Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency

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Integral guidance document for phosphorus recovery and recycling

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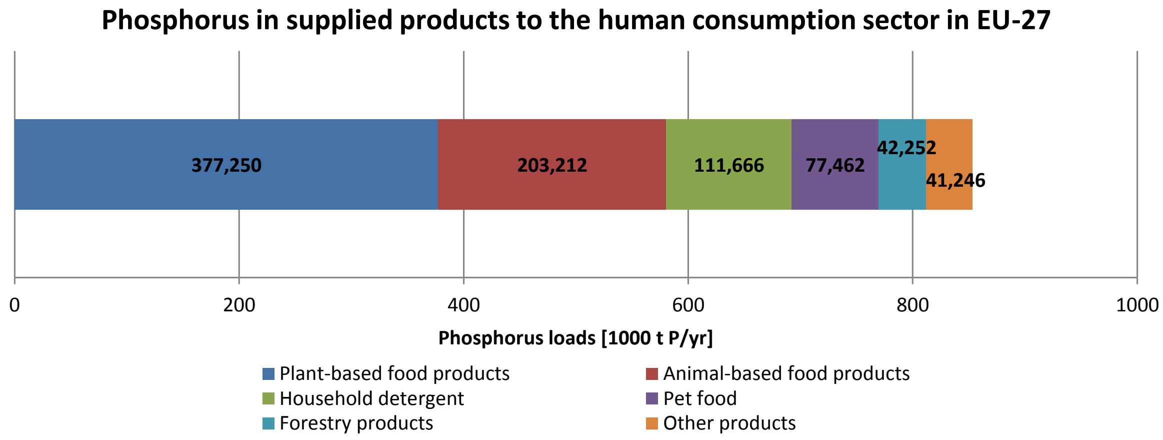
1 Introduction

Whether or not there will be a phosphorus (P) peak within decades, centuries or millennia, (Cordell and White, 2011; Scholz and Wellmer, 2013) one thing is for sure – phosphorus is a limited and, in its function as a nutrient, an essential and irreplaceable resource (Asimov, 1959; Smil, 2000; Filippelli, 2008). The debate on P limitation is often mentioned as motivation to foster activities regarding P recovery and recycling. The ambition of the European Commission (EC) to establish a circular economy in Europe goes far beyond that and is not primarily motivated by limitations of certain raw materials. From the European perspective and in the light of having just one small mine in Finland, the geopolitics and economic vulnerability are issues to be taken seriously. Europe is highly dependent on phosphorus imports (De Ridder *et al.*, 2012) as reflected by the quantities given in figure 1.



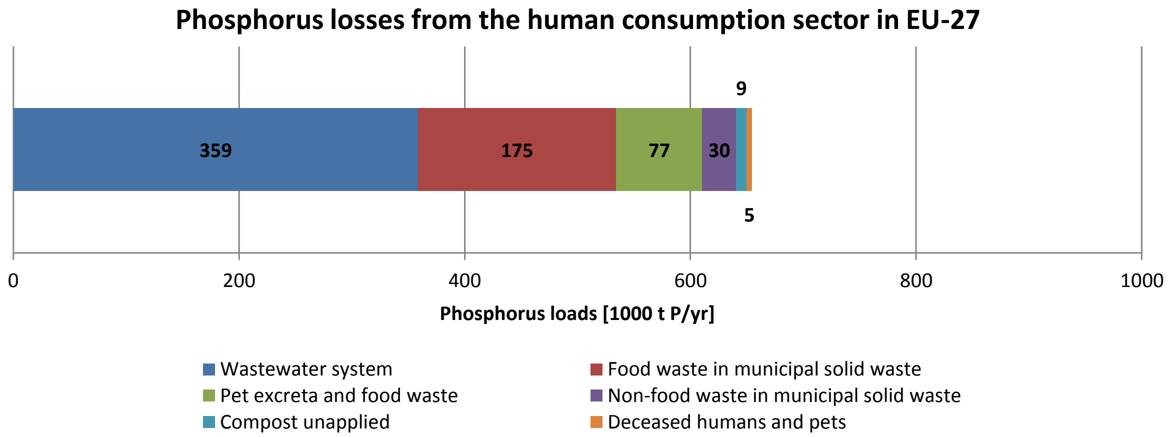


Figure 1: Phosphorus supply and losses for the human consumption sector within EU27 in 2005 (van Dijk *et al.*, 2016)

In contrast to the above mentioned issues, the waste and dissipation of phosphorus that exists in developed countries may lead to a different conclusion. The global resource efficiency for P along the supply chain from mine to fork is only 20% (Schröder *et al.*, 2010). Given the figures of 225 million tons P rock globally mined in 2013 (USGS, 2015) and assuming that 90% of the mined P is used for food production, only 45 million tons of the mined quantity finally ends up in form of food on our tables. So, what can we do to increase the resource efficiency of P? Recently, the implementation of a coherent package of nutrient management strategies and measures to close the European P cycle has been proposed – the 5R strategy (Withers *et al.*, 2015). The five R's are **Realign** P inputs, **Reduce** P losses to waters, **Recycle** P in bio-resources, **Recover** P from waste and finally **Redefine** our food system.

So, recovery and recycling can play an important role in improving resource efficiency and sustainable nutrient management. Although, there are various relevant waste streams carrying huge quantities of phosphorus dissolved in liquids or fixed in solids like in manure or organic waste, the focus of P-REX was laid upon P recovery and recycling from wastewater and sewage sludge.

2 Background

Relevance of the wastewater stream

The relevance of the wastewater stream as renewable resource for bio-nutrients, especially phosphorus is reflected in Figure 2 and explained in the P-REX policy brief "*Phosphorus Recycling - Now!*" (Hukari *et al.*, 2015) published for the 2nd European Sustainable Phosphorus Conference – ESPC2 in March 2015 in Berlin.

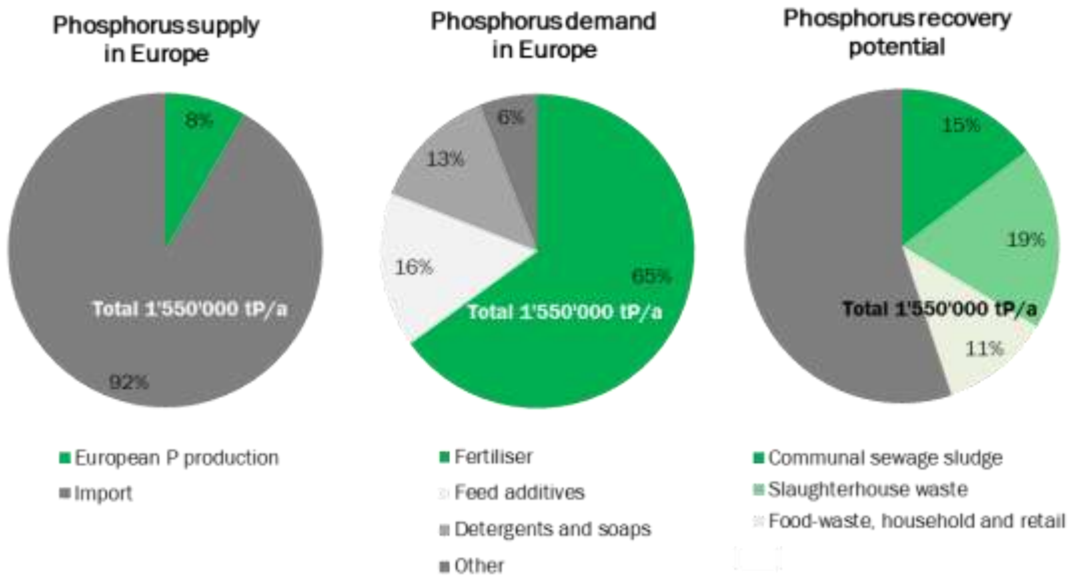


Figure 2: Relation of European phosphorus supply (domestic mining and imports), demand and recovery potential in selected waste streams, not including manure, which is considered more or less completely recycled without going into details whether it is done according to meet nutrient demands of soils or just to get rid of it this agricultural waste. (USGS 2013, CEFIC 2009, EUROSTAT 2012, Schröder 2012, van Dijk et al. 2016).

The EU's only phosphorus mine is situated in Finland. The European Union faces a 92% import dependency today [EC COM(2013) 517], explaining why phosphate rock has recently been announced as one of the 20 Critical Raw Materials of the EU [EC COM(2014) 297].

Phosphorus is cycled between animal and crop production in the form of manure and animal feed. The food produced goes to human consumption. The nutrients concentrate in the sewage sludge of wastewater treatment plants (WWTP) and thereafter are often lost for the economic cycle, depending on the valorization and disposal routes allowed and applied.

Rates of the conventional recycling by direct application of sewage sludge on arable land vary from zero to 90 % within the EU-27. Yearly more than 200'000 tons, or 60%, of phosphorus within the sewage sludge remains unutilized for crop production (Milieu Ltd., RPA 2010). Recyclable phosphorus in the wastewater stream could be further increased by implementing completely the Wastewater Framework Directive. Tapping the full potential of phosphorus from the wastewater stream could theoretically almost triple the domestic supply from 8% towards 23% providing simultaneously a decrease of Europe's import dependency!

