

Phosphate recycling in the phosphorus industry

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INTRODUCTION

Interest in phosphate recycling is steadily increasing in the industrialized world. There are large amounts of phosphate available in waste streams from e.g. agriculture, sewage treatment and from industrial side streams which pose an increasing problem. To avoid wasting these in e.g. landfills, and to counteract the depletion of natural phosphate sources, routes for re-use are explored.

One possibility is to replace phosphate rock by recycled materials in the production of white phosphorus.

Worldwide, P production is limited to China, Kazakhstan, the USA and The Netherlands. The latter producer, Thermphos International, has decided to replace 40 kt a⁻¹ of their P₂O₅ intake (17.5 kt P) by recovered materials

LIMITATIONS FOR PHOSPHATE RECYCLING IN THE PHOSPHORUS PROCESS

The phosphorus process

The phosphorus process consists of two parts. The first part is a wet granulation and sintering of phosphate rock, producing hard pellets of 1-2 cm. This treatment is necessary to prevent blocking of the furnaces further downstream. The rock pellets are then mixed with cokes (reducing agent) and pebbles (SiO₂, for slag formation) and fed into a furnace. The furnace is heated to 1500 °C by means of electric resistance. At this temperature, phosphate is reduced to P₄ which leaves the furnace as a gas, together with the by-product CO and some dust. This dust is removed in an electrostatic precipitator and recycled into the process. The P₄ is then condensed. The resulting CO gas stream is used as fuel for the sintering plant and other on-site processes. The calcium oxide which is left in the furnace after the phosphate has reacted, combines with the SiO₂ to form a liquid slag. This slag is tapped, cooled, crushed and used for e.g. road construction.

Iron, present as an impurity in the rock, is also reduced in the furnace. These form a separate slag, ferrophosphorus, which contains roughly 75% Fe and 25% P, with small amounts of other metals. It is used as a steel additive.

