



**Global Water  
Research Coalition**

# **Global Compendium on Phosphorus Recovery from Sewage/Sludge/Ash**

Lead Agent: Kompetenzzentrum Wasser Berlin (Germany) and P-REX®  
Environment (Germany)

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**February 2019**



## Global Water Research Coalition

### Global cooperation for the exchange and generation of water knowledge

In 2002, twelve leading research organisations established an international water research alliance: the Global Water Research Coalition (GWRC). GWRC is a non-profit organisation that serves as a focal point for the global collaboration for research planning and execution on water and wastewater related issues.

The Coalition focuses on water supply and wastewater issues and renewable water resources: the urban water cycle. The function of the GWRC is to leverage funding and expertise among the participating research organisations, coordinate research strategies, secure additional funding not available to single country research foundations, and actively manage a centralised approach to global issues. GWRC offers its members the opportunity to leverage resources through cooperative planning and implementation of research.

The present members of the GWRC are:

Canadian Water Network (Canada), KWR Watercycle Research Institute (Netherlands), PUB – Public Utilities Board (Singapore), Stowa- Foundation for Applied Water Research (Netherlands), SUEZ (France), TZW - Water Technology Center (Germany), UK Water Industry Research (UK), Veolia (France), Water Research Australia (Australia), Water Research Commission (South Africa), The Water Research Foundation (US), and the Water Services Association of Australia.

The US Environmental Protection Agency has been a formal partner of the GWRC since 2003. The Global Water Research Coalition is affiliated with the International Water Association (IWA). A new partner has joined the Coalition in 2018, namely the Chinese Academy of Sciences.

GWRC members represent the interests and needs of 500 million consumers and has access to research programs with a cumulative annual budget of more than €150 million. The research portfolio of the GWRC members spans the entire urban water cycle and covers all aspects of resource management.



## Disclaimer

This study was jointly funded by GWRC members. GWRC and its members assume no responsibility for the content of the research study reported in this publication or for the opinion or statements of fact expressed in the report. The mention of trade names for commercial products does not represent or imply the approval or endorsement of GWRC and its members. This report is presented solely for informational purposes.

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Global Water Research Coalition

## Preface

The Global Water Research Coalition is an international organisation that is dedicated to the exchange and generation of knowledge to support sustainable development and management of the urban water cycle. The research agenda is developed by the member organisations of the GWRC and reflects their priorities and recognises global trends and drivers that affect the urban water cycle. The present research agenda includes Resource Recovery as one of the priorities areas.

The objective of this joint effort was to provide an overview of various technology implementations in the field of phosphorus recovery from sewage/sludge in form of a compendium. It focuses on centralized infrastructures and covers operational and regulatory issues. Besides general information on specific technologies or recovery concepts, regional aspects regarding the implementation are addressed. An exhaustive list of technology suppliers should enable potential users to get in direct contact with suppliers in the market. It will not address decentralized concepts, nor will it provide details on R&D projects. The intention of the compendium is to enable potential users (wastewater utilities) of P recovery technologies to identify available and suitable solutions for their needs and to enable them to get insights on related operational, but also legal, aspects to be considered.

GWRC expresses the wish that our joint effort and resulting reports will be useful to all who are active in the field of understanding and venturing into phosphorous recovery from sewage/sludge.

Stéphanie Rinck-Pfeiffer  
(Managing Director GWRC)

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*Watercycle Research Institute*



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## Glossary

AD	Anaerobic Digestion
AN	Ammonium Nitrate
BAM	Federal Institute for Materials Research and Testing
CHP	Combined Heat and Power Plant
DAP	Diammonium Phosphate
DAS	Diammonium Sulfate
DCP	Dicalcium Phosphate (mineral brushite)
DPP	German Phosphorus Platform
DS	Dry Solids
EBPR	Enhanced Biological Phosphorus Removal
EC	European Commission
EGTOP	Expert Group for Technical Advice for Organic Production
EPA	Environmental Protection Agency
ESPP	European Sustainable Phosphorus Platform
EU	European Union
GLOBALG.A.P.	Global Standard for Good Agricultural Practices
HAP	Calcium Hydroxyapatite
HTC	Hydrothermal Carbonization
IFOAM	International Federation of Organic Agriculture Movements
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MAP	Monoammonium Phosphate
Mg	Mega Gramme (metric ton)
MGP	Merchant Grade Phosphoric Acid
N	Nitrogen
NNP	Netherlands Nutrient Platform
OF	Organic Farming
ORC	Organic Rankine Cycle
P	Phosphorus
PA	Phosphoric Acid
PAO	Phosphorus Accumulating Organisms
PRPCJ	Phosphorus Recycling Promotions Council of Japan
ROI	Return on Investment
SPA	Sustainable Phosphorus Alliance
SS	Suspended Solids
SSP	Single Super Phosphate
STP	Sewage Treatment Plant (like WWTP)



