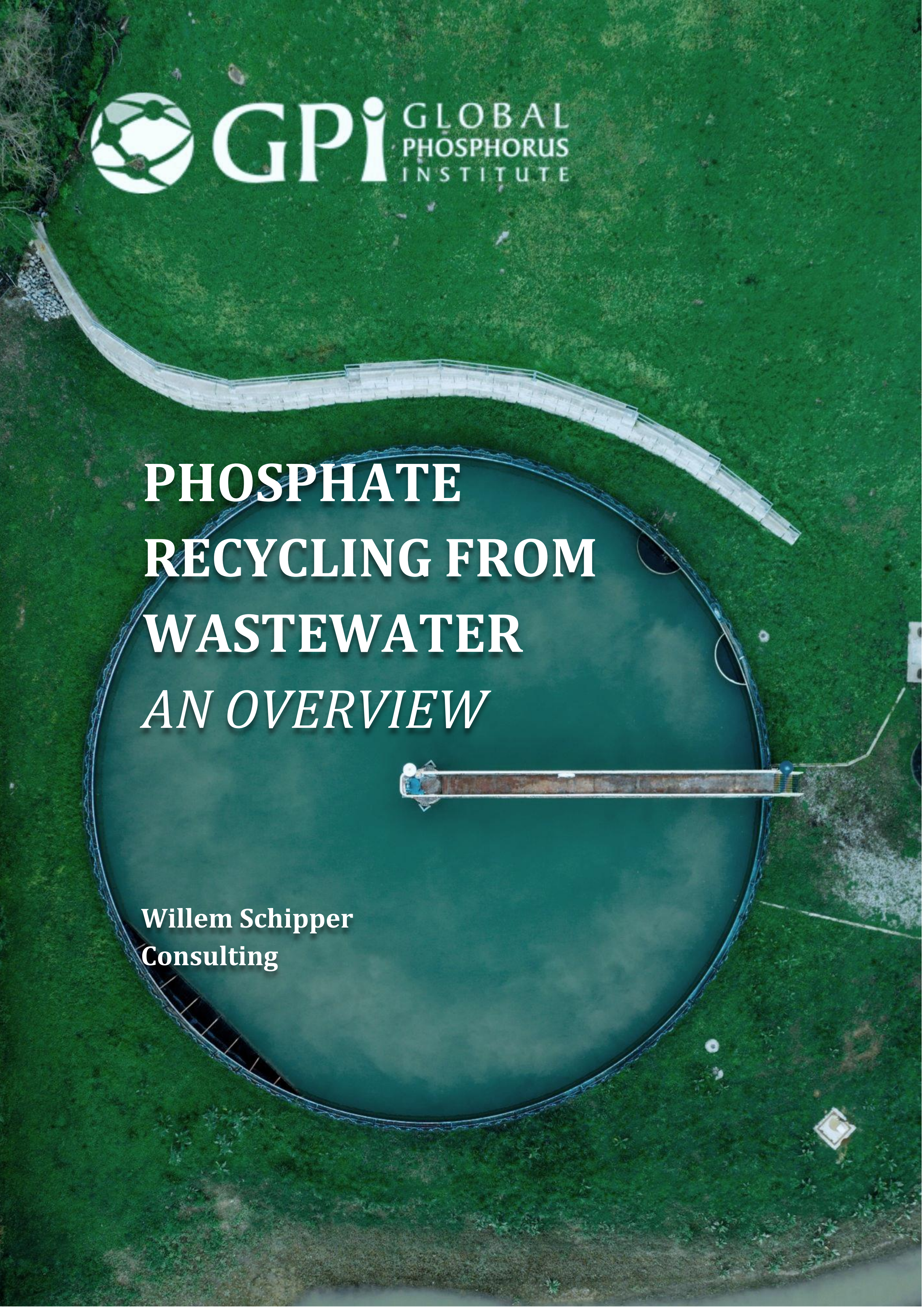


GPI GLOBAL PHOSPHORUS INSTITUTE

PHOSPHATE RECYCLING FROM WASTEWATER

AN OVERVIEW

Willem Schipper
Consulting

Contents

This study was commissioned by the Global Phosphorus Institute
DOI: https://doi.org/10.20944/preprints202510.0581.v1

Summary

The element phosphorus plays a crucial role in our society. It is one of the three essential nutrients to make crops grow and feed the world. It also has smaller but important applications in diverse areas like lithium-ion batteries, fire safety, lubricant additives, and crop protection agents.

As is the case with many materials used in modern society, phosphate is mined from surface deposits and processed in a downstream value chain, chiefly in the form of fertilizers. Fertilizer phosphate may end up being bound in soils, flushed out to surface waters and eventually the oceans, or absorbed by plants.

It enters our food via food crops and animal products. Phosphate also enters our food through animal feed additives (partially ending up in meat) and food additives.

The phosphate we ingest is eventually excreted and enters a form of wastewater, with minor contributions from detergents, industry, food waste and surface runoff. Depending on local circumstances, it ends up in the local environment, a septic tank, or a sewage system. About 57% of the world's population is connected to sewers [1b]. The collected sewage contains nitrogen, organic matter, and phosphate, all of which can negatively impact surface water quality if discharged untreated. For this reason, sewage is directed to a wastewater treatment plant (WWTP), which removes organics, nitrogen, and phosphate by means of settling and action from bacteria (called active sludge), resulting in a clean effluent ready to be discharged into the environment. The bacterial sludge accumulates steadily over time and needs to be purged as a stream called sewage sludge or sometimes biosolids. Additional phosphate may be removed by precipitation with iron or aluminum salts. These precipitates also join the sludge.

The WWTP and its sludge form a primary entry point for phosphate recovery. One reason is because sludge use is subject to control and regulation in several geographies. An option is to use the sludge as is, with positive effects on soil biota, but this approach is met with increasing resistance because it may also carry pollutants (per- and polyfluoroalkyl substances (PFAS), drug residues, and heavy metals). At least in Europe, it is increasingly banned on fields. Incinerating the sludge to a phosphate-rich ash opens numerous technological pathways to produce fertilizers or other phosphorus compounds. Incineration in cement kilns is also common, providing carbon credits to the cement industry, but this makes the phosphate unrecoverable as it ends up in cement. Apart from that, the WWTP may offer targeted phosphate harvesting routes, such as forming a magnesium phosphate (struvite) at a WWTP,, although it is not efficient in overall P recovery and can only be applied to a certain type of WWTP. Some options starting from sludge itself are also described.

This document explores various types of recovery, their pros and cons, and their implementation status. Ash-based technologies offer the highest phosphate recycling rate (80%-90% of phosphorus recovery). These can be separated into inclusive technologies

(transformation of essentially all ash, leading to a new type of fertilizer) and separative technologies (extraction of phosphoric acid or phosphates, which are products with a long- established market, if made of sufficient quality). However, these separative technologies inevitably yield byproducts that need valorization. The latter can be a challenge.

Developments in P recycling technologies mainly take place in Japan and Europe.

The amount of recoverable sewage phosphorus (i.e., that contained in sewage sludge or sewage-derived products) is estimated to be 1 Mt/y worldwide, expressed as P, out of a total of 3.7 Mt/y -comprising 3.1 Mt excreted by humans and the remainder from other sources such as industrial wastes, compared to 29-30 Mt/y mined from fossil resources.

1 - Introduction

1.1 General

In a world where resources are being depleted at an ever-increasing rate, there is a pressing need to recycle materials as much as possible. This is especially true for materials that are essential to our society, such as nutrients, which we need for food production.

The element phosphorus deserves a special mention in this context as one of the three essential elements used in fertilizers, along with nitrogen and potassium. Unlike nitrogen, which can be fixed from the air, or potassium, which is available abundantly, phosphorus supply is more restricted, and its reserves (mineral deposits of apatite) are limited in a geographical sense. These deposits have formed over geological time periods and are finite.

Phosphate, being an element, is indestructible, usually undergoes a single pass use in our society, and ends up being discarded. It is mainly used as a fertilizer, meaning it enters our food chain and finds its way to end points, the most common of which are dilution in the sea, binding in agricultural soils or in lake and river sediments, or deposition as waste (e.g. landfilled). Because it is inaccessible for further use, more pressure is put on existing fossil phosphate resources to ensure food supply worldwide.

For these two reasons, it is logical to make the use of phosphorus more circular by recovering it before it ends up in places where it is not accessible for future use.

Diffuse losses of phosphorus, through fertilizer not used by crops, include lockup in soils and flushing out to surface waters and eventually to the sea. These system leaks are quite difficult to address. However, a considerable part of phosphorus passes through our wastewater systems. In Europe, this is estimated to be about 20% of phosphate in mineral fertilizer [1a]. Because phosphorus acts as a fertilizer even unintentionally, discharging untreated sewage into the environment has a strong fertilizing effect on surface waters. As phosphorus is often the nutrient in deficiency, discharging large amounts of phosphorus into the environment will cause massive growth of algae in these surface waters (algal bloom), a process known as eutrophication. For this reason, sewage is often treated in a wastewater treatment plant (WWTP), which-among other pollutants-removes phosphorus and transfers it to sewage sludge. WWTPs are typically centralized, large operations. This opens viable pathways to the recovery and reuse of phosphorus from wastewater.

This study focuses on phosphorus recovery from such systems.

Because the element phosphorus usually occurs in the form of orthophosphate or polyphosphate in wastewater after treatment by sewage bacteria, the terms phosphorus and phosphate are used interchangeably in this text.

1.2 Types of Wastewater

1.2.1 Urban wastewater and its treatment

As the world becomes more urbanized and development progresses, the number of sewage systems steadily increases. In developed cities, effluents from households, businesses, industries, and public spaces are collected in a central system, where transport (of excrements and discharges) is essentially provided by large amounts of water.

In the 1950s-1990s, major sources of phosphate in wastewater were laundry and dishwashing detergents. A specific compound, sodium tripolyphosphate, constituted at least half of the content of detergent powders and tablets. This compound is very active at scale prevention, fine dust dispersal, and alkalinity control of the wash water. However, sewage treatment, especially dedicated phosphate removal, was not installed widely, so eutrophication occurred on a large scale. Since the use of phosphate has been banned in detergents in many geographies, the main input of phosphate to sewage is human excretion.

The human body uses phosphate in diverse roles, including DNA production; growth, maintenance, and repair of bones and teeth, and the cellular energy cycle (ADP-ATP exchange as part of the citric acid cycle). A certain level of dissolved phosphate is maintained in blood. The average adult contains 700 g of phosphorus and eats about 25 kg of phosphorus in the average lifespan.

The food we eat contains phosphate, so to avoid its accumulation, the adult body excretes the amount of phosphate taken up in the diet. This is done by the kidneys, where hormones such as FGF23 regulate the amount of phosphate going back to the body and the amount that is discharged into urine. The phosphate leaves the body with urine and enters the sewage system. In addition, undigested phosphates remain in solid matter in the gut and are excreted with feces. Generally, 70%-80% of the excreted phosphate leaves the body with urine.

Urine also contains appreciable amounts of dissolved nitrogen in forms such as urea.

Depending on diet, humans eat, so excrete 1 to 2 g of phosphorus (expressed as P) per person per day (p.p.p.d.) in the form of orthophosphate, PO_4^{3-}. The figure of 1 g p.p.p.d. is a rounded world average, but higher meat consumption and inclusion of processed food, which often contains phosphate additives, brings it closer to 2, a situation, for example, found in the US. The distinction is made further in Table 1.

Even though 1 g of excreted phosphorus per person per day may seem like a modest amount, it is not. With 8 billion people on the planet, that is almost 3.1 million tons of P per year compared to roughly 30 Mt/y (based on 220 Mt/y of rock with 30.5% P_2O_5) mined from fossil resources. Although a sizeable portion of the world's population is not hooked up to sewage treatment systems, hundreds of thousands of tons of phosphorus are ready to be recovered from sewage systems.

Minor additions of phosphorus to urban wastewater originate from food waste, industrial effluents, and detergents, which still contain a small amount of another class of P-containing ingredients: phosphonates. Surface runoff from urban areas, which may contain dog feces, organic matter, or garden fertilizer, are another minor source. In some places, a significant source is phosphates added to drinking water to prevent lead contamination from old pipes and soldering.

The wastewater thus obtained contains solid matter (feces, soil, toilet paper, etc.), dissolved nitrogen in the form of urea, various dissolved nitrogen compounds, dissolved organic material (e.g. from kitchen waste), and dissolved phosphate.

It also contains large amounts of other impurities, such as copper, zinc, lead, chromium, and nickel, along with drug residues (medicinal and recreational) such as chemotherapy agents, detergent and household ingredients, soap, and various substances people tend to flush down the toilet that they actually should not-e.g., deep fryer fat, turpentine and paint, engine oil, and objects like cotton tips, cigarette butts, and female hygiene pads. It also contains industrial chemicals such as PFAS or flame retardants originating from dust (via washing of household surfaces or clothes) or from atmospheric deposition and microplastics (e.g., from abrasion of synthetic textiles in washing machines and dryers and from abrasion of car tires flushed down sewage systems).

A WWTP typically has several stages:

- Removal of large objects by a grid
- Removal of solids (sand and silt) by settling
- Treatment by bacteria (usually present)
- Post removal of phosphate (in a minority of cases, chiefly driven by local regulations)

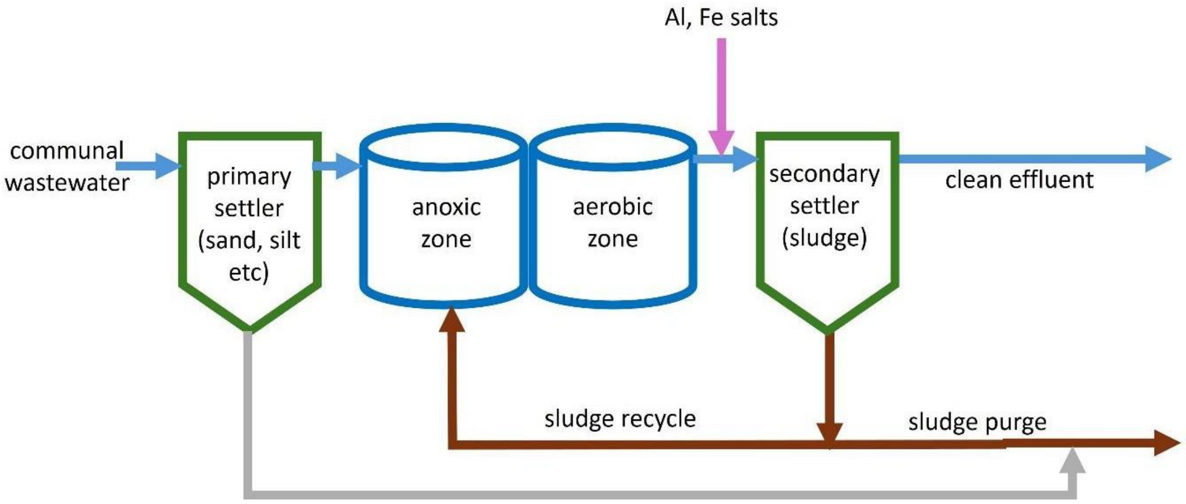
The formed sludge is settled and sent to the front of the bacterial part of the plant, with the excess purged. Sand beds and other filtration systems are used to remove traces of sludge. In addition, methods such as UV or ozone treatment may be used to disinfect the effluent, and activated carbon may be used to remove residual pollutants, especially if the effluent water is reused.

The first stage is the settling of solids by gravity. The now clear water is then subjected to treatment by bacteria (called the activated sludge process), which are present in the WWTP as a brown-greyish sludge. This main step is the reason why such wastewater treatment is called biological treatment. In some cases, a stage called nitrification-denitrification converts nitrogen compounds to nitrogen gas, which is released into the atmosphere (where nitrogen is also present naturally). In the next stage (or in combination with the previous stage), the bacteria consume the organic compounds, gaining weight and releasing part of the digested compounds as carbon dioxide. Like any living organism, the bacteria absorb phosphate as part of their biological makeup. Not all WWTPs have exactly this setup, but a majority do in some form, using activated sludge. Also, the first stage-settling-may involve some spontaneous bacterial action, so it acquires some of the characteristics of the activated sludge (second) stage, but the first stage is less efficient.

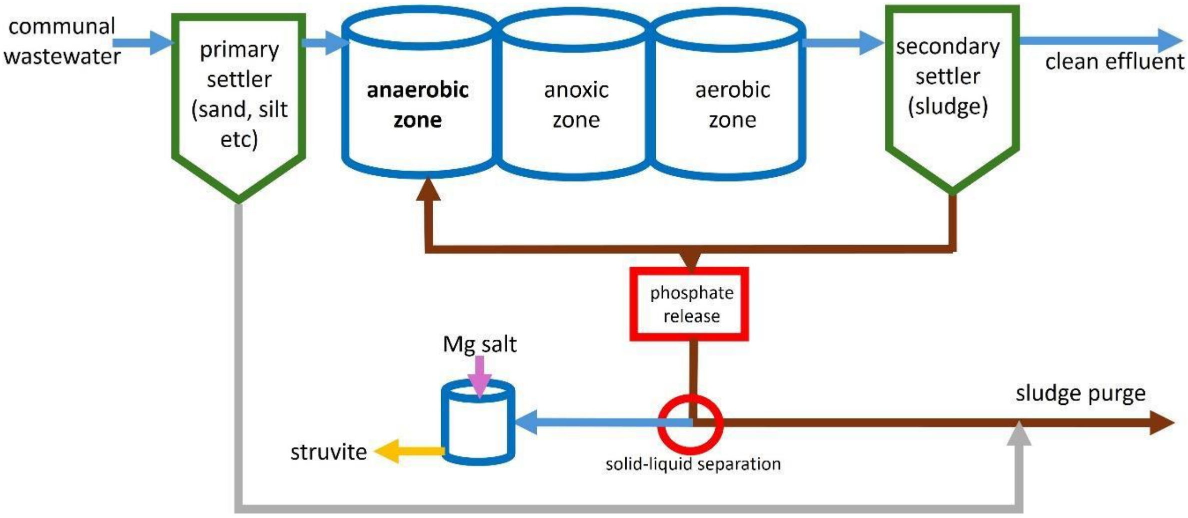
However, in communal wastewater, there is usually more phosphate present than that required by the bacteria. To remove this, the final step of the WWTP is a precipitation of phosphate using iron salts. This process makes the phosphate insoluble and helps remove fine organic matter by agglomerating it into bigger particles. The formed solids join the main bacterial sludge. Aluminum salts may also be used. Local regulations necessitate the use of this step when needed. For example, if the effluent flows into a sensitive or protected area that needs protection from nutrient influx, this step is necessary, but if the effluent is discharged into the sea or surface waters not particularly sensitive to nutrients, it can be omitted. An estimated 20% of WWTPs worldwide include the third stage.