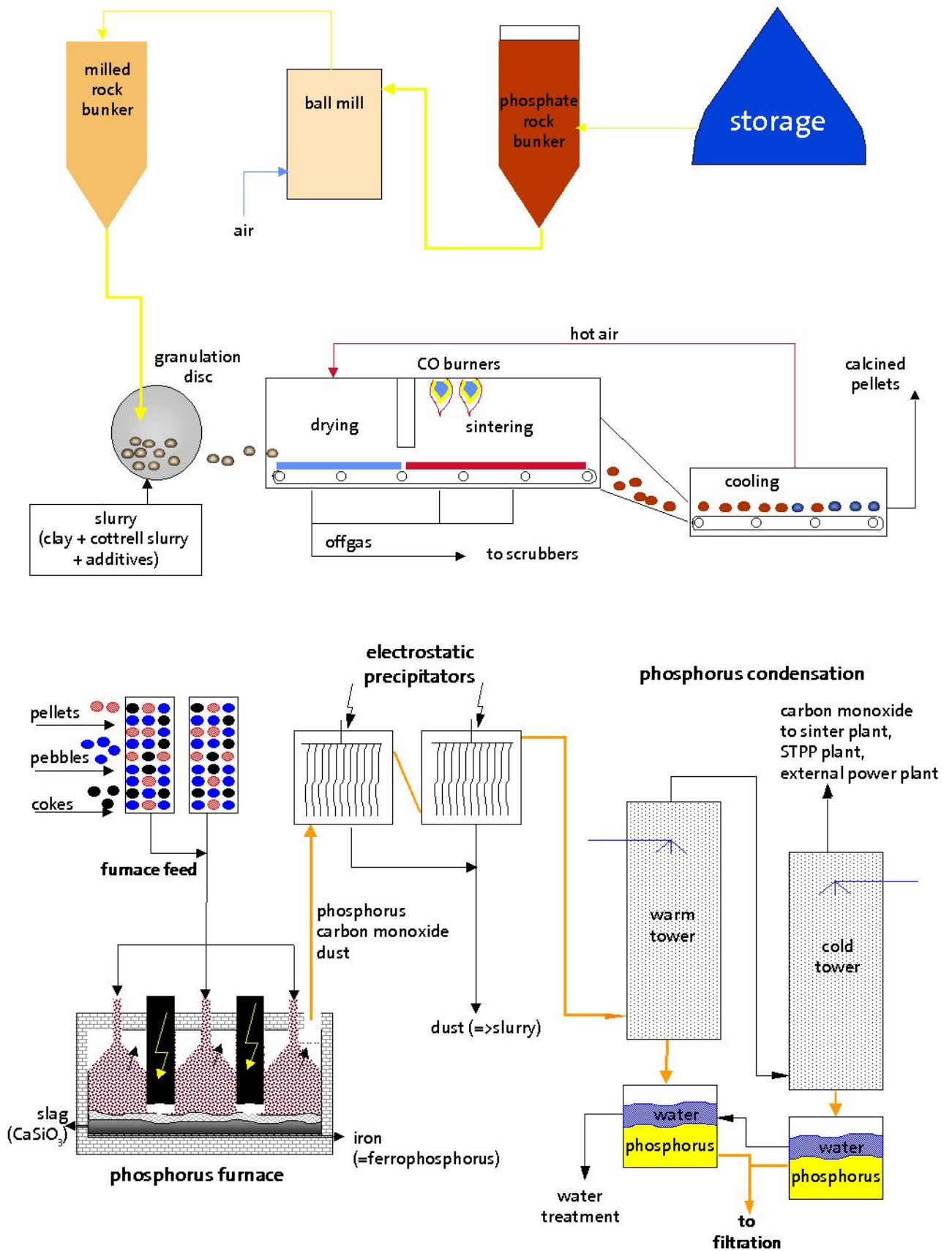


Figure 1 The phosphorus production process. Top: phosphate rock pelletizing and sintering stage. Bottom: Phosphorus furnace section.

The usual route for phosphate recycling is to mix the material with the rock before the grinding stage. This implies that it has to fulfil the same set of restrictions imposed on regular phosphates and the impurities it contains.

Phosphate content

The typical P_2O_5 content of phosphate rock is 30-40% (= 13-17.5% P) The phosphate content of waste streams is usually lower. If the remainder is made up by inorganic compounds, this will lead to more slag per tonne of P_4 . This will affect the energy efficiency of the process negatively. The heat in slag is lost since it requires a special cooling process in order to make it suitable for civil engineering purposes. The slag takes up a substantial amount, about one-third, of the total electricity consumption of the process; therefore extra slag should be avoided if possible. On the other hand, if the remainder of the secondary stream consists of SiO_2 , this has no effect on the energy balance since the process requires the addition of SiO_2 anyway. Aluminium compounds may replace SiO_2 in slag formation, so that recovered aluminium phosphates would make a good raw material for the process.

Impurities

Since the phosphorus furnace is a reduction process, it also reduces every (trace) element present which is more easily reduced than phosphorus. The most notable elements that can cause undesirable effects are:

- Iron.

This forms a separate slag and effectively removes phosphorus from the process. The compound formed is an alloy between Fe and P, with 25% P by weight. The presence of large amounts of iron poses P-depreciation and capacity problems, and the market potential for this side stream is limited. Actually, if pure $FePO_4$ is used, only one-third of the phosphorus is released as P_4 ; the remainder will end up in the ferrophosphorus. Also, the reduction of iron requires additional energy and cokes.

- Volatile metals.

Sewage sludges and manure often contain considerable amounts of zinc. This metal is volatilised in the furnace and subsequently precipitated on the furnace dust. Since this is recycled, zinc tends to build up in the system. This makes purges necessary. Similar problems occur for other volatile metals like lead, cadmium and tin. This stream also accumulates certain radioactive isotopes which are present in the rock as uranium decay products, such as ^{210}Pb . This makes this stream lightly radioactive, typically 800 Bq g^{-1} , which requires special handling and prevents its use as a Zn source, or landfill. Instead it has to be stored as a radioactive waste. Therefore, disposal of the purged stream will be very costly, even when small amounts are purged. Additional amounts of zinc make larger purges necessary.

- Chloride causes corrosion damage to the granulation/sintering plant, where metal parts are exposed to the raw materials at high temperatures.

- Copper ends up in the ferrophosphorus. Steel producers, the main clients for ferrophosphorus, limit their intake of copper for most high-grade steel types since too much copper weakens the steel. Natural phosphate rock contains very little Cu ($3\text{-}30 \text{ mg kg}^{-1}$ depending on the source), whereas the Cu content of manure ash or sewage ash is typically about two orders of magnitude higher (see below). Use of large amounts of these materials in the P production process may prevent the use of ferrophosphorus in industry and leaves (costly) landfilling as the only alternative.

Water content

Phosphate rock is usually supplied as a dry material. A considerable number of waste treatment processes generate wet sludges of organic or inorganic phosphates. The P process cannot use wet material on a large scale because of technical limitations (mixing, milling, interference with internal sludge processing capacity). Drying materials on-site could solve this problem, but there is no waste (low-grade) heat source available, so that drying would involve energy purchase and consumption and so be costly; more importantly, it is economically and ecologically undesirable to transport materials with a high water content over large distances.

Organic material and ammonium

The presence of significant amounts of organic material lead to a decreased pellet strength after sintering. This will seriously limit the capacity of the plant, which is unacceptable. Therefore, the material should consist of inorganic phosphates only (max. 5% carbon).