TC	Technical Committee
TOC	Total Organic Carbon
TRL	Technology Readiness Level
UF	Ultrafiltration
WAS	Waste Activated Sludge
WG	Working Group
WWTP	Wastewater Treatment Plant

## TRL – Technology Readiness Level Definitions

TRL 1 - basic principles observed

TRL 2 - technology concept formulated

TRL 3 - experimental proof of concept

TRL 4 - technology validated in lab

TRL 5 - technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 - technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 - system prototype demonstration in operational environment

TRL 8 - system complete and qualified

TRL 9 - actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)



## **Executive Summary**

This compendium provides an overview of technology implementations in the field of phosphorus recovery from sewage/sludge. It focuses on centralized infrastructures and covers operational and regulatory issues. Besides general information on specific technologies or recovery concepts, regional aspects regarding the implementation are addressed. An exhaustive list of technology suppliers should enable potential users to get in direct contact with suppliers to foster implementation. The compendium covers technologies already implemented or at the brink to the market. It will not address decentralized concepts, nor will it provide details on R&D projects. The intention of the compendium is to enable potential users (wastewater utilities) of P recovery technologies to identify available and suitable solutions for their needs and to enable them to get insights of related operational, but also legal aspects to be considered.

# 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). As Isaac Asimov stated in April 1959, in his essay 'Life's bottleneck', phosphorus limits the biomass potential on Earth. Essentially, all phosphorus in fertilisers and feed is originally mined from phosphorus-rich rocks, which are finite and distributed in just a few places on the planet. From the Global food security perspective, the geopolitics and economic vulnerability are issues to be taken seriously. Most countries are highly dependent on phosphorus imports (De Ridder et al., 2012; van Dijk et al., 2016). Concerns about the reliability of global P data related to reserves and mining and processing capacities already led to several proposals to establish a global committee for independent monitoring (Wellmer and Scholz, 2015; Acatech 2017).

In contrast to the above 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 5% (van Dijk et al., 2016). Given the estimate figures of 263 Tg P rock globally mined in 2017 (USGS, 2018) and assuming that 90% of the mined P is used for food production, only 12 Tg of the mined quantity finally ends up in form of food on our tables. Thus, 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 P cycle has been proposed – the 5R strategy (Withers et al., 2015).

