Cost effective and advanced phosphorus removal in membrane bioreactors for a decentralised wastewater technology

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Abstract Future stringent phosphorus regulations (down to 50 µg/L in some cases) together with the availability of more cost effective and/or innovative membrane processes, are the bases for this project. In contrast to conventional activated sludge plants, process parameters are not optimised and especially enhanced biological phosphorus (Bio-P) removal in membrane bioreactors (MBRs) are not proven yet. Current practice of P-removal in MBRs is the addition of coagulants in a co-precipitation mode. Enhanced biological phosphorus removal, when adapted to MBR technology, might be a cost-effective process. For very stringent effluent criteria additional P-adsorption on activated clay after membrane filtration can be also an interesting solution. The objective of this research project is to identify and test various phosphorus removal processes or process combinations, including MBR technologies. This should enable us to establish efficient and cost effective P-removal strategies for upgrading small sewage treatment units (up to 10,000 PE), as needed in some decentralised areas of Berlin. In particular, enhanced Bio-P removal technology was developed and optimised in MBR. Combinations of co-precipitation and post-adsorption will be tested when low P-values down to 50 µg/L are required in the effluent. One MBR bench-scale plant of 200 to 250 L and two MBR pilot plants of 1 to 3 m^3 each were operated in parallel to a conventional wastewater treatment plant (Ruhleben WWTP, Berlin, Germany). The MBR bench-scale and pilot plants were operated under sludge ages of respectively 15 and 25 days. In both cases, Bio-P was possible, and phosphorus effluent concentration of about 0.1 mg/L could be achieved. A similar effluent quality was observed with the conventional WWTP. Investigations with lab columns indicated that P-adsorption could lead to concentrations down to 50 µg/L and no particle accumulation occurred in the filter media. The three tested materials exhibited great differences in break-through curves. Granulated ferric hydroxyde (GEH®) showed higher capacity than activated alumina and FerroSorpPlus.
Keywords Enhanced Bio-P removal; membrane bioreactor (MBR); microfiltration; P-adsorption

Introduction

For the past 10 years the Berliner Wasserbetriebe (BWB) has been researching the combined use of coagulation and microfiltration for disinfection and advanced removal of phosphorus in secondary treated effluent to upgrade conventional wastewater treatment plants (Gnirss and Dittrich, 2000). Since BWB must recharge groundwater by artificial surface water infiltration, wastewater treatment must be of a high standard to prevent eutrophication and algae bloom in the receiving surface water. In Berlin phosphorus is generally the limiting nutrient in receiving water courses.

Future stringent phosphorus regulations (down to 50 µg/L in some cases) together with the availability of more cost effective and/or innovative membrane processes, are the bases for this project. In contrast to conventional activated sludge plants, process parameters and especially Bio-P removal in membrane bioreactors (MBRs) are not optimised yet (Adam *et al*., 2002). Current practice of P-removal in MBRs is the addition of coagulants in a co-precipitation mode (P-precipitation). This leads to an increase in chemicals consumption, sludge production, and salt concentration in the effluent, along with a yet unknown risk of membrane performance degradation over long term operation. Enhanced biological phosphorus removal (Bio-P) in the activated sludge reactor might be an alternative process. For very stringent effluent criteria additional P-adsorption on activated clay (PAAC) after membrane filtration can also be an interesting solution.

The objective of this research project is to identify and test various phosphorus removal processes or process combinations, including MBR technologies. This should enable us to establish efficient and cost effective P-removal strategies for upgrading of small sewage treatment units (up to 10,000 PE), as needed in some decentralised areas of Berlin.

This paper summarises the results of the investigations carried out on one MBR bench-scale plant (BSP, 200 to 250 L) and two MBR pilot plants (1 to 3 m^3 each) set up in parallel to a conventional WWTP.

Preliminary tests undertaken with the MBR bench scale plant since April 2001 have indicated a high potential for Bio-P removal (Adam *et al*., 2002), under operating conditions characteristic of conventional activated sludge plants (i.e. sludge age of 15 days). These first results were very promising for other regimes (higher sludge age) and process configurations. The two parallel MBR pilot plants have been operated since September 2001 in Bio-P configurations with a sludge age of 25 days. Further optimisation of the biological process with regard to configuration, sludge age, concentration, and recirculation rates, will be conducted as indicated in Table 1.