Also, nitrogen present in recovered materials causes a serious emission or gas scrubbing problem in the sintering stage, since NH_3 will be volatilised. This would be a major obstacle to the use of recovered ammonium struvite (ammonium magnesium phosphate) as a feed material for the process.

Pellet strength

If the presence of a secondary material leads to decreased phosphate pellet strength, for instance due to the presence of large amounts of alkali metal salts, this will limit the plant capacity (see under *Organic material*)

EXPERIMENTAL PROCEDURES AND DATA COLLECTION

All composition data as presented in tables 2, 3 and 4 were measured by X-ray fluorescence spectroscopy (XRF) and, for trace metal impurities, verified with dissolution in concentrated HCl/HNO_3 followed by ICP analysis. The error margins for these data are $\pm 5\%$. The data represent typical samples. The water treatment sludge data are averages over several samples from two incinerators which account for 50% of the Dutch sewage sludge and were confirmed by a range of data for untreated sewage sludge [1]. The bio-P-ash composition results from several laboratory incineration experiments at $800\text{ }^\circ\text{C}$ and complies with data supplied by the sludge supplier (Cuijk treatment plant, the Netherlands). Data for the crystallator pellets (table 3) are averages over 2000. The standard deviation of these data is 5%. The manure results were collected from various sources as indicated in the corresponding paragraph.

SEWAGE AS A SOURCE OF SECONDARY PHOSPHATES

In 1998 the Dutch sewage contained about 14 kilotonne/year phosphorus (as P) [1]. In the wastewater treatment plants about 10 kt P/year was removed by chemical and biological treatment methods. The intention is to increase this amount even further to approximately 12 kt P/year. Almost all the removed phosphorus is fixed in the primary and secondary sewage sludge. This sludge is treated and disposed of in several ways, but no more than 14% has a useful application as compost (table 1). As application in agriculture is no longer accepted the amount of sludge incinerated will increase.

Table 1 Disposal and utilisation of sewage sludge in 1998 in The Netherlands

Sludge disposal and utilisation	Sewage sludge (dry mass) kton	% to this disposal route
Incineration	162	46*
Controlled disposal	101	29
Compost	48	14
Other applications	27	8
Wet oxidation	12	3
Total	350	100

*expected to rise to 60% in 2007

The following three streams were identified as potential sources of recovered phosphates from municipal sewage :

A) sewage sludge : the sludge from sewage works operating chemical (chem-P) or biological (bio-P) phosphorus removal offers relatively high phosphorus contents;

B) end products of sewage sludge processing (incineration, drying, composting, wet thermal oxidation ...);

C) specific phosphate products produced by side stream processing (bio-P plants only taken into consideration).

Sewage sludge cannot be used directly as it satisfies none of the defined quality criteria. After drying, the sludge has an appropriately low water content, but its organics content is still too high. After composting or wet thermal oxidation, it would still need to be incinerated. Options B and C offer recycling possibilities which are discussed below.

The incinerator ash, as collected from incinerators which account for about 60% of the Dutch sewage sludge (2007), contains a significant proportion of dry iron- calcium- and/or aluminium phosphates, alongside with silicates, with up to 18% P₂O₅ (7% P) The large iron content of this ash, up to 10%, prevents use in the phosphorus process, since the amount of ferrophosphorus formed would exceed the processing capacity and the re-use application potential for this stream (phosphate rock typically contains only 0.4-1% of Fe). Iron originates mainly from the phosphate precipitation step in sewage treatment plants using chemical P-precipitation.