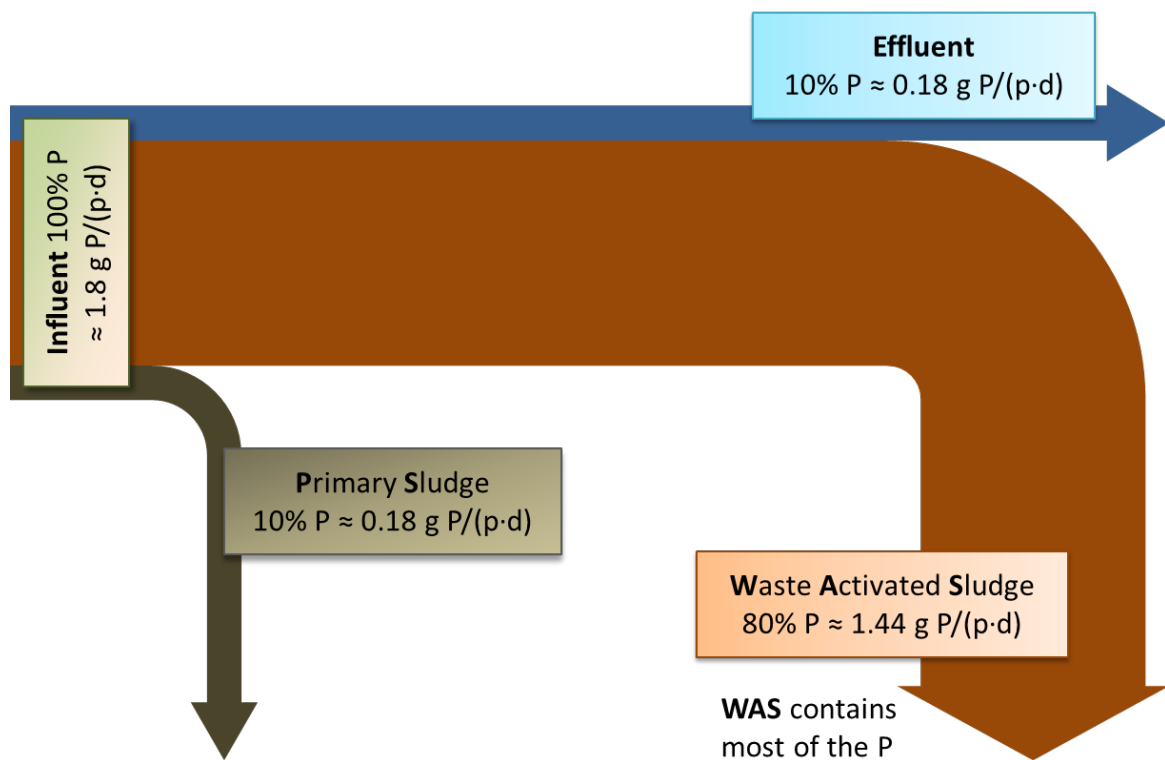
The five Rs are Realign P inputs, Reduce P losses to waters, Recycle P in bio-resources, Recover P from waste, and Redefine our food system.

Recovery and recycling can play an important role in improving resource efficiency and sustainable nutrient management. Although there are various relevant and in the case of manure even bigger waste streams, carrying huge quantities of phosphorus and other nutrients dissolved in liquids or fixed in solids, the focus of the compendium will be laid upon P recovery and recycling from sewage/sludge/ash.



## 2 Phosphorus recovery and recycling from sewage

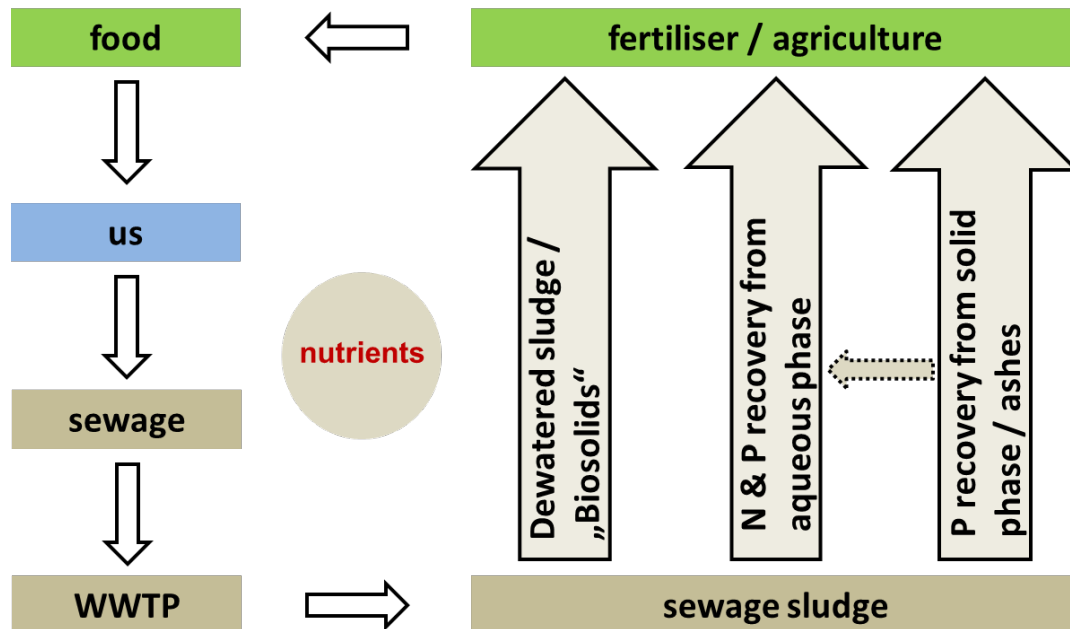
In industrialised countries, sewer systems and wastewater treatment have been implemented to protect human health and the environment and especially water bodies such as rivers, lakes and finally the sea. As a positive consequence phosphorus is collected and concentrated in a manageable mass flow providing 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. In consequence, nutrients such as P, which cause eutrophication, and contaminants such as heavy metals and non-polar organic compounds are concentrated in the sewage sludge. It can be assumed, that 90% of the P entering the WWTP are transferred into the sludge by intended so-called phosphorus removal. Phosphorus is typically removed from the wastewater by biological accumulation in biomass (Enhanced Biological Phosphorus Removal, EBPR) or by chemical precipitation, in the form of barely watersoluble phosphates (normally as iron or aluminium phosphates), leading to the highest P loads in the waste activated sludge (WAS), as illustrated in Figure 1.