This article also provides the first results of P-adsorption in MBR effluent. Research efforts are: to screen and assess three different adsorptive materials, and identify the influence of operational parameters in the MBR process.

This research project will enable us to set up recommendations and specifications for full-scale treatment facilities designed for advanced phosphorous removal and including MBR technology. The first demonstration site will be located in a remote area of Berlin. Since advanced phosphorus removal is one major requirement in Berlin areas with sensitive receiving water bodies, MBRs are technologies which, if proven robust, automated and cost-competitive, could be one elegant solution to meet stringent effluent quality for the upgrading of decentralised or semi-decentralised sewage schemes.

Experimental procedure

One MBR bench-scale and two pilot plants were operated in parallel. The units were continuously fed by degritted raw sewage (1 mm punch holes screen). Sizes and operation conditions of the plants are given in Table 2 and compared to the full-scale Ruhleben WWTP (trials site and reference).

The first phase of the study, undertaken on the bench-scale plant, consisted in operating a MBR pilot plant with similar operatiing conditions to the conventional full-scale plant (15 d sludge age). This was to establish Bio-P in MBR and to compare the performances of conventional Bio-P activated sludge plant and MBR Bio-P plant under similar influent characteristics. Further details on the results of this investigation can be obtained elsewhere (Adam *et al*., 2002).

Table 1 Range of operation conditions tested during the trials

Parameter	Unit	Min	Max
Sludge age	day	15	25
Sludge concentration	gMLSS/L	5	18
Sludge recirculation rate R1	% inflow	50	150
Sludge recirculation rate R2	% inflow	250	500
DO regulation in aerobic zone	mgO2/L	0.5	5
Total retention time	h	15	35

Table 2 Operational parameters of the MBR BSP and pilots, and the WWTP

Parameter	Unit		MBR	Conventional
		BSP	Pilot plants	Ruhleben WWTP
Flow	L/h	10	108 and 122	10,000 m^3/h
Biological reactor volume	m^3	0.21	2.0 and 2.2	198,500
Sludge age	d	15	26	15–18
Sludge concentration	gMLSS/L	6.2	10	3–5
Mass organic load	kgCOD/kgMLSS.d	0.22	0.10	~ 0.17
Volume organic load	kgCOD/m^3.d	1.3	1.15	0.6–0.9
Total retention time	h	21	18	18

The second phase of the study, undertaken on the two parallel MBR pilot plants, aimed at assessing Bio-P processes in MBR under a higher sludge age, characteristic of usual conditions in MBR.

Figure 1 presents a flow diagram of the configurations considered for the trials for the two pilot units, with the different process steps: anaerobic, anoxic, aerobic reactors, and membrane unit. This paper presents the results obtained so far with the Bio-P configuration 1. The number of compartments of the three zones and the recirculation flows are given in Figure 3.

The membrane system of the bench scale plant was provided by GKSS, Germany, and consisted of an immersed flat-sheet membrane module (pore size approximately 37 nm, and membrane area approximately 1.5 m^2). The filtration system of the two parallel pilot plants was developed by Memcor, Australia, and includes one immersed hollow fibre module (pore size approximately 0.2 µm, and membrane area approximately 10 m^2 per module). It is noteworthy that the membrane system performances were not the main focus in the first phase of the project, and the membrane units were operated below their optimum operation ranges.

Analytical methods. Substrate (COD), nitrogen- and phosphorus concentrations were determined in 24 h samples according to *Standard Methods* (DIN). P_T/o-PO_4-P and NO_3-N