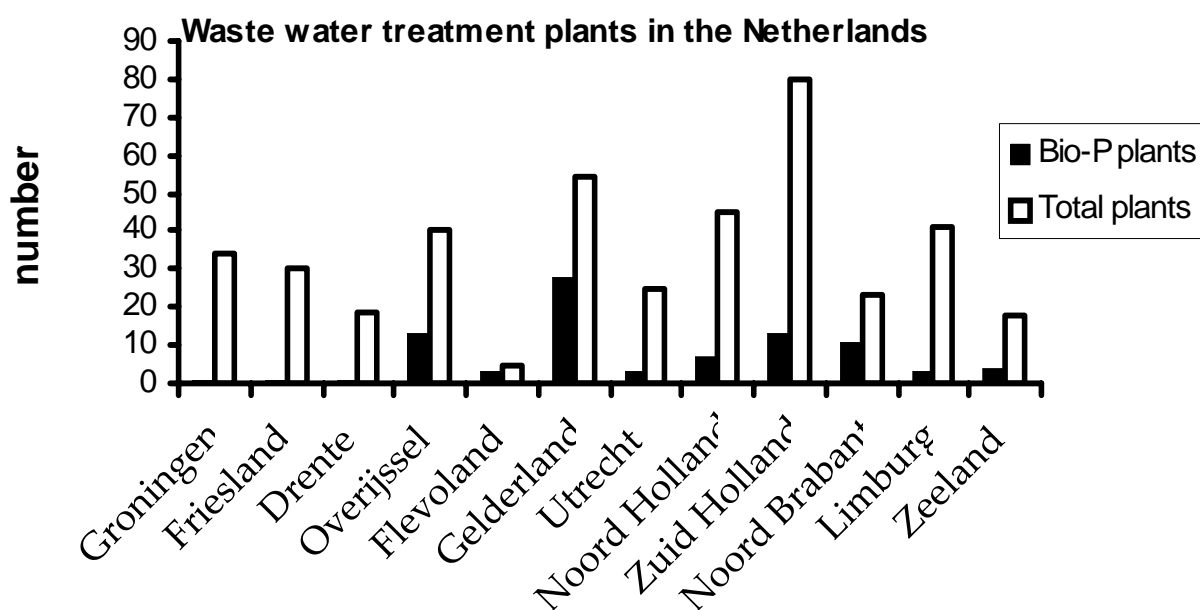


Figure 2 Wastewater treatment plants with biological P-removal in the different provinces of the Netherlands.

The iron used in sewage works P-removal can be replaced by calcium or aluminium, which would make ash processing in the P process much more feasible. At present, the use of aluminium in wastewater treatment is more costly, and calcium use in existing sewage works processes can cause sludge handling problems; it has to be evaluated whether the positive effect on the ash side will compensate for this. The general, government-induced tendency away from landfilling and towards recycling may be helpful here.

Bio-P removal

The problems associated with iron can also be avoided when the ash from sludge from biological phosphate removal treatment plants (bio-P plants) is used. In these plants, all phosphate is removed biologically and no additional phosphate precipitation is needed.

In table 2 the quality of ash from secondary sludge from bio-P plants is compared with the requirements for reuse by the phosphorus industry. The ash from bio-P plants has a higher phosphate concentration than ash from a mixture of all WWTP's (i.e. chemical P removal for the majority of the WWTP's) and is more or less at the same level as phosphate rock (30-40%). The iron content is close to the limit given by the P process. Since the iron in bioP sludge mainly originates from a small dosage during sludge digestion, the Fe content may be further reduced by using Al or Ca.

Table 2 Quality of sewage ash compared with the requirements of the P industry (Thermphos)

	P ₂ O ₅ (g kg ⁻¹ ash)	Copper (mg kg ⁻¹ ash)	Zinc (mg kg ⁻¹ ash)	Iron (g kg ⁻¹ ash)
Ash from current sewage sludge (primary + secondary sludge) (incinerator, the Netherlands, mix)	190	1600	3500	100
Ash from bio-P sludge (secondary sludge) (Cuijk plant, The Netherlands)	360	1500	3100	16
Requirements for reuse by the phosphorus industry	> 250	< 500	< 100	< 10

Although bio-P ash has a higher phosphate concentration and much less iron, it still contains too high levels of zinc and copper to be attractive for use in the P process. Also, the separate collection and incineration of bio-P sludge poses large logistical problems. Side-stream recovery of phosphate in a WWTP solves these problems.

Side stream recovery

It is also possible to recover phosphate selectively, at the treatment plant itself, especially at bio-P plants. There are several ways of doing this, such as the Phostrip-process [2] and the BCFS-process [3]. For an overview, see [4].

In the Netherlands the treatment plant of Geestmerambacht uses the Phostrip process. The phosphate is precipitated in a Crystallactor, a sand-seeded precipitation reactor which produces phosphate pellets with less than 20% moisture. In table 3 the quality of the precipitate from that plant is compared with the P industry requirements. It is concluded that this type of material may be used by the P industry without limitation.

Table 3 Quality of the precipitate compared with the requirements of the P industry

	P ₂ O ₅ (g kg ⁻¹ ash)	Copper (mg kg ⁻¹ ash)	Zinc (mg kg ⁻¹ ash)	Iron (g kg ⁻¹ ash)
Phostrip phosphorus precipitate (Crystalactor)	260	1.6	35	-
Requirements P industry*	> 250	< 500	< 1000	< 10

*indicative figures, deviations can be tolerable depending on overall composition

By recovering phosphate in a side stream according to these two alternatives, it isn't possible to recover all the removed phosphorus. A part of the phosphorus is used for normal metabolic needs and this phosphorus will not be released in an anaerobic phase. At the COD/P ratio as is found in the influx of WWTP's in the Netherlands, about 75 % of the phosphate removed can be recovered in a side stream, and 25 % leaves the wastewater treatment plant with the excess sludge.