**Figure 1:** P removal and where the P ends up in WWTP.

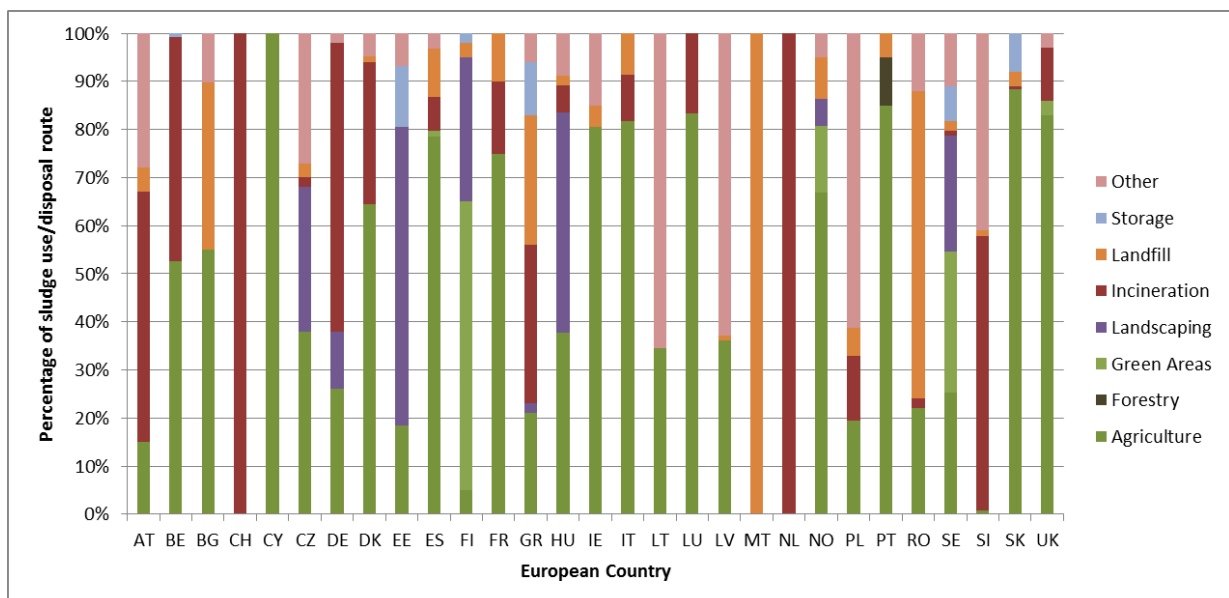
As shown in Figure 2 and given the fact that most of the phosphorus entering a municipal WWTP ends up in the sludge, three principal and complementary routes for closing the phosphorus cycle by recovery from sewage sludge appear to be reasonable.

Direct application of stabilised sewage sludge or biosolids on arable land is the traditional route to valorise all contained nutrients in agriculture. Since this valorisation route can be considered low tech and low cost, it will remain one of the main pillars for nutrient recycling on global scale.



**Figure 2:** The three principal routes for P recovery and recycling from the wastewater stream as a nutrient (Kabbe, 2013).

