

Recycling and Assessment of Struvite Phosphorus from Sewage Sludge

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ABSTRACT

This study presents an integrated approach for the recovery of P from the wastewater path. Since natural P sources are limited, recycling processes are making an increasingly important contribution to meeting the nutritional requirements of plant production. The groundwork for developing a new fertilizer from upgraded sewage sludge includes an evaluation of nutrients and heavy metal contents. Struvite ($\text{NH}_4\text{MgPO}_4 \cdot 6 \text{H}_2\text{O}$) derived from sewage sludge had a total P content of 6.1% with 3.5% being water-soluble. Plant availability was tested in pot experiments with wheat and maize. P uptake rates were 66.7% and 85.9%, respectively. In terms of heavy metal contents, struvite showed contaminant levels at least three times below the limiting values of the German Sewage Sludge Ordinance. Stricter rules of the German Federal Soil Protection Act are also fulfilled if the loading of heavy metals is considered during periodical fertilization. This implies that P recovery as struvite may be one way of declaring a new type of fertilizer.

Keywords: P recycling, wastewater treatment, sewage sludge, heavy metals, mineral fertilizer, plant availability, risk assessment

1. INTRODUCTION

The annual phosphorus (P) uptake of crops is up to 26 kg ha^{-1} . To meet this demand, about 17 million tons of P are extracted worldwide every year, primarily from sedimentary and magmatic deposits in Africa and Asia. Besides organic and mineral fertilizers, secondary raw material fertilizers play a minor role today. However, the decrease in P that can be extracted cost-effectively will strengthen the recycling of P from residual materials, as outlined by Balmer (2004) and Rulkens (2004).

A great nutrient potential is found in municipal wastewater, which undergoes an enhanced P elimination in the treatment plants. This is one way of water pollution control, when nutrients such as P are concentrated within the sludge. With a potential of $56,700 \text{ t P yr}^{-1}$, sewage sludge plays the major role among the secondary raw materials in Germany (table 1). Despite controversial discussion, it is the considerable P content of sewage sludge that seems to justify recycling and agricultural utilization.

Table 1. Content and potential of P in German secondary raw material fertilizers.

	% P ₂ O ₅	% P	t P/yr
Sewage sludge	4.8	2.1	56,700 ^a
" ash	13.4	5.9 ^b	
" struvite	14.0	6.1	7,300 ^c
Biowaste	1.0	0.4	15,300 ^a
Carcass meal	7.1	3.1	12,500 ^a
" ash	42.6	18.6 ^a	
Meat and bone meal	14.0	6.1	9,500 ^a

^aUBA (2003), ^bSchirmer et al. (1999), ^cCalculation from this study

A few research activities focused on new strategies from wet to thermal utilization of sewage sludges in order to advance the recovery of P (Schipper et al., 2001; Roeleveld et al., 2004; Heinzmann, 2005). From an economic point of view, spreading sludge on agricultural land means low-cost P recovery (Lundin et al., 2004). Negative effects on the food chain and human health risk, however, would argue for incineration and fractionation of sewage sludge combined with P recovery.

The wide range of technologies includes chemical precipitation, biological P removal, crystallization and other methods. Recovery of P from wastewater and sewage sludge can also lead to problems, however, because it may become a sink for heavy metals, pharmaceuticals, hormones and other xenobiotica, which derive particularly from households and industry (Joss et al., 2006). Incineration of sewage sludge eliminates organic pollutants and pathogens and yields even higher P contents in ashes. They range between 11 and 12% P₂O₅ (Schirmer et al., 1999) and may even reach 36% P₂O₅ in the ash of sludge from biological phosphate removal treatment plants (Schipper et al., 2001). On the other hand, however, drawbacks such as heavy metal accumulation cannot be prevented.

Looking for a technology that fulfills both economic and ecological demands, this study presents an integrated approach, from the treatment of wastewater to the reuse of recovered P as fertilizer.

The wet wastewater treatment process, which was developed by Berliner Wasserbetriebe (BWB), includes a biological uptake of P in considerable excess in the activated sludge process that is the enhanced biological P removal system. The combination of a crystallization stage allows controlled production of struvite (NH₄MgPO₄ • 6 H₂O) from an enriched P stream, following anaerobic digestion as described by Morse et al. (1998). First efforts were directed to incrustations, which are known to cause operational problems (Parsons et al., 2001). During the last few years, the process engineering technology has been modified in order to control the precipitation of struvite (Heinzmann, 2001; Doyle and Parsons, 2002; Adnan et al., 2003; Quintana et al., 2004). An advanced approach includes the reuse of recovered P for plant production as outlined by de-Bashan and Bashan (2004). The reuse as fertilizer, however, is only possible as long as P compounds are plant available and contents of heavy metals are within tolerable levels. These factors given by the political framework and the fertilizer industry determine the economic value of recovered struvite from sewage treatment (Ueno and Fujii, 2001; Roeleveld et al., 2004).