The sludge is settled by gravity in large tanks to separate it from the effluent. This is a major operation because sludge is light and tends to be very spongy-it retains a lot of water. Sometimes, settling is not sufficient to meet effluent norms and further filtration-type steps are necessary for the water before it can be discharged. The water content of sludge, when purged, is very important to transport cost and influences the energy balance in incineration. Sewage operators strive for the highest possible content of solids. Purged sludge is often digested anaerobically to reduce its mass, and allows for improved dewatering and removal of odor. It is then dewatered using centrifugation or a filter press. However, it is still quite wet, with typically only 21%-24% of dry solids.

The digested and dewatered sludge can then be sent for application on fields, or to further processing such as incineration.



Standard WWTP



EBPR WWTP

Fig 1 A typical WWTP and an Enhanced Biological Phosphorus Removal (EBPR) variant (characterized by the presence of an additional anaerobic tank). EBPR is shown with struvite recovery. Note: a large number of varieties exist; here, only a basic and typical configuration is shown, leaving out many details.

The output of the WWTP is a purified water stream that is ready to be discharged or reused. Its organic, nitrogen, and phosphate content are much reduced. If phosphate removal is present, the phosphate content, expressed as P, is mostly below 1 mg/l in European countries (local legislation regulates this - in sensitive environments, it may be 0.15-0.3). This means that most phosphate ends up in sludge - typically 80%-90%, sometimes even more. Dissolved metals such as copper and zinc also end up there, as do organic constituents not digested by the bacteria. Even without tertiary treatment, the sludge contains 30%-70% of the influx phosphate.

Because its amount is ever increasing, sludge needs to be purged. This purged sludge needs to go to reuse or disposal. Importantly, almost all of the incoming phosphate is contained in it. Dewatering is an important step because purged sludge is often transported via road, and any excess water increases the transport cost. Digestion of the sludge may reduce its weight and water content slightly without changing the overall makeup much; the phosphate content is preserved.

Purged sewage sludge is therefore a prime access point for P recovery.

In an alternative setup, the bacteria undergo a series of stages, typically anaerobic-anoxic-aerobic-the defining feature of this configuration. This causes growth of a bacteria type that accumulates (poly)phosphates. In this case, almost all of the phosphate from the influent, instead of a part, ends up in the bacteria. This setup is called the bio-P or Enhanced Biological Phosphate Removal (EBPR) process. It may not need post-treatment with iron or aluminum, but this depends on its efficiency and the effluent norm. This treatment scheme has become increasingly popular; although a minority of WWTPs use this system, newer ones tend to be of the EBPR type. Such a WWTP has better sludge dewaterability than a traditional WWTP, which is a major advantage to save transport and disposal costs.

The bacteria release most of their phosphate in a side stream at the WWTP when subjected to anaerobic conditions. This can be in the digester or in a dedicated tank. When the sludge bacteria are removed by centrifugation or a similar separation step, a small water stream relatively concentrated in phosphate is obtained. This forms another entry point for phosphorus recovery.

EBPR has mainly been implemented in the US, Europe, and Australia (5%-20% of WWTPs depending on the region).

Many varieties of WWTPs exist, depending on different climates, influx characteristics, effluent limits, land costs, technology providers, and available funds to operate purification. Nevertheless, in the end, all WWTPs produce a sludge containing a noticeable amount of phosphorus.

Table 1 Worldwide estimated phosphorus contents in sewage in 2024 (see text below for an explanation of the columns).

	Minhab	excr gPpppd	other estd	kt/y P	sewage conn	leakage	Pto sewage kt/y	Third stage impl%	Pto sludge kt/y
Europe	750	1.5	10%	456	84%	25%	287	65%	218
North America	400	2	10%	324	84%	25%	204	30%	127
Central America/MX	200	1.2	15%	103	50%	25%	39	10%	21
LatamCar	450	1.5	20%	308	50%	25%	115	10%	62
Subsah.Afr	1200	0.8	15%	412	25%	25%	77	2%	39
MENA	500	1.2	25%	292	65%	25%	142	25%	85
C+SAsia	2200	0.8	20%	803	50%	25%	301	5%	157
SEAsia	700	0.8	20%	256	30%	25%	57	10%	31
China	1400	1	10%	568	65%	25%	277	50%	194
JP/KR/TW	250	1.5	10%	152	90%	25%	103	75%	82
AusNZ	30	1.5	10%	18	90%	25%	12	85%	10
Oceania	15	1	15%	6	7%	25%	0	0%	0
TOTAL	8095			3699			1616		1027

Table 1 attempts to summarize the amounts of phosphorus (as P) ending up in sewage sludge in different regions. The table assumes negligible contribution from other sources since phosphate-containing detergents have been largely phased out (with Middle East/North Africa -MENA-, South Asia, and Sub-Saharan Africa being exceptions to some extent). Data have been aggregated from various sources [1-4] and contain some interpolations and extrapolations. Whereas this is by no means a definitive table, it provides a general perspective on the amount of phosphate available for recovery.

Columns 2, 3, and 4 list the numbers of people per region, the estimated excretions per person per day (in gram P), and the nonhuman-derived input estimates, respectively. The totals (in kt/y P) are listed in column 5. Human excretion is taken to be in equilibrium for adults. The average person accumulates 600--700 g of phosphate while growing, equaling 1-2 years of (non)excretion, which is considered insignificant in this approximation. Diets with higher levels of processed food tend to contain more phosphates (especially in North America and lesser so in Europe). More plant- and fresh-produce-based diets lead to lower P excretions. For this reason, excretion varies with region. Likewise, non-human-derived P estimates vary with region along with the implementation of phosphate bans for detergents (the main other source). The non-human contribution is based on aggregated data (e.g., see [6]) from various contributions, including those from surface runoff, food waste entering sewers, minor sources such as toothpaste, and residual/continuing use of phosphate-containing laundry and dishwasher detergents.

Columns 6, 7, and 8 contain the sewage connectivity (meaning households connected to a central treatment system, not to septic tanks), the amount of sewage leaking from pipes before it reaches the WWTP, and the total amount of sewage flowing into the WWTP, respectively. The weighted average of sewer connectivity in this calculation is 54% worldwide, which closely matches the UN number of 56.9% [1]. Column 9 indicates the proportions of WTTPs with third-stage phosphate removal, where the P removals in WWTPs without and with the addon are taken as 50% and 90%, respectively, and Column 10 lists the total amount of P ending up in sewage sludge, a potential entry point for large-scale recovery.

We note that out of 30 million tons of P mined worldwide, 3.7 million tons ends up in wastewater via excretion and other ways and 1 million tons ends up in sewage sludge (28% of wastewater).

Residual use of phosphate-containing detergents may add 5%-10% to the total content. Industries linked to communal systems may add a similar amount (see 1.2.2).

It should be noted that in rural settings, septic tanks or targeted local defecation are quite common, where the excretions are used for fertilizing fields locally. This forms a short reuse cycle that is outside the scope of this assessment, so the total amount of human-excreted P directed to reuse is considerably higher.

To validate this approach, we take an alternative calculation route. According to the EPA [7], about 7 Mt/y of sludge is generated in the US, expressed as dry matter. Using the general numbers of 25% ash content and 15% P_2O_5 in such ashes (6.5% as P), there is about 115 kt/y of P in sewage sludge. Correcting for the inclusion of Canada (for the total of North America) by multiplying this by a factor of 1.1 we end up at 126 kt/y of P for North America, which is close to the 127 kt/y value presented in the table.

In this approach, we do not assess sludges for recyclability. Sewage sludge from WWTPs without additional phosphate removal will be less rich in phosphate and thus not as suitable for phosphate recovery as those with richer sludges.

1.2.2 Industrial wastewater treatment

Many types of industries include a form of wastewater treatment. This is a very diverse sector that is too large to describe in detail here but a few major categories can be described:

Wastewater treatment at industrial parks, often of the biological type, is usually like that at an urban WWTP but with likely a larger and more intensive chemical stage that can include additional precipitation. Some large industrial parks include phosphorus chemistry operations, and sludge produced at such industrial parks contains an appreciable amount of phosphate, albeit usually in lower concentrations due to the influx of large amounts of other chemicals.

Industrial wastewater may be fed into communal WWTPs. For example, in China, 35% of WWTPs receive a form of industrial wastewater [4]. In other cases, such as the Wallonia region of Belgium, industrial wastewater is deliberately disconnected from communal WWTPs since the 2020s. However, the industries involved often operate their own WWTPs. A few examples in this regard are highlighted below.

Recycling versus Recovery

In wastewater treatment, focus was traditionally on removal of phosphate to meet effluent limits. However, the way phosphate is removed affects the potential to put it to use again. Processes under development need to make a clear distinction between making something that the process outputs versus something that the market needs. As an example, wastewater P removal rests on making P water insoluble, but the German recycling directive asks for it to be plant-available at the same time, which is virtually impossible. A certain degree of processing is needed between the stages of phosphate removal and reuse. Processes yielding non-standard materials will need to fight their way into the market; at the same time, large-scale implementation is not feasible because of the lack of a clear market perspective. Producing drop-in market products is a significant advantage for processes. Having to develop a market for a nonstandard product is a major challenge and not easy without access to large-scale piloting or a full-scale plant. The latter will not receive investment without a clear market perspective, so this is a serious quandary.

Potato and vegetable processing industries produce significant amounts of phosphate-containing wastewater. The treatment universally includes a washing stage, which normally sees appreciable amounts of phosphate being dissolved into the water. Potato processing uses sodium acid pyrophosphate to prevent purple-grey discoloration of the potatoes, which also joins the wastewater. The WWTP must deal with higher concentrations of organics and phosphate but less of the other contaminants than urban WWTPs. The setup is comparable and sludge is produced continually.

Likewise, dairy processing sees a lot of phosphate being released to the wastewater of the plant. A biological WWTP like that found in potato plants is usually present.

These food processing sludges are more likely to be used in direct fertilization because they do not contain heavy metals, drug residues, PFAS, or pathogens present. Some large processors harvest struvite, a phosphate mineral, separately (see 2.2).

Many industries, e.g., those involved in metal treatment, produce phosphate-rich wastewater streams without organic components. Large-scale pig and cattle rearing may also be associated with phosphate-rich effluents. These undergo a site-specific form of physicochemical treatment such as precipitation, with no biological treatment step. These cases are outside the scope of this study.

Other industries with phosphorus rich waste streams include:

- Phosphorus derivatives production may generate wastewater in the processing chain. Large industrial parks usually have their own WWTP with a similar setup as that of a communal one, with lower but still noticeable phosphate content
- Seafood processing wastewaters and sludges contain significant amounts of phosphate
- Grain processing to biofuels, corn syrup, and liquor involves organic phosphorus (such as phytate) and may generate phosphate-rich wastewaters

Phosphate fertilizer production usually is a net user of water, so wastewater from such facilities is rare.

Some industry sectors normally have a dedicated WWTP; others feed into the communal system. This makes quantification quite difficult.

A rough quantification may be approached as follows:

A large potato processor in The Netherlands reduces its phosphate discharge by 80% in its dedicated WWTP [8, 9]. It is quoted to be of a capacity of 150,000 or 250,000 inhabitant-equivalents, which would correspond to 80 or 135 t/y of P (the equivalents could also refer to organics or nitrogen). It produces 400 t/y of struvite [8] or 1000 t/y [9] - these data may differ because municipal wastewater is also treated; this amounts to 135 or 270 t/y of P, respectively. Even with conflicting figures, it is seen that a large potato processing plant produces P in the order of magnitude of 100-250 t/y. With 47 such plants in Europe [10], this sector produces 10-25 kt/y of P. Similar levels are expected in North America and to a lesser extent in Latin America.

One of the largest potato processing plants in Europe produces 4400 t/y struvite [11], which is indicated to be a wet material (18% dry matter) - this represents 700 t/y struvite with 100 t/y P.

Looking at Table 1, wastewater P from potato processing in the EU and North America is 10-20 times lower than the amount of communal P.

Phosphate loads are in the 10-100 mg/L range (as PO_4), and annual discharges are typically several hundred thousand to one million or even a few million m^3/y.

Dairy processing gives comparable phosphate loads to wastewater [12], but the amounts of wastewater are on average smaller, typically a few hundred thousand m^3/y, so roughly 2-4 times less in terms of phosphate - typically a few percent of communal phosphate loads. Dairy processing plants see a similar geographical spread as potato processors but would include South Asia as a significant region.

Several other processes may contribute minor amounts, varying with region.

In conclusion, it appears that the combined phosphate load to industrial wastewater lies between 5% and 20% of the amount found in communal wastewater.

1.2.3 Alternatives to WWTPs

Even though the WWTP described above is universally accepted nowadays and more than half of the world's population is connected to a form of centralized treatment, several other forms of excrement treatment exist or have been proposed. A brief inventory includes the following:

- Traditional rural settings, where in an ideal case, human excretions are collected and reused locally - an efficient form of reuse but not suited for larger communities and cities. Open defecation is mentioned by the WASH (WHO-UNICEF) database [1] as significant in certain geographies, e.g., sub-Saharan Africa. Toilets in rice paddies in East Asia also constitute a direct nutrient cycle.
- New alternatives to sewage, such as dry/separate urine collection: Many small-scale initiatives have been proposed or implemented, e.g., at festivals. The rationale is to skip the existing sewage system, which is indicated to be wasteful and expensive. In Japan, P recovery has been tried from local, rural treatment facilities serving a small area (Johkasou, a decentralized treatment unit).

Separate large-scale sewage systems, based on separative toilets but using the existing infrastructure. This allows the collection of a small, concentrated urine stream containing 70%-80% of the phosphate in excretions.

Often, the goal is to use the recovered nutrients locally.

Proponents and opponents of such alternatives can be vocal about their respective standpoints. Avoiding a full discussion, a few facts are highlighted here to provide some context:

Even though the existing sewage system is huge, expensive to maintain, and uses pumping energy, it does use a simple means of transport: water. Any alternative system (except separative sewerage) will involve road transport of excrements by a tanker to a processing facility, a fact that is sometimes overlooked. However, the use of water is much lower.

The present sewage system is not inefficient for phosphate removal. The solids formed upon tertiary phosphate removal (mostly iron phosphate) are completely water insoluble, and their formation is not strongly affected by dilution of phosphate in a large water stream. The chemicals used are often very cheap.

Doubling the existing sewage system is expensive, maybe prohibitively so; maintenance and keeping it leak free are major challenges. Also, urine systems tend to form struvite, so blocking over time by the formation of scaling in the urine piping is a real risk.

Urine collection at large sources, such as festivals, can allow access to relevant amounts of concentrated nutrients, increasing their application potential. Also, newly developed cities and areas lend themselves for rethinking classical sanitation.

Any short cycle from local collection to be used in city agriculture, gardens, etc. brings about the risk of recycling multiresistant bacteria, toxic substances (e.g., excretions from chemotherapy patients), and inappropriate discharges into toilets (paints and oils). The risk of contamination is larger than in traditional cycles via WWTPs, especially compared to cases where sludge incineration is implemented, which destroys such components.

Any split in treatment, e.g., going for the low-hanging fruit in the form of struvite, brings about the possible loss of phosphates in the remaining stream, which may become too diluted to be recoverable. For example, separating urine will leave only 20%-30% of the original phosphate in the sewage sludge (which needs to be formed anyway), the volume of which will not change a lot, so recovery becomes much less attractive. The existing system recovers about 90% of phosphate, an efficiency that is hard to improve.

Wastewater treatment with algae instead of bacteria has been proposed but is still in an early stage of development. It is unclear what benefits algae would bring compared to bacteria - dewatering of the sludge is also difficult, and impurities will accumulate in much the same way as in bacterial sludge. It is unclear if phosphate removal would be more efficient (but EBPR solves this) and if/how phosphate can be recycled in a targeted way.

2 - Recycling from a WWTP

2.1 Direct Sludge Application as Fertilizer

Excess sludge purged from a WWTP needs to be placed somewhere. It is an appreciable volume, tens of thousands of tons per year (depending on the WWTP size of course). Table 1 explores the yearly amounts corresponding to worldwide regions.

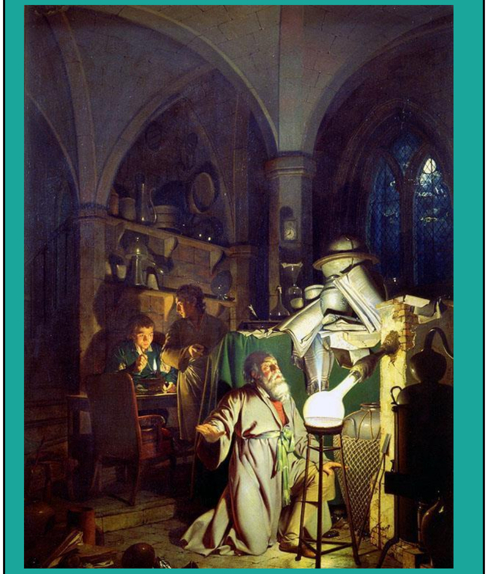
This sludge consists of about 20%-30% solids; the rest is water. All sludge used in agriculture has undergone digestion and may be subjected to further composting, which is a form of sanitizing.

Applying sludge to agricultural fields increases the organic and nitrogen contents and the moisture retention capacity of the soil, which may be an advantage in drier climates and for soils that tend to dry out quickly - this functionality is often called soil improvement. The organics and nitrogen in these organics act as fertilizers. However, multiresistant bacteria, drug residues, toxic organic substances like PFASs, and heavy metals (e.g., copper and zinc) also form part of the package, most prominently in urban and industrialized environments. Especially on vegetables such as spinach and lettuce, direct contact cannot be avoided; this poses a small risk to food quality. Sewage sludges from rural areas, without industries or hospitals linked to the sewage system, may be more amenable to direct application. This also applies to dairy and potato treatment sludges.