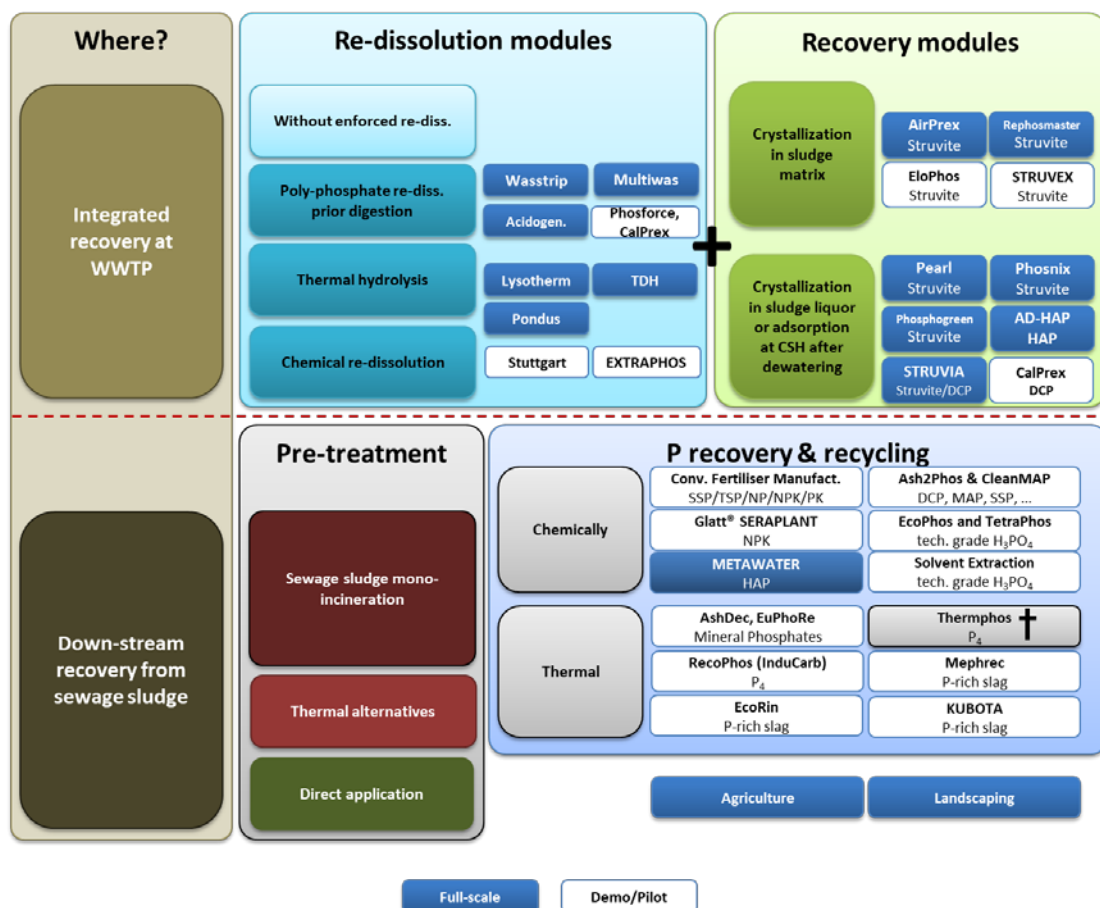
Figure 3 reveals the diversity of sewage sludge valorisation and disposal routes, covering the whole spectrum of valorization or disposal routes between 100% incineration and 100% agricultural use.



**Figure 3:** Sewage sludge valorisation or disposal routes in European countries (Eurostat, 2016; EurEau, 2016; Destatis, 2016).

