Sewage Sludge as a Resource for Phosphorus

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1. Introduction

In order to feed the world population sufficiently, the (limited) farmland needs to be fertilised, among others with the essential nutrient phosphorus. Natural resources of phosphorus are not in short supply as yet, but limited. Therefore it would be useful to close the phosphorus cycle by recovering phosphorus, and sewage sludge is a suitable resource for it.

Several recovery processes from sewage sludge have been developed, but so far none of them could be operated economically on a large scale.

In the following section we will give a vague estimate about the time frame, in which a recovery of phosphorus from sewage sludge might become economically efficient.

2. The element phosphorus and its occurrence

Phosphorus is an element, which all living things need for their growth. It is a component of the DNA, the carrier of genetic information, and of the molecule ATP, which supplies the cells with energy. Phosphorus is also needed for the development of bones and teeth, acts as a buffer in the blood plasma and regulates the acid-base balance. The daily requirement for an adult is about 700 mg of phosphorus.

Phosphorus stands in 12th place for the frequency of elements in the earth's crust. It doesn't occur in it's free form in nature, but in form of phosphate minerals such as apatite and phosphorite. The best known, technically accessible main deposits are found in North Africa, especially in Morocco, China, the Middle East and the US [1].

The global mining of phosphate ore is in the hand of a few countries. 70 % of the total amount is mined by the US, Morocco and China, with 70 % of the total phosphate reserves within Morocco alone. Therefore most countries, including Germany, are dependent on phosphate imports.

Around 80 % of globally mined phosphate ore is used by fertiliser industries, the other 20 % are used for other products like detergents and food additives [2].

The mining of phosphate ore results in environmental pollution. For example, for 1 ton of rock phosphate you have to move 5 tons of excavation material. Often uranium and cadmium can be found in the phosphate deposits. Mining gets these heavy metals to the phosphogypsum disposal site and into the produced fertiliser. The further the deeper layers are penetrated for the mining of phosphate, the more contamination with uranium and cadmium will be found in the phosphate ores. The availability of phosphate ores with small amounts of uranium and cadmium will decrease further and the price of these phosphates will continue to rise [3].

With the current mining and treatment processes it is unavoidable, that uranium and cadmium will enter agricultural land via mineral fertiliser from rock phosphate. Investigations have shown that fertilisers from recycled Phosphorus, for example from the waste water or sludge, contain only a very small amount of uranium, between a tenth and a hundredth of the amount in rock phosphate [4].

For the protection of resources and for reduced environmental pollution it would make sense to minimise the use of phosphorus gained from ore and to exploit the full potential of a practical phosphorus recycling.

A major part of the phosphates, which are consumed with foodstuffs, will, if not used for cell formation, be excreted again and ends up in the waste water and consequently in the sewage treatment plant. Because of the performed phosphate elimination in the sewage plant, 90 % of the phosphorus from the waste water will end up in the sewage sludge [5]. Therefore, the sewage sludge is particularly suitable as a resource for the recovery of phosphate.

That is the reason, why so far sewage sludge was often utilised in agriculture and directly used as a fertiliser. But sewage sludge contains, apart from nutrients like phosphorus, also harmful substances, as for example heavy metals, substances with hormonal effects, drugs and pathogenic organisms.

Therefore the application of sewage sludge to land is limited by the stringent regulations for sewage sludge. Nevertheless, the agricultural utilisation of sewage sludge is regarded increasingly very critical because of its capacity as pollutant sink. The German Federal Environmental Agency also declares itself in favour of a gradual abandonment of the agricultural utilisation [6]. The agricultural utilisation of sewage sludge in Austria is separately regulated in each federal state. In Salzburg, Tyrol and Vienna it is banned, in the other federal states it is only permitted under certain conditions. The application of sewage sludge to agricultural land in Switzerland has been prohibited outright since 2006.

Because of the land application prohibitions in some countries, significant efforts are being made to treat the sewage sludge in a way, that some harmful substances, particularly the heavy metals, are eliminated, and nutrients like phosphorus can be recovered.

