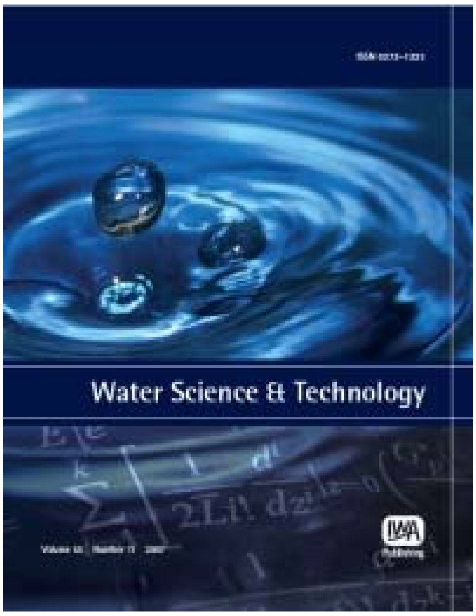
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Upgrading of sewage treatment plant by sustainable and cost-effective separate treatment of industrial wastewater

W. R. Abma, W. Driessen, R. Haarhuis and M. C. M. van Loosdrecht

ABSTRACT

The Olburgen sewage treatment plant has been upgraded to improve the effluent quality by implementing a separate and dedicated treatment for industrial (potato) wastewater and reject water. The separate industrial treatment has been realized within a beneficial public-private partnership. The separate treatment of the concentrated flows of industrial wastewater and sludge treatment effluent proved to be more cost-efficient and area and energy efficient than a combined traditional treatment process. The industrial wastewater was first treated in a UASB reactor for biogas production. The UASB reactor effluent was combined with the reject water and treated in a struvite reactor (Phospaq process) followed by a one stage granular sludge nitritation/anammox process. For the first time both reactors where demonstrated on full scale and have been operated stable over a period of 3 years. The recovered struvite has been tested as a suitable substitute for commercial fertilizers. Prolonged exposure of granular anammox biomass to nitrite levels up to 30 mg/l did not result in inhibition of the anammox bacteria in this reactor configuration. The chosen option required a 17 times smaller reactorvolume (20,000 m^3 less volume) and saves electric power by approximately 1.5 GWh per year.

Key words | anammox, nitritation, potato processing, reject water, struvite, wastewater

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INTRODUCTION

The sewage treatment plant (STP) of Olburgen has been upgraded recently. The plant has a capacity of 90,000 population equivalents (p.e.). Before reconstruction, the plant discharged concentrations of up to 50 mg N/l nitrogen and up to 15 mg P/l phosphorus to the river IJssel. Waterboard Rijn & IJssel had to take measures to be able to reach compliance with the European Water Framework Directive. For compliance, the discharge of N and P had to be reduced to 10 mg N/l and 1 mg P/l.

Waterstromen BV owns and operates industrial wastewater treatment plants. Waterstromen is an affiliate of the waterboard. One of the operations of Waterstromen is a wastewater treatment of a potato processing plant. The effluent of this plant made a big contribution of wastewater and nutrients to the wwtp. The potato processing (plant capacity 100 tons potatoes/hour) is accompanied by the production of wastewater containing proteins, starch and phosphate. The quantity equals an amount of 160,000 p.e. Since 1982 the organic components were already largely removed and converted into biogas by UASB reactors located at the site of the STP. The effluent of the UASB reactors on average contained 1,000 kg/d COD, 700 kg N/d ammonium and 200 kg P/d phosphate.

Another concentrated stream on the site of the STP that made a substantial contribution of nutrients is the reject water resulting from the digestion and thickening of sludge.

Evaluation of possible solutions

The waterboard and Waterstromen, in a public-private partnership, have evaluated the possible solutions to obtain

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the desired reduction of N and P discharge to the surface waters. The most important criterion for the evaluation was cost-efficiency based on total cost of ownership.

Roughly three basic options were considered:

1. To modify and enlarge the STP to meet the new discharge standards including the treatment of the effluent of the UASB reactors and the reject water.
2. To separately treat the effluent of the UASB reactors and reject water and discharge the effluent directly to surface water and make additional modifications to the STP.
3. To separately treat the effluent of the UASB reactors and reject water and discharge the industrial effluent to the STP, which is modified as well.