The implementation of this technology at all WWTP's in the Netherlands will be costly. However, it is possible to collect all filter-pressed bio-P sludges separately, transport them to a treatment plant near the central incinerator, and perform the side stream P recovery in one large reactor as described above. The sludge could then be pressed again and incinerated; also, the phosphate would become available at one site which will make transport to the P plant easier.

Current situation in The Netherlands

According to an inquiry [1], about 90 of the 414 Dutch wastewater treatment plants have included biological P removal in their process (Figure 2). We cannot conclude that also 22 % of the secondary sludge is from bio-P plants as the mean load of the bio-P plants is lower than the mean load of all the plants.

To have an idea of how much phosphate can be recovered theoretically we have calculated how much phosphate would be removed in each province in case the phosphate concentration in the effluents of the plants were lowered to 1 mg/l. Next we assumed that 65% of the removed phosphate could be recovered in a sidestream precipitation reactor in case all the plants had biological P-removal (Figure 3). The total amount of phosphate that can theoretically be recovered is about 18 kton P₂O₅/year (8 kt P/year).

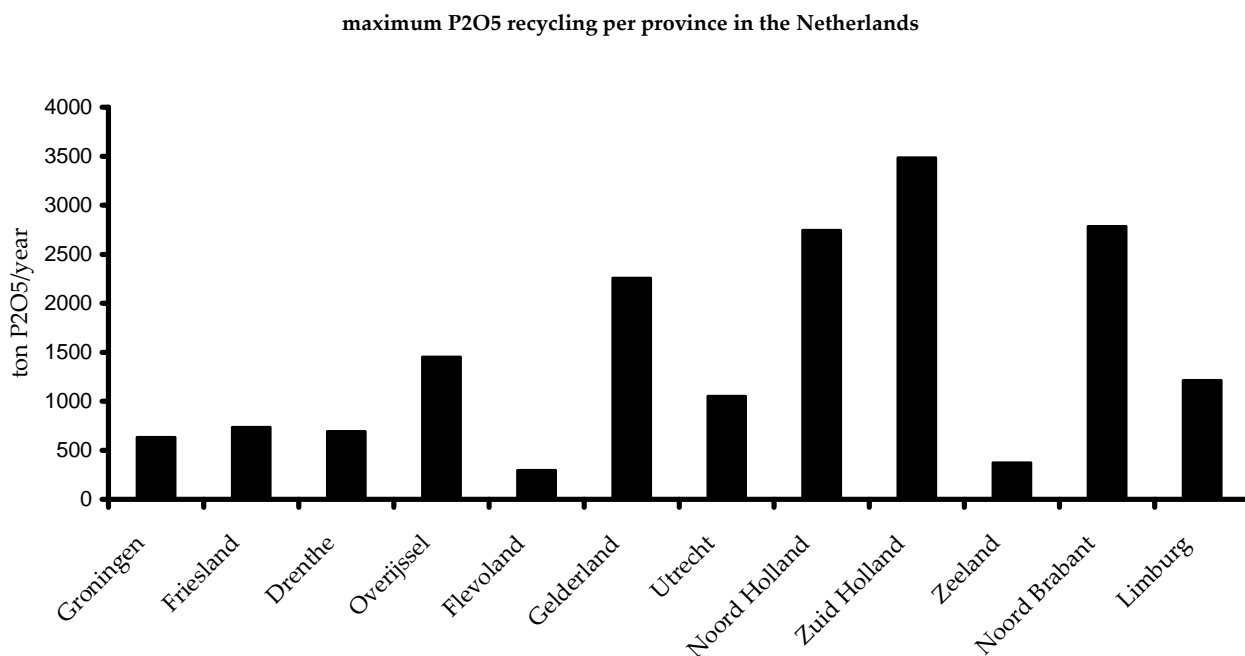


Figure 3 Maximum amount of P₂O₅ that can be recycled in the Netherlands via bio-P plants

Large-scale experimental recycling of sewage sludge ash in the P process

[added to original article – January 2007]

In 2006, a joint initiative between Thermphos and sludge incinerator SNB (Moerdijk) was launched to produce an iron-poor ash. By separately incinerating sludges from bio-P WWTPs and WWTPs that use aluminium for chemical P removal, it was possible to produce an ash with molar Fe:P ratio of 0.20. It is not possible to avoid the presence of Fe altogether, since surface waters, sludge conditioning and other sources contribute to the iron content of the sludge even without dosage of iron chloride for P removal. Although the iron, zinc and copper content are still outside the initially defined range, a large scale test was performed to test its behaviour in the P process.

In 2006 and early 2007, a total of 2700 t ash was / will be processed in the P process. At the time of writing, no adverse effects were observed.