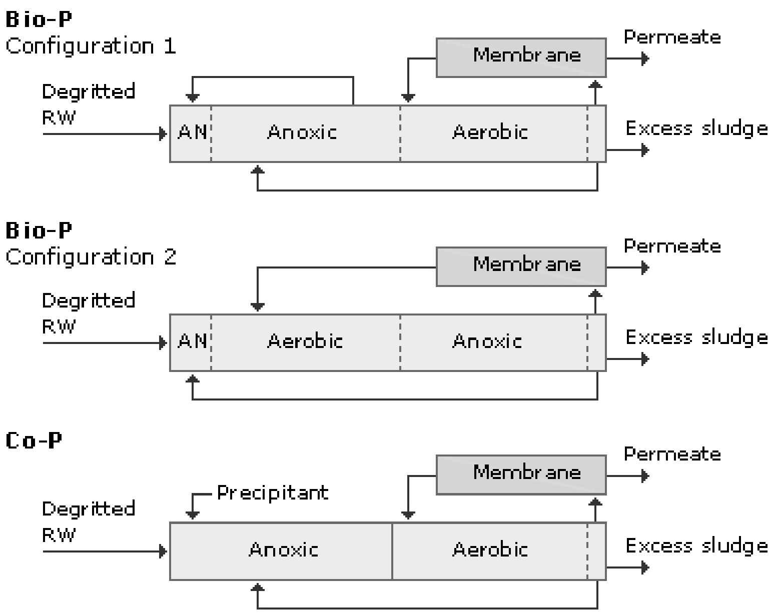

Figure 1 Schematic of the pilot plant

concentrations were measured online with PHOSPHAX SIGMA and NITRATAX plus, DR LANGE GmbH. Besides daily analysis of the plant effluent, profile measurements along the reactor zones were undertaken for dissolved COD-, N-, and P-fractions with Dr. Lange kits. The sampling of each reactor zone was carried out with small membrane modules (plate and frame) to insure in situ conditions. The determination of the P-concentration of the mixed liquor was done after dilution (1:50) and digestion with persulfate.

P-adsorption. To achieve P-concentrations of 50 µg/L fixed-bed adsorbers filled with different sorbents were tested in the effluent of the MBR. First, with phosphorus sorption isotherms influence of pH-value, DOC, sulphate, silicate were determined. The breakthrough behaviour of phosphorus and of important competitive substances are observed in small sorption filters (2.5 cm diameter) with continuous feeding at two different P-concentrations: 0.1 mg/L and 0.3 mg/L. The empty-bed contact times of 10 to 30 min were investigated. Three adsorptive materials were selected: activated alumina (ATE), a new granular ferric hydroxide (GEH®), and a new product of the German company Ego Biotic (FerroSorpPlus®, FER).

Results

Average influent and effluent qualities of the MBR plants and Ruhleben WWTP are shown in Table 3. All MBR plants were operated under the Bio-P configuration 1 showed in Figure 1, without any chemical dosing, and over 2 sludge ages before assessing the process. The effect of Bio-P could be clearly demonstrated with the MBR systems. All plants showed comparable effluent concentrations for COD, nitrogen and phosphorus. The higher values of the conventional WWTP for P_T were related to suspended solids in the effluent (around 9 mg/L). Slightly lower COD effluent concentration could be caused by lower COD influent concentration in the pilot plant, compared to the BSP. The effect of lower COD effluent concentrations due to higher sludge age in the pilot plant could not be demonstrated.

The average MLSS concentrations were respectively 10 g/L and 6.2 g/L in the aerated zone of the pilot plant and the BSP. The concentration of MLSS in the pilot plant increased along the reactor zones (anaerobic-anoxic-aerobic-filter) from about 9 to 14 g/L. This is a typical profile of MLSS in MBR. It was observed, that the sludge from the MBR pilot plants (26 day sludge age) did not settle whereas the sludge from the MBR bench-scale plant (15 day sludge age) settled well and showed sludge characteristics similar to the conventional WWTP. The specific excess sludge production calculated over the three months of operation with the pilot plant was around 0.4 kgMLSS/kgCOD . The value lies within the range for conventional WWTP and MBR plants (0.3–0.5 kgMLSS/kgCOD) given for comparable organic loads (ATV-DVWK, 2000). A longer period of operation has to be considered for further discussion.

Table 3 Influent and effluent concentration of the MBR plants and the conventional WWTP

Mean values (24 h-samples)	COD (mg/L)	COD_f (mg/L)	N_T (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	P_T (mg/L)	P_{Tf} (mg/L)	o-PO_4-P (mg/L)
Influent BSP	(998)	(322)	(70)	(41)	(0.4)	(10.5)	(4.0)	(3.8)
Influent pilot plant	740	282	61	43	–	9.1	3.9	3.5
Effluent BSP	(36)	n.d.	(9.2)	(0.49)	(6.0)	(0.10)	n.d.	(0.07)
Effluent pilot plant	32	n.d.	11.0	< 0.5	9.0	0.06	n.d.	0.05
Effluent WWTP	40	n.d.	11.0	0.05	9.0	0.4	0.3	<0.05

n.d. = not determined; mean values from October–December 2001; mean values in bracket from April–July 2001