Since there is little information about the agronomic effectiveness of struvite, the objective of this study is to assess wastewater-born struvite in terms of bioavailability and fertilizing potential on the one hand, and heavy metal contents on the other. This should show how far the recycling process developed by BWB is a suitable operation that can produce a new mineral P fertilizer for plant production.

2. MATERIALS AND METHODS

2.1 Induced struvite precipitation

Enhanced biological P removal has been established for the treatment of wastewater at the treatment plant at Waßmannsdorf near Berlin. In order to prevent incrustations by spontaneous formation of struvite on the walls of centrifuges and pipes of the sludge chain, an induced struvite precipitation was introduced on a large scale (fig. 1).

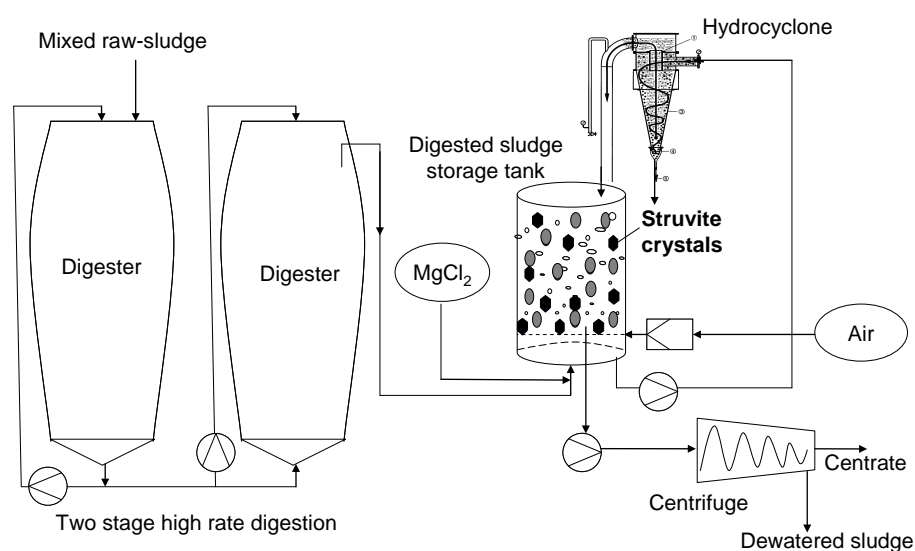


Fig. 1. Flow chart of phosphoric sludge treatment with induced struvite precipitation

This was realized by a few steps such as:

- Intensive mixing of the anaerobic sludge by pumping the sludge from the bottom of a digestion tank (8,000 m³) and re-injecting it at the top in the digester cascade of the intensified sludge digestion process.
- In order to avoid spontaneous and sudden degassing, the anaerobic sludge flowed through an exhaust pipe at the bottom of the first sludge digestion tank and under pressure into the second sludge digestion tank (8,000 m³) of the high-rate digestion process, which was operated at 36° C.
- By injection of air at a rate of 25 m³ min⁻¹ at the bottom of the digested sludge storage tank, CO₂ was stripped and pH rose to approximately 8, inducing struvite precipitation.
- Just before the sludge entered the sludge storage tank, MgCl₂ was added in order to enhance nucleation and growth of struvite crystals (fig. 1). At N : Mg : P mole ratio 1 : 1.5 : 1 thoroughly P removal is reported (Lei et al., 2006).

P recovery required separation of precipitated struvite from the digested sludge. The struvite might already be separated within the digested sludge storage tank by settling. Another approach to separation included hydrocyclones, which were fed several times by the sludge struvite mixture. A pressure of 2.0 bar was used to achieve separation of particles > 0.05 mm.

2.2 Physico-chemical properties of struvite

Analyses of the precipitated struvite from the hydrocyclone were conducted at BWB according to standard methods. All data from the non-washed struvite were available at the beginning of the study (table 2).