From the evaluation it appeared beneficial to treat the effluent of the UASB reactors and the reject water separately. Because of the high temperature (30–35°C) of the UASB effluent and the reject water compared to the temperature in the STP of 10–20 °C, reactor volume and space can be saved due to increased biological activity. In addition, the UASB effluent and reject water are much more concentrated. N and P concentrations of the mixed UASB effluent and reject water are 300 and 80 mg/l respectively, whereas N and P concentrations in the raw influent of the STP are 5–10 times lower. Treatment of concentrated wastewater offers other treatment possibilities. For phosphate removal struvite precipitation becomes possible, allowing phosphate recovery. For nitrogen removal anammox technology can be used as an alternative to nitrification/denitrification, saving significant amounts of energy (Jetten *et al.* 1997; Abma *et al.* 2007). This combination of struvite and anammox technologies results in further savings of reactor volume and space as shown in Figure 1.

From the evaluation, it appeared to be most cost-efficient to first treat the UASB effluent and reject water before discharge to the STP (option 3). Treatment costs for treatment in a STP (option 1) are ca. €35 per p.e. (Unie van Waterschappen 2003). In case of separate treatment of the UASB effluent and reject water, these costs can be lowered to ca. €20 to €25 per p.e. due to savings on equipment and the use of modern wastewater treatment technology. These costs however are increased back to a level of €35 per p.e. when surface water discharge standards have to be met (option 2). Separate treatment with discharge to the STP (option 3) turned out most economical.

Figure 1 | Reduction of space requirement by separate treatment of industrial wastewater and reject water (upper circle) with a capacity of 40,000 p.e. compared to the sewage treatment plant with a capacity of 90,000 p.e.; picture of the separate treatment in frame.

Table 1 | Mass flows of the industrial and reject water treatment plant, for comparison we have added the data for the municipal wastewater

	Potato processing plant	Reject water	Municipal wastewater	
Flow	3,000	360	32,000	m^3/d
COD	17,000	200	5,940	kg/d
NH_4-N	1,000	250	1,320	kg/d
PO_4-P	225	20	220	kg/d

This paper describes an example of beneficial public-private cooperation. By separate treatment of the industrial wastewater the performance of the STP is upgraded. This is accomplished by first time applications of a Phospaq reactor and a one-step Anammox reactor. The implementation and operation aspects of these reactors are described in this paper.

METHODS – PROCESS DESCRIPTION

The treatment of the wastewater of the potato processing plant and reject water from the STP consists of:

1. Three UASB reactors (existing) of 1,200 m^3 each to convert COD into biogas.
2. Two Phospaq reactors of 300 m^3 to remove phosphate by struvite precipitation and to remove residual COD from UASB effluent and reject water.
3. One-step Anammox reactor (CANON process (Strous *et al.* 1997; Sliekers *et al.* 2002)) of 600 m^3 for ammonia removal.

The design was based on the following wastewater characteristics in Table 1.

The wastewater treatment process is schematically depicted in Figure 2.

The potato wastewater first passes the UASB reactors, where the bulk of the COD (approx. 90%) is removed anaerobically and converted into biogas. The effluent of the UASB is introduced into the Phospaq reactors. When the decanter centrifuges of the sewage works are in operation, the reject water is also introduced into the Phospaq reactors. Here phosphate is being removed by precipitation as struvite (magnesium-ammonium-phosphate).

