</td>
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<tr>
<td>kg O₂/kg COD removed</td>
<td>0.29</td>
</tr>
<tr>
<td>COD demand</td>
<td></td>
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<tr>
<td>kg COD/kg N removed</td>
<td>1.4</td>
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<tr>
<td>Methane production</td>
<td></td>
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<tr>
<td>kgCH₄-COD/kg COD removed</td>
<td>0.28</td>
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<tr>
<td>Sludge production</td>
<td></td>
</tr>
<tr>
<td>kg sludge-COD/kg COD removed</td>
<td>0.29</td>
</tr>
<tr>
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<td></td>
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In wastewater treatment, increasing sustainability is often associated with decentralized treatment schemes, which are then compared to conventional centralised systems without any recovery. Owing to recovery of COD and phosphate, the proposed centralised plant should be competitive with decentralized treatment schemes.
Conclusions
A sustainable BNR plant for sewage treatment is proposed in this article. Recovery of COD as methane and recovery of phosphate as struvite are emphasised in the proposed BNR plant. Because the BCFS® process for denitrifying dephosphatation and the CANON process for autotrophic ammonium removal can significantly contribute to saving COD in integrated N and P removal, an optimal treatment system is possible with minimal use of energy and resources. The mass balance of the proposed BNR plant indicates that the rest of COD after being mostly regained as biomass is still enough to accomplish denitrifying dephosphatation and that no chemical precipitants are needed for P-removal. A significant amount of P in the sludge water is worthy of being recovered as struvite. Compared to a conventional low loaded activated sludge process, the optimal treatment system is quite attractive for minimisation of energy and resources as well as recovery of phosphate. Technological difficulties will not be a problem in application of the proposed BNR plant to practice.

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