The plant availability of the phosphate content in sludge may vary. Precipitated iron phosphate cannot be expected to act as an efficient fertilizer, being water insoluble, but EBPR sludge contains biologically bound phosphate, which may be easier to access for plants. Plant availability can also be influenced by additions to the sludge. How far direct sludge application to fields is efficient as a recycling route for phosphate is the subject of debate [13].

Not a New Idea

The recycling of phosphorus from human excreta is not new. In 1669, Hennig Brandt of Hamburg, an alchemist in search of the legendary Philosopher's Stone, heated his urine with charcoal and accidentally produced white phosphorus. This was the first time an element was made that does not occur natively on Earth and marks the birth of modern chemistry.



Joseph Wright of Derby, The Alchemist Discovering Phosphorus (1771/1795)

Beyond consideration of the exact benefits and disadvantages of sewage sludge, its disposal is costly and associated with a negative value.Processers, whether farmers or sludge incinerators, collect a gate fee. This may differ with sector and drives the sludge management system to its various end points to some extent.

Regional differences are large for direct sludge application. In some countries, it is banned completely (e.g., The Netherlands) or largely (Germany), whereas some countries (e.g., France) see it implemented on a large scale, actively supported by farmers. In the US, it is allowed, but the risk associated with it causes many farmers to restrict access to fields for up to a month to avoid any risk of contact with the public. It is also the prime subject of a book on how to spin unfavorable subjects in a positive way in the public relations industry [14]. Dairy and potato processers in Europe ban the use of sludge on fields for farmers delivering to their processing units. Lawsuits have also been won for contamination of properties by sludge [15], and a company selling sludge as a fertilizer alternative was sued successfully for damage caused by strongly elevated PFAS levels in the sludge [16]. PFASs, widely found in sewage sludge, have caused Maine (where 88 of 120 tested farms were found to have PFASs on their fields) to ban sewage sludge in agriculture as the first US state [17], with the US Environmental Protection Agency looking into the matter [18]. Meanwhile, Alabama and Virginia continue to encourage and expand the use of sludge as a fertilizer, without testing the PFAS content. A phaseout of PFASs in sectors where environmental spread is likely (e.g. as co-formulants in crop protection agents, or in extinguishing foams) would remedy this but might be hard to achieve on a short term.

The EU allows and encourages the agricultural use of sludge, but there are strict regulations to ensure that it is used safely and that soils and ground water do not get contaminated [19].

In China, agricultural use of sludge is minimal except in a few provinces, with landfill dominating and incineration locally the most common option, especially in the south and east [3].

Japan has implemented extensive incineration capacities. Direct application to land is minimal.

An estimate of the application of sludge in large geographies with significant sewage treatment installed is given in Table 2.

Table 2 Sludge uses in key geographies [3, 4, 7, 20]. NA = North America

	LAND APPLICATION	**LANDFILL**	**INCINERATION**	**OTHER**
NA	56%	27%	16%	**1%**
CHINA	None	56%	40%	**4%**
JAPAN	None	None	70%	**30%**
EU	**55%**	**10%**	**27%**	**8%**

In geographies such as South America and MENA, data are more difficult to obtain. For Brazil, agricultural uses are mentioned, whereas in countries such as Morocco, the management of sludge is underdeveloped, leading to more or less formalized forms of landfill [21].

Countries questioning the safety and effectiveness of this route shift toward sewage sludge incineration - Chapter 3.

Besides being applied to agriculture, arguably a form of phosphate recycling, sewage sludge is also used as a fuel on a large scale in cement works. Its heating value is low; even though the solids have a considerable energy content, water evaporation from the sludge consumes most of this energy during burning. Using waste heat to (pre)-dry the sludge can remedy this problem and is increasingly implemented, thus greatly increasing the fuel value of the sludge. As dry matter, sludge contains 10 to 17 MJ/kg, slightly below organic materials like wood or straw.

Due to the biological origin, using sludge as a fuel decreases the use of fossil fuels and thus has a benefit in reducing cement kilns' CO_2 footprint. The sand, iron, aluminum, and calcium in the sludge are useful additions to cement. Unfortunately, its phosphate is not a useful component, and it ends up fatally diluted in cement. This route, still widely practiced, is an unsustainable way of sludge processing from a phosphate viewpoint and a sustainable way from a CO_2 footprint/energy viewpoint, indicating a difficult tradeoff. Some countries like Germany, Austria, and Switzerland are ending such routes by making phosphate recycling mandatory by the end of the 2020s [22]. Selective extraction of phosphate from sludge will allow beneficial results for phosphate and energy recovery. Such technologies exist (e.g., see the use of vivianite below) but currently do not achieve very high recovery rates.

Separate incineration of sludge gives access to an ash rich in phosphate - see Chapter 3. If done properly, the energy of incineration can be recovered and used for various purposes (e.g., industrial or district heating), also leading to a net reduction in the consumption of fossil fuels.

For sludge gasification and pyrolysis, see 3.2.

Sludge is also landfilled, but this is claiming large areas and has an associated risk of spontaneous fermentation, leading to methane emissions, a powerful greenhouse gas. It may also pose a health risk because of accumulation of pathogens, and leach PFASs. In the US, it is usually landfilled together with household waste [7].

In the past, sewage sludge was dumped in oceans, but this has been largely banned by international treaties because of environmental concerns (e.g., in the US in 1988).

2.2 Struvite and Calcium Phosphate Recovery at WWTPs

In EBPR-type WWTPs, the presence of dissolved magnesium, phosphate, and ammonium causes spontaneous precipitation of a mineral called struvite, $NH_4MgPO_4 \cdot 7\ H_2O$. Reasons include locally much higher phosphate concentrations (not found in standard WWTPs) and pH increase due to localized conditions. This can completely block various pipes around the WWTP in months, needing regular shutdown and expensive cleaning. Using the tendency of struvite to precipitate from parts of the EBPR system, recovery units have been set up to precipitate struvite in a controlled way by adding dissolved magnesium (on top of the existing natural level) to complete struvite precipitation. The EBPR phosphate release section (see 1.2) provides a suitable stream for that. Typically, magnesium is dosed in a controlled way to a stirred vessel, where struvite is suspended as small- or medium-sized particles. New struvite settles on the existing material preferentially. Part of the formed particles are purged constantly, keeping the system in balance.

The advantages of this setup are many:

- Avoidance of scaling and blocking in the WWTP - cost reduction and less downtime
- Better dewaterability of sludge - another clear cost advantage for the WWTP operator
- Clean and predictable product - hardly any impurities enter struvite
- Locally produced material that acts as a controlled-release fertilizer
- However, there are some disadvantages:
- This only works with EBPR or in noncommunal settings such as food and manure processing
- Only part of the total WWTP phosphate can be recovered - 3%-25%, or 45% in extreme cases involving thermal sludge treatment under pressure (lysis) [23]; the WWTP still makes sludge in which the remaining phosphate is more diluted, and recovery from it may become unfeasible
- The struvite has been in contact with wastewater and is not guaranteed to be totally clean and sterile (compatible with application on fields), even though the risk is much smaller than for direct urine or sludge applications [24]
- Struvite is a controlled-release fertilizer and increasingly used in compound fertilizers, but is not water soluble like many fertilizers used today, so its market needs to be developed
- Fine struvite tends to be moist and incorporates residual sludge, making valorization hard-impossible; granular struvite is much easier to apply

Many technology providers for struvite with different technical setups are found in the market, but most of these systems are based on a fluidized-bed-type precipitator. The product form also depends strongly on the specific technology, from fine particles forming dense sludge to well-dewatered pellets of 2-5 mm. The latter can be blended directly with compound NPK fertilizers and are more readily sellable.

Examples of technology suppliers with multiple installations built include Ostara (Pearl), NuReSys, Paques (Phospaq), AirPrex, Colsen (Anphos), and Suez (Phosphogreen).

The Ostara company provides a full package for the WWTP operator, including the takeback and sale of struvite pellets at premium prices, which unburdens the WWTP operator - these are usually not experts in selling fertilizers themselves. However technology license fees apply.

Struvite precipitation uses modest amounts of energy for stirring (strongly depending on reactor type) and requires the use of a source of magnesium, which can be magnesium chloride, magnesium oxide, or magnesium hydroxide, sometimes available as low-cost byproducts from magnesium mineral processing. The water also needs to be adjusted to alkaline conditions, which may require sodium hydroxide addition. Magnesium salts can be relatively costly compared to iron chloride and can add 100-200 USD/t cost to struvite formation.

Struvite can be added to compound fertilizers, or used as such. The N:P ratio is much lower than in standard fertilizers, and struvite is mainly a phosphate fertilizer for that reason. It releases its phosphate under the influence of rain, weathering, and plant roots, and can also be applied as a standalone product. Applications on grass (e.g., on golf courses) are increasingly popular, and controlled-release fertilizers are a growing niche in agriculture.

Markets vary a lot with location and appearance - granular struvite has a relatively high-value market, but sludge-type fine struvite can be unsellable and may need to be fed back into purged sludge. In that case, struvite technology benefits the operability of the WWTP, but no separate product is generated.

Its value ranges from zero to a dollar per kg, depending on the region and quality. Some technology providers include a guaranteed buy-back scheme as part of their technology licensing package.

As struvite technologies keep being rolled out, a market is seen to emerge slowly. Whether it will grow beyond a (considerably sized) niche application remains to be seen.

The Mg content can in some cases add to its value if Mg is needed as a secondary nutrient in fertilizers.

Struvite precipitation may also be applied in treatment of potato processing wastewater or agricultural wastewater, such as piggery effluents (e.g., see [25]).

2.3 Other Options for WWTPs

A variant of struvite recovery involves precipitation of calcium phosphate in a fluidized bed. This process works from the same side streams as struvite precipitation, uses similar equipment, and only works in EBPR WWTPs. An example in The Netherlands involved a Crystallactor reactor which was added to a full-scale urban WWTP. The unit operated for 20 years before shutting down [24]. The unit was expensive to operate because of its need for heavy dispersion of the pellets (pump energy) and consumption of caustic soda. Several units were installed in dairy plants, however. Calcium phosphate is more difficult to precipitate in a controlled way (risk of excessively fine precipitate), and calcium source dosing is less convenient than magnesium salt dosing. Calcium phosphate has not seen major scale implementation, even though it gave a quite pure product, which was valorized in the production of elemental phosphorus [59].

Straight precipitation of calcium phosphate has been tried in some cases, but it yields a very fine precipitate that is hard to settle and dry.

Recovery of hydroxyapatite (a form of calcium phosphate) in conditions comparable to those in struvite recovery is seen predominantly in Japan, e.g. in the Heatphos process (see below).

Calcium phosphate can serve as a rock phosphate replacement in traditional processing (e.g., the production of phosphoric acid, white phosphorus, or superphosphates) and has a comparable value. In acidic soils, such as those in rice fields in Japan, it can also be used as a direct fertilizer.

When sewage sludge is digested, an operation aimed to reduce its weight and increase its dewaterability, anaerobic conditions prevail. This causes iron (III) in the sludge to be reduced to iron (II). The amount of Fe (II) also depends on the exact layout of the sewage works, which may contain anaerobic zones, and the level of iron dosage. This causes the formation of an iron (II) phosphate, vivianite(Fe3(PO4)z·8HzO), which is present as very fine particles. This compound is paramagnetic and can therefore be removed with a high-field collector magnet from the sludge slurry. Sludge entrainment is prevented by pulsating the sludge, which allows sufficient separation of the particles. The Vivimag process makes use of this method. If sufficient iron is present, up to 90% of phosphate can be captured as vivianite, but the yield can also be lower than 50%. Recovery rates of 80% vivianite from the sludge have been reported [27]. Together, the likely overall P recovery rates are 50%-60%.

As iron phosphate/vivianite is currently not an actively produced material, its market is limited and needs to be developed. Vivianite can be added in small amounts to compound fertilizers that combat iron chlorosis (iron deficiency in plants), which is prevalent, e.g., in the calcareous soils around the Mediterranean; it can also be reprocessed into phosphoric acid and an iron precipitation agent for WWTPs. Because it is quite pure and well defined, separative recovery processes may work on it more efficiently than on incineration ashes.

The separation process is best suited to WWTPs using iron as the phosphate precipitant. However, iron is present as Fe^{2+}, where most separative processes can only, or preferably, deal with Fe^{3+}, so a form of oxidation will be needed - for the solid phase, or after acid digestion, which is probably easier because the iron is in solution.

Calcium silicate hydrate (CSH) can be used to absorb phosphate from wastewater (e.g., the Terranova and P-Roc processes use this method), giving a mixed calcium phosphate-silicate. Terranova indicates a large pilot operation in China and smaller ones in Europe.

2.4 Other Direct Sludge Processes

A process, Extraphos, was developed by Chemische Fabrik Budenheim [28] to extract phosphorus from sludge with pressurized carbon dioxide (6 bar) at slightly elevated temperatures. By expanding the carbon dioxide to atmospheric pressure and removing it from solution (allowing to run it in a cycle) and providing a source of calcium, dicalcium phosphate is formed at 70% efficiency (in/out). The process was never developed beyond the pilot stage. It had an encouraging LCA.

All information about Extraphos was removed from the Budenheim website, indicating that further development is unlikely.

Processes to release phosphate from sludge by using mineral acids have been piloted, such as the Stuttgart process [29-31], but were never commercialized, presumably because of their high operational costs, which are more than an order of magnitude higher than the price of P in fertilizers when expressed per ton of P. This likely concerns the use of acids and precipitants for, e.g., struvite formation, and possibly the expected issue of what to do with the acid-degraded organic components of the sludge. The presence of phosphate as phytate or phospholipids likely poses a challenge to release it with mineral acids. Yields of up to 65% were reported.

The Heatphos process (developed in Japan) uses heating of EBPR sludge to about 70^{o}C, which releases most of the phosphates stored in the bacteria. These are then precipitated as calcium phosphate by adding calcium chloride without the need for any pH adjustment. Energy for heating can be obtained from biogas generated in sludge digestion, which is indicated to be more efficient after the Heatphos treatment.

3 - Sewage Sludge Incineration and Similar Processes

3.1 Sewage Sludge (Mono) incineration

If agricultural use of sewage sludge is banned, landfill is banned or costly, and use in cement works is discouraged, the obvious disposal route for sewage sludge is monoincineration. For clarity, this chapter refers to dedicated sludge incinerators (monoincinerators), unlike sludge co-incineration with household waste or use as a fuel in cement works.

In a sewage sludge incinerator, the sludge is first dried, e.g., on a perforated moving belt (in most cases using the offgas of the process) and then incinerated on a grate or in a fluidized bed. The sludge adds to the heat of the process because its organic components are incinerated, but sometimes a support with a natural gas flame is needed. Hot flue gases are used to dry the sludge and then undergo a series of gas treatment steps to remove pollutants. These include sulfur dioxide-trioxide, nitrogen oxides (NO_x), dust, dioxins, and heavy metals. Even mercury, present in minute amounts, needs to be scrubbed. NO_x removal is performed in a separate section, but some of the other components can be scrubbed together. This is conducted either by absorption into water in a spray tower or by absorption onto activated carbon and/or calcite in a dry bag filter unit, which are injected as powder into the gas stream.

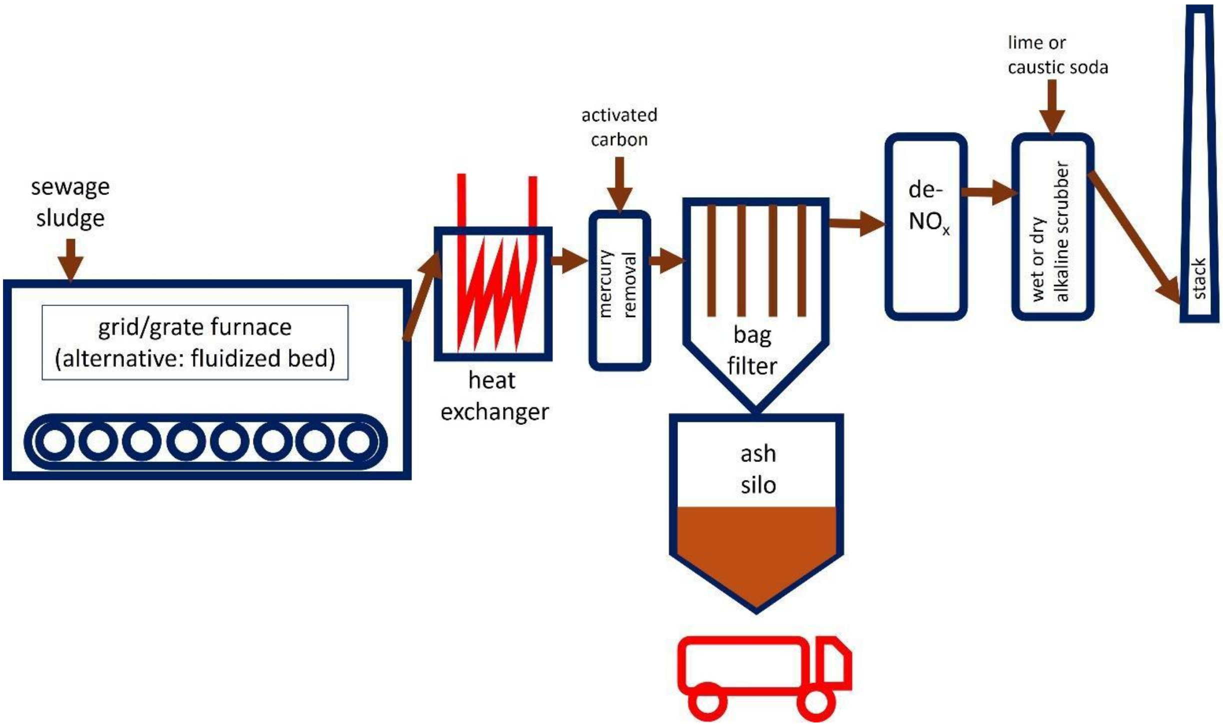


Fig 2 Sludge incinerator and flue gas treatment, typical scheme – many varieties exist.