Table 2. Properties of non-washed struvite recovered from digested sludge compared to the limiting values of the German Sewage Sludge Ordinance (AbfKlärV), German Federal Soil Protection Act (BBodSchG) and the German Fertilizer Ordinance (DüMV)

		Measured value	Limiting value		
			AbfKlärV	BBodSchG	DüMV
pH		7.4			
Dry weight	%	73.0			
Loss on ignition	%	27.5			
<i>Nutrients</i>					
N	g/kg	28.0			
P	g/kg	61.1			
K	g/kg	2.2			
Ca	g/kg	27.9			
Mg	g/kg	78.4			
<i>Heavy metals</i>					
Pb	mg/kg	44	900	100	150
Cd	mg/kg	< 0.6	10	1	1.5
"	"	"	"	"	70*
Cr	mg/kg	42	900	100	
Cu	mg/kg	160	800	60	70
Ni	mg/kg	19	200	50	80
Hg	mg/kg	< 1	8	1	1
Zn	mg/kg	340	2,500	150	1,000
<i>Organic xenobiotica</i>					
AOX	mg/kg	55	500		
PAH	mg/kg	7.2	20		

* related to kg P₂O₅ if the fertilizer contains more than 5% P₂O₅

Besides relatively high contents of magnesium (Mg) and P, considerable contents of nitrogen and calcium were found in the precipitated struvite. Dry matter content expressed as loss on ignition was also high and is a subject of further purification. As regards toxic matter, the two heavy metals copper (Cu) and zinc (Zn) displayed relatively high contents.

2.3 P extraction procedures

Recovered struvite was treated with different extractants in order to obtain a detailed insight into its solubility and to classify the struvite precipitate.

Standard extractions were performed in accordance with the German Fertilizer Ordinance (DüMV) using four different approaches. Extracting agents were distilled water, citric acid (2%),

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water and neutral ammonium citrate and mineral acid (0.6 M H₂SO₄). 1 g dry weight of struvite was extracted with 250 ml of each extractant in a shaking machine for 30 minutes. Then the extracts were filtered over a paper filter and analysed for PO₄-P applying the molybdenum blue method.

2.4 Plant pot experiments

P uptake from different fertilizers was studied in pot experiments with wheat (*Triticum* sp.) and maize (*Zea mays* L.) in a greenhouse from March 22 to May 14, 2007. The plants were grown in 2.5 l pots each with 15 plants per pot in a mixture of siliceous sand (5 parts by volume) and perlite (1 part by volume). All pots were uniformly supplied with macronutrients except P (42.7 mMol KNO₃, 35 mMol NH₄NO₃, 25 mMol Ca(NO₃)₂ • 4 H₂O, 8.1 mMol MgSO₄ • 7 H₂O) and micronutrients (0.5 μMol H₃BO₃, 0.04 μMol MnSO₄ • H₂O, 0.012 μMol CuSO₄ • 5 H₂O, 0.04 μMol ZnSO₄ • 7 H₂O, 0.00082 μMol (NH₄)₆Mo₇O₂₄ • 4 H₂O and 1 mMol Fe-EDTA). P supply was varied in two treatments, a control with no P amendment and a trial with 50 mg P pot⁻¹ as struvite from wastewater and sludge treatment by the BWB. For the purpose of comparison with a highly soluble P mineral fertilizer, one more trial with 50 mg P pot⁻¹ in form of KH₂PO₄ was tested. Since the uptake efficiency of P from KH₂PO₄ was surprisingly low (maximum 16.8%), these results were not used for further comparisons. Methodological problems might have occurred due to P precipitation in a calcium-rich nutrient solution.

The plants were harvested 53 days after sowing. Shoots and roots were dried at 65° C. To measure the P concentrations, the dry matter was ashed at 500° C and dissolved in 25% HCl. P was measured colorimetrically at 366 nm as phosphomolybdate.

2.5 Assessment of struvite

Nutrient potential of the precipitated struvite was given by the analysis of the total element contents listed in table 2. Plant availability was obtained from extraction procedures as described above. A risk assessment was performed by comparing the contents of heavy metals with those from triple superphosphate fertilizer. Different approaches were applied by considering the concentration and the loading rate of heavy metals according to the three German acts, the Sewage Sludge Ordinance (AbfKlärV) of 1992, the Federal Soil Protection Act (BBodSchG) of 1999 and the Fertilizer Ordinance (DüMV) of 2003.