3. Application locations for the recovery of phosphorus

The recovery of phosphorus from the waste water and sludge has been investigated intensively for a number of years. Principally several locations for application are possible (Figure 1):

1. Drain of sewage plant
2. Sludge water
3. Dewatered sewage sludge
4. Sewage sludge ash

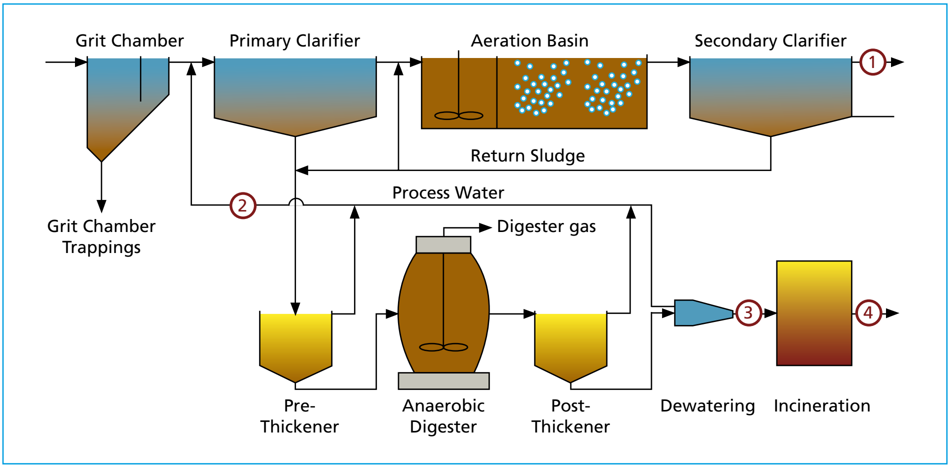

Figure 1: Possible locations for the phosphorus recovery in a waste water treatment plant

Source: Pinnekamp, J.; et al.: Rückgewinnung eines schadstofffreien, mineralischen Kombinationsdüngers *Magnesiumammoniumphosphat – MAP* aus Abwasser und Klärschlamm. UBA Forschungsbericht 25, Umweltbundesamt, 276 S., Dessau 2007

The inflow to the sewage treatment plant is not suitable as a location for the phosphorus recovery, because the extremely dirty water here has a low concentration of phosphorus and the volume flow is very high.

The application location 1, the drain, has a phosphorus concentration of 5 to 8 mg/kg in sewage treatment plants without phosphorus elimination by metallic salts, whereas the application location 2, sludge water, has a concentration of around 20 to 100 mg/kg. Dewatered sewage sludge, location 3, shows already an average of 10 g/kg phosphorus, and the sewage sludge ash has a very high average phosphorus concentration of 62 g/kg [2].

The potential recovery of phosphorus in relation to the incoming load of the sewage treatment plant are considered the highest for location 3, dewatered sewage sludge , and location 4, sewage sludge ash from the mono-combustion, with around 85 %, while the recovery potential of the locations 1 and 2 are considered much lower, at just 15 – 50 % [2].

The aim of the phosphorus recovery is to make the product suitable as fertilizer. Therefore it has to be made accessible to the plants, which means basically, the phosphorus has to be in its water- and/or acid-soluble form. On the other hand, heavy metals need to be removed to a large extent from the product.

Another word about the accessibility to plants: It is not only the quality of the fertiliser, that determines whether a plant can take phosphorus up or not, but it also depends on the type of plant (i.e. grains or legumes) and the composition of the soil (acidic or alkaline). Because of the complexity it is very difficult to determine beforehand, whether and to what extent the fertiliser will be accessible to the plant.

The locations for application differ from each other not only with regard to the recovery potential, but also with regard to the state of phosphorus. Locations 1 and 2 have the advantage of phosphorus being in its dissolved form. Sewage treatment plants with conventional sludge treatment can keep phosphorus largely bound in biomass. In that case, a recovery as mineral fertiliser through a secondary precipitation is not possible [2].