The advantages of sludge incineration are the following:

- Formation of a dry, fine phosphate-rich ash, an industry-compatible material (at least judging from its physical characteristics)
- Central, large facilities enabling large-scale ash treatment
- Modest energy recovery - the sludge has a fuel value, but it is largely spent in driving off the contained water (typically, a large sewage incinerator produces 10-20 MW of power, depending on design, and low-pressure steam)
- Removal/destruction of all drug residues, bacteria, and organic toxic substances (but not the heavy metals, which mostly end up in the ash, with a very minor fraction going to the gas treatment)
- No phosphate losses

The disadvantages are the following:

- Costly equipment, including a large multistage offgas scrubber
- Loss of organic compounds and nitrogen (fertilizing and soil improving components)
- Heavy metals join the product (but can be removed in downstream processing)

Monoincineration infrastructure already existed before phosphorus recycling was developed, with the ashes mostly going to landfill, or used as an asphalt filler. Both routes are associated with a considerable negative value (gate fee), around 50-100 €/t ash depending on local conditions. This fact drives many business cases and allows for relatively complicated processing to take place. How long this situation will remain once phosphate recycling is rolled out on a large scale is to be seen.

Sewage sludge monoincinerators are increasingly installed in, e.g., Germany (see Figure 3; [34]), but locally agricultural use dominates, e.g., in the Hannover area.

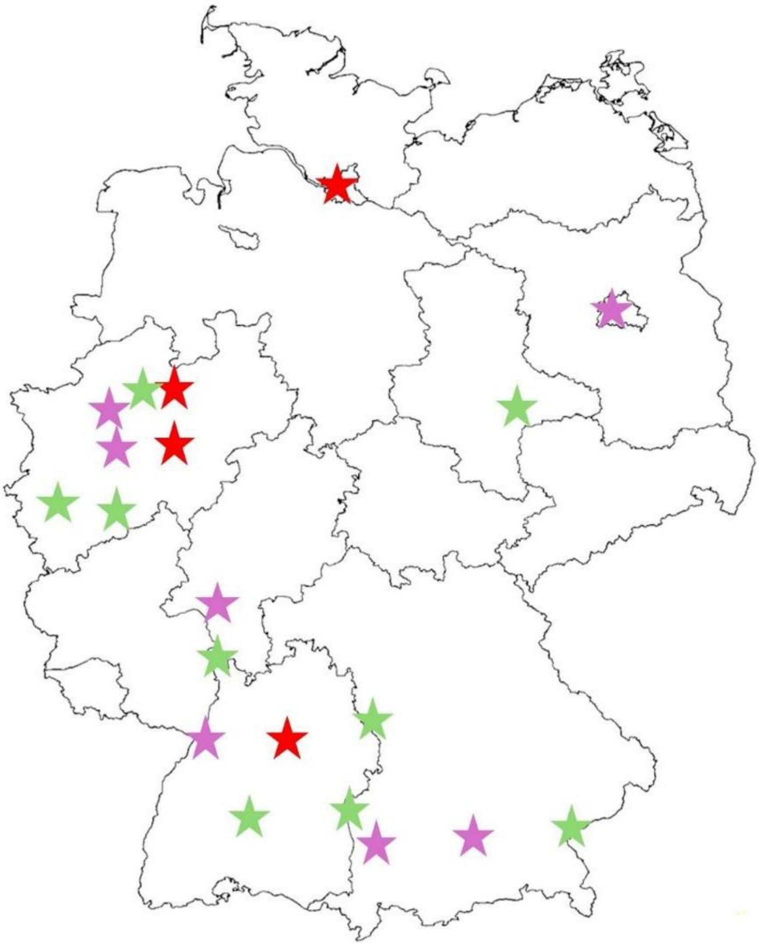


Fig 3 Sewage sludge monoincinerators (communal sludge) in Germany [adapted from 32]. Red: >40 kt/y ash. Purple: 20–40 kt/y ash. Green: <20 kt/y ash.

The Netherlands and Switzerland have almost completely converted to incineration after bans on agricultural spreading. In Switzerland, the canton of Zurich is leading in this regard, covering 20% of the country's population. In The Netherlands, two incinerators cover most sewage in the country, equaling about 5 kt/y P.

Outside of Europe, Japan sees widespread implementation of sludge incineration. Some US and Canadian cities have installed incineration (see below). Expectations are that China will also go down this route in the future.

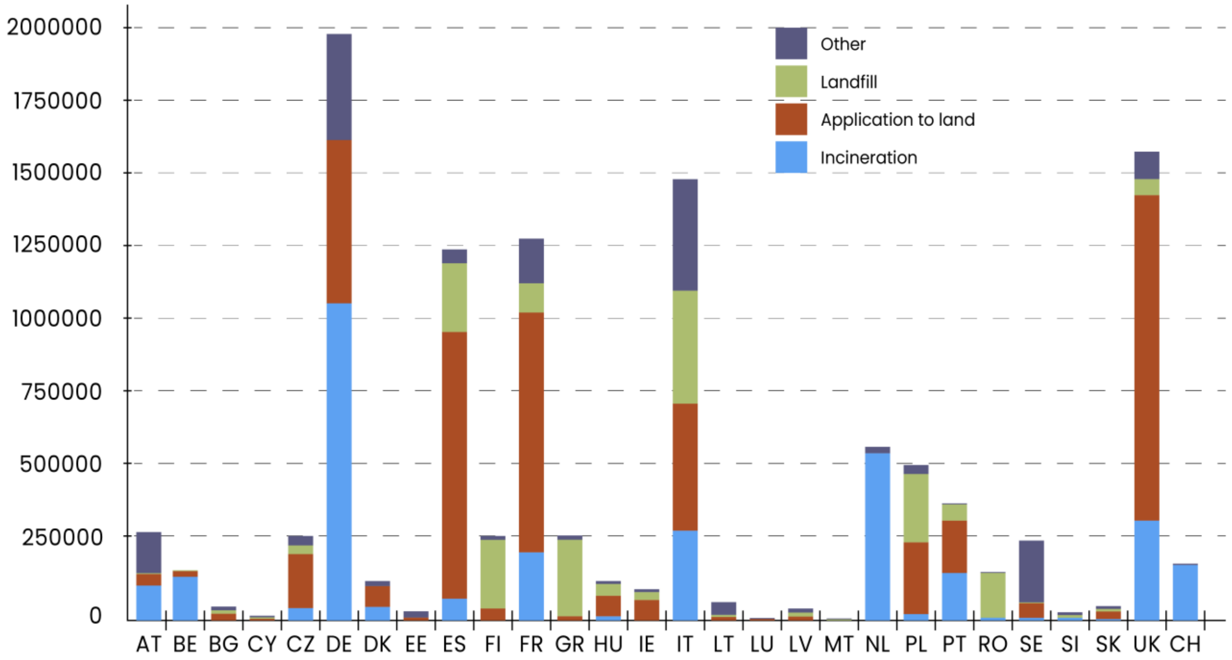
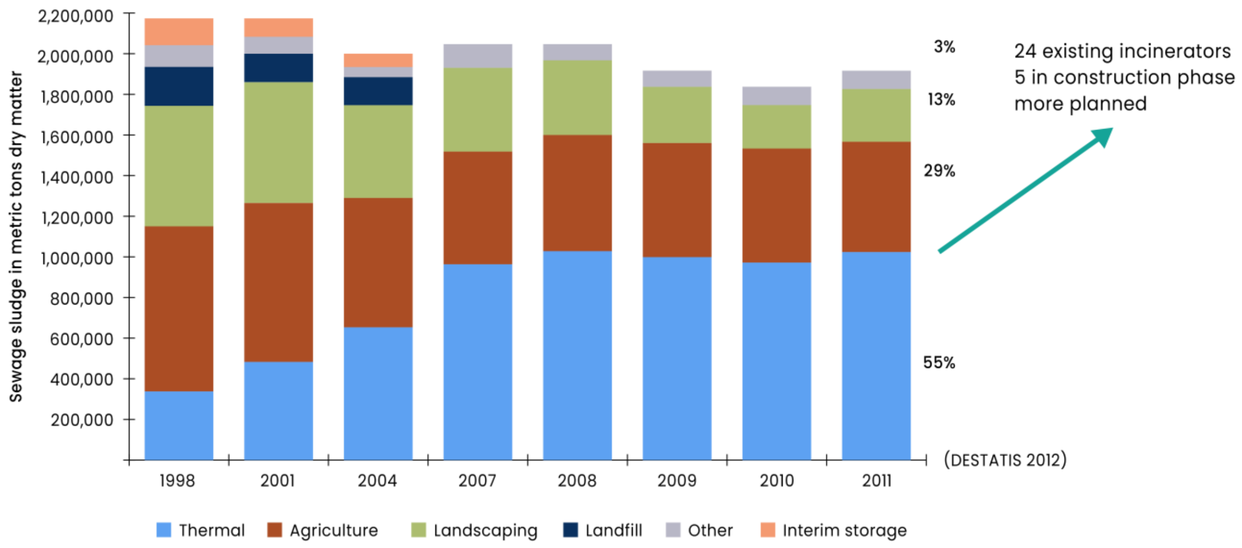


Fig 4 European sludge routes, 2011.

Sewage sludge routes in Germany – time development



source: P-REX

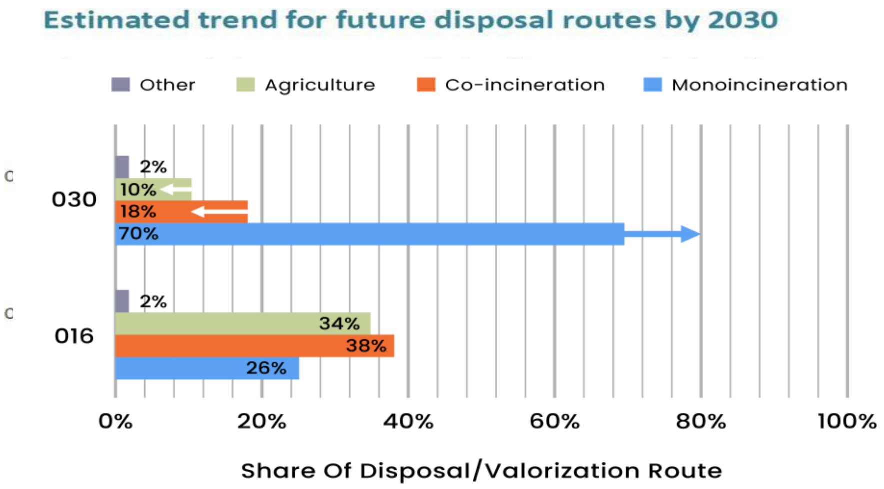


Fig 5 Sewage-sludge disposal routes, Germany, 2011 and projection up to 2030 [33].

In Germany, at the time of writing about 55% of sludge is monoincinerated, with about five more monoincinerators planned or under development. Co-incineration and monoincineration are gradually replacing agricultural spreading. The federal government recycling directives area distinctive driving force towards further monoincineration.

Sewage sludge ash is a major entry point for phosphorus recovery, and many technologies depart from it.

In Europe, there is currently 500000 t/y of sewage sludge ash, with 45 kt/y of phosphorus (as P). By 2030, this is set to more than double by new incineration capacity coming onstream from, for instance, Bielefeld-Herford and Cologne, Germany [34].

In Japan, 70% of sludge is incinerated (with a minimum standard for energy recovery), 10% is composted, 5% is used in cement works, and 5% is used in "melting" (likely the Kubota process; see Chapter 5). Notably, 90% of the population is connected to sewage, and 1.65 Mt/y of sludge (as dry matter) is produced. This means that 300 kt/y of ash is produced with about kt/y P_2O_5 (25 kt/y P) [35].

In Montreal (Canada), sludge is incinerated to give a significant 47 kt/y of ash, of which 26% is used as a direct fertilizer; this proportion is intended to increase to 80% by 2030 [36]. A form of treatment may be necessary in the future.

Further large sludge incinerators exist in, e.g., St Petersburg, Russia [37].

3.1.1 Ash composition

Even though ash is an industry-compatible material, it differs in a few essentials from the fossil source of phosphate, so-called phosphate rock, mainly calcium apatite - $Ca_5(PO_4)_3F/OH$. Sewage sludge does contain calcium phosphate, but it also contains very major amounts of iron and aluminum.

The ash phosphate content can be affected negatively by incinerating industrial sludges with communal sludges - the former are often poorer in phosphate.

A typical sewage-sludge ash composition is given in Table 3.

Table 3 Typical composition of sewage sludge ashes (ranges observed, aggregated from various sources) compared to a standard commercial phosphate rock. Components are expressed in constituent oxides, as is usual in the industry. Weight percentages unless otherwise noted.

COMPONENT	PHOSPHATE ROCK	SEWAGE SLUDGE ASH
P_2O_5	30	**12-23**
SIO_2	1-10	**5-35**
CAO	42-52	**10-20**
NA_2O	<1	**1-2**
K_2O	<1	**0.5-2**
AL_2O_3	0.3	**3-25**
MGO	0.3-1	**1**
FE_2O_3	0.1-1	**4-23**
SO_3	0.5-7	**1-4**
CL	0.05	**0.1**
CU MG/KG	2-15	**600-1200**
ZN MG/KG	20-150	**1200-3000**
CD MG/KG	1-20	**<10**
U MG/KG	**20-300**	**<10**

Apart from the much larger percentages of iron and aluminum found in sewage sludge ash, the presence of copper and zinc is noticeable. Although these are micronutrients in certain types of fertilizers, their presence is well in excess of requirements for such fertilizers, and often higher than EU fertilizer regulations maximum level, which cap Cu and Zn at 600 and 1500 mg/kg, respectively. The ash also contains minor amounts of chromium, nickel, arsenic, and lead. Each ash is different, depending on what is connected to the local sewage system (see 4.8). A high silica content in ash might lead to difficulties during its processing. In contrast, cadmium is virtually absent from ash. Cadmium is considered, particularly in Europe, as a major problem in fertilizer manufacture from phosphate rock, which contains this toxic metal in small but significant amounts. Taking into consideration the precautionary principle, the EU tends to limit the content of cadmium allowed in fertilizers, currently at 60 mg per kg of P_2O_5. Phosphate rock also contains uranium, which is absent from ash. Another difference is the absence of fluoride in ash; in rock processing, it presents an additional challenge because it may form scales and tends to evaporate from reactor vessels. This necessitates a gas scrubber on the exhausts (allowing fluoride recovery in some cases). Such measures are not needed in ash processing.

Aluminum and iron levels are seen to vary a lot in sewage sludge ashes. This is caused by the type of third stage phosphate removal in the WWTPs feeding their sludge into the incinerator. The salt may be iron or aluminum chloride. The latter could be economically viable if a local source of aluminum solution waste is available.

It cannot be said that sewage sludge ash is free of heavy metals, but it does provide a virtually cadmium-free source of phosphates, which is a major in advantage in regions with limits on cadmium content in fertilizers. As discussed, the EU imposes a maximum of 60 mg/kg P_2O_5 on fertilizers, where P_2O_5 is an industry standard to express phosphate content. Not all phosphate rocks allow this limit to be met.

In a mineralogical sense, most phosphate is of whitlockite type, $Ca_9Fe(PO_4)_7$. Iron phosphate is significantly converted to calcium phosphate and iron (hydr)oxide under the influence of heat generated in incineration [38]. Next to that, sand (silica, SiO_2) is present in significant amounts. If flue gases are treated with solid calcium carbonate, it will also end up in the ash, partially after decomposition to CaO [39].

Standard processing of phosphate rock to fertilizer-grade phosphoric acid is done by dissolving the rock in sulfuric acid. This gives phosphoric and calcium sulfate (gypsum). The latter is virtually insoluble in phosphoric acid and can be removed by filtration. This separation relies on the insolubility of gypsum in the phosphoric acid product, which allows to remove the calcium from the process. The phosphate is almost exclusively bound to calcium, so the separation to give phosphoric acid is very efficient.

Because of the large amounts of iron and aluminum in sewage sludge ash, this route cannot be employed, given that iron and aluminum sulfate are very soluble in phosphoric acid Separation of iron and aluminum is too incomplete to give a reasonably clean phosphoric acid, at least in water based technologies, which are commonly applied.

For this reason, a great number of specific ash processing methods have been developed, which deviate from the standard processing route.

Processing of this ash can be done in two principally different ways:

- By digesting the ash with an acid, followed by separative steps, giving multiple streams each containing a subset of the ash contents
- By changing the nature of the ash by means of additions or thermal treatment, with most or all ash components ending up in the final product

These technologies are explored in Chapters 4 and 5.

3.2 Wet Oxidation

In this process, an alternative to incineration, sludge is oxidized in water by oxygen under mild pressure at about 200°C. The result is a moist cake, much resembling sewage ash. Onward processing in wet processes can be envisaged without drying. A single full-scale plant using the so-called Athos process [40] has run for two decades in Brussels, but not without problems, e.g., those caused by sand abrasion. The Aqua Reci process also derives from this process [31] with additional extraction by acid on the wet solids.

The main advantage of the method is that it avoids the need for an expensive (construction and operation) flue gas scrubbing section. However, it does consume pure oxygen (not free, unlike air) and needs costly pressurized equipment.

Its output is similar to sewage sludge ash but with moisture present.

3.3 Sludge Pyrolysis and Gasification

Sludge gasification and pyrolysis is a minor processing route, although several pilots exist and several full-scale plants are operating. Typically, sludge is dried and then subjected to heating under exclusion of oxygen, or a limited amount of that. The product of pyrolysis is termed sewage sludge biochar. Gasification may yield an ash-type residue with some carbon left.

The providers of these technologies generally claim that the phosphate in ash made under the exclusion of oxygen, or with limited oxygen ingress, is more plant-available than that in ash from straight incineration, even though it may be baked into the char structure. Char, if present, may add to the fertilizing properties and improves soil moisture retention.

An advantage compared to incineration is the absence of an expensive offgas treatment system or the construction of a much simpler version.

The output of these processes is usually indicated to be a product, not an input for further processing.

Without debating the fertilizing value of such products or the validity of plant-growth pot trials to test them, these fertilizers remain unorthodox products that need a marketing development cycle. For that, typically, multi-ton amounts are needed, which are hard to access without a full-size production unit. Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) registration in Europe may be a hurdle. Meanwhile, the investment in such a large unit will only happen if full confidence in the existence of a market is present. This quandary makes full-scale implementation of such processes difficult.

