PHOSPHORUS RECOVERY FROM PHOSPHATE RICH SIDE-STREAMS IN WASTEWATER TREATMENT PLANTS

E. Levlin and B. Hultman

Dep. of Land and Water Resources Engineering,
Royal Institute of Technology, S-100 44 Stockholm, Sweden
(E-mail: levlin@kth.se; bgh@kth.se)

ABSTRACT
Phosphorus can be recovered from phosphorus rich side-streams in wastewater treatment plants with biological phosphorus removal. Different variants exsist for instance the PhoStrip process, in which phosphorus is recovered from the return sludge. Soluble phosphate is released at anaerobic treatment of return or excess sludge of phosphorus rich sludge from the activated sludge processes with biological phosphorus removal. Another alternative is to recover phosphorus from a side stream taken out from the anaerobic part of the activated sludge process, where phosphorus have been released to the solution. Phosphate rich streams can also be combined with ammonium rich streams for recovering of phosphorus as struvite, magnesium ammonium phosphate. Anaerobic treatment of sludge in digestion chambers gives a supernatant with high concentration of ammonium and depending on the sludge composition under certain conditions also phosphate. Phosphate can be released from the sludge but also be reprecipitated by metal ions or by adsorption. Phosphorus recovery from phosphorus rich partial side-streams is estimated to give a degree of phosphorus recovery of 60 - 65 % and thereby comply with the requirement of the Environmental Protection Agency on 60 % phosphorus recovery in year 2015.

Keywords
PhoStrip, phosphorus recovery, biological phosphorus removal, side-stream process

INTRODUCTION

Phosphorus recovery from wastewater has been discussed during the latest years since a report to the Swedish government proposed that 75% of the phosphorus should be recovered before year 2010. The motive for recovery has been based on that phosphorus in the future may be a limiting component for food production and that a low degree of phosphorus recovery may give different diffuse discharges for instance from land deposits. A controlled recovery of phosphorus from wastewater can also give an economical contribution due to the fertilizer value of the phosphorus and decrease the environmental impact from mining and further processing of phosphate minerals, if the needed amount of mined minerals can be decreased.

On the commission by the Swedish Environmental Protection Agency, Naturvårdsverket, an expert group evaluated six different methods for phosphorus recovery (Balmér et al, 2002). One of the evaluated methods for phosphorus recovery is to use phosphorus rich side-streams in a wastewater treatment plant with biological phosphorus removal. This method is used at many wastewater treatment plants in Europe, where processes with phosphorus recovery has been installed. In the wastewater treatment plant Geestmerambacht in the Netherlands (Klapwijk et al. 2001) a process with precipitation of calcium phosphate exists in full scale operation and the calcium phosphate is used as raw material in a phosphate industry with a thermal technology for production of phosphoric acid. These systems can be designed in different ways and should be seen as a variant of the system of phosphorus recovery from nutrient rich side-streams. Precipitation from side-streams gives a phosphorus product with such a low content of pollutions, that is required for use of raw material for the phosphate industry (Schipper et al, 2001).

A large wastewater treatment plant in Sweden with chemical precipitation for phosphorus removal and biological nitrogen removal (see figure 1), is often operated with two point precipitation. This design is used for instance by Henriksdal, Käppala and Bromma wastewater treatment plants in Stockholm. On many other plants secondary precipitation with flocculation and sedimentation are used as alternatives for contact filters.