Finally, the economic value of struvite was roughly estimated. This was done on the basis of a current price of 1.45 €kg⁻¹ P₂O₅, which was paid for the raw material of a commercial P fertilizer in January 2008.

3. RESULTS

3.1 Struvite precipitation

CO₂ degassing from the digested anaerobic sludge was accompanied by an increase of pH to about 8. This condition induced a precipitation of phosphates such as magnesium ammonium phosphate and to a lesser extent as calcium phosphate. By addition of MgCl₂, struvite precipitation and dewatering of the anaerobic sludge was accelerated.

A part of the precipitated struvite mixed with digested sludge settled and about 30 t could be removed from the digested sludge storage tank every 3 months. The remaining precipitates in the

digested sludge were continuously pumped to the centrifuges. In another approach using hydrocyclones, precipitated struvite was separated from the anaerobic sludge due to its high crystal density of 1.7 kg dm^{-3} . Struvite could be enriched in the base outflow of the hydrocyclones, while P concentrations were reduced in the supernatant outflow of the hydrocyclones. A combination of 2 hydrocyclones allowed an increase in the P concentration from around 5 to approximately 40 kg m^{-3} . This means that P recovery in the second stage amounted to 18% of the P inlet load in the wastewater treatment plant at Waßmannsdorf. This experimental process enabled separation of struvite from the raw anaerobic sludge, corresponding to a P load of approximately 316 kg d^{-1} at the treatment plant in Waßmannsdorf.

Separation and final purification of struvite have not been fully realized in this study yet as reflected by the organic content expressed as loss on ignition and the relatively high portion of Mg (table 2). This is evident when the N : Mg : P ratio of recovered struvite at 0.5 : 1.3 : 1 is compared with the pure chemical $\text{NH}_4\text{Mg PO}_4 \cdot 6 \text{ H}_2\text{O}$ with an N : Mg : P ratio of 0.5 : 0.8 : 1. 67% of the particles were smaller than 0.63 mm. Even larger struvite crystals with a length of about 0.3 mm could be received in the hydrocyclone base outflow (fig. 2). According to the Fertilizer Ordinance, at least 98% of the crystals should belong to the grain size fraction $< 0.63 \text{ mm}$. Consequently precipitated struvite has to be ground before being used as fertilizer.

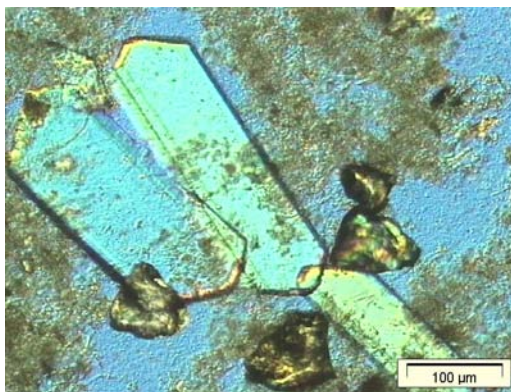


Fig. 2. Microscope photo of orthorhombic struvite crystals in the base outflow of the hydrocyclone.

3.2 Solubility and plant availability of struvite P

Only 0.26% of the struvite under study was found to be water-soluble P, which accounted for 3.5% of the total P in the struvite (fig. 3). That was rather low by contrast with the amounts extracted by citric acid, neutral ammonium citrate and mineral acid. With these extractants, P was released from the struvite to an equal level encompassing nearly 100% of the total P.