$$Mg^{2+} + NH_4^+ + PO_4^{3-} \leftrightarrow MgNH_4PO_4{\cdot}6H_2O$$

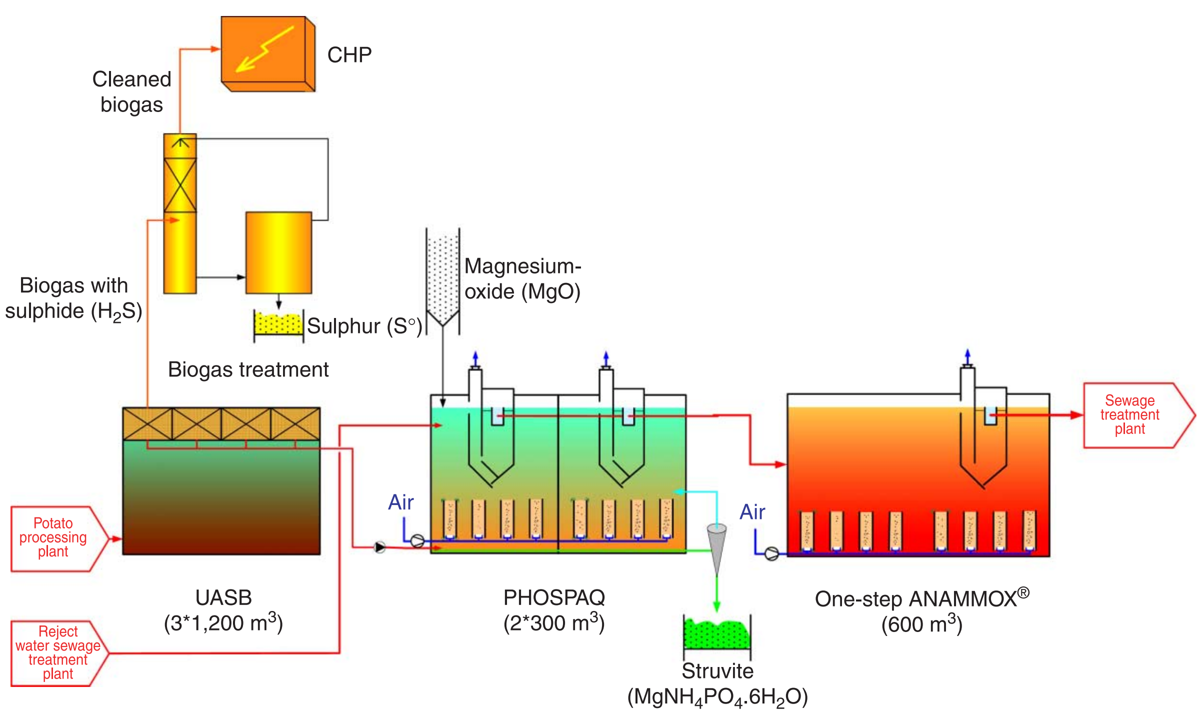

Figure 2 | process layout for the industrial & reject wastewater treatment at the STP Olburgen.

In addition residual COD is being removed aerobically in order to reduce heterotrophic growth in the anammox reactor. By combining P- and COD-removal in one reactor a few synergetic advantages are obtained. Aeration provides for the oxygen for the biological conversion, but also for the mixing required to obtain a good struvite quality. In addition it provides for stripping of CO_2 which raises the pH and stimulates the struvite formation. To obtain the desired removal, additional MgO is added. The reactors are equipped with separators that retain struvite and some biological sludge in the reactor. The sludge residence time in the reactors is limited to less than one day in order to prevent nitrification. Nitrification would counteract on struvite formation as it would lower the ammonium concentration, and decrease pH. Struvite is harvested from the bottom of the reactor by means of a hydrocyclone followed by a screw press and transferred into a container. The struvite is intended to be used as slow-release fertilizer.

The phosphate removal reactors have been scaled-up from a pilot plant test of 60 l. In the full scale plant phosphate removal is executed in two parallel reactors of 300 m^3 each. In case of problems due to the scaling, these could be solved whilst the wastewater treatment can be kept in operation.

In the one-step Anammox reactor (Strous *et al.* 1997; Van der Star *et al.* 2007) ammonium is converted into nitrogen by a combination of nitritation and anammox bacteria. The simplified conversion in this reactor is:

$$2NH_4^+ + 1.7O_2 \rightarrow 0.9N_2 + 0.2NO_3^- + \text{a small amount of biomass}$$

In contrast to conventional nitrification-denitrification the conversion of ammonium does not require organic carbon and energy is saved. A bypass of the UASB reactors to supply COD is avoided and a maximal generation of biogas is secured.

The reactor is based on granular sludge, which can easily be retained in the reactor by the separator on top of the reactor. The reactor is continuously aerated. In the effluent of the reactor ammonium and nitrite are measured by means of online analyzers. The aeration flow of the reactor is adjusted based on these measurements in order to obtain the desired effluent quality.

The effluent of the process is discharged to the sewage works where the wastewater is treated to reach surface water discharge quality. The construction of the plant was completed early 2006.

RESULTS – PERFORMANCE

The plant reached the design performance within 6 months after start-up. The average annual treatment performance of the effluent of the UASB reactors and the reject water is given in Table 2:

In Figure 3 the influent and effluent concentration of phosphorus in 2008 is depicted.

The P removal is conducted at a pH of 8.2–8.3. An average amount of nearly 150 kg P per day was recovered in the plant. In January the P effluent concentration is increased due to mechanical failure of the MgO dosing. In July/August both struvite reactors are taken out of operation successively for overhaul and expansion of the grid for struvite harvesting, giving a decreased efficiency in this period.