The sewage sludge is typically used for landscaping, incinerated or landfilled. The valuable nutrient phosphorus is often lost either due to dilution with waste or by incorporation into other matrices such as concrete. Valorization of these phosphorus quantities has a recovery potential almost twice as large as the current European mineral phosphorus supply (see Figure 2).

Major challenges for higher recycling rates include concerns regarding pollution of the sludge with heavy metals, organic pollutants, or pathogens, as well as transport and storage of large quantities (wet sludge). The needs and abundance of nutrients varies regionally, due to seasonality of agricultural production, spatially separated food production in rural areas and food consumption in urban areas. In particular nutrient surpluses are found in regions with high livestock density.

3 Recovery Options

In industrialised countries, wastewater treatment has been implemented to protect the environment and especially water bodies such as rivers, lakes and finally the sea. The regulative framework is set by the Water Framework Directive EC/60/2000. As a positive consequence P is collected and concentrated in a manageable mass flow providing several hot-spots for recovery. In centralised sanitation schemes, the wastewater is collected in sewer systems and transported to wastewater treatment plants (WWTP). There, mechanical, chemical and biological processes are applied to remove pollutants from the wastewater by separation from the aqueous phase or degradation, providing a purified effluent to be returned into the water cycle. In most cases sludge is produced, serving as a sink for material and chemical compounds which are suspected of causing harm to the environment when released into receiving waterbodies. As a consequence nutrients such as P, which cause eutrophication, and contaminants such as heavy metals are concentrated in the sewage sludge. It can be assumed, that 90% of the P entering the WWTP are transferred into the sludge by the so-called phosphorus removal. Phosphorus can be removed from the wastewater by biological accumulation in biomass (Enhanced Biological Phosphorus Removal, EBPR) or by chemical precipitation, in the form of barely soluble phosphates (normally as iron or aluminium phosphate).

As shown in Figure 3, and given the fact that most of the phosphorus entering a WWTP ends up in the sludge, three principal and complementary routes for closing the phosphorus cycle by recovery from sewage sludge appear to be reasonable.

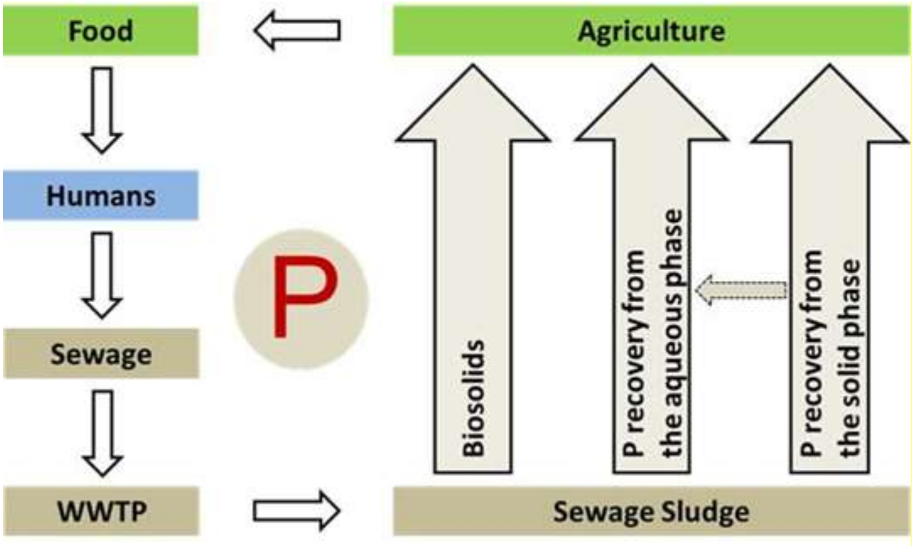


Figure 3: The three principal routes for P recovery and recycling from the wastewater stream as a nutrient. Wastewater REUSE for irrigation is not included. (Kabbe, 2013).

Direct application of stabilised sewage sludge or so-called biosolids on arable land is the traditional route to valorise all contained nutrients in agriculture. It plays an important role in countries such as Luxemburg (90%), the UK (70%) and France (65%) as shown in Figure 4. Since this valorisation route can be considered low tech and low cost, it will remain one of the pillars for nutrient recycling on global scale.

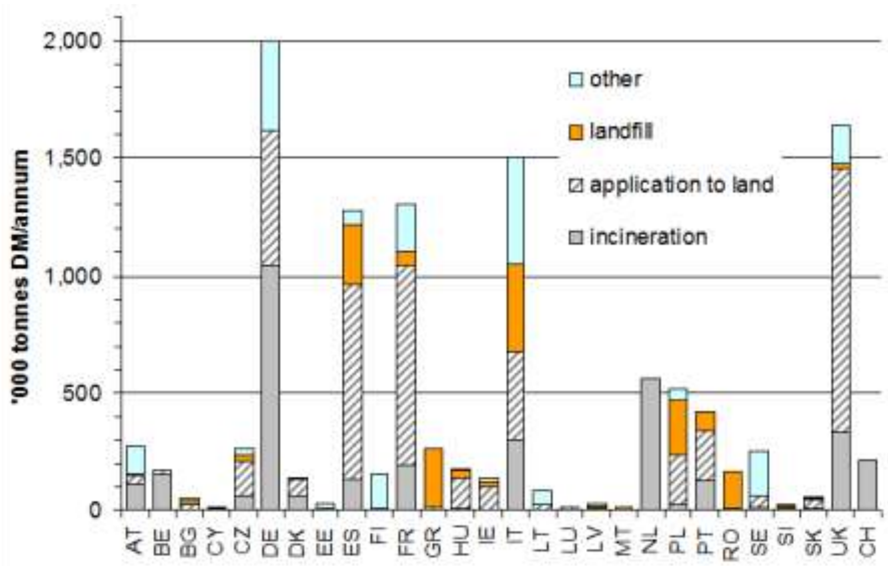


Figure 4: Sewage sludge valorisation and disposal routes in E27 + CH in 2010 (Milieu Ltd., 2010).

But, due to increasing concerns about pollutants, whether known (heavy metals) or unknown (organic contaminants and pathogens), this route is being increasingly questioned by the public and authorities, and some European countries have even banned the application of sewage sludge in agriculture (e.g. Switzerland). Therefore, solutions for technically advanced P recovery and recycling have been developed to provide alternatives.

Depending on the infrastructure for wastewater treatment, dissolved phosphorus can be technically recovered from the aqueous phase of the sludge prior (2a in **Fehler! Verweisquelle konnte nicht gefunden werden.**) or subsequent to the sludge dewatering process (2b in **Fehler! Verweisquelle konnte nicht gefunden werden.**). If sludge is incinerated undiluted in mono-incineration plants, the resulting ash contains the highest available concentrate of P within the wastewater stream (3 in **Fehler! Verweisquelle konnte nicht gefunden werden.**). But, due to the very limited plant-availability of the nutrient within most of the ashes, further treatment is required.

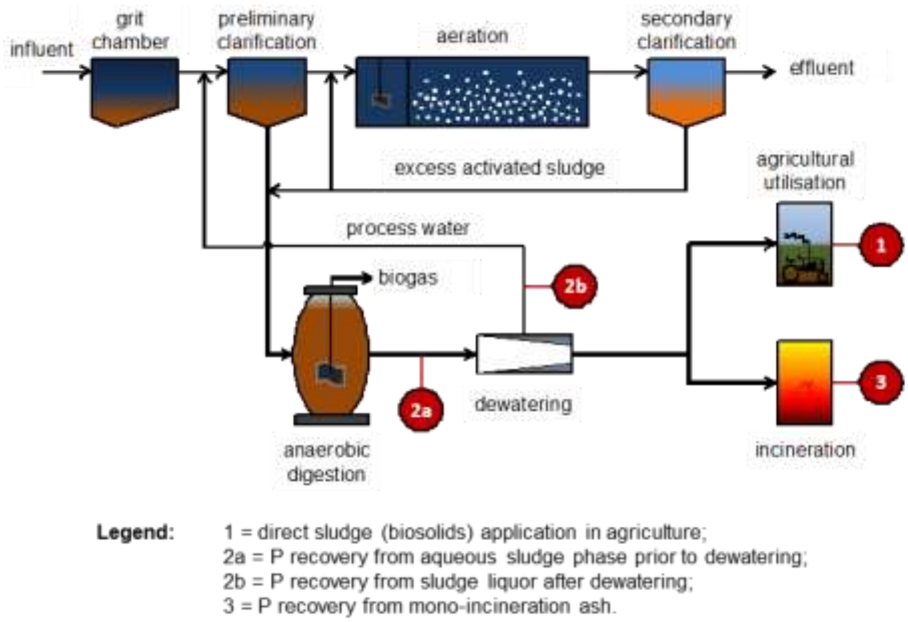


Figure 5: Hotspots for P recovery from the wastewater stream (in centralised sanitation systems), (Kabbe, 2013).