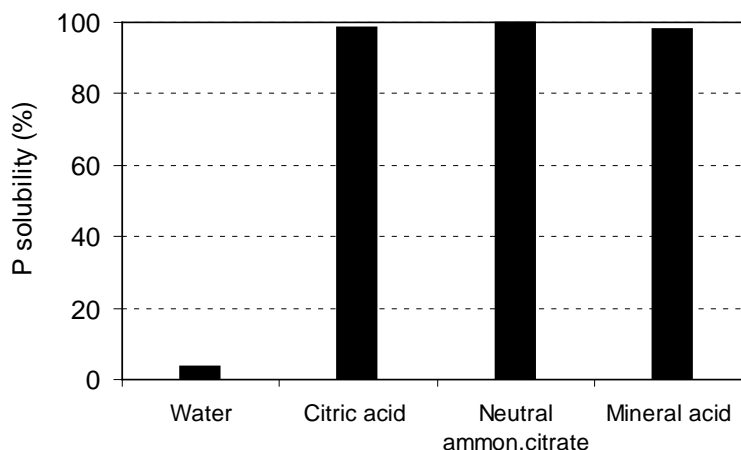


Fig. 3. P content of struvite obtained with different extractants

Both the nutrient contents and impurities in the struvite produced were analyzed to assess the possible agronomic value of the struvite precipitate as fertilizer. In terms of P, struvite was characterized by a P content 10 times higher than that found in composted sewage sludge (Casado-Vela et al., 2007). By comparison with the minimum nutrient contents for different kinds of fertilizer (Thomas phosphate 4.4% P, Superphosphate 7.0% P, dicalcium-phosphate with Mg 8.7% P) defined by the German Fertilizer Regulations, the precipitated struvite was within the range of other legally certified fertilizers. A content of 7.8% Mg conferred an additional fertilizer potential (table 2). With respect to plant availability, the form of struvite under study may be assigned to the type of fertilizer “Partially decomposed raw phosphate with Mg”.

In order to assess contaminants in the struvite precipitate, contents of organic pollutants (such as AOX and PAH), cadmium (Cd) and other heavy metals were compared with the limiting values set by the German Sewage Sludge Ordinance. The struvite separated to a considerable extent from the organic fraction was characterized by contaminant levels three times and more below the limiting values of the German Sewage Sludge Ordinance, as shown for some pollutants in table 2. If the stricter rules of the German Federal Soil Protection Act (BBodSchG) are considered, then the tolerable limits for Cu and Zn were exceeded.

3.3 P uptake by wheat and maize

Within 53 days P uptake from struvite was highest in the shoots and roots of maize with 44.3 mg P followed by wheat with 34.7 mg P per pot (fig. 4). The control plants contained 1.3 mg P reflecting the P reservoir of the seeds in each pot. If the initial P content of the seeds was taken into account, P uptake into the shoot and root biomass of wheat and maize plants corresponded to 66.7% and 85.9% respectively of the P supplied in the form of struvite.

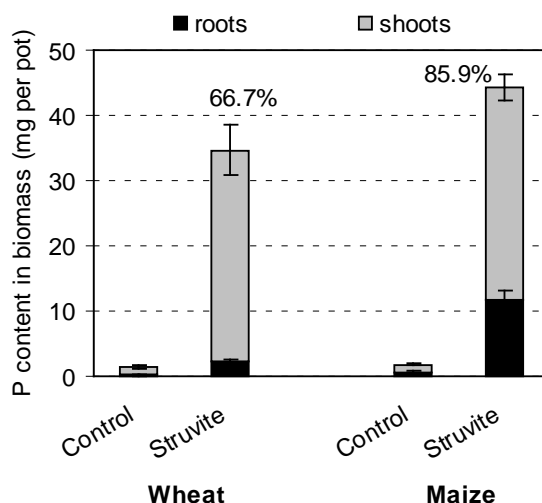


Fig. 4. P content in root and shoot biomass of wheat and maize. Percent values reflect the fraction of total struvite P that was taken up by the plants

4. DISCUSSION

4.1 Struvite production

Enhanced biological P elimination leads to efficient reduction of the P load in the treated wastewater stream, so that the limiting value for treated wastewater set up by the water authorities was met. A positive effect of induced precipitation of struvite is the prevention of incrustations during sludge treatment. At the same time this chemical technique opens a new way for recycling P as a valuable agricultural resource from the wastewater path. Substantial amounts of P may be fixed in the struvite precipitate, which may be separated from the anaerobic sludge by physical processes such as simple sedimentation in the digested sludge storage tank, or by further separation in hydrocyclones.

4.2 Fertilizing potential

Struvite, which derives from the upgraded sewage sludge, has a considerable fertilizing potential and has shown promising uptake in experiments with wheat and maize plants. Particularly sludge from biological P removal is characterized by a high P extractability, which depends on the kind of bonding and the molar ratio between P and a metal compound. Through the chemical bond to Mg, P is attached to sludge particles to a lesser extent than if precipitants which contain iron or aluminium are used (Smith et al., 2002). The same could be shown in studies which used slag as filter material for P retention in constructed wetlands. Calcium and magnesium oxides were most responsible for reversible P sorption (Grüneberg and Kern, 2001; Hylander and Simán, 2001). Reversibility of sorbed P on precipitates is a crucial advantage, which ensures its reuse in agriculture.