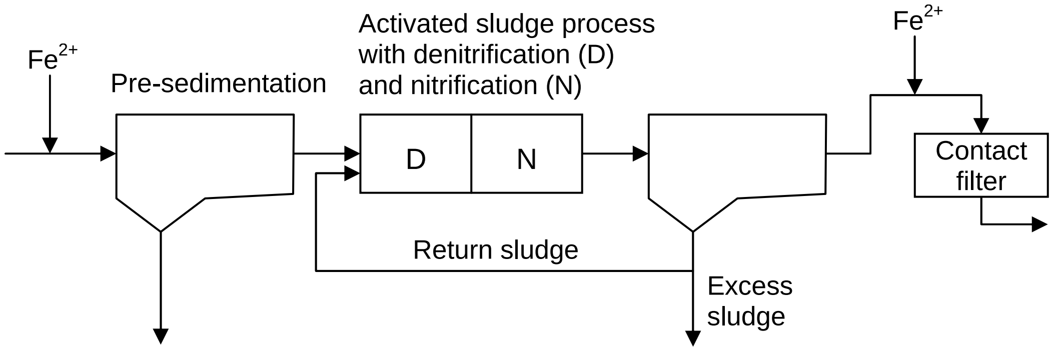

Figure 1. Process schedule with pre-sedimentation, pre-denitrification and contact filter.

To achieve a side-stream with a high phosphate concentration it is necessary that the process is operated with biological phosphorus removal. However, a process based only on biological phosphorus removal can not achieve the high demand on low phosphorus content in the effluent. Therefore the process must be based on partial biological phosphorus removal. Research and development in Sweden is made to combine biological phosphorus removal with chemical precipitation. Examples are the licentiate thesis by Eva Tykessons (2002) at Lund Technical University and different works at Käppala wastewater treatment plant (Fujii, 2000 and Borglund, 2003). These works show on good potentials to reduce addition of precipitation chemicals and biological sludges can be achieved that can release phosphate to a side-stream. Sweden is dominated – in contrast to many other countries – by removal with use of precipitation chemicals and only thirty plants in Sweden use or have been studying the technology with biological phosphorus removal (Tykesson, 2002).

Then constructing a plant with biological phosphorus removal with the main stream technology all wastewater passes through an oxygen and nitrate free zone. This technology has been the most used. An example on process design is the UCT-process (University of Cape Town) shown by figure 2. The differences compared with figure 1 are that a completely oxygen and nitrate free zone is inserted in the activated sludge process, that new recycling flows are included and that there are no additions of precipitation chemicals before the active sludge stage. For Swedish conditions the stringent effluent requirements for phosphorus means that a small dose of precipitation chemicals often is required as secondary precipitation. Performance of the main stream technology influenced by chemical precipitation has been studied at the Käppala plant (Fujii, 2000).

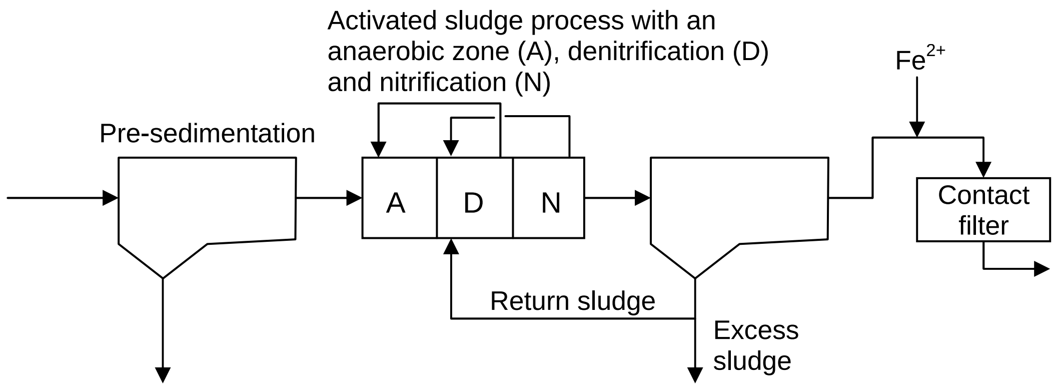

Figure 2. Process schedule for a main stream process with pre-sedimentation, biological phosphorus and nitrogen removal (UCT-process) and contact filter.