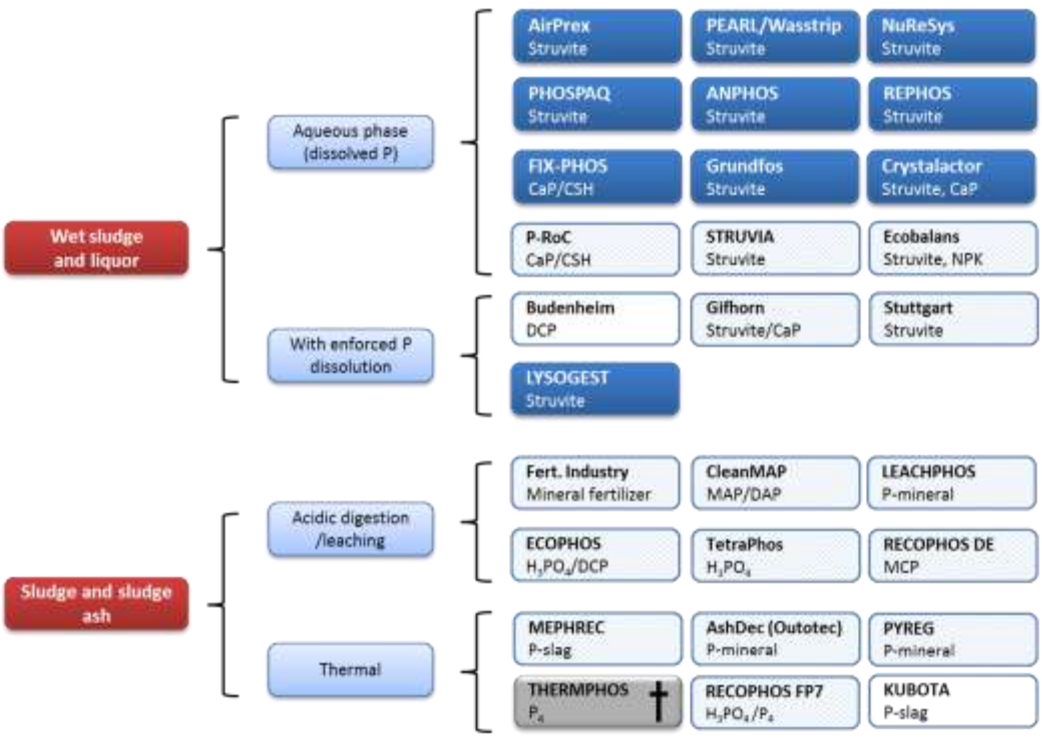


Figure 6: Promising and already applied P recovery and recycling technologies with indication of their state of maturity (updated from Kabbe *et al*., 2015).

Depending on their technical maturity and economic feasibility some of these have already been implemented. **Fehler! Verweisquelle konnte nicht gefunden werden.**6 gives an overview of promising approaches and their state of maturity. These alternative routes for nutrient recovery are intended to provide products or raw materials suitable for reuse in the nutrient cycle.

Two alternative routes for phosphorus recovery and recycling from sewage sludge can be distinguished in P recovery and recycling: from the aqueous phase and from the sludge solids. Combinations of both are feasible as well. Table 1 gives an impression of the recent developments and status of maturity or even implementation.

Table 1: Operations and concretely planned technical P recovery/recycling from wastewater facilities in Europe (Kabbe, 2013; Stemann et al., 2014; Schoumans et al., 2015; Kabbe, 2015).

Technology	Location and operator	Status	Recovered material or product
AirPrex®	Wassmannsdorf (DE), BWB MG-Neuwerk (DE), Niersverband Echten (NL), Reest & Wieden Amsterdam-West (NL), Waternet BS-Steinhof (DE), SE|BS / AVB Uelzen (DE), SE Uelzen Salzgitter (DE), ASG Wolfsburg (DE), AVW	2009/11 2009 2013 2014 construction construction construction planned	Struvite
ANPHOS	Land van Cuijk (NL), Aa en Maas	2011	Struvite
Biofos	Kopenhagen	pilot	
Budenheim	Mainz (DE) and Itzehoe (DE)	2 pilots (plan)	DCP
CleanMAP®	EasyMining Sweden, Ragn-Sells (SE)	planned	MAP/DAP
Fertiliser industry	Various companies already apply or consider use of secondary P sources	planned	Commercial fertiliser
EkoBalans	Helsingborg and other (SE), EcoBalans	pilot	Struvite, NPK
EcoPhos	Varna (BG), DecaPhos Dunkerque (FR), EcoPhos	planned planned	H_3PO_4/DCP/ MCP
Fix-Phos	Hildesheim (DE), SEHi	2012	CaP/CSH
Gifhorn	Gifhorn (DE), ASG	2007	Struvite/CaP
Grundfos	Aaby (DK), Aarhus Water Herning (DK), Herning Water	2013 construction	Struvite
LysoGest®	Lingen (DE), SE Lingen	2014	Struvite
MEPHREC	Nürnberg (DE), SUN	planned	P-slag
NuReSys®	Harelbeke (BE), Agristo 2x Niewkuerke (BE), Clarebout Potatoes Waasten (BE), Clarebout Potatoes Geel (BE), Genzyme Leuven (BE), Aquafin Schiphol Airport (NL), Evides Land van Cuijk (NL), Logisticon Apeldoorn (NL), GMB-Imtech	2008 2009/12 2012 2014 2013 2014 2015 2015	Struvite
WASSTRIP/PEARL®	Slough (UK), Thames Water Amersfoort (NL), Vallei & Veluwe Reading (UK), Thames Water Madrid (ES), Veolia Iberica	2013 2015/16 planned planned	Struvite
PHORWater	Calahorra (ES), El Cidacos	construction	Struvite
PHOSPAQ™	Olburgen (NL), Waterstromen Lomm (NL), Waterstromen Nottingham (UK), Severn Trent Water Tilburg (NL), Watershap de Dommel	2006 2008-13 2014 2016	Struvite
P-RoC	Neuburg (DE), City of Neuburg /Danube Giessen (DE), MWB	planned	CaP/CSH
REPHOS®	Altentreptow (DE), Remondis Aqua	2006	Struvite
STRUVIA™	Brussels North (BE) and other, (Veolia)	pilots	Struvite
Stuttgart	Offenburg (DE), AZV	Large pilot since	Struvite

		2011	
TetraPhos®	Hamburg (DE), Remondis Aqua	pilot	H_3PO_4
Thermphos	Vlissingen (NL)	until 2012	P_4

The ongoing developments and implementation of P recovery and recycling is continuously mapped and can be followed here: https://de.batchgeo.com/map/0f9d56a3aa57a51379a3cb23af27d202

Within P-REX nine technical P recovery processes had been assessed regarding toxicity, plant availability, potential risks and their ecologic and economic performance. These processes are:

- **AirPrex** struvite precipitation in sludge (2a)
- **Pearl** struvite precipitation in sludge liquor (2b)
- **Struvia** struvite precipitation in sludge liquor (2b)
- **Stuttgart** sludge leaching (2a) and struvite precipitation in sludge liquor (2b)
- **Gifhorn** sludge leaching (2a) and struvite/Ca-P precipitation in sludge liquor (2b)
- **Mephrec** metallurgic sludge or ash treatment (3)
- **AshDec** thermo-chemical ash treatment (3)
- **LeachPhos** ash leaching (3)
- **EcoPhos** ash leaching (3)

For comparability the traditional way of nutrient recycling (agricultural valorisation) and conventional phosphorus fertilizer production had been considered within the assessments as well.

It has to be mentioned, that both, data availability and reliability is an issue to be solved in the near future, since sustainability and implementation strategies have to be developed on reality based data which cannot be found in official statistics today. Here the sound data alliance or initiative "DONUTSS" (**D**ata **O**n **NU**trients **T**o **S**upport **S**tewardship") of the European Sustainable Phosphorus Platform in cooperation with EC DGs GROW, ENV and R&I should be further elaborated.

4 Existing and potential value chains for recycling

- ***Struvite***

Berliner Pflanze by Berliner Wasserbetriebe (BWB) and *Crystal Green* by Ostara are officially approved fertilisers. Both companies sell the struvite under their brands. Whereas BWB has contracted a retail organisation, since their task as water utility is the wastewater treatment and not fertilizer production and marketing, follows OSTARA a so-called all-inclusive package.

The struvite produced in Berlin, roughly 400 tons a year is picked up, stored, customized and sold by a retail organization based in Germany, the Crystal Green is fully handled by the technology provider OSTARA, being responsible for pick-up, storage and sales.

Both products are registered under REACH and can be therefore traded within Europe as a product.

The struvite produced by WATERNET at WWTP Amsterdam West is directly transported to ICL Fertilizers to their nearby fertilizer production plant, where the struvite is directly fed into their production process. Although the Dutch government adapted legislation to allow struvite application as fertilizer in the Netherlands since 1st January 2015, this route is the most convenient for WATERNET. Also their struvite was registered under REACH as required by ICL.