Struvite processing

[added to original article – January 2007]

Since 2004, Thermphos is processing potassium struvite (KMgPO_4) from calf manure as secondary feedstock. The regular form of struvite, ammonium struvite hexahydrate ($\text{NH}_4\text{MgPO}_4 \cdot 6 \text{H}_2\text{O}$) was also tested. The thermal stability of this material is low, as it tends to lose its ammonium in the form of NH_3 at temperatures above 80 °C. A large scale test in the Thermphos P plant revealed that all NH_3 is effectively driven off in the drying stage of the pelletizing plant, the first section of the process. It is consequently emitted with the flue gases as the offgas scrubbers for a P plant typically operate under alkaline conditions, and do not capture NH_3 efficiently.

If quantities become larger, a separate thermal treatment, possibly also including a drying section, may become feasible. NH_3 can then be captured and re-used separately, with the resulting MgHPO_4 or $\text{Mg}_2\text{P}_2\text{O}_7$ as feedstock for the P process.

MANURE AS A SOURCE OF SECONDARY PHOSPHATES

In countries with intensive livestock agriculture, such as the Netherlands, animal manure storage and disposal can pose a large problem. In some cases the production of manure exceeds the need for nutrients of the land. Agricultural spreading of the manure will then lead to excess fertilisation and eutrophication. In order to protect the environment and the water quality regulator have set limits to the allowed amount of nutrients. Therefore it is not allowed to use the full amount of produced manure as natural fertiliser and several projects have been started to dispose of manures in some useful way. These projects include drying the manure or concentrating it so it can be transported to areas where the nutrient limits have not been reached yet. At the moment, however, there is still a manure/nutrient surplus in all areas of The Netherlands, and different approaches are needed.

The phosphate in the manure could also be used as a raw material for the P industry. In untreated manure, the organic and water content are high and the phosphate content is low, so it needs to be incinerated before usage in the P industry. The total yearly amount of P in Dutch pig and poultry manures is 86 kilotonne. In theory, the Dutch P industry could recycle a considerable amount of this phosphate and help solve the manure surplus problem of The Netherlands. A major advantage of this is that the phosphate is taken out of the agricultural P cycle which is encouraged by the Dutch environmental government policy. Unlike agricultural spreading of manures, the P industry can take recovered phosphates all year round, avoiding manure storage problems.

When the manure is not too wet, it may be incinerated without further drying, and the released energy may be converted to electricity. Amongst other projects, a large scale plant for poultry manure incineration in Moerdijk, the Netherlands, is currently being engineered. The residue of this process is a dry product containing a high proportion of calcium phosphate. Unfortunately, the zinc and copper content are relatively high, just as is the case with sewage sludge ash, which at present prevents use of large amounts of manure ash by the P industry (see table 4). Pig manure poses the same problem. Copper and zinc originate from animal feeds. Since these metals are also becoming increasingly problematic for other manure applications, such as agricultural spreading, it is expected that the Cu and Zn content in manure ash will decrease in the future. It may be necessary to develop a process that separates the metals and the phosphate present in the ash.

TABLE 4. COMPOSITION OF POULTRY AND PIG MANURE ASH

	P ₂ O ₅ (g kg ⁻¹ ash)	Copper (mg kg ⁻¹ ash)	Zinc (mg kg ⁻¹ ash)	Iron (g kg ⁻¹ ash)
Incinerator bed ash from poultry manure incinerator*	189	630	1500	8.3
Ash from pig manure**	286	240	3200	20

*mixed ash from laying hens and table poultry, 1:2, the expected ratio for a poultry manure incinerator to be constructed in Moerdijk, The Netherlands, which will process 20-25% of the Dutch poultry manure. Data pertain to a mixed sample from an experimental incinerator; part of the volatile elements and compounds are separated into a cyclone ash which is not included here. The ash values were validated against a mass balance over the poultry industry and have error margins of 5%.

**typical incinerated sample from Arendonk, Belgium. The data for pig manure may vary; this analysis is included for global comparison. Currently there is no central incinerator for pig manure which prevents the collection of average data or samples.

BONE MEAL ASH AND DICALCIUM PHOSPHATE

The recent developments in the livestock industry (BSE, foot-mouth disease) have led to a change in the market for bone meal ash and DCP from gelatin producers. Both materials are technically suitable for use in the P process, provided that the chloride content is not too high.

INDUSTRIAL AND FOOD INDUSTRY WASTE STREAMS

Many industries produce phosphate waste streams, for example food and dairy processing, metal treatment and etching, electronics manufacturing and other processes that use phosphorus, phosphoric acid or phosphates. A large variety of phosphate-containing wet and dry materials result from the treatment of these waste streams. In The Netherlands these contain at least 5 kt/y (as P). A large part of these materials is suitable for processing in the P process, depending on the nature of the material.