Several reviews on biological phosphorus removal have been made for instance by Arvin (1985), Balmér and Hultman (1988), Morse et al (1998) and Rybicki (1997). In these reviews also side-stream technology (where not all wastewater passes an oxygen and nitrate free zone, instead a part of the return sludge, for instance 10 - 20 %, is treated in such a zone) has been discussed. The most well known example is PhoStrip which in full scale was installed in the end of the 1970 decade at Reno/Sparks in USA (Drnevich, 1979). The process is illustrated in figure 3. Since phosphorus recovery was in that time not on the agenda the lime precipitated sludge was recycled to the pre-sedimentation basin. Thereafter a large number of plants have been installed this technology. The principal motive for the technology was in the beginning that a considerable reduced amount of lime (ca 10-20%) was used compared to what was needed for precipitation in the main-stream. The reason for this is that needed dose for precipitation of phosphorus with lime mainly depends on the pH-value and the lime consumption will be small if the precipitation can be done in a small partial flow (instead in the entire wastewater stream). Instead of recycling precipitated calcium phosphate to the pre-sedimentation, calcium phosphate can be used as a product. In the Dutch wastewater treatment plant Geestmerambacht calcium phosphate is used by the phosphate industry (precipitation is done in a crystalactor) (Gaastra et al, 1998).

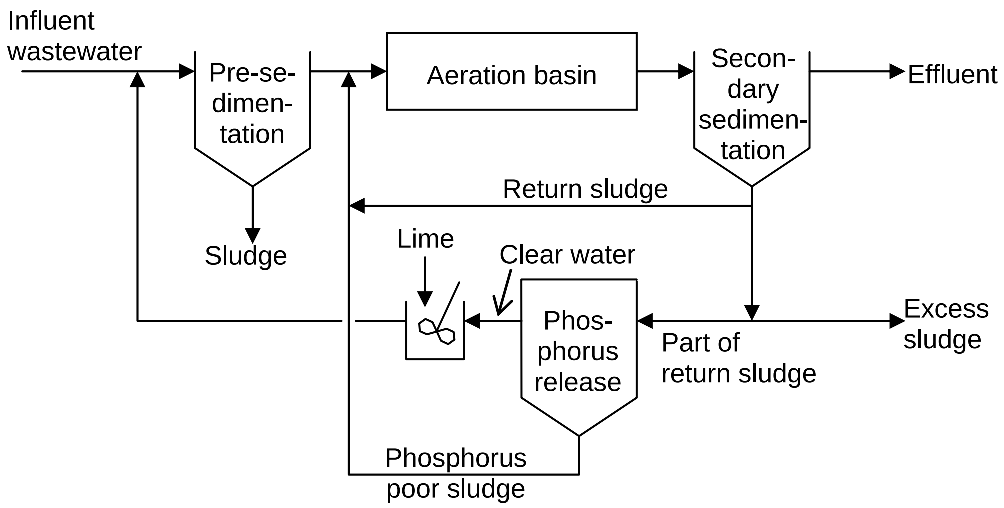

Figure 3. Schematic process scheme of PhoStrip (Drnevich, 1979).