The struvite was harvested with a dry weight of 45 to 50%. The precipitant crystals had an average size of around

Table 2 | The average annual conversions of the combination of the struvite- and nitritation/anammox reactor (2006 including start-up period)

	2006	2007	2008
Influent load (kg/d), p.e. (–)			
NH_4-N	605	637	714
P	162	184	196
COD	1,583	1,824	1,635
p.e.	31,975	34,808	36,017
Effluent load (kg/d) p.e. (–)			
NH_4-N	254	89	67
P	78	51	47
COD	859	600	717
p.e.	14,848	7,408	7,534
Removal efficiency			
NH_4-N	58%	86%	91%
N-total	46%	68%	73%
P	52%	72%	76%
COD	46%	67%	56%
p.e.	54%	79%	79%

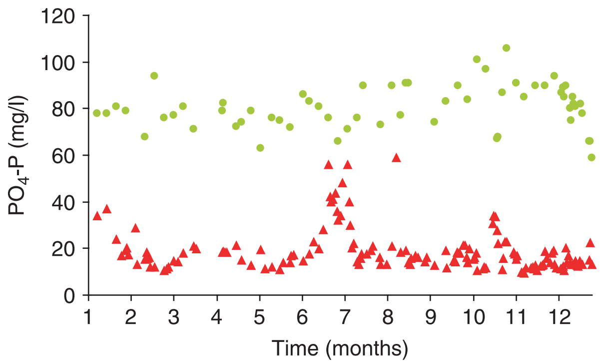

Figure 3 | Phosphate removal in the Phospaq reactor in 2008. ● influent phosphate concentration ▲ effluent phosphate concentration.

0,7 mm (Figure 4). The composition of the struvite product has been analyzed by grab samples twice a week for one month. The results have been compared to the requirements for use of the struvite as fertilizer according to EU regulation (Staatsblad 2007), see Table 3.

The struvite has been tested for one season on potatoes, carrots, sprouts and lilies and two seasons on grass. The outcome of these tests is that the struvite product showed equal performance to commercial fertilizers. The product can therefore substitute commercial fertilizers (DLV Plant 2008).

The conversion of nitrogen during 2008 is given in Figure 5. The ammonium removal efficiency of the plant was 91% on average in 2008. In January 30 m^3 biomass was removed from the reactor. In the same month problems occurred in one of the two compressors, which was out of operation until July. The effluent quality was temporarily disturbed as back-up aeration capacity had to be arranged and the control needed to be adjusted. In July the Phospaq reactors were under maintenance, accompanied by unusual fluctuations in load and wastewater quality that also affected the discharge quality. When all wastewater was processed by one Phospaq reactor, the performance of the struvite reactor went down. The solids concentration in the effluent of the Phospaq reactor increased from <1 ml/l to up to 10 ml/l, while COD concentration doubled. In spite of these fluctuations, the nitrogen removal remains high, the anammox population or its activity is not affected. Peaks in the effluent ammonium concentration result from increased aeration requirement when one of the struvite reactors is being stopped, whereas one of the two compressors is still out of order.

In August the nitrate content in the effluent increased from ca. 35 to 50 mg N/l. This increase was preceded by too low settings in ammonium discharge concentration. The ammonium content was kept for at least a week at <5 mg N/l. The nitrate level was decreased again after the ammonium set-point was around 15 mg N/l. Despite these fluctuations the operation complied to the design discharge standards. The reactor has been loaded up to 911 kg/d or 1.5 kg/m^3 d. High N-loading did not have an adverse effect on the removal efficiency; the process has not reached its maximum capacity. The biomass content in the reactor was around 200 ml/l during this period, where a maximal biomass content of 600 ml/l is possible indicating that the process can potential be loaded three times higher.

Figure 6 shows the increment of the conversion by anammox bacteria during start-up and the nitrite

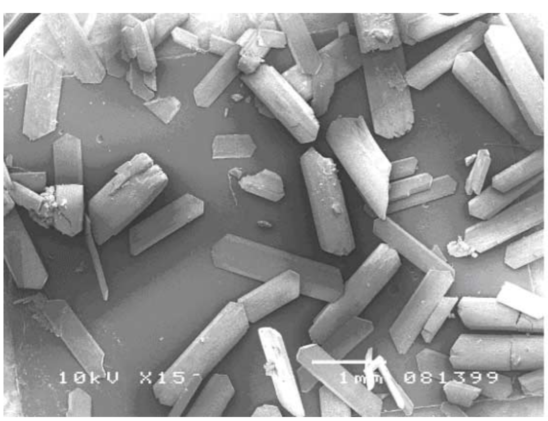

Figure 4 | SEM picture of produced struvite crystals and a container with produced struvite.