Since the number of struvite producing facilities will increase, various valorization models can be thought of. Depending on available quantities, company based approaches like the one of OSTARA or even regional/national approaches can be considered. Of course the latter may only make sense for sufficient quantities available, starting at several thousand tons of struvite per year. The total struvite production in Europe today is estimated to add between 6,000 and 7,000 t/y with potential to double or even triple within the next five years. These quantities seem to be sufficient for a premium quality market rather than a bulk market.

Besides valorization as fertilizer ready to be used or mixing component, struvite can also be applied in non-fertilizer applications. But here, where mainly the P itself is of interest, Calcium phosphates might be preferred to avoid spoiling the nitrogen contained in the struvite. For these applications, plant-availability is absolutely no issue.

- ***Sewage sludge ashes (SSA)***

Sewage sludge ashes appear to be comparable to fossil based low-grade phosphate rock. Depending on their composition, so-called premium ashes can be used directly to partly substitute P rock in commercial fertilizer production, as already tested by ICL Fertilizers (Langeveld and ten Wolde, 2013). But, these premium ashes are very limited in availability which calls for a smarter upstream sewage sludge incineration management or even wastewater management. Absolute limits besides heavy metal contents and possible organic residues are P (>8%) content and Fe/Al contents in the ashes.

The SSA monitoring conducted in Germany revealed, that purely incinerated municipal sludge delivers ash with P contents of 9.6% in average and low contamination, whereas the mono-incineration of a mixture of municipal and industrial sewage sludge leads to P dilution and elevated heavy metal contamination. Following the recent discussion in Germany about mono-incineration capacities, they should be exclusively reserved for municipal sludge only to make the best out of the already existing capacities. But this would need a smarter sludge logistic than we see today and calls for regional sludge management rather than plant based solutions. Regional clusters will also enable the beneficiation of the economy of scale effect.

Another, less vulnerable route appears to be the production of phosphoric acid out of SSA. The company EcoPhos declares to be able to process SSA independently from the Fe/Al content, which opens their business model for the big fish among the SSA, since current P removal in WWTPs is manly done by precipitation as hardly soluble Fe or Al phosphates. H_3PO_4 can be considered a commodity and market sales are therefore secured. A similar approach is followed by the German company Remondis-Aqua, currently running a pilot of their TetraPhos technology in Hamburg.

- ***P_4 production***

Thermphos, a former phosphorus chemicals producer from the Netherlands, integrated suitable sewage sludge ashes to their existing industrial production of white phosphorus (P4), as a complementary raw material to phosphate rock. By this, Thermphos reduced their operational costs, as the price of suitable ash was lower than the price of the rock phosphate. Additional challenges, such as higher iron, copper and zinc concentrations of the new raw material were overcome. Essential partners were sewage sludge incinerators, attracted by the offer to turn the ash, a typical waste and cost factor, into an asset. The price also enabled Thermphos to procure high quality ashes, relatively low in impurities. Meat and bone meal ashes were also processed on a large scale. Thermphos, the only white phosphorus (P4) producer in Europe, produced for high end markets such as chemical and food industry, etc. The recycling operation of the company with reputation as a reliable European supplier was not questioned by the customers. Thermphos went bankrupt in 2012, due to causes unrelated to the recycling activities.

- ***Ammonium nitrate (AN)***

Besides phosphorus, another valuable nutrient can be recovered from wastewater. Although nitrogen is not considered physically limited, its availability for food security is strongly dependent on energy. The usual process to transform elemental N_2 into NH_3 is the energy intensive Haber-Bosch process. Since nitrogen is dissolved in wastewater in ionic form it would be rather reasonably to tap it from this renewable resource instead of blowing it back into the air and then transforming it again worth a lot of energy into NH_3. A common N-material in fertilizer production is NH_4NO_3, which can be recovered at WWTP by ammonia stripping and trapping in nitric acid. The fertilizer company YARA and a WWTP in Norway cooperate and have established a value chain with AN as product recovered by ammonia stripping from wastewater.

These examples show, that there are various business options to valorize nutrients recovered from the wastewater stream already, even with the existing legal framework. But a lot more of reasonable recycling could have been done already with a legal framework allowing a level playing field for both, primary (fossil) material based fertilisers and secondary (renewable) based fertilisers.

5 Legal environment

Table 2 gives an overview on European Regulations and Directives relevant for activities aiming at placing recycled phosphates on the market. The summary of relevant legislation is divided in three categories:

- Legislation governing the product covers obligations on physical/chemical characteristics, packaging and trading of products in general and fertilizer in particular.
- Legislation governing the production plant covers the requirements for building a production plant for recovery of mineral phosphorus and fertiliser production, including the permits for construction, operation and the environmental impact of the facility.
- Legislation governing waste management regulates wastewater treatment, use and treatment of sewage sludge and protection of water and (agricultural) soil.

Table 2: European legislation relevant for recycling of phosphorus in mineral form for fertilizing purposes

Title	**Number/Abbreviation**	**Enactment/Implementation**	**Focus**
Regulations	Automatically enforced in all Member States		
Registration, Evaluation, Authorisation and Restriction of Chemicals	Reg. (EC) 1907/2006 REACH	01.06.2007	Safe use of chemicals
Classification, labelling and packaging of substances and mixtures	Reg. (EC) 1272/2008 CLP/GHS	20.01.2009	Safe use of chemicals
Fertiliser Regulation Under recast aiming at enabling recovered phosphate materials Type definition in annex I	Reg. (EC) 2003/2003	11.12.2003	Free trade. Scope, types, declaration, identification, properties and testing of EC-fertilisers
Organic Products Regulation	Reg. (EC) 834/2007	28.06.2007	General rules on organic farming
Production, labelling and control of organic products Type definition in annex II	Reg. (EC) 889/2008	05.09.2008	Production, labelling and control of organic products
Shipment of Waste Regulation	Reg. (EC) 1013/2006	14.06.2006	Safe transport of waste
Animal By-products Regulation	Reg. (EC) 1069/2009	21.10.2009	Use of animal by-products, human health protection
Directives	Implementation in Member States' legislation needed		
Directive on Industrial Emissions (Integrated Pollution Prevention and Control)	Dir. 2010/75/EU IED (IPPC)	06.01.2011	Permission for polluting activities, emission limits, BAT
Directive on the Assessment of the Effects of certain Public and Private Projects on the Environment	Dir. 2011/92/EU EIA	13.12.2011	Environment and health protection, assessment of impacts of projects and installations
Waste Framework Directive	Dir. 2008/98/EC WFD	12.12.2008	Environment and health protection by waste management; definition of end of waste status
Landfill Directive	Dir. 1999/31/EC	16.07.1999	Safety of waste disposal
Water Framework Directive	Dir. 2000/60/EC	23.10.2000	Inland, coastal and ground water protection

Title	Number/Abbreviation	Enactment/Implementation	Focus
Nitrate Directive	Dir. 91/676/EEC	31.12.1991	Nitrates from agricultural sources including farmyard manure; code of good agricultural practices
Groundwater Directive	Dir. 2006/118/EC	12.10.2006	Prevention and control of groundwater pollution
Urban Wastewater Treatment Directive	Dir. 91/271/EEC	21.05.1991	Environment protection from wastewater discharge
Sewage Sludge Directive	Dir. 86/278/EEC	12.06.1986	Use of sewage sludge on cropland

An extensive review of the legal frameworks on EU level and the states Germany, Czech Republic, Spain and Switzerland is provided in D11.2 *Pre-Normative matrix. Review of fertilization schemes. Review of current legal framework for phosphorus recovery.*

The following policy implications have been proposed in the policy brief:

1. **Long-term stability and reliability for establishment of efficient treatment technologies** Business experiences presented above were "add-ons" to existing systems. Long-term advantages of recycling efforts in Europe such as security of supply and internalized environmental costs are not accounted for in market-based decision-making today. Efficient phosphorus recovery and recycling systems call for new market players needing market drivers and long-term reliability of the enabling legal framework to back up their investments. A systemic change from exclusive use of fossil phosphorus to a mix of fossil and recovered phosphorus is needed. **Possible solutions:**
    - An achievable European long-term goal for phosphorus recovery rates from wastewater or import dependency reduction combined with a European overall implementation road map, based on sound and reliable mass flow data.
    - Sectoral (wastewater treatment, agriculture, etc.) toolboxes describing the best available technologies for different boundary conditions.
2. **Regional solutions for smart P-recovery and recycling scenarios, meeting the overall goals, are needed.**
   Use of sewage sludge and nutrient demand in agriculture differ from country to country and region to region. Due to existing infrastructure and needs some technologies are better suited for use in certain places than the others. Overall coordination enables efficient, coordinated investments on country-level. One example is phosphorus recovery from ash. It enables the highest recovery rate, but needs centralized sludge management and high investment costs for incineration facilities. Challenges in raw-material supply contracting need to be overcome. Another example is that individual steps in the treatment chain such as high WWTP phosphorus removal rates and EBPR provide synergies for phosphorus recovery, but are not necessarily the cheapest solution. Collaboration along the value-chain will lead to higher efficiencies, when disadvantages of system change at one point are compensated by the advantages of the subsequent recycling steps.