PHOSPHATE RECOVERY BY PRECIPITATION OF CALCIUM PHOSPHATE

PhoStrip and simular side-stream processes are a competitive technology for phosphate recovery which is used in almost newly constructed plants for instance Darmstadt in Germany (Hillenbrandt et al, 1999) and Geestmerambracht (Gastra et al, 1998) and Haarlem Waarderpolder in Holland (Brdjanovic et al, 2000). In PhoStrip the phosphorus is recovered by anaerobic treatment of a part of the return sludge flow in a stripper. Through addition of acetic acid the bacteria's are induced to release phosphorus, thereby a concentration of 60 – 80 mg P/l is achieved (Piekema and Giesen, 2001). After separation of the sludge phase the dissolved phosphate is precipitated with lime. Calcium phosphate produced from a side-stream in the treatment plant has a sufficient enough content of pollutants to be used as raw material in the phosphate industry. Phosphorus can also be recovered as in figure 4 by taking out a flow with dissolved phosphorus from the anaerobic zone in the active sludge process, thereafter the sludge is sedimented and returned to aeration basin. Biological phosphorus removal requires easily biodegradable organic material in the oxygen and nitrate free zone in order to achive release of phosphate from the sludge. This amount is smaller for a side-stream process than for a main-stream process (for instance 10%) due to that needed concentration of polyphosphorus biomass is about 10 times smaller in a side stream process compared to a main stream process (Smolders et al, 1996, compare also Arvin, 1985). Required amount of easily biodegradable organic material can thereby be produced at the treatment plant for instance by hydrolysis of primary sludge.

Chemical consumption for the Phostrip process is organic acids as acetic acid for the stripper and lime for the calcium phosphate precipitation. To precipitate apatite with lime about 3 g is needed per g precipitated calcium phosphate phosphorus, which gives a lime consumption of about 30-40 g CaO/m^3 (calculated on influent wastewater flow). According to Woods et al. (1999) is lime consumption for precipitation from side-streams 7.6 kg/kg P (3.18 mole $Ca(OH)_2$/mole P). The same amount of lime is probably needed the PhoStrip process. Rensink et al. (1997) found that the Renpho process, used a dose of 10 - 20 g/kg DS of acetic acid in the stripper at a retention time of 4 hours. The acetic acid consumption depends on the retention time, thereby a longer retention time decreases the amount of needed acetic acid. To maximize release of phosphorus in the stripper the pH-level should be adjusted with sodium hydroxide to 7.3 and to minimize the production of calcium carbonate in phosphate precipitation the pH-level of the separated phosphate rich solution should be adjusted to 5 with use of acid (Gaastra et al., 1998).

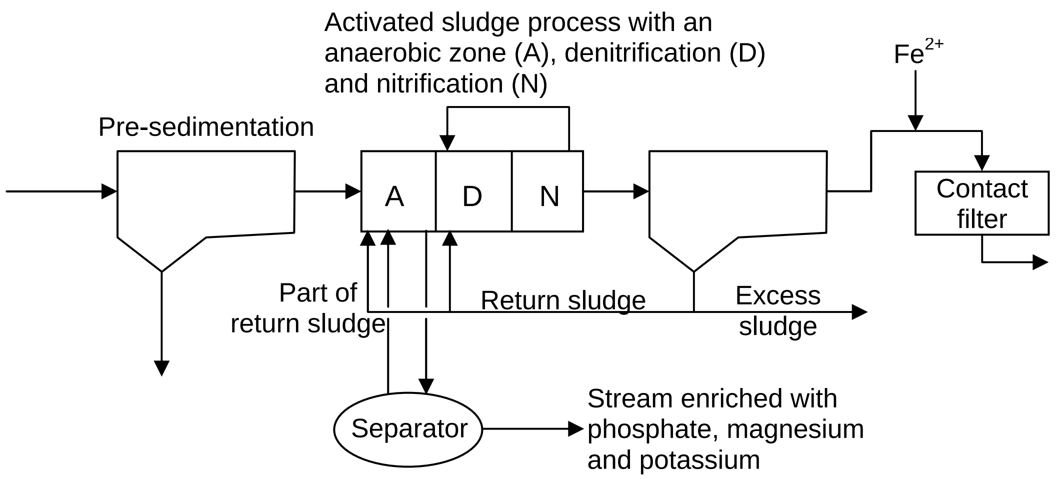

Figure 4. Process scheme with a side-stream process for biological phosphorus recovery with pre-sedimentation, biological phosphorus and nitrogen removal and contact filter.