Table 3 | Heavy metal content of the recovered struvite compared to EU standards for fertilizers

	Cd	Cr	Cu	Hg	Ni	Pb	Zn	As
EU standard (mg/kg P)	31	1875	1875	19	750	2500	7500	375
Struvite product (mg/kg P)	0.9	17	42	<0.3	26	6.6	336	<6
Content relative to allowed value	3%	1%	2%	$<2\%$	3%	0%	4%	$<2\%$

concentration versus time. The conversion doubled in less than 10 days, comparable to the reported maximal growth rate of anammox bacteria (Strous *et al.* 1998). The nitrite concentration was generally between 20 and 30 mg/l. These data show that the type of anammox bacteria in this reactor are not negatively influenced by the moderate nitrite concentration in the reactor.

Since the UASB effluent and the reject water have been treated separately and the STP has been reconstructed, the discharge quality of the STP has improved. The nitrogen concentration is <10 mg N/l. The phosphorus concentration has decreased to <4 mg P/l. To achieve the limit of 1 mg P/l the waterboard is working on improvement of the biological P removal process.

DISCUSSION

The combined treatment of UASB effluent and reject water has been in operation for 3 years with good performance. Phospaq and one-step Anammox have been demonstrated on full scale for the first time. The combination with anaerobic treatment has proven successful. Recovery of phosphate, sulfur and biogas, saving of energy combined with improved cost-effectiveness is relevant for a wide range of applications. Wastewaters with a high content of organic carbon, nitrogen and phosphorus are for instance common in the food industry, fermentation industry, agriculture and sludge and waste treatment.

Phosphorus removal

The struvite reactor in Olburgen can remove phosphorus by more than 80%. In 2008 the average removal efficiency was 76% this average removal efficiency has been lowered due to successive stops of the reactors for overhaul and optimization.

The removal could be increased further by addition of more MgO. However the ratio of consumption of MgO to P removal will show a steep increase. The potential removal efficiency of the struvite reactor shows a strong dependence on the wastewater composition (magnesium, ammonium and phosphate concentration, pH and buffer capacity). For instance for the potato processing wastewater, with ammonium contents of 300 mg N/l, 80% removal is economically feasible. For wastewaters containing over 1,000 mg N/l removal efficiencies of 90–95% may be feasible.

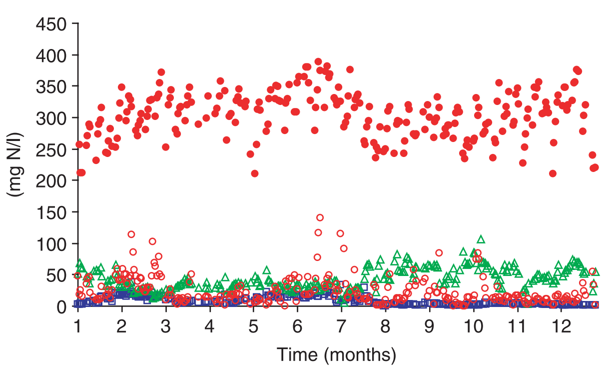

Figure 5 | Nitrogen conversion of the nitritation/anammox reactor in 2008. ● influent ammonium concentration ○ effluent ammonium concentration □ effluent nitrite concentration △ effluent nitrate concentration.

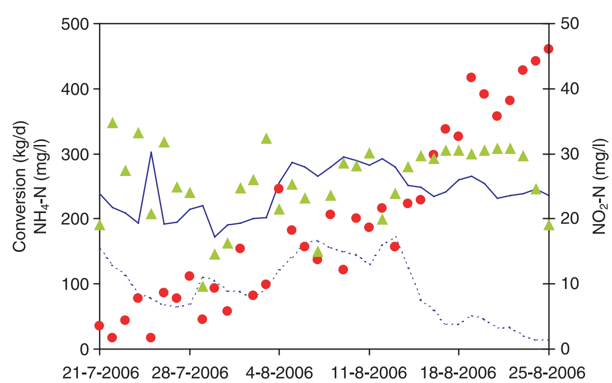

Figure 6 | Increase of anammox conversion and nitrite concentration during start-up. ● anammox conversion ▲ nitrite effluent concentration (solid line) ammonium influent concentration (dashed line) ammonium effluent concentration.