At the locations 3 and 4 the phosphorus is chemically bound and needs to be dissolved before the recovery procedures. However, these locations have a very high concentration of phosphorus, so that the recovery potential here is very high.

In recent years, mainly wet-chemical recovery methods for all four possible locations have been investigated, as well as thermal metallurgical processes for locations 3 and 4.

4. Technical procedure for the recovery of phosphorus

Many procedures for the recovery of phosphorus have been developed so far. The best-known examples are given in Table 1. Only very few recovery procedures from waste water

Table 1: Main procedures for the recovery of phosphorus

Source waste water and process water (Location 1 and 2)	Source sewage sludge (Location 3)	Source sewage sludge ash (Location 4)
Crystallisation and precipitation processes	**Crystallisation processes**	**Wet chemical extraction processes**
CSIR fluidised bed reactor	AirPrex-MAP	BioCon
DHV Crystalactor	FIX-Phos	Eberhard
Ebara	Peco	LEACHPHOS
Kurita fixed bed reactor	**Acidulation processes**	PASCH
MAP crystallisation		RECOPHOS
Nishihara	KEMICOND	SEPHOS
NuReBas	Seaborne	SESAL
Ostara PEARL	Stuttgart process	**High temperature processes**
Peco	**Hydrothermal processes**	ATZ iron bath reactor
Phosnix		
Phostrip	Aqua-Reci	Mephrec
PRISA	CAMBI	SUSAN (Ash Dec)
P-RoC (PROPHOS)	KREPRO	Thermphos
REPHOS	Phoxnan-Loprox	**Electrokinetic processes**
Sydney Waterboard Reaktor	**High temperature processes**	EPHOS
Ion exchange processes	ATZ iron bath reactor	
PHOSIEDI	Mephrec	**Bioleaching process**
REM NUT		P-bac
Combined and special processes		
Magnetic separation		
RECYPHOS		

Sources:

Mocker, M.; et al.: Phosphorrückgewinnung aus Klärschlamm. In: Thomé-Kozmiensky, K. J.; Pelloni, L. (Hrsg.): Waste Management, Vol. 2. Neuruppin: TK Verlag Karl Thomé-Kozmiensky, 2011

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have been realised on a large scale, the economical valuation hasn't been done so far (but a specialised procedure for dairy waste waters has proven to be economically efficient on a large scale).

Wet-chemical processes, which recover phosphorus from waste water (drain and also feeding inflow) in the form of magnesium ammonium phosphate (MAP), are promising, because MAP is very suitable as fertiliser due to its high accessibility for plants. The disadvantages of these processes are the relative high organic proportion remaining and the relative low yield of recovery.

The thermal metallurgical processes are technically very complex. The advantages are the high recovery potential, the degradation of harmful substances during combustion and the small volume that has to be processed.

Due to these advantages we can assume from our present state of information, that thermal metallurgical processes are the most promising for the future.

5. Economic efficiency of the phosphorus recovery

Since there is no procedure for the recovery of phosphorus, especially from sewage sludge or sewage sludge ash on a large scale as yet, it is difficult to estimate the process costs.

Nevertheless, some authors tried to specify cost estimates [9, 10]. Cost locations for these estimates are listed in Table 2.

Table 2: Cost estimates for the recovery of phosphorus

Location	Costs EUR/kg P
Source waste water and process water	1.00 – 12.50
Source sewage sludge	2.00 – 12.00
Source sewage sludge ash	1.18 – 7.50
Estimation realistic costs	4.00 – 8.00

Sources:

Dockhorn, T.: Ökonomische Aspekte des Phosphor-Recyclings. Präsentation. TU Braunschweig, 2008

Pinnekamp, J.; et al.: Verbundvorhaben *Phosphorrecycling – Ökologische und wirtschaftliche Bewertung verschiedener Verfahren und Entwicklung eines strategischen Verwertungskonzeptes für Deutschland* (PhoBe). Abschlussbericht. Bundeministerium für Bildung und Forschung, 463 S., Bonn, 2011