Possible solutions:

- Implementation regional action plans for phosphorus recovery, with private and public sector participation, taking into account the local nutrient demand, sources and other boundary conditions
- Legal and organisational support to enable reliable supply with ash as input material for the recovery from ash facilities
- Establishment of value chains from WWTP to farm is needed to enable efficient P-recovery and recycling, fitting the needs of agriculture

3. **Support for fulfilling the legal obligations, within and apart from the fertiliser framework**
Legislation affecting the recycling is interpreted differently in the member states. Recyclers and authorities alike would profit from unambiguous guidelines describing how to best address all legal obligations relevant to phosphate recycling from the wastewater stream. For safety assurance and acceptance of the recycled phosphates Europe-wide quality standards within and outside of the Fertiliser Regulation are of central importance. Allowing raw-material from secondary sources in the Fertiliser Regulation is essential for market penetration of products containing recovered phosphorus. Allowing a wider range of possible starting materials for fertilisers together with heavy metal and other limit values were planned to be integrated into the Fertiliser Regulation recast. Rapid incorporation of these aspects is central for end-users and recyclers alike.
Possible solutions:
    - Guidelines for meeting the legal obligations regarding valorisation of recovered phosphorus, covering the Waste Framework Directive, Sewage Sludge Directive, Fertilisers Regulation and REACH. Differentiation between the cases
        - wastewater derived mineral materials with and without fertiliser status (e.g. underlying Fertiliser or Waste Framework Directive) and
        - high quality (safe) sewage sludge.
    - Follow through the work started: integrate secondary raw materials and quality standards into the European Fertilisers Regulation.

4. **Financing**
Who pays, who benefits? - Phosphorus recovery, as most of the environmentally sound actions benefiting the society as a whole, come with cost. Transparent discussion on acceptable cost and allocation of these costs, as well as transition timeframes and market entry need to be started now! Hard legislation such as mixing quota or recycling obligations lead to forced market entry in a given timeframe. It provides planning reliability for investments, encourages initiatives due to clear transition periods and can help enforcing adequate quality criteria for phosphorus recycling. Soft legislation such as tariffs on fossil phosphorus or subsidies for recovered materials is beneficial, but lacks the clarity of the hard legislation. Both types of legislation can be used to implement a European roadmap.
First Movers Risk - Innovation and start-ups are typically challenged by large up-front investments, which can, in time, be paid back completely or at least partially. First movers making long-term investments face the risk that a competitor within few years will have a similar technology which is more competitive.
Possible solutions:

- Mechanism for distribution of cost. Either hard legislation such as mixing quota for fertiliser production or recycling obligations from phosphorus rich wastes or soft legislation such as tariffs on fossil and subsidies for recycled material.
- Substantial financing of and investments support for demonstration plants would speed up implementation, which would in turn lead to product market development and lessons for policy and further process development. A market will only develop with references.

6 Assessment results

Detailed assessment results and methodologies for assessments can be downloaded at www.p-rex.eu.

Table 3: Table of relevant deliverables and link to www.p-rex.eu/download section

Deliverable/output	Title
D4.1	Technical comparison on the design, operation and performance of ash processes
D5.1	Comparison of sludge related processes
D6.1	Full-scale performance of selected green polymers in sludge dewatering
D7.1	Guidance document for safe sludge monitoring
D8.1	Quantification of nutritional value and toxic effects of each P recovery product
D9.1	Risk Assessment of secondary P fertilizers
D9.2	Environmental footprints of P recovery technologies via LCA
D10.1	Report on LCC of European P recovery scenarios
D11.1	Report on market for P recycling products
D11.2	Pre-normative matrix for P recovery products regarding product type and required/obtainable quality
D11.3	Policy brief - P recycling now!
D12.1	Integral guidance document for phosphorus recovery from the waste water stream
Fact Sheets	For the Recovery Technologies assessed in P-REX and the applied hypothesis for reference
Animated film	P-REX in 2 minutes animated film with subtitles in several languages http://vimeo.com/78539404
eMarket	Match making platform for supply with and demand for recovered nutrients http://e-market.phosphorusplatform.eu/

6.1 Assessments on toxicity

Toxicity and avoidance tests were realised on freshwater shrimps, duckweeds and earthworms. Phyto-toxicity was tested on turning rape and oat. Furthermore unspecific tests for microorganisms on carbon and nitrogen transformation were conducted. From all tests the earthworm avoidance test showed the most sensitive results. Generally avoidance or mortality effects could only be observed for high concentrations, which are very unlikely under conditions of exposure in environment. Major distinctions between recycled fertilizers and conventional fertilizers could not been detected. Toxic effects correlate more with (P) solubility of products. Concluding these matrices based results, it is not possible to estimate absolute or relative ratios between the observed toxicity and still tolerable doses based on matrix effects, since a concept and convention of a “matrix-based PNEC” is missing. Based on available Guidance Documents for singular (organic) substances (IHCP 2003) further long-term toxicity test on different organisms and trophic levels are recommended to cope with current uncertainties. Furthermore, to enable matrix based risk assessments in the future, reliable methodologies should be developed and agreed within the European standardization bodies under the umbrella if CEN.

6.2 Assessments on plant availability, pot and field experiments

Pot experiments were conducted for all recovered materials except the Struvia and the EcoPhos “products”. All materials except the Mephrec[1] slag have shown relative fertilizer effects above 80 % related to triple super phosphate. Struvite products showed on neutral soils (pH 7.1) even slightly higher yields than the conventional fossil P based fertilizer TSP. Comparing sludge from WWTP with biological and chemical P removal, the sludge from the WWTP with the Bio-P resulted in a 50 % higher yield than the sludge from WWTP, where Fe salts were used for Chem-P removal. Good correlations were achieved between plant availability, yield and citric acid and neutral ammonia citrate acid solubility of P_2O_5 in recyclates. None of the P recyclates had a high water solubility of P_2O_5; indicating that water solubility alone is not a reliable indicator to predict fertilizer efficiency as expected since dissolved P is immobilized at soil particles within few weeks.

Results of the field experiments revealed no effects between the products and control; since P content in arable soils of the field demonstration plots were too high. P depleted soils are very hard to find in Europe. To obtain reliable data, it is also important to run such field experiments for several seasons, as just started in the German project InnoSoilPhos coordinated by the Science Campus Rostock. The project has a duration of 9 years and therefore can be expected to generate reliable data on fertilizing efficiencies for both, renewable and fossil based fertilizers. Since the P recovery and recycling technologies are still in implementation and maturization phase, it can be expected, that new recyclates will enter the market in the coming years, calling for an EU-wide initiative to evaluate renewable fertilizers in the near future over a longer period.

6.3 Contaminant risk assessment

The contaminant risk assessment was conducted assessing risks by target substances within the products for the endpoints soil organisms, groundwater and humans. Based on the background of made assumptions, risks regarding Zn could not be excluded for the endpoint soil organisms for specific conditions. For the endpoint groundwater, risks regarding Cd and Zn could not be excluded for specific conditions, due to high leaching rates of these mobile metals at levels below pH 6. Risks for humans by plant consumption cannot be expected. Nevertheless risk reduction measures are recommended for almost all substances and endpoints. The risk assessment also pointed out that the main input of the observed persistent organic pollutions (PCDD/F, dl-PCB and PAH) into arable soils does not come from sewage sludge application under normal conditions. The annual atmospheric

[1] To be mentioned, that the results based on the only batch of Mephrec slag from pilot tests in 2008 shall not be generalized. Another batch provided good results in pot-tests conducted in Saxony. So, the process conditions for producing a good quality fertilizer still have to be determined.

deposition of these substances is at least 10-fold higher, leading to the conclusion, that for these substances, the IED should be adapted accordingly to reduce the related risk. For heavy metals; sewage sludge and fertilizers (conventional and secondary) are more relevant than diffuse sources in most cases. Struvite (AirPrex, Pearl, Struvia, Stuttgart and Gifhorn) showed the lowest contaminations and risk ratios; their recycling instead of conventional phosphorus fertilizer or sewage sludge reduces risks. Overall the risk ratios of secondary phosphates are in the same magnitude as for conventional phosphorus fertilizers.

6.4 Life-cycle assessment

In a comparative life-cycle assessment the different "recovery systems" (including technical processes, chemical/electricity demand, their emissions and product and by-product valorisation) had been evaluated according to ISO standards 14040/44 (ISO 14044 2006). The indicators for impact assessment cover cumulative energy demand (fossil and nuclear), metal depletion potential, global warming potential (100a), terrestrial acidification potential (100a), freshwater and marine eutrophication potential, eco-toxicity (freshwater) and human toxicity. As one example for an LCA indicator, the relation between P-recovery rate and total cumulative energy demand of fossil fuels for the technologies is reflected. It reveals that struvite recovery from sludge or liquor is energetically beneficial, but has only a limited P-recovery rate (5-12%). In contrast, wet sludge leaching processes have a higher recovery rate (up to 50%), but the leaching chemicals require a high energy input for their production. Phosphorus recovery from mono-incineration ash provides the highest recovery rates (up to 98%), comparable with direct sludge valorisation in agriculture. However, energy demand of ash treatment can vary depending on the process (ash leaching, thermo-chemical, metallurgic) and the potential integration of thermal processes into existing incineration facilities for efficient heat management. Overall, LCA results for energy demand show that P recovery can be realised with energy benefits via struvite recovery from sludge/liquor without leaching or via ash treatment after mono-incineration. For ash processes, it has to be kept in mind that undiluted mono-incineration of sludge is prerequisite to produce a suitable ash with high P content, ruling out co-incineration of dewatered or dried sludge in power plants or cement kilns which would lead to higher energy recovery from sludge compared to already existing mono-incineration.