Technology descriptions sometimes ignore or underestimate the energy needed to dry the sludge. About three quarters of the sludge is water, which needs to be driven off before it can be incinerated. In incineration, the fuel value of the sludge solids is sufficient to do that, but in processes that do not incinerate the organic sludge content fully, the associated energy may be inadequate, and the process may need considerable heat inputs. Technology providers are not particularly forthcoming to provide details about this aspect. Also, formation of tar and other sticky deposits in a plant may pose a challenge.

Biochars may find use in steelworks as climate-neutral "biocoke", aiding them to reach climate-neutrality targets. The associated phosphate is lost and cannot be recovered in that case.

Pyrolysis and gasification produce a fuel gas, the valorization of which (e.g., as a fuel for a nearby chemical plant) may be part of the business model or used onsite.

Pyrolysis is known to generate not just gases but also oils and tars which can accumulate in the installation. A pilot operation [42] was indicated to suffer from operational issues.

The fate of organic pollutants such as PFASs and microplastics remains to be seen in such processes, but these should be destroyed if sufficient temperatures are reached, e.g., 500°C.

The Pyreg process [41] pyrolyzes sewage sludge to a carbon matrix, which incorporates ash-like particles rich in phosphate. The process yields a fuel gas that is incinerated separately to drive the drying and pyrolysis stages of the process. Its offgas scrubbing is less costly and complicated than that of a regular monoincinerator. The product is a nonstandard fertilizer/soil improver that probably needs separate market development. The technology supplier indicates that the phosphorus is plant-available without providing details.

The Charlene-ReCord process combines slow pyrolysis with washing and leaching of the phosphate in the char. This allows separate processing of the phosphate and P-depleted biochar.

Processes with pyrolysis or gasification integrated with a further form of P recovery are treated in the Thermal Processes section.

Some processes using this concept include the following:

- Karlsruhe gasification [42]
- MePhrec [43]
- EuPhoRe (followed by incineration) [44]
- Pyreg [41]

3.4 Cement Works

Sewage sludge is often used as a fuel in cement works. This causes the ash (phosphate) to become locked up in cement. Separate onsite incineration has been considered but has not been implemented on large scales.

4 - Wet Separative Ash Processing

Wet processing of ash has seen a proliferation of technologies since the early 2000s, with most efforts taking place in Japan and Europe.

This chapter does not strive to give a complete overview of all existing processes but rather highlights several main categories.

These processes share that the phosphate matrix in the ash is exposed to a mineral acid, chiefly sulfuric acid or hydrochloric acid. This dissolves part or all of the metals (iron, aluminum, copper, and zinc) in the ash as well and creates a suspension in a liquid of insolubles; much of the follow-up processing is aimed at further separating the phosphate and the metals.

Some processes [38] employ dissolution of the ash in the process output, phosphoric acid, but that's just an intermediate stage; the ultimate source of the acidity employed is still sulfuric acid or hydrochloric acid. When using sulfuric acid, solid gypsum is formed, optionally with an external source of calcium. The use of hydrochloric acid normally requires additional steps to remove the calcium chloride dissolved in the product; this is soluble in phosphoric acid, unlike gypsum and in full analogy to iron and aluminum salts described above.

The nature of the acidic attack determines if any metals go into the solution as well. A full-blown digestion in a strong mineral acid at an elevated temperature - the most extreme case - will release not only the phosphate into the solution but also all other metals (Fe, Al, Ca, etc.), leaving only sand as the insoluble. Because the dissolved metals will have to be removed at a later stage, it is advantageous to have a form of "softer" leaching that leaves some metals in the solids. For instance, by using phosphoric acid as the leaching medium, a large part of the iron (chiefly in the form of free iron oxide-hydroxide) is unaffected by the acid and stays in the solids, which is a major advantage.

Using phosphoric acid for digestion and then adding sulfuric acid allows to separate out the ash insolubles before gypsum is formed in the next stage. This will enhance the prospects of using gypsum in plasterboards, instead of landfilling it.

Recovering the released iron and aluminum salts (chlorides and sulfates) for sale as precipitants and coagulants can add to the business model. Aluminum salts have additional higher-value applications if recovered separately.

These ash-based processes may also work on other materials, such as meat-and-bone meal (MBM) ashes, vivianite, and struvite. Single, relatively pure compounds such as vivianite would be easier to process compared to ashes, but these processes need scale to be affordable, so working on small streams may not be economically feasible.

A few examples of processes are provided that employ these main categories of conversion.

4.1 Tetraphos

Tetraphos was developed by Remondis (Germany), one of the largest handlers of waste in Europe, which includes wastewater, sewage sludge, and various ashes. The process is based on mild digestion of sewage sludge ash in phosphoric acid (which is also the product and partially runs in a loop). The advantage is that it puts only a minor part of the iron in the ash into the solution. Calcium is leached for a major part. Heavy metals remain largely in the solid residue (copper, nickel, cadmium, chromium, and lead); no data for zinc are provided, but it is expected to remain there too.

The solids are filtered off, washed, and sent to recycling, e.g., to the construction industry as cement additive.

The phosphoric acid containing, e.g., dissolved calcium, is subjected to sulfuric acid addition, which precipitates calcium out as gypsum while providing the ultimate source of acidity in this process. The gypsum is filtered off and dried. Its purity is such that recycling into plasterboards is possible.

The resulting acid is now stripped of its major impurity, calcium, but still contains minor levels of iron and aluminum. These are removed by ion exchange (IEX). The resulting purified phosphoric acid is partially returned to the digestion section. The surplus, equaling the freshly formed phosphoric acid, is then concentrated in a vacuum evaporator. Preferably, this uses waste heat such as that found in a sludge incinerator.

The product is indicated to be 99% pure with some traces of iron remaining. This allows high-end technical applications such as metals etching and possibly some specialty fertilizers.

The P yield of the process is above 80%, a typical value for many such processes and the legally required minimum for phosphate recycling in Germany, where it will become mandatory by 2032 at latest.

The IEX resin is periodically regenerated with, e.g., hydrochloric acid, giving an iron-aluminum chloride solution which can be used in a WWTP to precipitate phosphate, completing the cycle.

The process is currently at technological readiness level (TRL) 9, one of the highest TRLs in the field, in Hamburg, Germany, where it is integrated into a WWTP and sludge incinerator. The technology is foreseen for public-private partnership and various business models but has not seen further implementation at the time of writing.

Its economics are chiefly driven by variable costs:

- Sulfuric acid
- Hydrochloric acid
- Heat
- Ash (usually a gate fee)

- Insoluble revenues or cost
- Gypsum revenues
- Valorization of the Al-Fe salt solution
- Phosphoric acid revenues

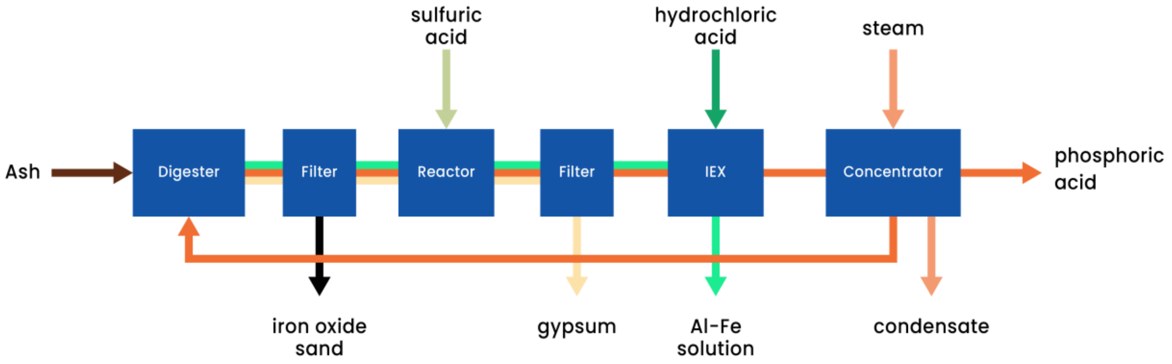


Fig 6 Tetraphos process.

4.2 Prayon Ecophos Loop Process

The Prayon Ecophos Loop Process (PELP) [45] was developed by the company Ecophos. After its bankruptcy in 2018, the process was acquired by Prayon, who further developed it and offers it in their phosphoric acid portfolio, which also includes classical, sulfuric acid-based fertilizer-grade acid processes and dicalcium phosphate production processes.

The process is divided into different steps/modules aiming to produce phosphoric acid of technical-grade quality and aluminum chloride and iron chloride products that can be used for water treatment.

The process is modular, including the following steps:

- Digestion - Ash digestion in diluted phosphoric acid: by choosing the right conditions, dissolution of phosphate is achieved while limiting the digestion of heavy metals (see also Tetraphos). Most of the impurities of the ash are retained in the solid residue (including heavy metals and a significant part of iron) and separated from the phosphate solution by pressure filtration.

The residue is washed and neutralized for landfill.

The obtained solution then undergoes three IEX purification steps:

- First IEX step to remove calcium, potassium, magnesium, and sodium. The resin is then regenerated with a hydrochloric acid solution, and a solution of calcium chloride is obtained. This can be disposed of or valorized.
- Second IEX step to remove iron. The second resin is then regenerated with hydrochloric acid, and an iron chloride solution is obtained. This solution can be

concentrated to provide a coagulant-precipitant for e.g phosphate in wastewater treatment.

- Third IEX to remove aluminum. The resin is then regenerated with a hydrochloric acid solution, and aluminum chloride is obtained, which is a coagulant/precipitation agent for, e.g., phosphate in wastewater treatment.

The resulting phosphoric acid can then be recycled to the digestion unit, with the excess undergoing concentration to give pure phosphoric acid, which is in the company's product portfolio. The process includes integration of HCl streams between the different purification stages to reduce its consumption.

All P-containing side streams are returned to the process to maximize the yield, which is typically higher than 95%.

A pilot installation exists in Bulgaria to operate the different process units separately or in sequence. The company plans further investment into a larger-scale pilot unit.

The PELP process is offered commercially by Prayon, but no implementation announcements have been made until the time of writing.

The advantages of the process are the following:

- Known products, phosphoric acid (distributed by Prayon, a known supplier of this material), $AlCl_3$, and $FeCl_3$
- Flexible for different ash types
- High phosphorus yield (>95%)

Its disadvantages are the following:

- Relatively complicated process with more steps than usual
- Relatively high energy consumption
- Dependence on cheap hydrochloric acid and cheap energy
- Production of calcium chloride; the plant needs to be built at the seaside for discharge of the calcium chloride brine, or in other locations allowing brine discharge

Its economics are chiefly determined by variable costs:

- Use of hydrochloric acid
- Energy consumption (for evaporators)
- Disposal cost for sand-iron oxide solids
- Revenue from sewage-sludge ash offtake
- Phosphoric acid, aluminum chloride, and iron chloride revenues

The operator indicates that the plant needs to be large enough to reduce the fixed cost and the CapEx (expected minimum 70kt/y ash). This is quite typical of most recycling processes that only can be implemented sensibly at large scales to dilute the investment.

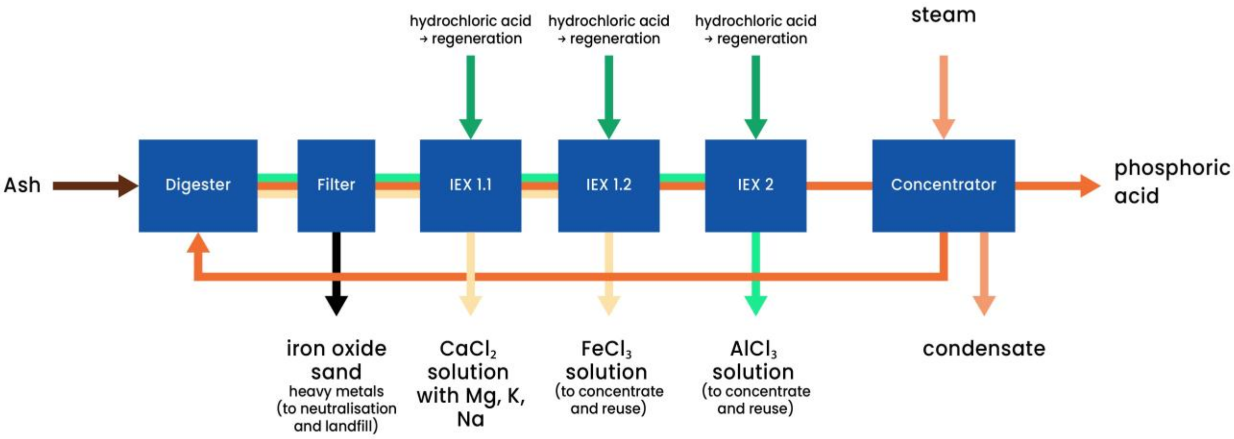


Fig 7 Ecophos process.

4.3 Ash2Phos

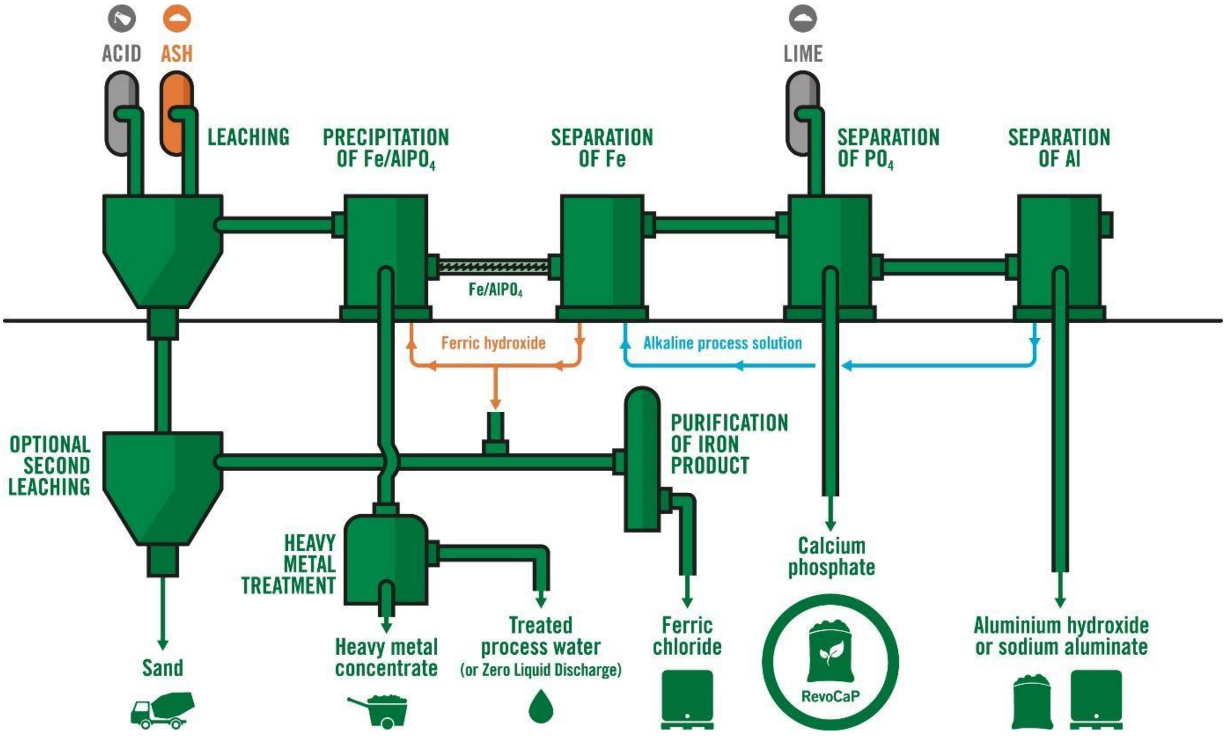


Fig 8 The Ash2Phos™ process (courtesy of EasyMining)

A variant of hydrochloric acid digestion is the Ash2Phos™ process, developed by EasyMining (Sweden). Also here, the ash is digested with hydrochloric acid, leaving much of the iron and all the sand in the insoluble fraction, which is filtered off, washed, and used in construction.

From the filtrate, aluminum, phosphate, and iron are separated and precipitated as solids by pH shifts, eventually (after further treatment) leading to iron chloride, pure calcium phosphate and aluminum salts (aluminate or aluminum hydroxide).

The product (called RevoCaP™), a noncrystalline calcium phosphate, is offered on the market as a direct fertilizer, with an indicated high plant availability (80% neutral ammonium citrate soluble). It also meets the purity specifications (e.g., those by the EU) for use as feed phosphate and is indicated to have the same digestibility for livestock as the standard feed-phosphate product, monocalcium phosphate.

The effluent - now stripped of the iron, aluminum, and phosphate and comprising chiefly calcium chloride - is treated by precipitating and filtering off heavy metals. The remaining liquid is discharged or concentrated and valorized. The heavy metals are landfilled but can be valorized at a later stage, when volumes have reached market relevance.

(Heavy) metal removal is >95%, meaning that the phosphate is pure.

A full-scale plant is being developed in Schkopau, Germany by Gelsenwasser and Easymining, to be commissioned in 2027.

The advantages of this process are the following:

- Iron chloride as a sellable coproduct in sufficient strength (allowing reuse at the WWTP)
- Aluminum salts are valorized separately
- Known phosphate product, widely applicable

The disadvantages are the following:

- Local settings govern availability of attractive hydrochloric acid, but this ends up in the iron product in the end as a revenue
- Calcium chloride effluent may limit location choice

The economy is mainly governed by variable costs:

- Hydrochloric acid cost
- Lime cost
- Ash gate fee
- Calcium phosphate revenues
- Iron chloride and aluminum salt revenues

4.4 SusPhos

A specific variant of this type of process is the SusPhos process [48]. In the first stage, ash is acidulated by mixing it with pure sulfuric acid, without water. The result is a near-dry somewhat sticky mass-containing phosphoric acid and calcium-iron-aluminum sulfates, like a single superphosphate. The phosphoric acid is extracted from the solid mixture by adding an organic solvent, which is subsequently boiled off using only a minor amount of energy compared to that required for evaporating water, yielding phosphoric acid. Most of the zinc and iron remains in the solid residue, and the acid is indicated to be suitable for fertilizer manufacture. As with other sulfate-based processes, the residue can be used as an additive in cement manufacture.

No public data are available on energy use, but the heat of evaporation of simple organic solvents is three to eight times lower than of water, so evaporation-concentration should be significantly less energy consuming.

The first full-scale plant is under development, to be realized by 2027. About a third of the investment is covered by subsidies, underpinning and supporting the viability of the technology.