COMBINATION OF PHOSPHATE AND AMMONIUM RICH STREAMS FOR STRUVITE (MAGNESIUM AMMONIUM PHOSPHATE) PRECIPITATION

Different technologies exist for recovery of ammonium products separately (for instance through ammonia stripping) and phosphate products separately (for instance as calcium phosphate) or as combinations (for instance precipitation of struvite, magnesium ammonium phosphate). Phosphorus and/or ammonium rich side streams can also be achieved from sludge. From processes similar to PhoStrip a side-stream with a high phosphate content can be obtained. After dewatering of digested sludge a supernatant with a high content of ammonium is obtained, which can be handled separately with different methods and a digested sludge (see figur 5). If the phosphate rich stream is combined with the ammonium rich supernatant there is good possibilities for producing struvite. Phosphate rich streams also contain a high content of magnesium since in phosphate release also magnesium and potassium are released to maintain the ion balance (Imai and Endoh, 1990). A process schedule is shown in figure 6. Magnesium is obtained either in connection to phosphate release and can also be recovered. By removing phosphate before the digestion chamber problems caused by struvite precipitation are avoided.

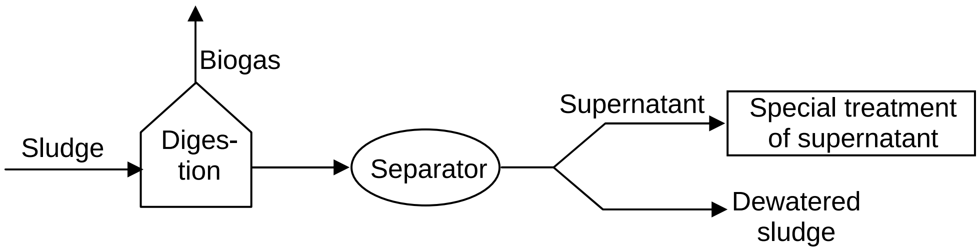

Figure 5. System for treatment of sludge with digestion followed by possibilities of separate treatment of supernatant.

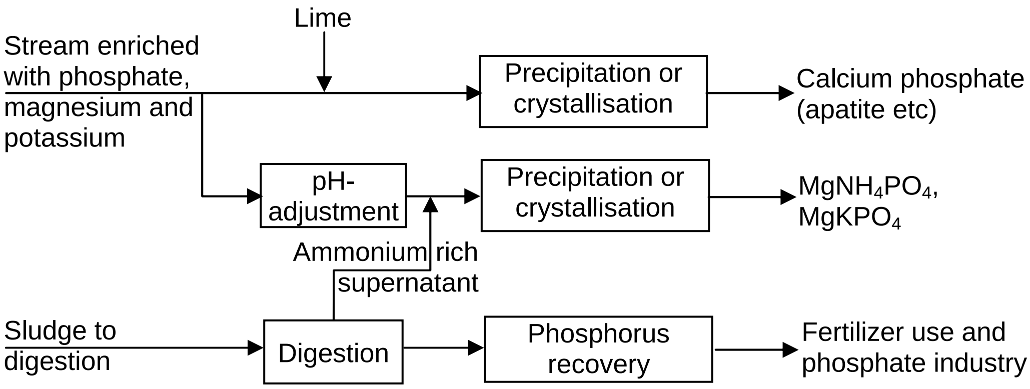

Figure 6. Two-stage phosphorus recovery process based on process technologies in figure 4 and 5.

At the wastewater treatment plant of east lake Shinji in the Shimane prefecture, Japan, phosphate is recovered by struvite precipitation from supernatant after sludge digestion (Ueno and Fujii, 2001). In this plant the phosphorus recycling with the supernatant was so large that the supernatant was 70 % of phosphorus load of the plant. In struvite precipitation sodium hydroxide is added so the molar ratio magnesium to phosphorus becomes 1 and the pH-level is increased to 8.2 – 8.8 through addition of sodium hydroxide. Struvite precipitation from supernatant has also been tested at Sloughs wastewater treatment plant, UK (Williams, 1999). Of the phosphorus content in the wastewater (690 kg P/day) 34 % was found in the digested sludge, 4 % was separated with the supernatant and 17 % with the water that was separated at sludge thickening before the digestion chambers. However, water from sludge thickening had a too low ammonium content (34 mg /l) for struvite precipitation. Since the supernatant had a high ammonium content (750 mg/l) optimal conditions for struvite precipitation was achieved by mixing the two streams.