6.5 Cost assessment

The cost of the phosphorus recovery process as well as the transition costs when moving to from a system without to a system with phosphorus recovery was assessed. The latter includes for example the cost of additional mono-incineration capacities if this is needed for the recovery process. The cost of recovery processes was assessed in the cost types CAPEX, energy, material (chemicals and others), personnel and other operational costs. Savings for operational benefits and guaranteed offtake of recovered materials was considered as well. The costs were of sludge based processes were assessed for a reference plant with 1 million person equivalents (p.e.) and ash based processes were assessed for typical plant sizes (2.5-2.7 Mio PE). All costs were assessed using German prices[2].

[2] Please note, prices may vary from country to country!

Transition cost vary from -4 EUR/ kg P to 4 EUR/ kg P for precipitation processes, about 10 EUR/ kg P for sludge leaching and 0 EUR/ kg P to 5 EUR/ kg P for processes based on dry sludge and ash when the current disposal is mono-incineration. If the current disposal is co-incineration of agricultural use, the transition cost is about 2 EUR/ kg P higher. The cost range per capita and year is from -4 EUR/cap y to 2.50 EUR cap y which can be compared to wastewater (net and treatment) costs of 108 EUR/cap y[3]. Thus the decision to pass legislation making recovery mandatory can be seen as affordable and it can be passed if the benefits such as overall lower environmental impact, creation of jobs and less dependence on the critical raw material phosphate rock are considered important.

Sensitivity analyses show that higher phosphorus content decreases the specific cost as most cost types are constant. Increased plant size and lower depreciation rates are also lowering specific costs, namely the CAPEX. However, the transport costs to larger plants have to be considered (see Chapter 7 Europe-wide implementation of P recovery and recycling)

6.6 Lessons learned from assessments

The assessment results indicate a number of distinctions in processes and products. Also the current status of implementation differs as well as the potential to even improve the technologies. Table 3 and Table 4 give a qualitative overview on sludge and ash processes assessed within P-REX; a number of crucial process and product characteristics, costs, limits and recommendations by the P-REX consortium.

[3] Lamp, H., & Grundmann, T. (2009). Neue Entgeltstatistik in der Wasser- und Abwasserwirtschaft. *Wirschaft Und Statistik*, *6*(L), 596–601. Retrieved from https://www.destatis.de/DE/Publikationen/WirtschaftStatistik/Umwelt/EntgeltWasser.pdf?__blob=publicationFile

Table 3: Lessons learned table on sludge processes

Process type	***Precipitation processes***			***Sludge leaching processes***	
Process	***AirPrex***	***Pearl***	***Struvia***	***Stuttgart***	***Gifhorn***
Input material	Digested sludge (dissolved P fraction)	Sludge liquor/process water (dissolved P fraction)		Digested sludge (dissolved and partly fixed P fraction)	
Method	Precipitation in sludge	Precipitation in sludge water		Acidic leaching in digested sludge, precipitation in sludge water	
Recovery rate *(% of total P in sludge)*	5-20 %	10-20 %		Up to 50 %	
Recyclate/Product	Struvite				Struvite/Ca-P
Contaminants	Low (Cd, Hg < 0,5 mg/kg; Cr, Ni, Pb < 20 mg/kg; Cu < 50 mg/kg; Zn < 100 mg/kg)				
Influence of sludge/ash contamination on quality	Low due to formation of relatively pure crystals				
Plant availability	High (relative fertilizer efficiency at least 80 % compared to triple super phosphate)				
Energy efficiency	Very good; high energy benefits (improved dewatering)	good; even energy savings		High; very energy intensive due to production of needed chemicals	
Coupling of P and energy recovery from sludge	coupling with co-incineration possible				
Costs per kg recovered P *(dependency on plant-size)*	Cost saving due to better dewatering (< 0 EUR)	Low (0-5 EUR)		High (>10 EUR)	

Continuation of Table 3

Process type	***Precipitation processes***			***Sludge leaching processes***	
Process	***AirPrex***	***Pearl***	***Struvia***	***Stuttgart***	***Gifhorn***
Implementation	Onsite at WWTP				
Infrastructural limits	Dissolved ortho-P (EBPR plants only?)			Availability of chemicals	
Potentials	Combination with thermal hydrolysis or biological pretreatment (WASSTRIP) increases recovery rate due to increased re-dissolution of P			Trade-off between chemicals demand/costs and recovery rate	
Full-scale operations	> 5 commercial full-scale plants per process		None, pilots		None in current use, former full-scale for test production
Reasons for current status	Economic feasibility, short pay-back due to operational benefits	Business model of technology provider	No technology roll-out by technology provider yet	High operational costs and energy consumption	
Legislative aspects for recycling	Struvite is registered in REACH and approved as mineral fertilizer in some member states		Once P is dissolved, it can be crystallized (i.e. struvite, Ca-phosphates)		
Recommendations	Best practice – Implementation should be promoted where applicable			Not suitable (operational barriers and high cost)	

Table 4: Lessons learned table on ash processes

Process type	***Metallurgic sludge treatment***	***Recovery from Ash***		
Process	***Mephrec***	***AshDec***	***Leachphos***	***EcoPhos (H_3PO_4)***
Hotspot in the WWTP *(P fraction)*	Dried sewage sludge (P fraction in solid phase)	Ash (P fraction in solid phase)		
Method	Metallurgic phase separation	Thermo-chemic	Ash leaching and precipitation of phosphorus	Ash leaching and acid purification by Ion-Exchanger
Recovery rate *(% of total P in sludge)*	≈ 80 %	> 95 %	≈ 70 %	≈ 90 %
Product	P-slag and Fe-slag as by-product	Ca-Na-P	Ca-P	H_3PO_4 and Fe-/Al-Cl_3 as by-product
Contaminants	Medium (Cd, Hg < 1 mg/kg; Ni, Pb < 20 mg/kg; Cr, Cu, Zn ≈ 100 mg/kg)	Medium (Cd, Hg < 1 mg/kg; Cr, Ni, Pb ≈ 100 mg/kg; Cu, Zn > 500 mg/kg)	Medium (Cd, Hg ≈ 1 mg/kg; Cr, Ni, Pb < 40 mg/kg; Cu, Zn > 500 mg/kg)	Very low (Cd, Hg, Ni, Pb < LOQ; Cu, Cr, Zn < 20 mg/kg)
Influence of sludge/ash contamination on quality	Medium	High	Medium	Low
Plant availability	Low (relative fertilizer effect < 50 % compared to triple super phosphate)	High (relative fertilizer effect at least > 80 % compared to triple super phosphate)		Not tested, since product is not a fertilizer
Energy efficiency	Good or bad, depending on whether the process is integrated into another incineration plant	Good; especially when process is integrated into a mono-incineration plant	Medium; efforts for production of chemicals	Good; efforts for production of chemicals, but trade-off due to product values
Coupling of P and energy recovery from sludge	Only for integrated process	requires mono-incineration; recovery of steam instead of electricity in incineration		
Costs per kg recovered P *(dependency on plant-size)*	Low (5-10 EUR, but cost for sludge disposal disappear)	Low (0-5 EUR)	Medium (5-10 EUR)	Low (0-5 EUR)

Continuation of Table 4

Process type	***Metallurgic sludge treatment***	***Recovery from Ash***		
Process	***Mephrec***	***AshDec***	***Leachphos***	***EcoPhos (H_3PO_4)***
Implementation	Regional solutions are preferred, due to cost savings (> 2.5 Mio pe)			
Infrastructural limits	None, primary designed for sludge with high Fe content	Mono-incineration is compulsory	Mono-incineration is compulsory, problems with ashes with high Fe-content	Mono-incineration is compulsory
Potentials	Costs decrease with integration into existing infrastructure		none	Synergies or combination with plants processing phosphate rock
Full-scale operations	None, pilot in 2017	None, test production		None, pilot, leaching process using commercial acid and purification starting 2017 in full-scale
Reasons for current status	No technology roll-out by technology provider yet	higher costs compared to conventional fertiliser production		Currently roll-out by technology provider
Legislative aspects for recycling	Not produced in significant quantity, REACH registration unclear			REACH registration very likely due to high product quality
Recommendations	Full-scale data needed for evaluation (integrated process promising)	Full-scale data needed for evaluation (but high product price compared to current market)		Promising technology, full-scale data needed for evaluation

6.7 Life-cycle and cost assessment on sludge disposal

In contrast to former studies, e.g. (Pinnekamp et al. 2013), P-REX demonstrates by a systematic assessment the relevance of sludge disposal regarding Europe-wide implementation of technical P-recovery schemes. It became apparent that this is at least as important regarding cost and environmental efficiency like the design and selection of the recovery process. A pure focus on the valorisation of P-recovery products out of mono-incineration ashes might be the right option, if these ashes are already produced. The comparison of sludge disposal routes revealed that a transition of currently agricultural used or co-incinerated sludge to mono-incineration in terms of technical P-recovery with high recovery rates may not be the best solution in terms of cost-, energy and climate efficiency and is also discussable regarding resource efficiency in terms of nitrogen and carbon. Figure 7 gives a comparison of different sludge disposal routes in the P-REX reference system for costs, fossil cumulative energy demand and climate change.