Phosphate recycling has a growing significance. The produced struvite has been tested and found suitable as substitute for commercial fertilizers. The concentration of heavy metals in the struvite is more than 20 times lower than the EU standards for fertilizers for all metals concerned. The small heavy metal impurities are probably caused by the small amount of sludge present in the struvite product. The use of recycled struvite as fertilizer is yet uncommon. The market for struvite is currently developing. An outlet of struvite against a modest profit is already possible.

One-step granular sludge anammox reactor

The one-step Anammox reactor has removed ammonium for 91% and total nitrogen for 73% in 2008. This performance is amply sufficient to meet the design discharge standards. Removal of 95% ammonium and 81% total nitrogen has been achieved for prolonged periods. Since the effluent of the plant is discharged to the sewage treatment plant, additional removal is not needed and not economic. Substantial additional removal would require different process configurations and or additional equipment.

In the one-step Anammox reactor granular biomass is being utilized. Because of its high settling velocity, the biomass is easily retained in the reactor. The granular biomass has appeared not to be sensitive to incidents with high influent solids or COD. Incoming solids and flock-type biomass growth resulting from the incoming COD are easily separated from the granular biomass and washed out of the reactor. The granules consisted of a mixture of nitration and anammox bacteria.

An important control parameter during operation of anammox reactors is the nitrite concentration (Strous *et al.* 1998). In floc-type systems a decrease of anammox activity is reported (Wett *et al.* 2007) at nitrite concentrations as low as 4.8 mg/l. During the start-up of the reactor in Olburgen using granular biomass the anammox activity was doubled in less than 10 days at nitrite concentrations between 20 and 30 mg N/l. In steady state operation daily average concentrations up to 20 mg N/l are common. Incidentally concentrations up to 42 mg/l have occurred in 2008. Inhibition is not observed in these cases. Tolerance for nitrite toxicity of granular biomass appears at least 6 times higher compared to flock-type biomass. Granular biomass systems appear to be more robust with respect to nitrite concentration, incoming solids and COD.

Economical and sustainable benefits for the private and public partners

The separate treatment of UASB effluent and reject water is beneficial for both the industrial wastewater treatment as for the sewage treatment plant. Benefits for the industrial wastewater treatment are:

- Saving on discharge costs of over €1.5 million per year, due to N, P and COD removal.
- Complete removal of N and P is not required. The removal is designed for balancing pollution discharge to the STP and pollution acceptance from the STP by treatment of the reject water. High rate / compact (1,200 m^3) technology (Figure 1) can be used to remove the bulk of N and P, resulting in savings of investment costs.
- An extra 1.5 GWh net electric power is annually produced. Bypassing the UASB reactors for COD supply is not required for the autotrophic nitrogen removal. The biogas/electric power production is therefore secured. The Anammox technology in addition results in saving on power consumption due to reduced aeration requirement compared to nitrification–denitrification (Jetten *et al.* 1997).
- Sludge production is reduced by 600 tons dry solids annually. Sludge growth in autotrophic systems is substantially lower compared to heterotrophic systems. By producing struvite instead of iron-phosphate the sludge yield is further reduced.

Benefits for the sewage treatment plant are:

- Reduced loading of max. 1,170 kg NH_4-N and 200 kg PO_4-P per day
- Saving of reactor volume of ca. 21,300 m^3 (current reactor volume of STP 22,500 m^3 for 1,320 kg N/d)
- Risk of disinvestments in the potato processing plant is now with the industrial wastewater treatment plant itself instead of with the STP.

In potential the cooperation could be further extended by combined facilities for power production and sludge treatment.

CONCLUSIONS

The Olburgen wastewater treatment shows that separated treatment and nutrient removal from industrial wastewater can be cost-effective. In the public-private partnership, both parties benefit considerably from the separate industrial wastewater treatment.

The combination of Phospaq and one-step Anammox has proven to be suitable for cleaning wastewater at low costs and improved sustainability. The struvite produced in the Phospaq reactor complies to EU standards for fertilizers. The struvite product has been tested a suitable substitute for commercial fertilizers.

Prolonged exposure of granular anammox biomass to nitrite levels up to 30 mg/l does, in contrast to flock-type biomass, not result in inhibition of the bacteria.

Prolonged exposure at higher levels has not been tested. Frequent cases of elevated COD and suspended solids in the influent could be handled without affecting the anammox reactor operation.

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