The yield is indicated to be above 80%.

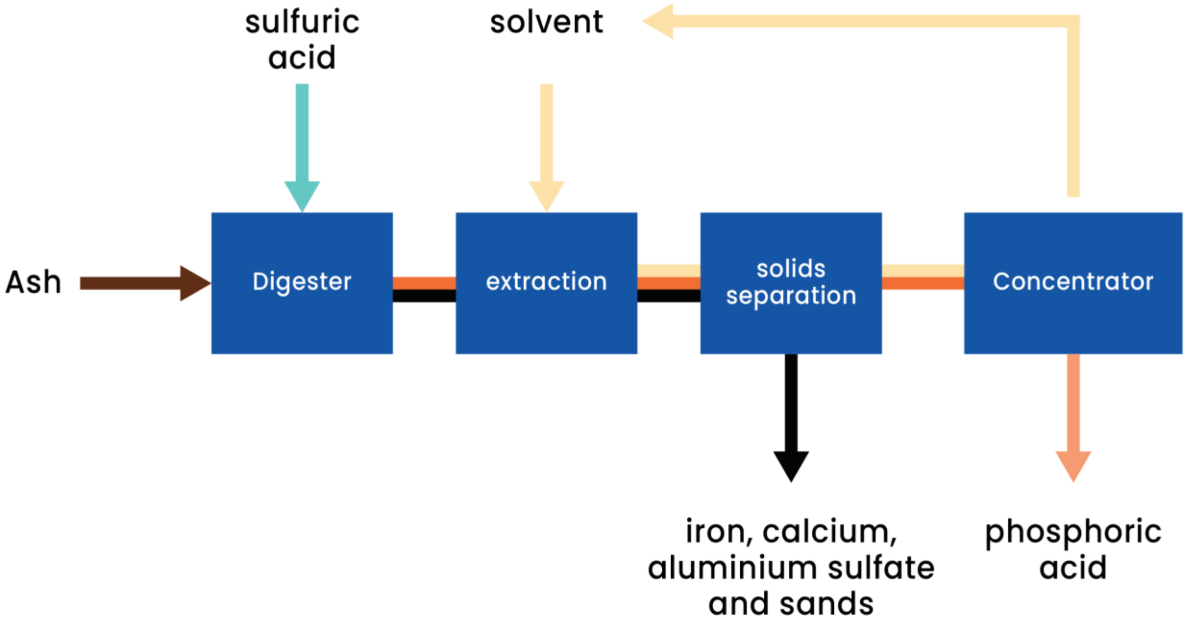


Fig 9 SusPhos process.

Advantages of the process include the following:

- Less steps than in water-based systems
- Higher degree of process-inherent purification (i.e., purification is an effect of the process step, not a targeted extra purification step); many impurities are retained in the solids, including most of copper and zinc
- No need for energy-consuming concentration steps from watery solutions
- Just one solid byproduct containing everything except the product acid; if this is valorized, the process becomes quite straightforward

Disadvantages include the following:

- Use of flammable solvents needs more expensive Atex equipment (but there are less process steps)
- Relatively large volume of byproduct, but this is indicated to be valorized by the operator, so it is not a disadvantage

4.5 Other Acid-Based Processes

Other varieties based on the HCl or H_2SO_4 motif include Leachphos, Phos4Life, REALphos, and Parforce. Phos4Life [49], a Spanish/Swiss development (Tecnicas Reunidas), uses soft leaching with sulfuric acid (90% P efficiency) followed by solvent extraction to purify phosphoric acid, which is a known technology in the regular phosphate industry to produce feed and food-grade phosphoric acid. Additional treatment with hydrochloric acid and another extraction step gives iron chloride for (re)use as a phosphate precipitant. The underflow of phosphoric acid extraction with the impurities ("raffinate") undergoes precipitation. The solids are combined with the insolubles from the digestion step and can be landfilled or used in construction. The version with iron chloride allows more recycling but is more expensive to build and run.

A full-scale plant for an estimated 30 kt/y ash is being planned. The acid is planned to be used in a triple superphosphate (TSP) unit based on sewage and bone meal ashes as input solids.

Leachphos (originally BSH, now AIK; Switzerland; [50]) also uses soft sulfuric leaching (80%-95% P dissolved) followed by addition of caustic soda or lime to precipitate a calcium phosphate, which is filtered off. Heavy metals are only partially leached and partially precipitated - the filtrate contains the remainder, which is precipitated under more-alkaline conditions. The fate of leached aluminum and iron is not known, except that some of it ends up in the product. It is also not clear if the process has an effluent.

REALphos (AIK, Switzerland) [50] is likewise based on sulfuric acid leaching, followed by filtration of insolubles with most of the heavy metals. The filtrate is treated with a mercapto-based precipitant to remove the remaining copper and then concentrated to give fertilizer-grade acid.

Concentration and Drying

A constant feature of these separative processes, at least all of those using water, is that they require concentration of the product phosphoric acid (when not reprecipitated). They also produce solids (gypsum and insolubles), which usually need to be dried.

Most processes run in the 20%-25% P_2O_5 range, but commercial phosphoric acid has 55% P_2O_5.

Although equipment, heat efficiency, and solids' moisture content vary, energy use can be estimated as follows:

Taking phosphoric acid from 27% P_2O_5 to 55% (commercial strength) uses about 6 GJ/t P_2O_5 (13.7 per ton of P) of thermal energy at 80% heat efficiency, a normal value for industry.

Drying a wet cake with 40% moisture requires 1.8 GJ per ton of dry solids. This may be necessary for, e.g., gypsum valorisation. The ratio of solids varies per ton of P, but at, e.g., 5 t/tP residue, this amounts to 9 GJ/tP.

In an average wet or dry process, moving parts, offgas fans, and pumps typically use 4 to 7 GJ per ton of P recovered.

In addition, dilute iron and aluminum salt solutions may need similar amounts of energy to make them sellable and transportable over longer distances.

Parforce [51] uses HCl soft digestion and then extraction and/or IEX to remove iron and aluminum, followed by membrane electrodialysis for purification of the phosphoric acid. The product of this step is concentrated to commercial strength. The residue of the electrodialysis is treated with lime to precipitate heavy metals, leaving a calcium-magnesium brine that can be dried to give road salt. A pilot is planned.

TTBS also offers a sulfuric acid leaching-based process (Rubiphos), with additional purification and concentration based on IEX membranes, nanofiltration, and reverse osmosis. Unlike the other processes, it has a filtration residue; in addition, it gives access to iron sulfate as a precipitation agent for wastewater treatment. A pilot is running in The Netherlands.

Both liquid extraction and further advanced techniques such as electrodialysis are capital-intensive operations. Solvent extraction, although mature, is not a trivial process for phosphoric acid, requires a tailor-made setup, and is prone to disruptions if not designed and operated properly.

4.6 Deoxychlorination

The Sinfert process uses a deoxychlorination agent to produce a volatile phosphorus intermediate, which can be converted to organophosphates or high-purity phosphoric acid. It is in an early stage of development, and details have not been made public. Byproducts include iron and calcium chlorides. It provides a novel approach to organophosphorus compounds directly from mineral or secondary phosphates, which can otherwise only be made via white phosphorus (chapter 6).

4.7 Alkaline Leaching

In this process, the ash is subjected to a dilute solution of sodium hydroxide at slightly elevated temperatures. This leaches about 30% of the phosphate into the solution - the yield chiefly depends on the calcium level of the ash, with more calcium leading to lower recovery rates. By keeping phosphate leaching at this level, the leaching of heavy metals is suppressed. These are further fixed onto the residue by adding a ferric sulfate solution. The obtained solution is treated with calcium hydroxide to give calcium hydroxyapatite, which is sold to the fertilizer industry at near-commercial rates.

The residue consists of iron and aluminum (hydr)oxides and sand.

A plant developed by Metawater has been operating in Gifu prefecture, Japan, since the mid-2000s on 700 t/y of sewage sludge ash, producing 230 t/y of apatite [52].

Another unit is operating in the Tottori municipality.

Although no actual cost data are public, the process is indicated to cost only 3% of the total wastewater treatment cost and to be cheaper than the previous ash treatment into bricks. This is in accordance with other estimates (see below).

4.8 General Remarks and Conclusions on Separative Ash Processes

All these separative processes need an outlet for the solids formed as byproducts and potentially one for the heavy metals in a separate stream. The composition of these byproducts comprises iron (hydr)oxides, silica, and in the case of sulfuric acid digestion, iron-aluminum-calcium sulfate. These materials can have cement-enhancing properties [47] or are used as fillers (sand replacement). Even though the actual value of these materials is likely to be very little or even zero, it is crucially important to have an outlet for the solids because these are generated in a ratio of 0.5-1 per ton of ash put into the system. Landfill is costly and undesirable from an environmental point of view, and if the solids contain (partially) soluble compounds such as sulfates, they may not fit leaching criteria for landfills. For this reason, securing an outlet for the solids is crucial, or the process cannot be run.

The separative processes also need a concentration stage. Much like the classical fertilizer acid process, conversions typically take place in an acid with 15%-30% P_2O_5. Commercial strength is 55%-62% P_2O_5, so all processes share a concentration stage, which is energy consuming, at least when water is the solvent. An exception to this are processes that precipitate a solid such as calcium phosphate or diammonium phosphate (DAP), which is actually also a form of concentration but does not give the more versatile product phosphoric acid.

Processes using sulfuric acid in combination with earlier digestion in another acid (phosphoric acid and hydrochloric acid) yield gypsum, which can be sold to the gypsum/plasterboard industry at modest valuation.

Wet processes may have an effluent in the form of a calcium chloride brine, but sulfuric acid-based processes are generally without effluent because they are water consuming. Hydrochloric acid processes take in water with the HCl used, but this is driven off as water vapor in the concentration stage. Processes with iron or aluminum salt byproducts have another outlet for water - these are often sold as (concentrated) solutions. In the few cases (Phos4Life) where an effluent is present, this is treated by physicochemical operations to ensure compliance with local discharge limits.

Air emissions are generally limited to suction on vessels for acidic digestion and concentration. Alkaline wet or dry scrubbing is the standard technology to abate vapors of hydrochloric and sulfuric acids below legal emission limits.

Any such processes rely on the following factors:

- valorization of the product (pure phosphoric acid, technical phosphoric acid, or calcium phosphate) - usually straightforward, as these are drop-in products
- valorization of the aluminum/iron salts (if dilute, transport is limiting)
- disposal of residues (Fe hydroxides, sulfates, sand, and heavy metals) - use as a cement additive is at least not a cost factor; prevent landfill where possible. It seems that most technology providers have solved this

- gate fee, usually achievable for the ashes
- disposal options for calcium chloride brine, if applicable
- energy use if diluted streams need to be concentrated
- valorization of gypsum if generated

Even though it sounds counterintuitive, no two ashes are alike. This has to do with factors such as regional sewage connectivity (number and type of industries connected), the local groundwater quality, the presence of zinc roof gutters, the type of phosphate removal at the WWTP, the amount of sand not captured before the sludge stage in the WWTP, post-treatment such as sludge digestion (which needs additives), and the flue gas treatment in the incinerator (which may add lime). Also, seasonal variation is seen. Phosphate contents in the ashes vary considerably, and ashes from industrial parks may contain lower amounts of phosphate than those from communal ones.

This is not immediately compatible with the need for a constant, predictable product quality. Installations can be made resilient to adapt to such changes, meaning that they will need some scaling. A separative processing plant, more than an inclusive one, is a full-blown chemical installation. Incidentally, a large scale is also needed to support a business case - below a certain capacity, the fixed cost and investment depreciation will weigh too heavily on the business case relative to the product revenues. Therefore, such plants are best built to serve several ash providers in a centralized location, making use of, e.g., the local availability of digestion acid.

A separative process will deal with ash composition fluctuations by varying the amount of the product, not the quality, which gives more predictability on the market side.

5 - Inclusive Ash Processes

In contrast to the processes in Chapter 4, inclusive ash processes give a product that is essentially a converted ash, with most or all of the constituent components still present.

A distinction is made between mixing-type processes and thermal processes. The latter allow for removal of heavy metals, while the first do not.

5.1 Superphosphates

Superphosphates are solid, near-dry mixtures of phosphate and sulfuric acid (single superphosphate, SSP) or phosphoric acid (triple superphosphate, TSP). The acid attacks the phosphate structure and forms monocalcium phosphate, or mixed iron-aluminum-calcium acid phosphates in case of ash.

In the classical setup, the acid is sprayed onto a mass of phosphate in a rotating drum. The material is then discharged and left alone on a pile to mature for about a week ("denning") to allow the acid to react fully with the solids. Such a setup has been used by ICL Amfert (The Netherlands) since the late 1990s to process sewage sludge ash and struvite [53]. In the process, sewage sludge ash (and/or struvite) is added to phosphate rock, making up a fraction of the total. The existing production unit is used to replace phosphate rock, but it has a limit; the increased iron content of the product causes operational issues [55a] and becomes noticeable in the product, which may affect marketability, although the company has announced the ambition (and possibility) to go to 100%. Indeed, it is now selling ash-based superphosphates under its Puraloop brand as a separate product. Because it's not a standard superphosphate, it may require some marketing efforts.

This route may lead to non-negligible zinc and copper levels in the product. This is especially relevant in Europe. Depending on the ash origin, the EU fertilizer regulations limits for these elements may be exceeded (copper, zinc). The straightforward nature of the process excludes any heavy-metal removal. Selecting ashes for their heavy-metal content will alleviate this.

A variant of this process, which used only ash, was performed on full scale for some years in Tangermunde, Germany, but the site has stopped producing.

The process saw a successor in the full-scale Seraplant unit in Germany, which used a wet mixing process followed by spray drying of the slurry to give a type of superphosphate. The disadvantage of this route is that it requires heat input, unlike a straight superphosphate process., to drive off water used in the mixing stage If gas prices spike, the process becomes prohibitively expensive. This led to suspension of the Seraplant operations in 2021 because of the European gas crisis [54], but the company is looking to restart in 2025 [54d]. Also, in this case, heavy metals are not removed. If TSP is made from ash, with a rock-based fertilizer-grade phosphoric acid, the critical impurities in that (above all cadmium) are combined with copper and zinc from the ash, which may affect the market value and legal possibilities to sell it as a fertilizer.

In Switzerland, the project Phosphor26 is planning a superphosphate unit based on sewage sludge and MBM ashes, to be acidified with the output of the REALphos process to give medium-grade TSP, with high-grade TSP obtained with the Phos4Life output [50].

Japanese fertilizer producers are also using this route, such as NPA blending EBPR-derived monoincineration ash with phosphate rock and converting it to superphosphates.

In all purely ash-based cases, the superphosphate is rich in iron and aluminum, unlike regular SSP/TSP. It is more difficult to be sold purely because it is not a standard grade and market acceptance may be lower.

The advantages are the following:

- Uses an existing unit (ICL) and/or a simple process (cheap to build)
- Low chemicals use
- No byproducts

The disadvantages are the following:

- Heavy-metal level unaffected, could be too high in a legal sense; no options to separate
- Nonstandard market product (in the 100% case)
- Energy use if slurried

5.2 Thermal Processes

In this type of processing, the ash is heated, often with minor additives, to achieve two effects:

- Modification of the mineral structure to increase plant availability of phosphate
- Removal of heavy metals by volatilization

The first example of such a process is AshDec [55b], which was developed in the 1990s. Ash is heated to about 800ºC in a rotary kiln, with some sodium carbonate, sulfate, and/or magnesium chloride added. The salts addition causes heavy metals (copper and zinc) to evaporate by forming chlorides or other compounds that are volatile under these conditions. They are scrubbed out of the waste gas, precipitated from the scrubber liquid, and landfilled.

When using sodium, the ash undergoes a mineral modification to $CaNaPO_4$, a phase with more plant-available phosphate. The result is a slow-release fertilizer. Like in the case of superphosphates, iron and aluminum remain in the product.

The product, not a standard fertilizer, needs considerable market development. This, in turn, is not easy if large quantities cannot be accessed. This is an important dilemma; without a market, it is unlikely that investments will be forthcoming, whereas the market cannot be developed without a large-scale facility. The AshDec process has only recently seen implementation (planned). The Rhenania-P project in Altenstadt, Bavaria (Germany), will try a variant on the AshDec process on a large scale [56].

Heating requires considerable energy input. The process can be much more energy efficient when integrated into an incinerator, which delivers ash out of its central incineration unit at suitable temperatures, as is the plan in Altenstadt. Admixing of the magnesium/sodium source at these temperatures may be a challenge.

The Euphore process [44] is a variant on the integrated AshDec process. Sewage sludge receives additives (alkali and alkaline earth metal chlorides or sulfates), which help drive off heavy metals further down the process. The sludge undergoes pyrolysis, after which the formed biochar is incinerated. The plant availability of the transformed ash is indicated to be increased due to a reductive-oxidative treatment in two steps. A full-scale plant with MVV (Mannheim, Germany) is planned.

The Mephrec process [43] replaces a sewage sludge incinerator with additional phosphate recovery in the same process. It uses a shaft furnace in which briquetted dry sewage sludge is gasified with lime and metallurgical coke to yield a phosphate ash melt (which is solidified by cooling) and a fuel gas. Iron is also formed; the operator does not indicate its phosphorus content, but the content is likely to be non-negligible (see 5.3). The process needs to be preceded by sludge drying and briquetting. This stage is likely to consume energy, but the process energy balance is unclear. The sale of the fuel gas is an important part of the business case, which needs to have a high enough fuel value to be of commercial interest. Zinc leaves the process as dust with the offgas. The phosphate product, depleted in zinc, is an unconventional fertilizer that needs market development, like the preceding case. A pilot was operated in Nurnberg, Germany, but after its dismantling, no further announcements were made about the development of this process.

Kubota (Japan) has operated 22 plants around Japan for the high-temperature processing of waste like sewage sludge (ash) [57]. The process involves a high-temperature vertical furnace giving a melt, which is solidified to yield a product like that of the AshDec process (a solid with about the same composition as the input ash, but with changed minerology). Although three units were designed to produce a fertilizer-type product based on sewage sludge, this phosphate rich product is currently applied in the construction industry. This fact implies that it has limited market acceptance.