High P utilization from struvite is in accordance with studies from Johnston and Richards (2003), who studied different precipitated phosphates as a P source for plants besides the recovered struvite from the BWB. It was found that in two test soils perennial ryegrass (*Lolium perenne* L.) took up

about 90% of the P supplied in the form of struvite, which was derived from the wastewater treatment plant of BWB. It could be shown that plant P uptake from struvite derived from wastewater treatment was as effective as plant P uptake from chemical struvites and monocalcium phosphates. The same struvite material was studied by Römer (2006), who also reported very good availability of struvite P for rye plants in a 21-day growth-chamber trial. The author observed a high P uptake from struvite, which was not significantly different from $\text{Ca}(\text{H}_2\text{PO}_4)_2$ and from commercial mineral fertilizers such as superphosphate and triple superphosphate.

4.3 Risk assessment

Traces of toxic substances are relatively low in the struvite under study. Additionally, recovered P products from activated sludge processes often have a better quality than currently available phosphate rocks (Jeanmaire and Evans, 2001). A broad assessment of heavy metal input into agro-ecosystems was conducted by KTBL (2005) and showed that besides airborne deposition, heavy metals derive from organic and mineral fertilizers on agricultural fields. Particularly P fertilizers may contain high amounts of heavy metals. One example is slag from iron and steel production. Formerly known as Thomas phosphate, it exhibits enhanced contents of chromium (VI). By contrast, raw phosphates, which mostly derive from natural deposits in North Africa and Russia, are often rich in Cd, one of the most toxic heavy metals (Tiessen, 1995; Massanyi et al., 2007). The study of Keller and Schulin (2004) had shown that P management is a primary factor determining the variation of metal accumulation in soil. Besides uncertainty in crop concentrations, atmospheric deposition and leaching parameters, variation of net Cd fluxes resulted from uncertainty in Cd/P concentration ratio of commercial fertilizers.

One great advantage of the struvite precipitation relies on the fact that pollutants present in the anaerobic sludge are only transferred into the struvite in small portions. In the case of heavy metals, this can be explained by a discrimination of heavy metals that are not involved into the crystallization process of struvite. However, the tolerable limits of the BBodSchG for Cu and Zn were exceeded, probably due to organic impurities. The same problem with increased concentrations of Cu and Zn was reported by Schipper et al. (2001) for sludge ashes, and by Casado-Vela et al. (2007) for composted sewage sludge. In future, however, it is suggested for risk assessments that the loading rate will become more important than the concentration of a pollutant. This means that agricultural disposal is possible as long as the load of heavy metals is considered during periodical fertilization. Maximum loading rates are defined in Germany by the BBodSchG (table 3), which contains much lower annual heavy metal loadings as reported for Canada and the USA by Mittal (2007). In terms of heavy metals, the recovered struvite is characterized by relatively low contents as shown in table 2. Only in the case of lead (Pb) and Cu would fertilization with $150 \text{ kg struvite ha}^{-1}$ lead to considerably higher loading rates by comparison with triple superphosphate (TSP) as shown in table 3.

Choosing an advanced approach, considering the loading rates after adaptation of struvite fertilization to a maximum of 30 kg P ha^{-1} shows that loading rates of heavy metals are increased. Yet they still fall below the tolerable limits for loading rates defined by the BBodSchG. For Cd, the loading rate would even be lower by a factor of 10 compared with triple superphosphate.

Table 3. Loading rates of heavy metals by fertilization and tolerable limits fixed in the German Federal Soil Protection Act (BBodSchG)

		TSP*	Struvite	Struvite adapted to 30 kg P/ha	BBod- SchG
Fertilizer application rate	kg/ha	150	150	492	
Pb	g/ha	2	6.6	21.6	400
Cd	"	4	< 0.1	< 0.3	6
Cr	"	43	6.3	20.7	300
Cu	"	4	24.0	78.7	360
Ni	"	5	2.9	9.3	100
Hg	"	0.01	< 0.3	< 1.0	1.5
Zn	"	50	51.0	167.3	1,200

* State Office for Consumer Protection and Agriculture, Potsdam

4.4 Economic value

Economic feasibility of P recovery from sewage sludge is not achieved today because the prices of treatment techniques are higher than the prices of phosphate rock (Roeleveld et al., 2004). A profit of about €300 per ton recovered struvite can be realized according to Ueno and Fujii (2001) and Jaffer et al. (2002). Related to the pure P element, this is not more than €40 per ton. This is much less than the fertilizer industry can earn today with mineral fertilizer deriving from phosphate rock. Only when there is no adequate supply of natural P sources, or when the Cd content of the P remainder exceeds a critical level will the market value increase and P recovery from upgraded sewage sludge via struvite has a chance to become established. First indications of this development were given by a rapid increase in the P₂O₅ price for raw phosphates on the world market in 2007. Additionally, struvite P deriving from digester supernatant has already been described as economically beneficial when savings for reduced sludge handling and disposal are also taken into consideration (Shu et al., 2006).