DEGREE OF ACHIEVED PHOSPHORUS RECOVERY

Phosphorus recovery from phosphorus rich partial streams with Phostrip is estimated to accomplish a phosphorus recovery of almost 60 % (Balmér m fl, 2002) and thereby comply with the suggested requirement of the Environmental Protection Agency on 60 % in year 2015 (Naturvårdsverket, 2002). The degree of recovery is limited due to that only about 75 % of the phosphorus in the sludge is dissolved to the solution at anaerobic treatment.

Klapwijk et al. (2001) has calculated the phosphate recovery in the Phostrip process and a process with phosphorus precipitation in a side stream taken out from the activated sludge process. Figure 7 shows the two processes and also the Renphos process (Rensink et al, 1997) there the phosphorus poor sludge achieved by anaerobic treatment of a part of the return sludge is taken out from the process as excess sludge. Since excess sludge from the Renpho process should have a lower phosphorus content than excess sludge from the PhoStrip process, the Renpho process should give a little higher degree of recovered phosphorus.

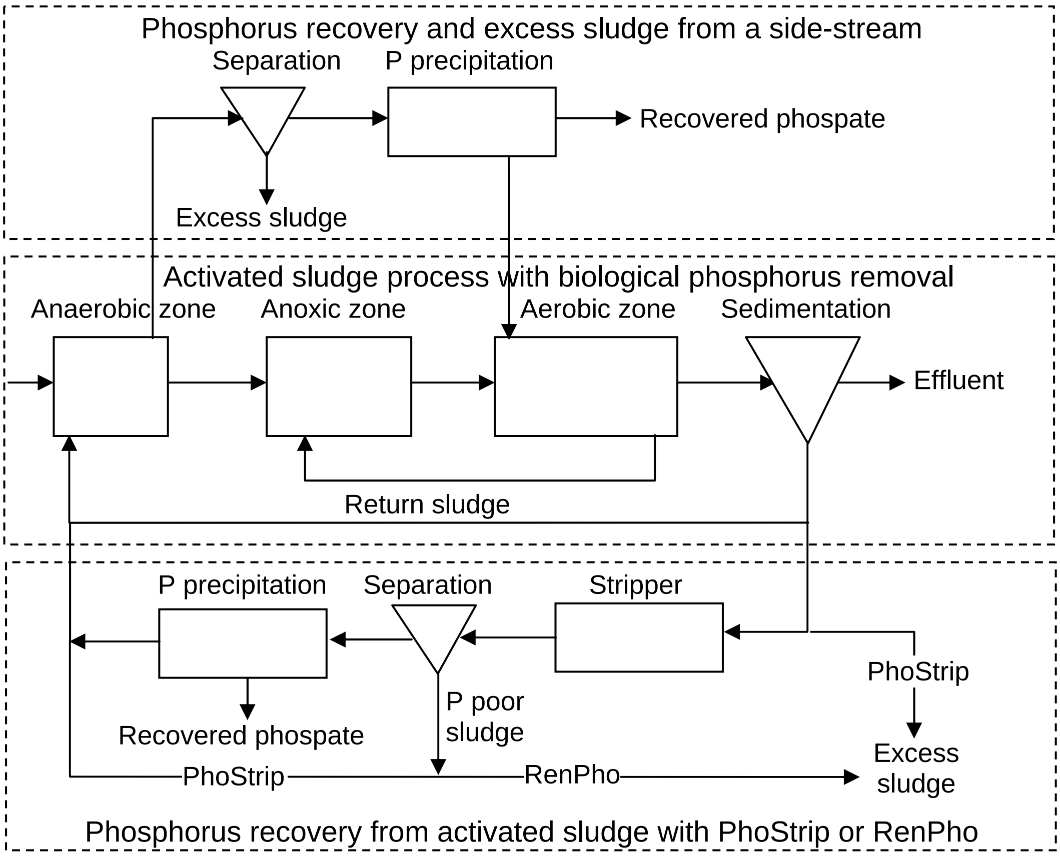

Figure 7. Different system technology for recovery of phosphate from phosphorus rich side-streams.

An overview of phosphate recovery with different processes is shown in table 1. Strickland (1999) has calculated the degree of phosphorus recovery for two systems; the Phostrip process and a process with struvite (magnesium ammonium phosphate) precipitation from supernatant after sludge digestion. In both cases it was estimated that 7 % of the phosphorus goes out with the effluent. In the Phostrip process 70 % of the phosphorus is recovered and 23 % is taken out with the excess sludge. With struvite production from supernatant the degree of recovery varied from 13 % up to 80 %. Klapwijk et al. (2001) has not specified the part of phosphorus that is going out with the effluent, which is assumed to be 10 %, which is between 12.5 % and 7%, thereby 75 % recovered phosphorus is reduced to 67.5 %. Klapwijk and Strickland have not included in the calculation the amount of phosphorus that is taken out with the primary sludge, which is assumed to be about 10%. With 10 % phosphorus in the effluent and 10 % in the primary sludge the recovered phosphorus will be 75 % of 80 %, which gives 60 %.

Table 1. Overview of phosphate recovery in processes wit biological phosphorus removal.

Method	Recovered P	P in sludge	P in effluent	Reference
Phostrip (return sludge)	60 %	30 %*	10 %**	Klapwijk et al., 2001
Phostrip (return sludge)	63 %	31 %*	6 %	Strickland, 1999