Biological phosphorus elimination. The influent and effluent P-concentrations recorded during the considered period for the MBR pilot plant are shown in Figure 2. The influent P_T-concentration ranged between 6 and 13 mg/L. Effluent P-values were very low and stable between 0.05–0.16 mg/L for total P and 0.04–0.1 mg/L for ortho-phosphate. The P-content of biomass was measured with around 2.3% PT/TS and 6.5 PT/oTS at 26 day sludge age. This very low P-content has to be validated. However, it correlates with A131 (ATV-DVWK, 2000), if TSS, influent/BSB, influent ~ 1.2 and the MLSS concentration is around 10 g/L.

Two cascaded measurements were carried out to investigate the dynamics of the Bio-P process and one is shown in Figure 3. The schematic of the plant indicates the sampling point along the reactor cascade. The mixing points (M1 and M2) were calculated and

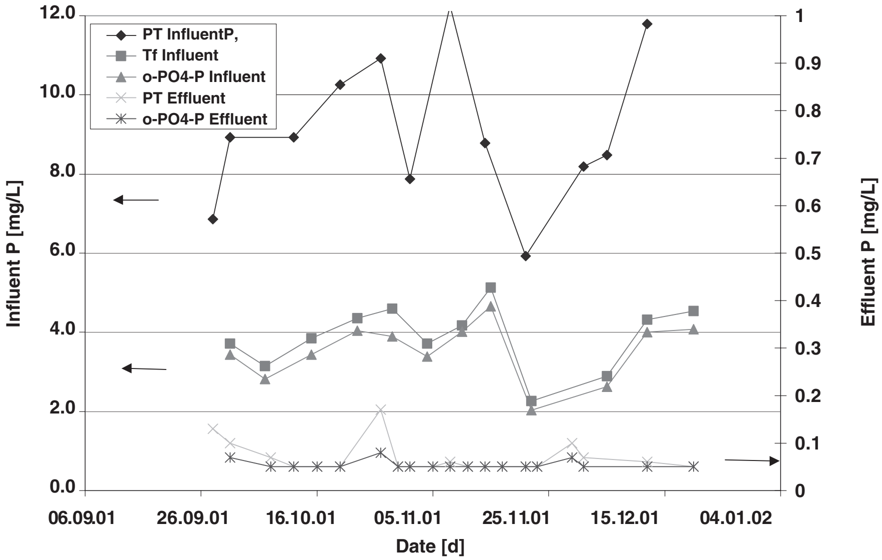

Figure 2 Influent and effluent P-concentrations of the MBR pilot plant

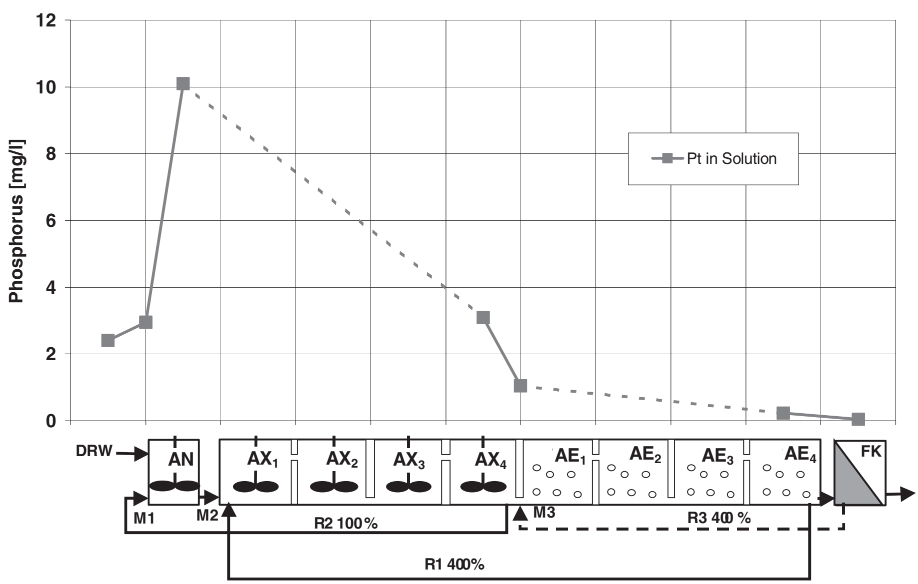

Figure 3 Total P-concentration in solution for the different zones of the MBR pilot plant