The theoretical P recovery of 200,000 m³ wastewater at the Waßmannsdorf treatment plant is 316 kg d⁻¹ and can be related to about 1.3 million personal equivalents. By extrapolation to the total wastewater volume of Germany, 7,300 t P yr⁻¹ may be recovered. In 2005/2006, 120,000 t P were applied as mineral fertilizer in Germany (Statistisches Bundesamt, 2007). This means that about 6% of mineral P fertilizer could be saved today by reusing struvite P from the treatment of wastewater. The economic value of this fertilizer substitute would add up to €24 mill. per year.

Scientific and engineering progress may advance the declaration of struvite as a new mineral fertilizer and will contribute to overcoming the limitation of P resources.

5. CONCLUSIONS

Struvite recovered from upgraded sewage sludge has been proved an effective P fertilizer for the future. Besides a high plant available P content, low contents of heavy metals - particularly Cd - may be emphasized. This is one important advantage considering the handling of mineral P fertilizers which derive from natural sources, and which may contain high Cd amounts. Although the P demand for plant production is still satisfied by the supply of organic and mineral fertilizers, on a long-term scale secondary raw material fertilizers will be established when they become more profitable. The competitive advantage of recycled P will increase when a standard

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is applied for both secondary raw material fertilizers and raw phosphates, which are undergoing depletion connected with price increase. Raw phosphates with low heavy metal contents will be the first to be depleted. Exact information is needed about the ingredients of fertilizers in order to balance the chances and the risks of using mineral and recycled fertilizers. When these qualifications are satisfied, new types of P fertilizers will be introduced to agriculture.

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REFERENCES

- Adnan, A., D.S. Mavinic and F.A. Koch. 2003. Pilot-scale study of P recovery through struvite crystallization - examining the process feasibility. *J Environ Eng Sci* 2:315-324.
- Balmer, P. 2004. P recovery - an overview of potentials and possibilities. *Water Sci Technol* 49:185-190.
- Casado-Vela, J., S. Sellés, C. Díaz-Crespo, J. Navarro-Pedreño, J. Mataix-Beneyto and I. Gómez. 2007. Effect of composted sewage sludge application to soil on sweet pepper crop (*Capsicum annuum* var. *annuum*) grown under two exploitation regimes. *Waste Manage* 27:1509-1518.
- de-Bashan, L.E. and I. Bashan. 2004. Recent advances in removing P from wastewater and its future use as fertilizer (1997-2003). *Water Res* 38:4222-4246.
- Doyle, J.D. and S.A. Parsons. 2002. Struvite formation, control and recovery. *Water Res* 36:3925-3940.
- Grüneberg, B. and J. Kern. 2001. P retention capacity of iron-ore and blast furnace slag in subsurface flow constructed wetlands. *Water Sci Technol* 44:69-75.
- Heinzmann, B. 2001. Options for P-recovery from Waßmannsdorf bio-P wwtp, Berlin. Implications for wwtp operation and P recovery potential at different locations in the bio-P and sludge treatment process. *Proceedings of the second international conference on recovery of phosphates from sewage and animal wastes*, Noordwijkerhout, Netherlands, 12-13 March.
- Heinzmann, B. 2005. P recycling in sewage treatment plants with biological P removal. *Water Sci Technol* 52:543-548.
- Hylander, L.D. and G. Simán. 2001. Plant availability of P sorbed to potential wastewater treatment materials. *Biol Fert Soils* 34:42-48.
- Jaffer, Y., T.A. Clark, P. Pearce and S.A. Parsons. 2002. Potential P recovery by struvite formation. *Water Res* 36:1834-1842.
- Jeanmaire, N. and T. Evans. 2001. Technico-economic feasibility of P-recovery from municipal wastewaters. *Environ Technol* 22:1355-1361.
- Johnston, A.E. and I.R. Richards. 2003. Effectiveness of different precipitated phosphates as P sources for plants. *Soil Use Manage* 19:45-49.