A large problem in obtaining secondary phosphates from other countries is the waste legislation. It is usually not permitted to transport waste across the border, and many secondary phosphates are currently classified as waste. There is need for less rigid legislation and regulation on national and European scale, especially regarding the difference

between waste materials and recyclable raw materials. This should prevent landfill of valuable materials. The current legislation creates barriers which discourage or prevent recycling.

ENVIRONMENTAL EFFECTS

The economic and environmental effects of using phosphate from sewage and from manure in the elementary phosphorus have been calculated in comparison with the use of phosphate ore. The environmental effects are expressed in terms of money using the shadow price method. This is a method to value products for which there is no market yet. To find these prices for environmental effects we use the preventative cost method. This method assumes that the (Dutch) government sets environmental targets, and that in order to reach these targets measures have to be taken. The second assumption is that the targets are to be reached at the lowest possible cost. Therefore the most expensive measure that still has to be taken to reach the environmental target would be the market price if there would be a market for reduction of environmental impact. This price at the virtual market is the shadow price for the reduction of the environmental impact (for CO₂ we used a shadow price 0,10 NLG per kg, for more information see www.ce.nl or [4]). The environmental and economic benefits of using Dutch manure for the Dutch elementary phosphorus industry are calculated as shown in fig.4. The calculations are based on data from 1995 to 1999 obtained from the Dutch Central Bureau for Statistics CBS[1], Centrum voor Energiebesparing en Schone Technologieën [5,6,7] and oral or written information from sewage treatment plants, Thermphos, and the Centre Européen d' Études des Polyphosphates. The environmental effects are dominated by the prevention of excess fertilisation (about 90% of the benefit). In the Netherlands the government needs to take harsh measures to combat excess fertilisation to comply with EU-regulations. These measures are costly and therefore the shadow price for excess fertilisation is high. The use of manure in the white phosphorus industry prevents excess fertilisation and therefore results in a large environmental benefit when expressed in shadow prices. The environmental benefit of using manure for phosphorus production in another country (without excess fertilisation) would therefore be totally different. The economic effects are dominated by the measures that need to be taken to remove water and organic compounds from the manure. By drying and burning the manure the phosphate content of the source is raised as well, satisfying three of the five input restrictions. Because there is no excess heat the energy for this needs to be purchased, making it costly. As a result the poultry manure is cheaper to use because it contains less water.

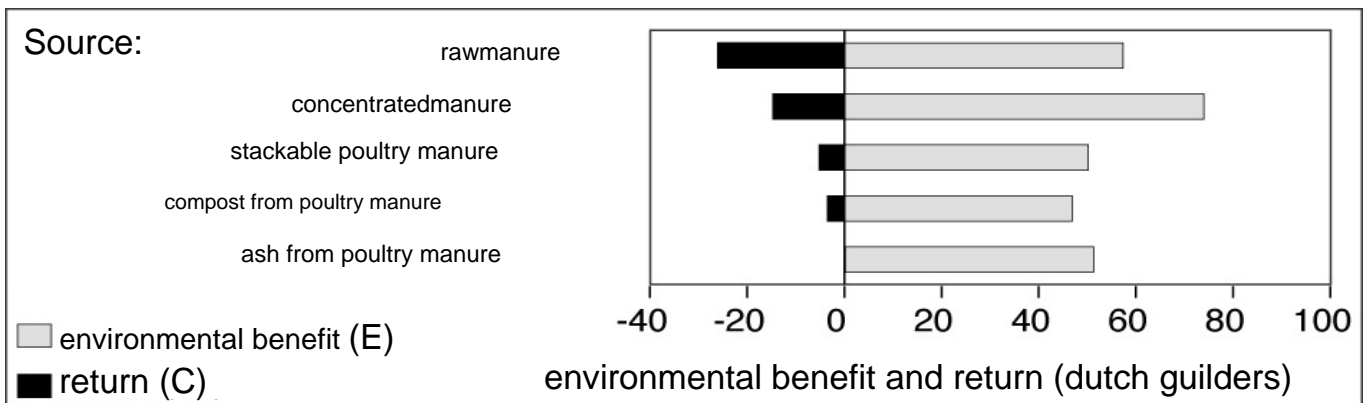


Figure 4 Environmental and financial effects in the phosphorus chain of utilisation of manure at Thermphos (from [6])

When we evaluate the usage of sewage sludge as a phosphorus source for the elementary phosphorus industry in the Netherlands in the same way it results in environmental and economical benefits according to fig. 5.