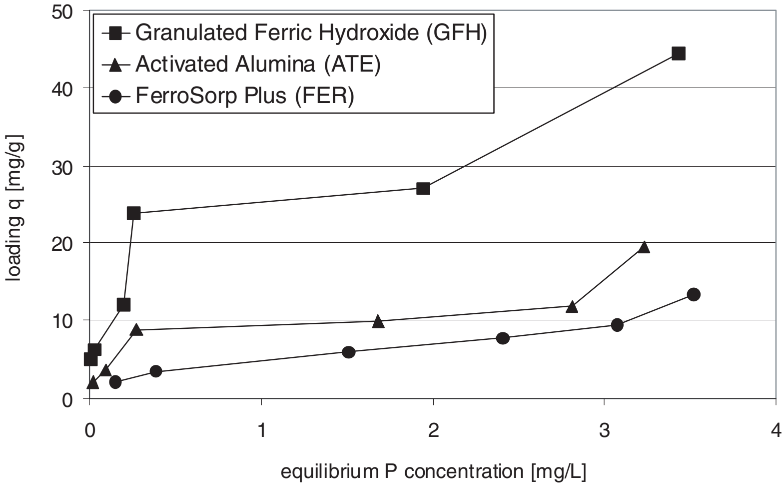

Figure 4 P-Isotherms for the three sorbents

printed "on the lines" in the graphic. Anaerobic P-release can be measured with 10 mg/L, which lies in the range of the bench-scale plant (8–14 mg/L). However, it is much lower than in the conventional WWTP. P-uptake occurs in the anoxic and in the aerobic reactor.

Bio-P dynamics could be clearly demonstrated through on-line monitoring, profile measurements, batch-tests and P-fractionation analysis. However the effect of calcium and ferric precipitation also plays a role in the overall P-removal performances. The authors acknowledged that this could help in gaining the very stable and low P-values, but this could not be clearly quantified.

Phosphorus co-precipitation. Co-precipitation of phosphorus with coagulant (configuration presented in Figure 1) was not tested given to the low P-values achieved with the Bio-P configurations.

Phosphorus elimination by adsorption. Results for the three sorbents are shown in Figure 4. The best P-sorption was achieved for GFH®, followed by ATE and FER. The loading of GFH is about 2.5 times higher than of ATE and at least 5 times higher than of FER.

The isotherms were repeated four times and results were reliable up to 2 mg/L P-concentration. For GFH a loading of approximately 25 mg P per g GFH dry mass was observed, corresponding to an equilibrium concentration of 500 μg/L. For ATE and FER, the loadings were respectively 10 and 5 mg P per g dry mass. Using these values, the stochiometric breakthrough points in a fixed-bed adsorber can be estimated: with P-concentration in the influent of 0.3 mg/L and an effluent concentration of zero in the columns, an empty bed volume of more than 25,000 and 18,000 can be estimated, for respectively GFH and ATE. During the trials it could be also shown that TOC was partly removed, especially with GFH. Also, adsorption rates with membrane effluent were higher compared to synthetic solutions. It is assumed, that the complex water matrix had a promoting effect on the sorption of phosphate. It is well known that for example calcium can have such an effect on the sorption of anions. However, definitive results cannot be given in respect to competitive adsorptions and the effects have to be investigated further.

Conclusions

The objective of the study was to assess performances of different phosphorus removal processes in MBR technology. The Bio-P process has been implemented for many years at

Berlin-Ruhleben WWTP and intensive experience have been gained. Bio-P was tested in the MBR bench-scale pilot plant in parallel to the conventional plant under different operating conditions. It could be shown that Bio-P is possible in MBR. The effluent concentrations of all parameters are comparable and very low. P_T and P-PO_4 concentrations in the effluent were always lower than 0.2 mg/L. During steady state conditions the P-content of biomass was around 2.3% P_T/TS. Further investigations will consist in optimising Bio-P process for remote areas. An important objective of the following trials will be to determine if raw sewage from decentralised households have the same potential for Bio-P removal.

Results with P-adsorption showed very good performances due to low effluent concentration and very long filter run time. Three materials were compared with sorption isotherms. The GFH showed the highest P-sorption capacity.

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