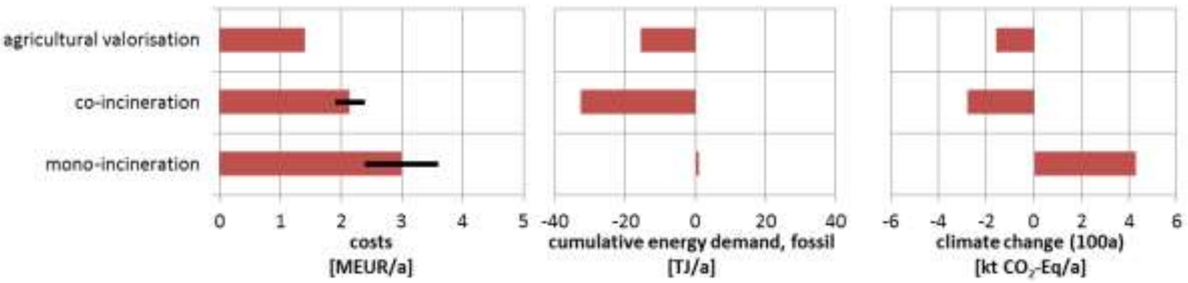


Figure 7: costs, fossil cumulative energy demand and climate change (100a) for different sludge disposal routes for a 1 million p.e. waste water treatment plant (P-REX reference system)

The comparison shows differences in costs (higher costs for mono-incineration compared to other sludge disposal options) but also major distinctions in the selected environmental impact categories. Regarding the energy demand, co-incineration is assumed with a higher energetic utilization ratio than mono-incineration. Agricultural sludge valorization is also assessed with a better energy balance than mono-incineration, since P- and partly N-fertilizer production is substituted. Especially the manufacturing (Haber-Bosch process) of conventional N-fertilizer is high energy consuming. These energetic benefits also conclude in the impact assessment for climate change. Mono-incineration has to be reflected critically, since other studies (IPCC 2006); (ATV 1996) showed high N_2O-Emissions and thereby a high greenhouse gas potential. Also sludge transportation can be considered as a relevant parameter regarding costs- and energy-efficiency. Regional studies reflecting these local boundary conditions thereby help to quantify impacts more accurate.

7 Europe-wide implementation of P recovery and recycling

As already mentioned one key element of sustainable phosphorus management is closing the nutrient cycle by recovery and recycling. Although enabling technologies for recovery and recycling are already there, only some of them are economically viable under current conditions. In the case of wastewater treatment, the only technologies applied today have not been exclusively installed to recover phosphorus. The key drivers were and still are operational issues like process stability and monetary benefits.

The following issues can be seen as a challenge for, or even barrier to, the wide-spread implementation of technical phosphorus recovery and recycling options:

- Low market prices for fossil P based raw materials and products challenge the economic viability of many recovery technologies, especially when these technologies do not provide operational benefits and yield recovered material that is not directly marketable. If there is no prospect of profits, investors will spend their money in other sectors and markets. Here realistic recovery targets could motivate or even enforce recovery and recycling. It is important not just to foster recovery alone. The recovered materials need to find a market. Otherwise, and as a worst case scenario, recovered materials end up as waste and have to be disposed of as such.
- Technologies and recovered materials that cannot be integrated into existing infrastructure and markets have to cope with strong competition from established structures. Therefore the more varied the ways in which the recovered product can be used, the better. White phosphorus P_4 or phosphoric acid (H_3PO_4) are examples of versatile phosphoric intermediates. But it is not only the downstream market potential that determines the vulnerability of a technology or value chain. The security of supply of the raw material is also crucial. The more versatile the technology is in terms of input material, the better. For example, a technology that can process various fossil and/or secondary P sources is less vulnerable compared to a technology depending on, for instance, sewage sludge ash alone.
- The legal framework is tailored for existing structures and is very slow at adapting to future challenges. In relation to resource efficiency and sustainability, we are still a long way from implementing what is being discussed. For example, the upgrading of recovered material from being treated as a waste to being considered a product is proving to be a challenge. The re-definition of End-of-Waste criteria is a tough process but is a prerequisite to enable value chains to bridge the gap between recovery and recycling, and making a circular economy really happen. Therefore, the revision of the EU fertiliser regulation (EC 2003/2003) needs to be supported to provide a level playing field for fertilisers, irrespective of whether they are produced from fossil or secondary sources. (Hukari *et al.*, 2015) Another issue that needs to be considered is the application of appropriate products for use in organic farming, for instance by adding recovered struvite and other suitable recyclates to the list of approved fertilisers in EC 889/2008.
- Market penetration and replication will only happen with full-scale demonstrations (references). There is simply no chance for replication without full-scale demonstration! Instead of spending public money for broadening the range of technologies, the focus should be on setting up full-scale demonstrations of the most promising options to allow the essential step forward from non-matured towards matured technology. This should be augmented by making the most out of the existing infrastructure.

7.1 Results of regional case studies

In a European context, advices for Europe-wide implementation of P-recycling have to be adjusted on the current sludge disposal infrastructure in the specific regions. Within P-REX regional case studies for implementation of technical P-Recycling were performed. One essential result is that an overall change of the existing sludge disposal infrastructure into an isolated, just on P recycling focussed mono-incineration scheme is not the answer to everything. Fostering a circular economy on a broad level for nutrient recovery and recycling in combination with energy efficiency, low greenhouse gas emissions of the sewage sludge disposal scheme and exposition of contaminants in European soils is complex and does not allow any one-fits-all solution. Furthermore with current state of research and demonstration there is no single method existing, which provides an optimal solution regarding all possible factors. As consequence for P recycling region-wise realistic short- and mid-term targets should be defined and supported. Considering the P-REX results three options for P-recycling are promising or already existing:

- **Sludge valorisation in agriculture** is as traditional way of nutrient recycling for many European countries also a god option towards P-recycling in the future. Most urgent advantage of direct sludge valorisation is due to its cost efficiency, the principal high P-recycling rate and the recycling of other nutrients like nitrogen and carbon compared to many technical P recycling schemes with incinerations. Due to a partly substituted conventional nitrogen fertilizer production, sludge valorisation is interpreted as energetic efficient way of P-recycling with comparably to incinerations low greenhouse gas emissions.

  Disadvantage of this traditional way is due to contamination of sludge and partly reduced fertilizer effect of sewage sludge considering phosphorus. Technical and non-technical measures for a cleaner wastewater and consequently a cleaner sludge partly had been improved and partly can be improve the sludge quality and decrease the concentrations of heavy metals and persistent organic pollutions. Technical measures like aerobic stabilization of sludge in the WWTP can reduce uncertainties regarding pathogens. Nonetheless, sewage sludge is and will be the matrix out of the WWTP where contaminants accumulate. The fertilizer effect of sewage sludge regarding phosphorus is related to the Fe: P-ratio in the sewage sludge. Thereby sludge valorisation from WWTP using EBPR can be considered as more effective P-recycling since a higher plant availability of phosphorus is reached compared to sludge from chemical P-elimination with Fe or Al.
- **Struvite precipitation in sludge/ sludge liquor and their valorisation** is from technical P-recycling options the only full-scale running process, which had been implemented in over 20 plants in Europe so far. Main reason for that was and is not the ambition to recover or recycle P, instead the reduction in maintenance cost and energy demand within the sludge treatment of some plants are crucial issue for the success of these technologies. Although the recovered struvite is plant available, low contaminated and produced to market-price, recycling is not automatically guaranteed, since WWTPs normally do not have access to the fertilizer market. A key issue towards circular economy within the next years will be to bridge the gap between recovery and recycling for struvite from WWTP as pioneer substance for other recycled materials. The respectively low P-recovery rate of the current full-scale plants of 5-20 % compared to the potential in sewage sludge can be increased by options forcing an additional dissolution of phosphorus, combining this with increasing energy efficiency in the sludge treatment.
- **P-recovery from mono-incinerated ash and valorisation of P-products from** has to be successfully proven in full-scale. Processes producing a marketable product (like technical

H_3PO_4) thereby seem more promising than others. A crucial issue for the financial set-up of these processes may be the P-content in ashes, which is quite diverse. With focus to sludge disposal it had become partly practice to incinerate mixtures of different types of sludge from sewage treatment and industry together. Consequence is an ash with respectively low P-content, which will probably not useful for P-recovery. In terms of P-recovery from ash this attitude has to be rethought. Under these circumstances it might be possible to increase the P-load in ashes, without increase the amount of ash and use existing infrastructures to increase the potential P recovery amount out of ashes.