The economic effect of the use of sewage sludge is dominated by the prevention of the costs of conventional processing. The sewage treatment plants have to pay to have their sludge landfilled, dried or incinerated. Because of a limited capacity to do this, especially since the prohibition of landfilling sewage sludge, the prices are quite high. For the disposal of the dried or incinerated sludge has to be paid as well.

The environmental benefits of using this sludge at the phosphorus industry are small or even negative. Normally the dried sludge is used in the cement industry or for electricity generation. Because this prevents the use of fossil fuels this option is environmentally preferable. The ashes from sludge incineration are assumed to have no environmental impact.

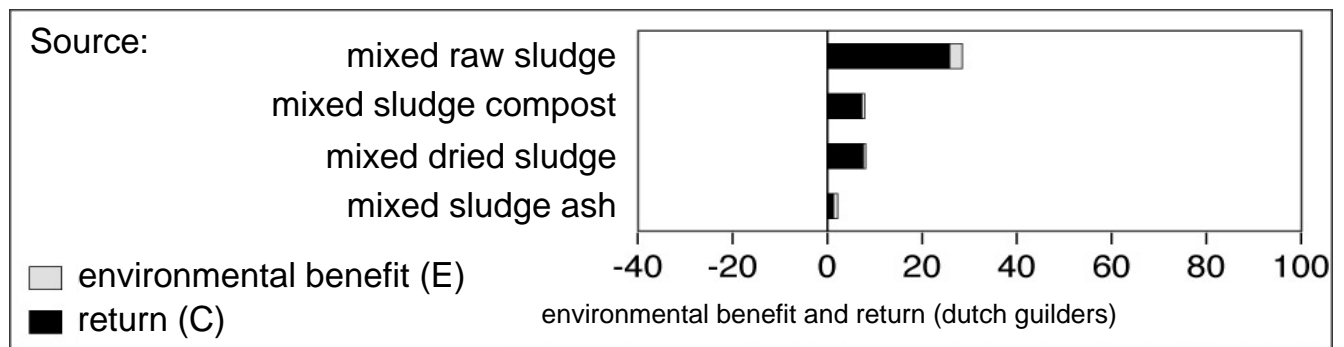


Figure 5 Environmental and financial effects in the phosphorus chain of utilisation of sewage sludge at Thermphos (from [6])

It needs to be said that the effects in the phosphorus process itself have not been taken into account. This is due to the fact that the behaviour of the substances in the process and possible built ups (as mentioned before with zinc) are unpredictable beforehand. The (partial) substitution of phosphate rock (mining and transportation), the prevention of other waste processing of manure and sludge and preparation for use in phosphorus process (drying and incineration) if necessary have been taken into account.

CONCLUSIONS

We conclude that there is potential for P recycling in the phosphorus process, but there are many practical difficulties to be overcome. P from sewage sludge has excellent recycling potential in the P process, provided the proper techniques for side-stream recovery are applied. BioP sludge ash is less suitable, but still a more interesting option than the current sludge ash; the high iron content of this ash makes recycling in the P process virtually impossible. The current sewage ashes and bioP ash also have too much copper and zinc. Recycling from industrial sources is possible in many cases, but depends on the source and nature of the material.

The presence of copper and zinc in manure ash makes recycling unattractive at present. Alternative techniques need to be developed to make recycling of P from manure possible.

Adaptations in legislation may accelerate the closing of the P chain.

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REFERENCES

1. Centraal Bureau voor Statistiek (2000) Waterkwaliteitsbeheer. Zuivering van afvalwater, 1998, CBS, Voorburg/Heerlen, The Netherlands, 59 pp.
2. Levin, G.V. and Shapiro, J. (1965) Metabolic uptake of phosphorus by wastewater organisms. *J. Water Pollut. Control Fed.* **37**, 800-821
3. Loosdrecht, M.C.M. van, Brandse, F.A. and Vries, A.C. de (1998) Upgrading of waste water treatment processes for integrated nutrient removal- The BCFS® process. *Water Sci. Technol.* **37**, 209-217.
4. Brett, S, Guy, J., Morse, G.K., and Lester, J.N. Phosphorus removal and recovery technologies, Selper Ltd, London, UK 1997.
5. Van Soest, J.P., Sas, H. and Wit, G. de (1997) *Apples and Oranges*, Centrum voor Energiebesparing en Schone Technologieën, Delft, The Netherlands
6. Potjer, B., Vermeulen, J., Weerd, G. de, Bergsma, G. en Croezen, H (2000) *Fosforkringloop voor Thermphos*, Centrum voor Energiebesparing en Schone Technologieën, Delft, The Netherlands
7. de Wit G., Davidson, M.D., and Bleijenberg, A.M., Economisch-Sociale Berichten 4159 (1998), 516-518