The specific costs for the recovery of phosphorus from waste water are around the range of 1.00 EUR/kg P for a process without depletion of heavy metals, up to 12.50 EUR/kg P when heavy metals are removed. The recovery processes from sewage sludge are set with specific costs between 2.0 EUR/kg P and 12.00 EUR/kg P. Costs for the recovery from sewage sludge ash are given at 1.18 EUR/kg P, for a single phosphorus back solution, up to 7.50 EUR/kg P. Costs for the thermo-chemical process SUSAN, which is seen as very promising, are given as 2.20 EUR/kg P [10].

The economical framework for the recovery of phosphorus is determined by the fact, that the costs for the production and marketing of the recovered phosphorus should not exceed the costs for the primary resource. As primary source can be considered phosphoric acid, obtained from rock phosphate, since many phosphate fertilisers are produced starting from this substance.

The price for phosphoric acid is very volatile and varies widely among dealers, so that average world market prices are not accessible. For a rough estimate they were therefore derived from the prices for rock phosphate. According to the World Bank, the price for rock phosphate in March 2012 stood at 192.50 US$/t, while phosphoric acid was traded in March 2012 at around 700 US$/t. With this information, and with regard to information from Pinnekamp [10], a simplified assumption is being made, that the US-Dollar price for phosphoric acid is equivalent to four times (six times for Pinnekamp) the price for rock phosphate plus a fixed amount of 50 US$/t. The price development for phosphoric acid from 2002 until 2012 can be seen in Figure 2.

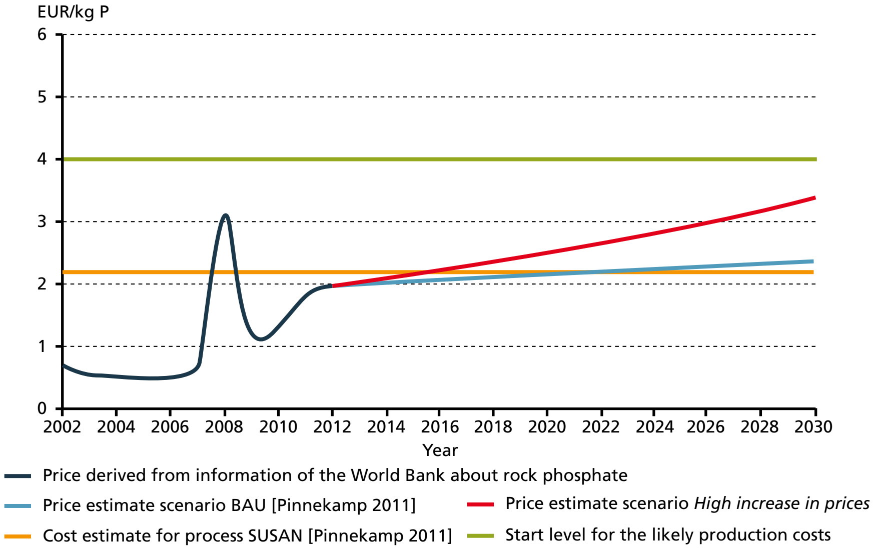

Figure 2: Price development for phosphoric acid

Source: Pinnekamp, J.; et al.: Verbundvorhaben Phosphorrecycling – Ökologische und wirtschaftliche Bewertung verschiedener Verfahren und Entwicklung eines strategischen Verwertungskonzeptes für Deutschland (PhoBe). Abschlussbericht. Bundeministerium für Bildung und Forschung, 463 S., Bonn, 2011

In 2008 the price for rock phosphate increased dramatically because of a temporary capacity bottleneck in companies processing rock phosphate. Prices fell again until 2009, but not as low as to the initial level. Since then, the price for rock phosphate has increased constantly again. This price pattern is also mirrored for phosphoric acid.