- Joss, A., S. Zabczynski, A. Gobel, B. Hoffmann, D. Löffler, C.S. McArdell, T.A. Ternes, A. Thomsen and H. Siegrist. 2006. Biological degradation of pharmaceuticals in municipal wastewater treatment: Proposing a classification scheme. *Water Res* 40:1686-1696.
- Keller, A. and R. Schulin. 2004. Modelling heavy metal and phosphorus balances for farming systems. *Nutr Cycl Agroecosyst* 66:271-284.
- KTBL - Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. 2005. *Assessment and reduction of heavy metal input into agro-ecosystems*. KTBL Schrift 432. Landwirtschaftsverlag, Darmstadt.
- Lei, X., S. Shimada, K. Intabon and T. Maekawa. 2006. Pretreatment of methane fermentation effluent by physico-chemical processes before applied to soil trench system. *CIGR Ejournal* 8:1-15.
- Mittal, G.S. 2007. Regulations related to land-application of abattoir wastewater and residues. *CIGR Ejournal* 9:1-37.
- Lundin, M., M. Olofsson, G.J. Pettersson and H. Zetterlund. 2004. Environmental and economic assessment of sewage sludge handling options. *Resour Conserv Recy* 41:255-278.
- Massanyi, P., N. Lukac, V. Uhrin, R. Toman, J. Pivko, J. Rafay, Z. Forgacs and Z. Somosy. 2007. Female reproductive toxicology of cadmium. *Acta Biol Hung* 58:287-299.
- Morse, G.K., S.W. Brett, J.A. Guy and J.N. Lester. 1998. P removal and recovery technologies. *Sci Total Environ* 212:69-81.
- Parsons S.A., F. Wall, J. Doyle, K. Oldring and J. Churchley. 2001. Assessing the potential for struvite recovery at sewage treatment works. *Environ Technol* 22:1279-1286.
- Quintana, M., M.F. Colmenareio, J. Barrera, G. Garcia, E. Garcia and A. Bustos. 2004. Use of a byproduct of magnesium oxide production to precipitate P and nitrogen as struvite from wastewater treatment liquors. *J Agr Food Chem* 52:294-299.
- Roeleveld, P., P. Loeffen, H. Temmink and B. Klapwijk. 2004. Dutch analysis for P-recovery from municipal wastewater. *Water Sci Technol* 49:191-199.
- Römer, W. 2006. Plant availability of P from recycling products and phosphate fertilizers in a growth-chamber trial with rye seedlings. *J Plant Nutr Soil Sc* 169:826-832.
- Rulkens, W.H. 2004. Sustainable sludge management - what are the challenges for the future? *Water Sci Technol* 49:11-19.
- Schipper, W.J., A. Klapwijk, B. Potjer, W.H. Rulkens, B.G. Temmink, F.D.G. Kiestra and A.C.M. Lijmbach. 2001. Phosphate recycling in the P industry. *Environ Technol* 22:1337-1345.
- Schirmer, T., K. Mengel and B. Wiebusch. 1999. Chemical and mineralogical investigations on clay bricks containing sewage sludge ash. *Tile & Brick Int* 15(3):166-174.
- Shu, L., P. Schneider, V. Jegatheesan and J. Johnson. 2006. An economic evaluation of P recovery as struvite from digester supernatant. *Bioresource Technol* 97:2211-2216.
- Smith, S.R., N.G. Triner and J.J. Knight. 2002. P release and fertiliser value of enhanced-treated and nutrient-removal biosolids. *J Chart Inst Water E* 16:127-134.

- Statistisches Bundesamt. 2007. Statistisches Jahrbuch für die Bundesrepublik Deutschland. <http://www.destatis.de/jetspeed/portal/cms/Sites/destatis/Internet/DE/Navigation/Publikationen/Querschnittsveroeffentlichungen/Jahrbuch>. Cited 25 April 2008.
- Tiessen, H. 1995. *P in the Global Environment*. John Wiley & Sons Ltd., Chichester.
- UBA - Umweltbundesamt Berlin und Institut für Siedlungswasserwirtschaft RWTH Aachen. 2003. *Rückgewinnung von Phosphor in der Landwirtschaft und aus Abwasser und Abfall*. Symposium in Berlin, 6-7 February.
- Ueno, Y. and M. Fujii. 2001. Three years experience of operating and selling recovered struvite from full-scale plant. *Environ Technol* 22(11):1373-1381.