Side stream from bio-P	60 %	30 %*	10 %**	Klapwijk et al., 2001
Side stream from bio-P	65 %	22.5 %	12.5 %	Woods et al., 1999
Effluent (without bio-P)	71 %	16.5 %	12.5 %	Woods et al., 1999
Supernatant	12 – 72 %	22 – 82 %*	6 %	Strickland, 1999

* 10 % of the phosphorus in sludge is assumed to originate from the primary sludge
** Assumed value

A possible explanation for the variation of the degree of recovery from supernatant is that if struvite is precipitated in the digestion chamber, more of the phosphorus is taken out with the excess sludge, reducing the degree of recovery. Struvite precipitation in the digestion chamber is mainly dependent on the hardness of the influent wastewater, which is the magnesium content (Münch and Barr, 2001). Besides magnesium also calcium and zeolite contributes to binding phosphorus of phosphorus to the sludge (Wild et al., 1996). If sludge from biological phosphorus removal is digested together with primary sludge the phosphorus release at digestion decreases, since primary sludge has a lower phosphorus content and a higher content of calcium and zeolite. To achieve an effective struvite precipitation the pH-level should be between 8.6 and 10.6 (Battistoni et al., 1997), which can be done with addition of sodium hydroxide or stripping of carbon dioxide through aeration.

Woods et al. (1999) have been calculating the degree of recovery of a process with phosphorus precipitation in a side-stream taken out from the activated sludge process and precipitation of phosphorus in the effluent. The highest degree of recovery is achieved by recovering phosphorus as calcium phosphate with a crystalactor in the effluent from a process without phosphorus removal. Such solution means that the plant does not need to be converted to biological phosphorus removal. To reduce the calcium consumption the carbon dioxide content in the effluent should be reduced either by addition of acid or stripping of carbon dioxide. Calcium is precipitated with carbon dioxide as calcium carbonate. In the Phostrip process organic material is added to the anaerobic stripper. If the biological phosphorus removal in the treatment plant requires addition of organic material, phosphorus recovery from the return sludge gives that a smaller amount of phosphorus is circulating with the return sludge and thus a smaller amount of organic material has to be added in the process. For all processes about 10 % of the phosphorus goes out with the effluent. Therefore, chemical precipitation is required to comply with the stringent requirement on phosphorus discharge with the effluent, which can be made in sand filters as final stage.