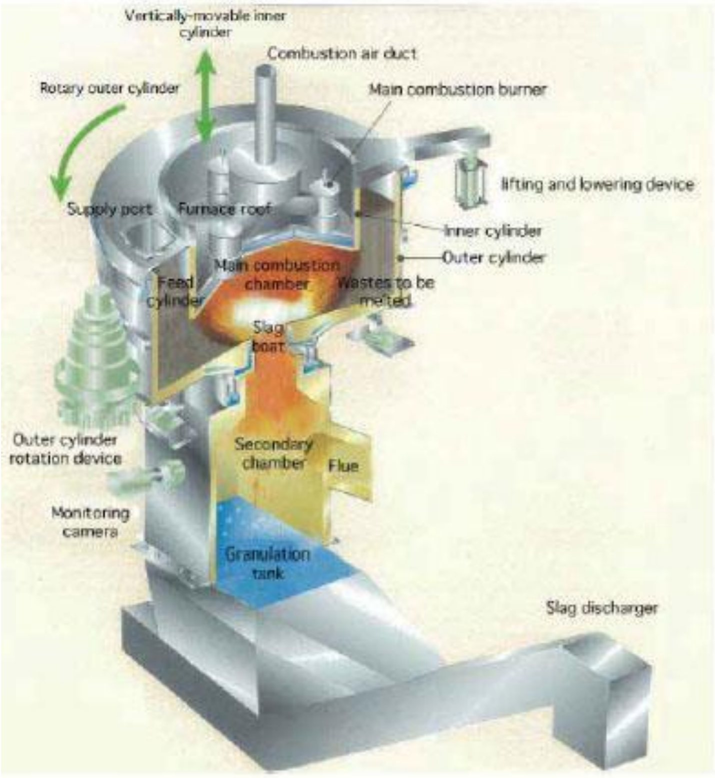


Fig 10 Kubota furnace [from 57].

The advantages of thermal conversion processes are the following:

- Very little waste
- All ashes accepted
- Possibility to remove heavy metals with additives
- Possibility to increase plant availability with additives

The disadvantages are the following:

- Nonstandard product, difficult market development
- High energy use when not integrated
- Relatively expensive to build (high-temperature equipment)
- Not all cases remove heavy metals

No water effluents are usually present, but there is an air emission. An integrated process can incorporate it in the incinerator, but a standalone process will need offgas scrubbing to remove the volatilized heavy metals, fluorides, sulfur di/trioxide, and perhaps NO_x. Like in the case of sludge incinerators, the offgas treatment is a relatively intensive operation. Offgas integration of the incineration and ash treatment stages might be considered.

Standard technologies exist to comply with local emission limits - alkaline wet or dry scrubbing and possibly some form of deNO_x treatment (SCR, etc.).

6 - White Phosphorus

About 2% of the worldwide use of phosphate rock goes into nonfertilizer products that can only be made via elemental (white) phosphorus (P_4) [58]. This includes not only the herbicide glyphosate but also lubricant additives, battery ingredients, and water treatment products. The production of white phosphorus is done by heating phosphate rock (or ash) to about 1600°C in the presence of metallurgical coke as a reduction agent and silica (SiO_2) as a slag-forming agent in a furnace which is electrically heated by passing a current through carbon electrodes that are immersed in the furnace feed. The product leaves the furnace as hot gas, together with the byproduct carbon monoxide. The phosphorus is condensed by water cooling, with the remaining carbon monoxide used as fuel, e.g., to pretreat (agglomerate) the phosphate ore. Nonreduced mineral constituents (calcium oxide) s combine with the silica to form a liquid calcium silicate slag, which is tapped, cooled, and used as a construction material.

Such a process is also possible based on sewage sludge ash. However, the iron content of the ash is also reduced, forming a low-value alloy with phosphorus, called ferrophosphorus. Most sewage ashes have much elevated iron oxide contents (usually in the 10%-25% range) compared to phosphate rock (often less than 1%). The appearance of large amounts of ferrophosphorus depresses the economics of the process, with up to half of the formed phosphorus ending up in the ferrophosphorus.

Nevertheless, several attempts have been made to develop this route: that by the Dutch phosphorus producer Thermphos (active until 2013), which used iron-poor ash admixture into larger amounts of phosphate rock in an existing, phosphate rock based furnace [59]; Recophos (pilot process based on an inductively heated vertical furnace), which indicated to avoid ferrophosphorus (not validated) [60]; and Flashphos [61], a novel fast incineration module for sewage sludge, which involves feeding the ensuing ash melt fed into a traditional phosphorus furnace. This benefits from the heat contained in the melt: the phosphorus process is energy intensive, with traditionally 13-14 MWh of electrical power spent to make the element, a figure comparable to that required for aluminum metal. This can be depressed by up to 30% by preheated ash melt input. However, the presence of iron and the avoidance of ferrophosphorus remains a challenge.

Reduction of phosphate in ashes by means of scrap aluminum metal (thermite reaction; Spodofos process) was recently proposed [62]. The economics revolve around the availability of cheap aluminum scrap and the formation of a higher-value slag due to its increased aluminum content. It needs a minimum amount of reducible oxides (phosphate and iron oxide in the ash) to provide the heat needed to drive the conversion.

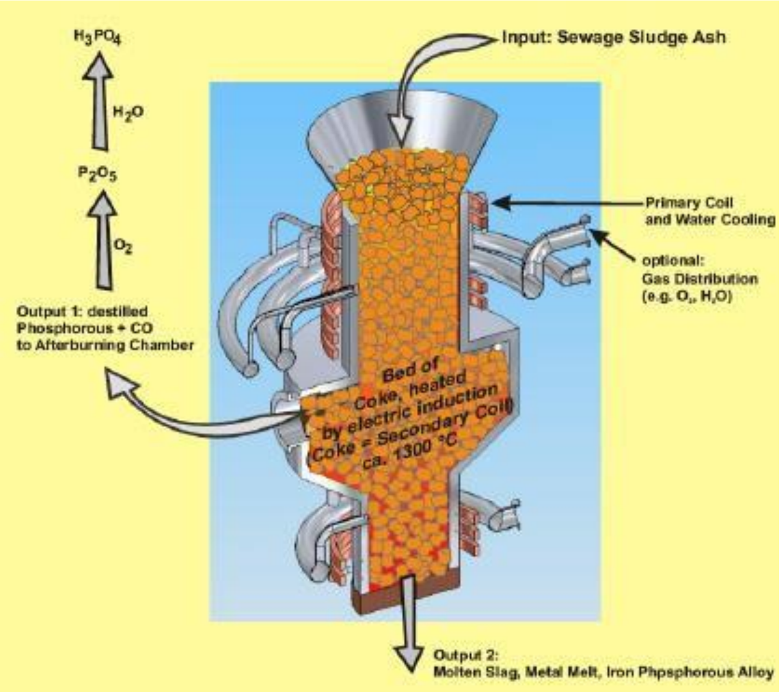


Fig 11 Recophos inductively heated reactor [from 60]. The phosphorus in this pilot is burned for safety reasons but would be captured as P_4 *in a full-scale plant.*

7 - Economics, Implementation, Further Aspects, and Conclusions

7.1 Economy and Societal Aspects

While acknowledging the fact that processes vary in their setups and operational costs, some more general points can be made.

An aggregated figure from various nonpublic sources puts the typical investment in medium- sized recycling plants (20–50 kt/y of ash) in the 30–100 MUSD bracket (greenfield and turnkey) at 2024 price levels. This, of course, totally disregards differences in complexity and equipment, geography, and exact capacity, but it serves as a reference point for estimating the magnitude of such investments.

The operational cost of recycling processes was evaluated in the P-Rex program [33], a large scale assessment of many recycling processes for cost and market potential that was finished in 2010. The conclusion was that out of the regular 40–120 euro wastewater treatment cost per person per year in industrialized geographies, phosphate recycling would only contribute about 5 euro on average, with a maximum of 10 euro. This means that in an existing sewage infrastructure, the implementation of P recovery is not cost prohibitive and can be implemented without dramatic budgetary consequences if the political will exists.

As an example, in a 2013 referendum, the inhabitants of the Swiss canton of Zurich overwhelmingly voted in favor of phosphate recycling to be implemented even if it would raise sewage taxes slightly. The referendum was preceded by an effective publicity campaign, explaining the necessity and benefits in terms that were understandable to the general public.

It is therefore concluded that the implementation of phosphate recycling is a modest proposition in view of the total sewage and sanitation cost.

However, when considering the revenues from the product, a different picture emerges. Again, only generalized statements can be made, but taking a delivered price of fertilizer-grade acid (MGA; to a major port) of 800 USD/t P_2O_5 in 2023, a recovery unit processing 20 kt/y of sewage ash at 18% P_2O_5 and 90% yield would generate phosphoric revenues of 2.5M USD per year - valued at standard fertilizer efficiency. Without going into operational costs and possible revenues from byproducts, it is easily understood on a qualitative level that this will be barely enough to cover payback of a typical investment of >30M USD, which is understood to be the order-of-magnitude capex for an ash-to-product plant. The number does not include personnel and chemicals cost. Generally, such processes do generate revenue but not enough to fit the general business requirement that processes should have a payback time of under 5-7 years.

Table 4 Energy and chemical use as provided by operators in the public P-Rex files; for competition reasons, several operators declined to share this information.

PROCESS	TYPE	ENERGY USE KWH/T P ELEC	ENERGY USE KWH/T P HEAT	AUXILIARY CHEMICALS T/T P	YIELD P %/INPUT WWTP OR ASH
ASHDEC	Thermal	0.9	5.2 (3.5 integr)	Na_2SO_4 3.3	**98%**
MEPHREC	Thermal gasification	1.2 (ash-based)/12 sludge	68 incl drying 55 out as fuel gas	2.5 coke, 0.6 O_2, 1.3 dolomite	**81%**
PEARL	Struvite	2.2	1.8	3.2 $MgCl_2$, 0.1 NaOH	**12%**
LEACHPHOS	**1.6**			**5.6 H_2SO_4, 0.6 NAOH, 3.9 CA(OH)$_2$**	**70%**

Added to that cost is the technological risk. Even if a full-scale plant is built after extensive piloting, it will be the first of its kind and therefore still be more sensitive to operational problems than a fully established technology. As explained in this document (par. 4.2, this chapter), both pilot and full-scale recycling operations have been shut down for a variety of reasons, which include technological challenges.

The general situation is that phosphate recycling does not pay itself back just on product revenues but requires additional support, such as from ash gate fees, subsidies, slightly increased sewage taxes, and penalties for noncompliance with recycling (e.g., as existing in Switzerland and imminent in Germany). This view is widely supported by technology suppliers and operators [55a, 63]

This situation can be understood when comparing the recycling processes to existing operations based on fossil rock. The differences are the following:

- Established rock-based processes are several orders of magnitude larger, benefiting from economics of scale
- The installations have mostly been fully paid back and depreciated
- They are integrated with mines and have huge buying power for sulfur, allowing low operational costs
- The costs of phosphate rock excavation are based on effort, not on its perceived value to humanity, and it draws from dwindling fossil resources

Put differently, the price of fossil phosphate has historically been quite modest, perhaps too low, which makes phosphate recovery business cases difficult. Upward swings in phosphate rock prices may give a large boost to recovery operations. A spike in phosphate prices in 2008 has kicked off an era where rock prices are less predictable and structurally higher than in much of the past.

An economically viable recovery operation needs to have a certain scale. A larger operation is relatively cheaper in investment, when expressed per ton of capacity. Capex does not scale linearly with capacity but roughly with its square root (depending on the technology type). Also, personnel can be utilized more effectively in a larger processing plant, and chemicals can be bought at larger scales, with advantages regarding price.

National policies are a strong driver for development of phosphate recycling processes. The countries seeing the most development are Japan, with its research culture and strong national policies on phosphate and fertilizer availability, and Germany, where a strong academic tradition coupled to far-sighted recycling enforcement policies has led to a proliferation of technologies, both under development and nearing implementation. Germany has also made phosphate recycling mandatory for all medium to -large WWTPs and sludge incinerators by 2032 at latest.

The European Union put phosphate rock on its list of critical raw materials in 2016. This list, with currently 37 materials, aims to identify raw materials to which the EU has no or limited access, but which play a critical role in industry, technology, and society. Even though there are no immediate consequences of being on the list, it nevertheless underpins the importance of phosphate. Domestic fertilizer production based on recovered phosphate fits well with this. In addition, white (elemental) phosphorus (P_4) was added to the list.

Germany and Switzerland will make phosphate recovery from sewage mandatory, with Austria to follow. The revised EU Urban Waste Water Treatment Directive 2024/3019 (art. 20) will make phosphorus reuse and recycling from sewage obligatory by the end of 2027.

In many cases, including sewage sludge ash in the EU, the material is classified as a waste. This hampers recycling because a waste processing permit needs to be granted by the relevant authorities before any processing can be done. An end-of-waste status can be applied for, but, generally, waste legislations are not well suited to such forms of recycling.

Also, in many jurisdictions, strict legislations for fertilizer products exist. Whereas these are understandable for impurities, their focus on origin prevents application of waste-derived fertilizers in several cases. Amendment of such legislations will make recycling easier. The European Fertilizer regulations were reviewed to allow several recycled products into the market. A stronger focus on composition and functionality, rather than origin, may be helpful to further boost recycling.

As has been noted, any new process that does not deliver a drop-in market product will have to go through a long market development phase, which in turn may be difficult if a large production plant is not available. Any new project should take notice of the difference between a recovered material (technology-driven) and a true recycled market product. This harsh reality is often ignored by enthusiastic developers and becomes apparent only after extensive pilot operations.

The conclusion is that economics alone are not a good driver for phosphate recovery - investment versus revenues can lead to longer payback times than sensible from a strictly economical view, but with societal and strategic considerations backing up the developments in phosphate recovery, its implementation is feasible. Several processes are about to be implemented on large scales at the time of writing (2025).

An in-depth exploration of factors influencing the success of a certain technology is found in [55a], Chapter 6. The eight factors that define success [55a] are the following:

1. The ability to generate a product with a clearly defined market potential as a finished product or an industry-compatible raw material (primarily for use in the fertilizer or white phosphorus industry, or as a fertilizer)

2. The power of the developer or seller of the technology for successful rollout (familiarity with the market for products, financial backing, and resources available for rollout)

3. General applicability in an existing system (such as a wastewater system); the more universally applicable the technology, the higher the chances of success

4. A high P recovery rate compared to the input to the system and contaminant depletion (note: recovery is always assessed in terms of input to the system in question, not to the local subsystem such as the EBPR sludge treatment loop, as the latter might be misleading and indicate too high recovery rates which only apply to that WWTP section

5. Low or moderate investment costs

6. Low or moderate operation costs and low amounts of waste generated

7. Societal and political acceptance, and the absence of legal barriers

8. Side benefits, such as reduced operational cost of a WWTP

In terms of future resilience of acid-based processes, hydrochloric acid has some potential to be derived from green chlorine. Sulfuric acid, the vast majority of which is derived from oil-based sulfur, will eventually become much less available as societies are weaned off fossil fuels, and can eventually only be derived from mining. However, sulfuric acid recycling from gypsum is possible. When the large thermal energy needed for that is derived from sustainable sources such as hydrogen, both routes can be performed in a carbon-neutral scenario. A similar argumentation can be applied to thermal processes.

7.2 Current implementation – a closer look

At the time of writing (2024), 90 struvite reactors are operating worldwide [64]. The data add up to 42 kt/y capacity (which includes estimates for very recent plants), with 30% of the installations not separating struvite out of the sewage plant output and not included in the sum. This is equivalent to 5 kt/y P being recovered, the typical output of two large sewage-ash processing plants. The average is 700 t/y struvite per plant. The technology can be considered as ripe, although struvite phosphate yields out of the total WWTP phosphate can be much improved (at least for communal WWTPs). This involves changes in the WWTP, not the struvite reactors themselves.

Ash-based processes are at TRLs 4-8, which means they are at laboratory (TRLs 4-5), small-scale pilot (TRLs 6-7), or large-scale pilot (TRL 8) stages with the following exceptions:

- Kubota Japan operates three of their plants with full-scale phosphate recovery, with the output aimed to be valorized as a special fertilizer but currently used in the construction industry.
- The caustic leaching process has been operating at a full scale in Gifu prefecture, Japan, with a yearly capacity of 230 T of apatite.
- ICL Amsterdam has used up to 10% of sewage sludge ashes, MBM ashes and struvite in their superphosphate plant since the early 2000s, with the rest of the feed being phosphate rock. This translates to several tens of thousands of tons per year. Increasing this percentage is indicated to be the long-term goal [53], which is now aimed for by introducing a new grade of superphosphate based on ashes.
- Remondis Aqua has been operating a full-scale Tetraphos plant (20 kt/y ash) in Hamburg, Germany, since 2023, although it has suffered startup issues.
- Thermphos International, now bankrupt, cumulatively processed 60 kt of sewage and MBM ash in their white-phosphorus production. Iron levels proved to be the main hurdle for further scaleup because they led to the formation of unacceptably high amounts of ferrophosphorus byproduct. Advances were made to selectively incinerate iron-poor sewage sludge at the supplier (SNB), the largest monoincinerator of sewage sludge in Europe,
- A type of TSP was made by Recophos-Germany, later Phos4Green, on a full scale in Germany, but the plant was halted, and the company went bankrupt, presumably because of increased energy costs. It is intended to reopen in 2025 after investments and improvements. This might be considered as TRL9.

Large-scale pilots have been running as mentioned below:

- EuPhoRe, in Germany (Dinslaken), on MBM and sewage sludge; a full-scale plant is being prepared in Mannheim, Germany, with MVV
- MePhrec; it used to operate a large pilot in Nurnberg, Germany, between 2017 and 2022, but the project has not advanced since then
- Pyreg is operating seven small-scale plants (each corresponding to around 1500 t/y sludge, expressed as dry matter) in Germany with unknown outlet for the product
- Terranova, in China
- Vivimag (Kemira) in Germany, serving one WWTP

The following projects are under full-scale development [65]:

- AshDec has signed a contract (together with Emter and sePura) for processing the Altenburg (Germany) monoincinerator ash, 15 kt/y. The full-sized demonstration project is expected to come onstream in 2025
- Ash2Phos and Gelsenwasser are engineering and preparing the site for a full-scale ash processing plant in Schkopau, Germany. It will process 30 kt/y of ash and open in 2027
- Susphos and SNB have reached a principle agreement to build a full-scale plant in Moerdijk, Netherlands, which is currently being designed. It is planned to open in 2027, processing 40 kt/y of ash
- Phos4Life, REALphos, and the derivative Phosphor26 project are aiming to start constructing medium-full-sized production plants to be running by 2030

Even though this constitutes an encouraging project pipeline, the current level of sewage phosphate recycling worldwide via other means than direct sludge application is negligible.