All three routes have their relevance in context of a Europe-wide implementation or expansion of P-recycling. Regions with prohibition or low proportion of agricultural sludge valorisation and high proportion of mono-incinerations should consequently try to establish the recovery route via ash. Regions with high proportion of agricultural sludge valorisation and no substantial mono-incineration-infrastructure should consequently choose this route since the transitions to a circular economy regarding P are respectively low that way. Additionally (or if necessary) measures to increase fertilizing efficiency and risk reduction should be established high quality sludge. Wherever sludge valorisation is prohibited or limited, since limits regarding sludge contamination are exceeded or a local nutrient surplus in soils exists, sludge valorisation may be contra-productive and other technical options should considered. Struvite precipitation should be implemented everywhere, where it is applicable; since operational benefits optimize cost and energy efficiency of the sludge treatment. Consulting long-term strategies and increasing efficiency of struvite processes in the next decade, the increase of the applicability of struvite processes (increasing the proportion of Bio-P plants) might be also an option.

8 Conclusions & Recommendations

In the following section, the key question for achieving high recovery and recycling rates for phosphorus from the wastewater stream are compiled providing a red line for potential operators, investors and decision makers.

General qualitative questions to be asked and answered by yes or no:

1. Are most households connected to a public sewer system?
    a. Centralized system?
    b. Decentralized system?
2. Are there P discharge limits for wastewater treatment implemented and enforced?
    a. Are they applicable to all WWTP?
    b. Is there a differentiation depending on WWTP size?
3. What valorisation options for nutrients from the wastewater stream are legally allowed?
    a. Water reuse/irrigation?
    b. Sludge/biosolids application on arable land?
    c. Are options and b limited in terms of quantity and application period (seasonal)?
    d. Are recovered nutrients allowed to be mixed or blended with other nutrients?
    e. Sludge incineration mono- and co-incineration capacity?
    f. Is there local/regional P based fertilizer production and retail?

4. Are recovered nutrients from sewage waste or product?
    a. Are End-of-Waste criteria available?
    b. Are the recovered nutrients obliged to REACH?
5. Are there measures in place to secure/improve the sludge quality?
    a. Reliable Indirect discharge monitoring/sewer police
    b. Effective and reliable QMS for sludge destined for land application
6. Is there a demand/market for certain recovered nutrient compounds?
    a. Within existing market structures (i.e. commercial fertilizer market)?
    b. Within new market structures (i.e. in organic farming)?

General quantitative and questions to be considered:

7. What is the rate of connected households to the public sewer system?
8. What size classes of WWTPs are there and what P loads per class are there (national/ regional/local levels)
9. What are the discharge limits (national/regional) and if applicable per WWTP size class.
10. What is the share of anaerobic sludge digestion per WWTP size class?
11. What is the share of EBPR vs chemical P removal applied?
    a. Pure EBPR
    b. EBPR backed up with chem-P
    c. Chem-P distinguished between Fe and Al salt application
12. How are the discharge limits enforced and monitored by authorities
    a. Annual average (providing more flexibility)
    b. 4 out of 5 rule as applied in Germany (no flexibility)
13. Fraction of applied sludge valorization routes?
    a. Share and quantity of sludge applied on arable land
    b. Share and quantity of sludge mono-incinerated
    c. Share and quantity of sludge co-incinerated (coal power plants, cement works, municipal waste incinerators)

Availability of reliable (hard) monitoring data:

14. P (total) concentration and load in WWTP influents
15. P removal efficiencies per WWTP size class and applied method (EBPR, chem-P)
16. P concentration and species in the sludge and sludge liquor (TP, ortho-P)
17. P (total) in WWTP effluents (discharge)
18. P, Fe and Al contents in mono-incineration ashes
19. Potential capacity of a nearby fertilizer manufacturer to partly substitute fossil based P raw materials by recovered raw materials be it for initial processing, mixing or blending.
    a. What are the minimum requirements in terms of supply volume and quality (P, Fe, Al, organics, physical parameters)
    b. Where in the process chain can recovered materials be introduced?

20. Are there other industries nearby to make specific functional use of phosphorus? (flame retardants, detergents etc. the misuse as filler in construction materials has to be avoided)

Questions to be asked by potential operators of technical P recovery and recycling facilities in the water sector – specifically meaning WWTP operators:

21. Are there legal requirements in place to enforce nutrient recovery and recycling?
    a. Cost distribution structure (who is actually paying for wastewater treatment and if applicable for nutrient recovery and recycling)?
    b. Are there specific recovery targets mandatory or agreed by a "green deal" or value chain agreement?
22. Treatment capacity and what is the P_{rec} potential?
23. Quality of wastewater treated (municipal, industrial) and sludge obtained
24. Type of P removal applied (EBPR, Chem-P)?
25. Anaerobic digestion installed?
26. Thermal hydrolysis for sludge disintegration installed or planned?
27. How is the mechanical dewatering performance?
    a. Dewatering devices applied (centrifuge, filter press …)?
    b. Achieved dry matter content in %
    c. Polymer consumption per t DM
28. P content in sludge (species fixed in sludge solids and dissolved in sludge liquor)
29. Sludge quantity
30. Sludge valorization routes (reliability for mid-and long-term disposal/valorization)
    a. Land application possible? Current cost?
    b. External (mono- and co-)incineration options and capacities nearby? Current cost?
    c. Own mono-incineration? Current or possible future cost? Has the ash disposal/valorization to be tendered frequently? Are there ash processing facilities available?
31. Are there concrete plans of neighboring operators for new infrastructural facilities (mono-incineration, central sludge treatment etc.)

Consumer perspective:

32. How can I be sure, whether my food bought at the market is safe or not?
    a. Would I like to be able to choose between food grown on fields with sludge or mineral fertilizers? (Question of labelling)?
    b. Would I like to see a label indicating the share of secondary nutrients on fertilizer packages? (more relevant for farmers than for private customers)
    c. Would I like to have a chance to check the sludge quality of WWTPs Europe-wide in an online emissions reporting platform? (as already implemented for industrial emissions according to IED)?
    d. Am I aware of nutrient recycling options?

e. Would I like to contribute (monetary) to sustainable nutrient management in Europe? Meaning: Am I ready to pay more for wastewater treatment and food?

9 Outlook

Being aware of Europe's vulnerability in terms of P imports and food security, facilitating the Commission's circular economy package should be high on political agendas. But, following the current discussion, rare earth metals and construction materials are the materials of priority. Nutrients, especially from bio-based materials are only somehow present in the revision of the European fertilizer regulation. This indicates, that there still is a strong need for lifting the nutrient related issues higher on political agendas. The case of Phosphorus is and can serve as the perfect template for circular economy, since it unites a strategically important, limited and non-replaceable and therefore essential resource. Everyone has to ask her- or himself, whether electronical devices are essential or not. For nutrients, there is only one answer – YES!

Given the current situation, hopes are not high, that P recovery and recycling from waste(waster) streams will be implemented without political pressure or positively spoken – motivation, if they are not providing operational benefits or competitive product sales prices.

At the first glance, the legal framework today is lacking a level playing field for primary material based products and secondary (renewable) based materials, obviously discriminating the latter. Here the recast of the fertilizer regulation (EC/2003/2003) can help to remove these barriers. This of course is a big challenge having in mind, that there is not only the European Commission, but also 28 Member States with national interests and lack of common sense as obviously proven in the course of this year. Policy making should be more based on facts instead of purely political interests.

Reality based recovery targets for relevant waste streams combined with recycling quotas may be supportive especially in bridging the gap between supply (recovery) and demand (recycling).

To ensure reality based action plans and road-maps, a sound monitoring and compilation of real data is prerequisite. Otherwise strategies can dramatically fail due to investments into the wrong direction. Where there is today uncertainty and guess, there hast to be certainty in the near future!

Since technologies are developing continuously, best available techniques should be frequently updated and benchmarked to enable decision makers to decide for the best suitable solution for their specific needs also regarding regional preferences.

When it comes to innovation, there is always a first mover's risk. The initiative of EC DG GROW in cooperation with the European Investment Bank (EIB) to support implementation by covering a certain risk of bankable projects (business models) can be seen as supportive measure.

It has to be clear focus for the future not to broaden the spectrum of semi-matured or even fancy recovery technologies, but rather more to enable the next essential step for matured technologies to enter the market. Without demonstration facilities as reference, no novel technology will be replicated.

Also to see, what's happening out there, meaning outside Europe can be inspiring. We do not always have to reinvent the wheel!

It is also of high importance to make the most out of the existing infrastructure instead of just calling for “innovation”, which is often mixed with developing new fancy and expensive high-tech. Integration of existing know-how from one sector into another is often much more effective. Seeing opportunities instead of analyzing and discussing problems is much more straight forward and helpful to provide solution.

Having said all that, it is now time to take the next step forward in implementing what we already have today available. Production of the commodity phosphoric acid out of waste looks very promising. But also enabling the production of safe sludge will remain a pillar in the P recycling scheme. Since struvite became a recognized fertilizer, it should also be recovered where ever applicable. Alltogether, there are already three routes waiting to be valorized in fully implemented value chains from recovery to recycling. Think forward, **act** circular!!!

10 Literature

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