THE COST FOR PHOSPHATE RECOVERY

The cost for phosphate recovery with Phostrip at the plant Geestmerambacht is according to Gaastra et al. (1998) about 7.3 euro per kg recovered phosphorus, of which 55 % is capital cost for the recovery equipment and 20 % is chemicals. The PhoStrip-process requires that the treatment plant is converted to biological phosphorus removal. A comparision of Ødegaard (1995) between a plant with chemical precipitation and a plant with biological phosphorus removal (see table 2), both with denitrification, shows that with biological phosphorus removal the energy consumption is higher and the biogas production smaller. With chemical precipitation a larger part of the organic material in incoming wastewater will be precipitated as sludge, 310 g SS/m^3 compared to 200 g SS/m^3 for biological phosphorus removal, thus increasing the biogas production. With biological phosphorus removal more of the organic material will be degraded to carbon dioxide and water in the activated sludge process. This requires a larger oxygen demand in the activated sludge process thus increasing the energy needed for aeration.

Table 2. Energy demand and energy production (Wh/m^3 wastewater) for a plant with chemical pre-precipitation compared to a plant with biological phosphorus removal both with biological nitrogen removal through post denitrification (Ødegaard, 1995).

Energy demand:	Chemicals	Aeration	Biogas(el)	Sludge transport	Difference
Chemical plant	-30 Wh/m^3	-150 Wh/m^3	+ 210 Wh/m^3	-19 Wh/m^3	+11 Wh/m^3
Biological plant	-8 Wh/m^3	-213 Wh/m^3	+115 Wh/m^3	-13 Wh/m^3	-119 Wh/m^3
Difference	27 %	142 %	55 %	68 %	

A comparison between the costs by Ødegaard (1995) showed that costs are nearly the same for biological phosphorus removal (about 2 % higher) than for chemical precipitation. For a plant with chemical precipitation the operational cost was 1.45 Norwegian crowns and the capital cost (20 years pay off and 7 % interest) 1.40 Norwegian crowns per m^3 wastewater, while for biological phosphorus removal was the operational cost 1.05 and the capital cost 1.85 Norwegian crowns per m^3 wastewater. The investment costs for a process such as PhoStrip is the volumes needed to release phosphate from the sludge and separation of sludge with low phosphorus content from the phosphate rich water and equipment for precipitation of phosphate as calcium phosphate from the phosphate rich stream. According to Irving (1982) almost all treatment plants can be adjusted to PhoStrip system if the necessary volumes are available. As volumes can be used a part of the activated sludge process or alternatively a not needed digestion chamber or thickener.

CONCLUSIONS

Phosphorus can be recovered from phosphorus rich side streams in wastewater treatment plant with biological phosphorus removal. In the PhoStrip process phosphorus is recovered from anaerobic treatment of the return sludge. Another alternative is to recover phosphorus from a side-stream taken out from the anaerobic part of the activated sludge process, where phosphorus has been released to the solution. Phosphorus recovery from phosphorus rich partial side-streams is estimated to give a degree of phosphorus recovery of 60 - 65 % and thereby comply with the proposed requirement of the Swedish Environmental Protection Agency on 60 % phosphorus recovery in year 2015. Phosphate rich streams can also be combined with ammonium rich streams for recovering of phosphorus as struvite, magnesium ammonium phosphate. For Swedish conditions the stringent effluent requirements for phosphorus make that a small dose of precipitation chemicals often is required as complementary precipitation.

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