The price extrapolation up to 2030 was done in accordance with the conditions described by Pinnekamp [10]. He assumed a scenario *Business as usual* (BAU), with an expected annual price increase of 1 %. In a second scenario, with the assumption of additionally yielded revenues due to the cultivation of crops for the production of fuel for vehicles, he estimates an annual price increase of 2 %. We have done a different second extrapolation with an annual price increase of 3 % (scenario *High increase in prices*). It accounts for a price increase to a level that was seen once in 2008 and could occur again.

These assumptions lead to the extrapolation of prices for 2010 until 2030 for phosphoric acid in the scenario BAU (light blue line) and *High increase in prices* (red line). As a consequence we will see price increases up to the year 2030, which lead to four times the price of 2002.

Today's price for phosphoric acid is according to dealers around 1.68 EUR/kg P. Price estimates of rock phosphate are around 2.00 EUR/kg P. Therefore the extrapolated prices for 2030 are between 2.38 EUR/kg P and 3.39 EUR/kg P.

As stated above, the costs for the recovery of phosphorus are quoted between 1.00 EUR/kg P and 12.50 EUR/kg P. A realistic cost range is likely between 4.00 and 7.00 EUR/kg P. The 4.00 EUR/kg P – limit as the lower limit of the expected procedural costs is marked as a green line in Figure 2. Nevertheless, the price for recovered phosphorus would still be at least double as high as the price for phosphoric acid. That makes the recovery of phosphorus under the currently assumed limiting conditions economically not efficient within the near future.

In Figure 2 the estimated price of 2.20 EUR/kg P for the recovery process SUSAN is also marked with a yellow line. With this procedural price and the made price extrapolation for phosphoric acid, the recovery procedure would work efficiently from around 2015 onwards for the scenario *High increase in prices* or from around 2021 onwards for the scenario BAU.

It becomes evident, that with the conditions to date an efficient recovery of phosphorus is difficult to achieve. Different framework conditions, like for example a substantial increase in the price for phosphoric acid, will have a strong influence on the profitability, so that the development of procedures for large scale recovery of phosphorus will remain a key issue in the next few years.

6. Interim Solution

The benefits of the recovery of phosphorus are not in question. With regard to the concentration of phosphorus in the base material and the recovery potential, the most efficient procedure would be the thermal metallurgical recovery from sewage sludge ash. Its requirement is the mono-combustion of the sewage sludge.

As long as no efficient process for the recovery of phosphorus from sewage sludge ash is available, in Germany and Switzerland an interim solution is recommended, i.e. to deposit separately the ash from sludge incineration, in order to make it again accessible in the future as a source of phosphorus, when the necessary framework conditions are given [6, 8].

In some locations in Switzerland sewage sludge ash is already stored separately. Also the City of Zurich has decided to use separate disposal, which will start with the commissioning of the new mono-incinerator in 2015.

7. Conclusion and summary

Sewage sludge is a suitable resource for phosphorus. Because of the presence of harmful substances, particularly heavy metals, the application to agricultural land is seen more and more critically and is already partially banned. The aim is therefore to treat sewage sludge in a way that harmful substances are eliminated and nutrients, particularly phosphorus, can be recovered.

The recovered phosphorus has to be suitable as a potential fertiliser. It has to have a low concentration of heavy metals and a good accessibility for plants, which means, that phosphorus has to be present in its soluble form.

At the moment there is no efficient recovery procedure on a large scale available, which offers a high recovery potential, an elimination of harmful substances and a product with a good uptake by plants.

A price estimate with the assumption of a very low cost recovery process has shown that the economical efficiency might be possible within the next few years, but that with realistic production costs the economic efficiency under the current framework conditions is unlikely.

Until an efficient procedure on a large scale is possible, particularly for the recovery of phosphorus from sewage sludge ash, the sewage sludge ash from mono-incinerators should be deposited separately, in order to stay available for a possible recovery.

For resource conservation and environmental reasons a recovery of phosphorus is advisable, and therefore an issue, that will remain relevant in the coming years.

8. Literature

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