The diversity of the pipeline is also typical for a development that is in the pilot-full-scale transfer stages. A fair number of processes are proposed, several of which will not make it to large-scale implementation. The surviving processes, which are likely to number between a few and 10, will then see additional ripening and eventual rollout. This development will take place first in Europe and Japan, with the rest of the world to follow.

The role of iron in wastewater treatment deserves a mention. As seen above, it is often an obstacle to recycling. Iron phosphates have very little applications. Extraction of phosphorus without extracting iron (and aluminum) is not entirely trivial. White-phosphorus manufacture is also not very compatible with elevated iron levels in raw materials.

As effluent limits on phosphate go down, to protect sensitive environments receiving the effluent, the iron dosage is expected to increase, which will hamper phosphate recycling efforts. These two developments unfortunately do not align.

7.3 Other Streams

Even though this is outside the scope of this overview, it needs to be mentioned that worldwide manure production contains several times the amount of phosphorus found in sewage. Manure is used in agriculture, which clearly represents a short recycling path, but it has several drawbacks:

- Nutrient demand of crops varies with seasons, whereas manure production does not
- In-field application by grazing livestock is not homogeneous
- The nutrient balance is fixed, although highly varying with type of livestock, and is usually not a perfect fit for the needs of crops being fertilized
- It may be a source of heavy metals (Cu, Zn) and antibiotics, depending on its origin, especially from intensive livestock rearing

- In some areas, there is a clear excess of manure, leading to spreading on fields up to the legal limits for phosphate and/or nitrogen, which is not an efficient use of nutrients and leads to increased runoff into the environment

The EU has recently approved manure-derived nitrogen products (Renure, not technology specific but a general name for such products) to be used on fields even beyond the imposed manure-N spreading limits. This is an encouraging step toward more sustainable use of nitrogen fertilizers. For phosphate, which can also be selectively extracted from manure, such a development would help in more targeted use of the vast potential of manure nutrients.

Manure incineration is rare. NDM has operated a pig/cattle manure-processing plant in Germany for some years, running on biogas production digestate, but after its bankruptcy and restructuring, the status is unclear. Manure processing remains a difficult issue; manure does have an intrinsic value, unlike sewage ash when its agricultural use is banned. Only in surplus scenarios, processing makes sense, but a gate fee is needed to make the economics work (manure, like sewage sludge, is usually very wet, so little sensible energy is recovered to support the business case). Once the plant starts operating, the surplus is lifted and the negative value becomes positive again, undermining the economy of the processing unit.

Several initiatives to process manure into its constituents, in wet technologies, are under development.

BMC Moerdijk (Netherlands) has been processing 100 kt/y of chicken manure since 2010. The dry nature of poultry manure makes processing straightforward, and energy can be recovered and sold as steam or electrical power. The phosphate in this material is indicated to be more plant-available than sewage sludge ash.

MBM Category I is being incinerated in three plants in the UK, which were constructed for meat destruction at the height of the UK BSE crisis in the 1990s but have since been converted to incinerate Category I MBM. This fraction of slaughter waste cannot be fed to ruminants because it risks a cycle of BSE prion accumulation; the surplus needs to be incinerated. In other countries, MBM Category I is co-incinerated in cement works and coal-fired power plants, but this remains an unsustainable route from the phosphate viewpoint. More such plants will come onstream in regions with intensive livestock rearing, such as Ireland and Bretagne.

Phosphate plant availability is indicated to be reasonable.

Table 6 Summary of product types.

PRODUCT TYPE	FROM PROCESSES	RECYCLING POTENTIAL IN/OUT	MARKET STATUS	POTENTIAL
PHOSPHORIC ACID	Extraction-separation with concentration	>80%, often >90%	Established product (drop-in)	**LARGE EXISTING MARKET (WORLD: 45 MT/Y P2O5), RELATIVELY HIGH VALUE**
CALCIUM PHOSPHATE	Extraction-separation with precipitation	>80%, often >90%	Established product	**LARGE EXISTING MARKET (WORLD: 45 MT/Y P2O5), RELATIVELY LOW VALUE (PRECEDES PHOSPHORIC ACID IN VALUE CHAIN)**
TRANSFORMED ASH	Thermal processes	>95%	New product needing development	**POTENTIAL UNCLEAR, MARKET VALUE UNKNOWN BUT NOT LIKELY TO BE HIGH**
STRUVITE	**WWTP SIDE-STREAM PRECIPITATION**	**2%-25%, 45% WITH EXTREME SLUDGE TREATMENT**	**UNDER DEVELOPMENT**	**MARKET IS SLOWLY DEVELOPING, VALUE DEPENDS ON PHYSICAL FORM**

Further Reading

The Nutrient Recovery Technology Catalogue of the European Sustainable Phosphorus Platform [66] contains a regularly updated list of recovery technologies (including those for manure and slaughter waste as well as nitrogen and potassium) and a description of each technology in a fixed format.

The book "Phosphorus Recovery and Recycling" [55a] contains extensive descriptions of technologies, as well as mapping of P flows. Developments have taken place since it was written (2018), but a lot of the information is still valid.

Acknowledgment

The author thanks Chris Thornton for his useful suggestions to improve the text.

References

[1a] K.C. van Dijk, J.P. Lesschen, O. Oenema, Phosphorus flows and balances of the European Union Member States, Sci. Total Environ. 542 (2016) 1078-1093. https://doi.org/10.1016/j.scitotenv.2015.08.048

[1b] Main data from washdata.org; checks from https://www.statista.com/statistics/1258932/global-population-access-sewer-connections-by-region/, and https://www.unwater.org/publications/progress-wastewater-treatment-2024-update

[2] https://www.epa.gov/biosolids/biosolids-generation-use-and-disposal-united-states

[3] D. Hu, P. Jiang, Y. Chen, F. Gao, S. Liu, Sustainable sludge management in China: Quantifying GHG emissions and exploring its reduction strategies, Processes. 12 (2024) 1481. https://doi.org/10.3390/pr12071481

[4] Q.H. Zhang, W.N. Yang, H.H. Ngo, W.S. Guo, P.K. Jin, Mawuli Dzakpasu, S.J. Yang, Q. Wang, X.C. Wang, D. Ao, Current status of urban wastewater treatment plants in China, Environ. Sci. Technol. 49 (2015) 4781-4782. http://doi.org/10.1021/acs.est.5b01455

[5] F. Hernandez-Padilla, M. Margni, A. Noyola, L. Guereca-Hernandez, C. Bulle, Assessing wastewater treatment in Latin America and the Caribbean: Enhancing life cycle assessment interpretation by regionalization and impact assessment sensibility, J. Cleaner Prod. 142 (2017) 2140-2153. https://doi.org/10.1016/j.jclepro.2016.11.068

[6] https://www.phosphorusplatform.eu/images/download/ScopeNewsletter103.pdf

[7] https://www.epa.gov/biosolids/basic-information-about-sewage-sludge-and-biosolids

[8] https://ovivo.getbynder.com/m/2aa2c5983fcb5a93/original/Aviko-Potato-Processing.pdf

[9] https://www.waternetwerk.nl/images/knw/20170126-15-jaar-industrieel-proceswaterzuiveren.pdf, https://www.nutrientplatform.org/succesverhalen/waterschap-rijn-en-ijssel/

[10] Personal communication, EUPPA (European Potato Processors' Association)

[11] https://www.colsen.nl/en/projects/recurring-water-treatment-lamb-weston-meijer-vof

[12] A. Kolev Slavov, General characteristics and treatment possibilities of dairy wastewater - A review, Food Technol. Biotechnol. 55 (2017) 14-28. https://doi.org/10.17113/ftb.55.01.17.4520

[13] A. Hernandez-Mora, O. Duboc, E. Lombi, E.K. Bunemann, K. Ylivainio, S. Symanczik, A. Delgado, N. Abu Zahra, J. Nikama, L. Zuin, C.L. Doolette, H. Eigner, J. Santner, Fertilization efficiency of thirty marketed and experimental recycled phosphorus fertilizers, J. Cleaner Prod. 467 (2024) 142957. https://doi.org/10.1016/j.jclepro.2024.142957

[14] J. Stauber, S. Rampton, Toxic Sludge is Good for You: Lies, Damn Lies and the Public Relations Industry, Common Courage Press.

[15] https://www.muskogeephoenix.com/local/x699462921/landowners-win-sludge-suit/

[16] https://www.theguardian.com/environment/2024/mar/01/texas-farmers-pfas-killed-livestock

[17] https://www.theguardian.com/environment/2022/may/12/maine-bans-sewage-sludge-fertilizer-farms-pfas-poisoning

[18] https://www.epa.gov/biosolids/risk-assessment-pollutants-sewage-sludge

[19] https://environment.ec.europa.eu/topics/waste-and-recycling/sewage-sludge_en

[20] A. Kelessidis, A.S. Stasinakis, Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries, Waste Manag. 32 (2012) 1186- 1195. https://doi.org/10.1016/j.wasman.2012.01.012

[21] https://www.jwld.pl/files/Ghacha-et-al-643a.pdf

[22] https://de.wikipedia.org/wiki/Phosphorruckgewinnung

[23] https://www.eliquo-we.com/en/news-details/completion-of-pearl.html

[24]A. Muhmood, X. Wang, R. Dong, H. Xiao, S. Wu, Quantitative characterization and effective inactivation of biological hazards in struvite recovered from digested poultry slurry, Water Res. 204 (2021) 117659. https://doi.org/10.1016/j.watres.2021.117659

https://doi.org/10.1016/j.watres.2021.117659, and K. Gell, F.J. de Ruijer, P. Kuntke, M. de graaff, A.L. Smit, Safety and effectiveness of struvite from 4 black water and urine as a phosphorus fertilizer, J. Agric. Sci. 3 (2011) 67. https://doi.org/10.5539/jas.v3n3p67

[25] H. Huang, C. Xu and W. zhang, Removal of nutrients from piggery wastewater using struvite precipitation and pyrogenation technology, Bioresour. Technol. 102 (2011) 2523. https://doi.org/10.1016/j.biortech.2010.11.054

[26] G. van Houwelingen, P. Piekema, The Crystalactor® at the WWTP Geestmerambacht (The Netherlands) In: Phosphorus: Polluter and Resource of the future, Removal and Recovery from Wasewater, ed. C. Schaum. IWA Publishing (2018).

[27] W.K. Wijdeveld, T. Prot, G. Sudintas, P. Kuntke, L. Korving, M.C.M. van Loosdrecht, Pilot-scale magnetic recovery of vivianite from digested sewage sludge, Water Res. 212 (2022) 118131. https://doi.org/10.1016/j.watres.2022.118131

[28] https://www.phosphorusplatform.eu/activities/p-recovery-technology-inventory?view=article&id=2621:extraphos&catid=93:nutrient-recovery-technology- catalogue

[29] E. Desmidt, K. Ghyselbrecht, Y. Zhang, L. Pinoy, B. Van der Bruggen, W. Verstraete, K. Rabaey, B. Meesschaert, Global phosphorus scarcity and full-scale P-recovery techniques: A review. Crit. Rev. Environ. Sci. Technol. 45 (2015) 336-384. https://doi.org/10.1080/10643389.2013.866531

[30] C. Meyer, V. Preyl, H. Steinmetz, W. Maier, R.-E. Mohn, H. Schonberger, T. Pierson. The stuttgart process (Germany). In: Phosphorus: Polluter and Resource of the Future, Removal and recovery from Wasewater, ed. C. Schaum. IWA Publishing (2018).

[31] K. Stendahl, K. Jafverstrom, Recycling of sludge with the Aqua Reci process, Water Sci. Technol. 49 (2004) 233-240.

[32] https://www.umweltbundesamt.de/sites/default/files/medien/publikation/long/2827 .pdf

[33] P-REX - https://cordis.europa.eu/docs/results/308/308645/final1-p-rex-final-report-final.pdf

[34] https://wolter-hoppenberg.de/allgemein/grundstein-fuer-die-klaerschlamm-monoverbrennungsanlage-bielefeld-gelegt, https://www.euwid- recycling.de/news/wirtschaft/mva-bielefeld-herford-legt-grundstein-fuer-neue- klaerschlamm-monoverbrennungsanlage-311024/, https://www.umweltwirtschaft.com/news/wasser-und-abwasserbehandlung/schlammverbrennung/Studie-zur-Entsorgung-von-Klaerschlamm-Zubau-an-Monoverbrennungsanlagen-fuehrt-zu-ueberkapazitaeten-22239, https://www.rwe.com/presse/rwe-power/2023-03-29-sewer-sludge-incinerator-groundbreak-ceremony

[35] M. Husek, R. Homma, J. Mosko, M. Pohorely, K. Oshita. P-recovery versus current sewage sludge treatment policy in the Czech Republic and Japan, Clean Technol. Environ. Policy 26 (2024) 1883-1899. https://doi.org/10.1007/s10098-023-02679-w

[36] https://montreal.ca/en/articles/wastewater-to-fertilizer-waste-recovery-65289

[37] https://www.nib.int/releases/st-petersburg-sludge-incinerator-set-in-operation, https://battus.co/portfolio-item/sewage-sludge-incinerator-st-petersburg-russia/

[38] A. Rak, H Hangen. The Remondis Tetraphos(r) process at the WWTP in Hamburg (Germany). In: Phosphorus: Polluter and Resource of the future, Removal and recovery from Wasewater, ed. C. Schaum. IWA Publishing (2018).

[39] https://www.bam.de/Content/EN/Paper-of-the-Month/2022/Environment/2022- 03-01-paper-of-the-month-environment.html

[40] https://www.aquiris.be/sites/g/files/dvc2886/files/document/2019/08/9527_Aquiris_signs_panel_11.pdf; https://corporateeurope.org/en/aquiris-veolias-lost-bet-brussels

[41] https://pyreg.com/

[42] N. Boukis, I. K. Stoll, Gasification of biomass in supercritical water, challenges for the process design-Lessons Learned from the operation experience of the first dedicated pilot plant, Processes 9 (2021) 455. https://doi.org/10.3390/pr9030455

[43] https://www.isa.rwth-aachen.de/cms/isa/forschung/abgeschlossene-projekte/~slol/krn-mephrec/?lidx=1

[44] https://www.euphore.de/euphore-process.htm

[45] https://www.prayon.com/en/processes/dcp-ecophos/

[46] https://www.easymining.com/technologies/ash2phos2/ash2phos/

[47] L.M. Ottosen, D. Thornberg, Y. Cohen, S. Stiernstrom., Utilization of acid-washed sewage sludge ash as sand or cement replacement in concrete, Resour. Conserv. Recycling 176 (2022) 105943. https://doi.org/10.1016/j.resconrec.2021.105943

[48] https://www.susphos.com/, https://www.snb.nl/actueel/snb-sushphos-uniek-fosfaatfabriek

[49] https://www.tecnicasreunidas.es/articulo/did-you-know-phos4lifetm-technology/

[50] https://www.aiktechnik.ch/en/phosphorus-recovery/ and for the Swiss plans https://www.bafu.admin.ch/bafu/en/home/topics/waste/sekundaere-rohstoffe/phosphorrecycling.html

[51] https://ptc-parforce.de/en/

[52] https://www.metawater.co.jp/eng/solution/product/sewer/rin_collection/

[53] https://2018.icl-group-sustainability.com/reports/producing-fertilizers-with-recycled-phosphate/

[54a] https://phos4green.glatt.com/projects/seraplant-haldensleben/

[54b] https://seraplant.com/

[54c] https://www.umweltwirtschaft.com/news/abfallwirtschaft-und-recycling/Wegen-hoher-Gaspreise-Seraplant-meldet-vorlaeufige-Insolvenz-an-27629

[54d] https://www.euwid-recycling.de/news/wirtschaft/phosphorduenger-aus-klaerschlammasche-seraplant-will-produktion-wieder-aufnehmen-110225/

[55a] Phosphorus Recovery and Recycling, H. Ohtake ans S. Tsuneda (ed.), Springer Nature (2019)

[55b]https://nutriman.net/farmer-platform/product/id_397, https://www.metso.com/corporate/media/news/2011/2/outotec-acquired- phosphorus-recycling-technology-business-of-ash-dec-umwelt-ag/

[56] https://www.bmbf-rephor.de/en/joint-projects/r-rhenania/

[57] https://www.kubota.com/corporatehistory/ourchallenges/japan-water-05/3/

[58] O. Gantner, W. Schipper and J.J. Weigand, Spotlight 8: Technological use of phosphorus: the non-fertilizer, non-feed and non-detergent domain. In: Sustainable Phosphorus Management, R.W. Scholz, A.H. Roy, F.S. Brand, D.T. Helllums, A.E. Ulrich (eds.), Springer (2014).

[59] W.J. Schipper, A. Klapwijk, A. Potjer, W.H. Rulkens, B.G. Temmink, F.D.G. Kiestra,
A.C.M. Lijmbach, Phosphate recycling in the phosphorus industry, Environ. Technol. 22 (2001) 1337-1346. https://doi.org/10.1080/09593330.2001.9619173

[60] http://www.recophos.org

[61] https://flashphos-project.eu

[62] https://thermusp.com/, https://www.stowa.nl/onderwerpen/circulaire-economie/produceren-van-grondstoffen/spodofos-witte-fosfor-terugwinnen-uit

[63] Private communications

[64] https://www.phosphorusplatform.eu/images/download/Kabbe_P-recovery_tech_implementation%20Table_2023-01-04.pdf

[65] https://www.phosphorusplatform.eu/activities/p-recovery-technology-inventory

[66] https://www.phosphorusplatform.eu/activities/p-recovery-technology-inventory

Declaration of Interest

The author has worked with, advised, and is working with SusPhos, Spodofos, and Flashphos, respectively, but currently has no substantial involvement in these companies.

Address: Lot 660, Hay Moulay Rachid
Ben Guerir 43150, Morocco
Email: communication@tgpi.org
www.tgpi.org