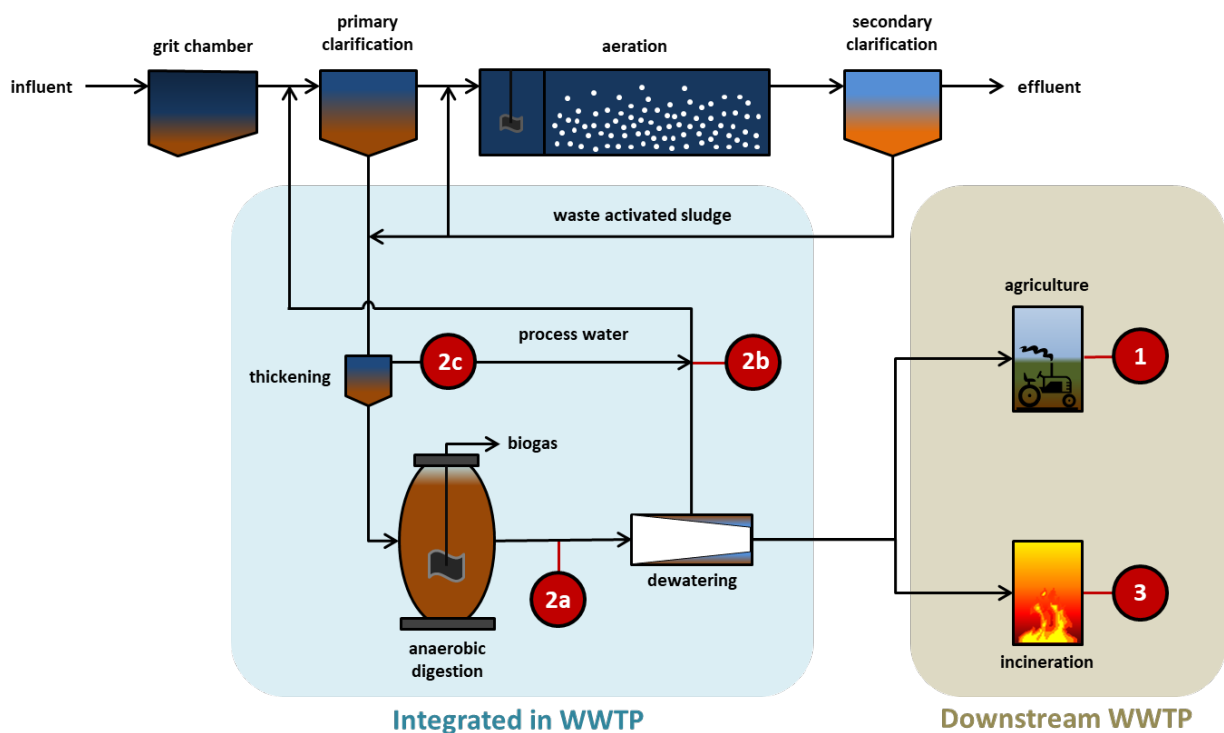
Due to increasing concerns about pollutants, whether known (heavy metals) or unknown (organic contaminants and pathogens), direct application of sewage sludge is questioned by the public and authorities in

industrialised countries. Some of them have banned the application of sewage sludge in agriculture (e.g. Switzerland) completely. Other countries will follow. As can be observed in Germany or the Netherlands, there is an increasing competition of various waste bio-based nutrient flows for the same limited arable land area. It is not surprising that farmers set their priorities on their on-farm waste streams for valorization or disposal. Thus, sewage sludge is more and more under pressure to be alternatively valorized or disposed of somewhere else. The pressure is the highest in hotspot regions with extremely high livestock densities producing more manure than the land can reasonably take. Therefore, the main driver for P recovery is not a potential scarcity, it is rather more an acute surplus or simplified: too much of the nutrient in the wrong place. Urbanisation and the centralization and specialisation of food production led to more and more dislocation of the nutrient flows making it continuously harder to bridge the gap between supply and demand for nutrients in the agricultural system. Therefore, solutions for technically advanced P recovery and recycling providing defined nutrient concentrates of good quality can be considered proper alternatives. Depending on their maturity and feasibility linked with other operational needs or benefits, some of these have already been implemented and replicated. Figure 4 gives an overview of approaches and their state of maturity for selected representative examples. These alternative routes for nutrient recovery and recycling are intended to provide products or raw materials suitable for reuse in the nutrient cycle.



**Figure 4:** Prominent and already applied concepts for P recovery and recycling from sewage sludge. Note: Pyrochar made of sewage sludge is not considered Biochar. Status for application as fertiliser or soil improver not clearly regulated. Therefore, Pyrolysis can only be seen as a thermal pretreatment of sludge, not a real recovery yielding a fertiliser product.

As seen in Figure 5, in general, one has to distinguish between phosphorus recovery integrated on-site WWTP (2a-2c) and downstream of WWTP (1 and 3). Depending on the design of the wastewater treatment process and type of P removal, several P recovery options can be integrated. All of them finally capture dissolved phosphorus from the aqueous phase of the sludge. Currently, the most applied option is the P recovery from the centrate after dewatering (2b). Another option is represented by P recovery directly within the digested sludge prior to the dewatering process (2a). Second generation enhanced P recovery concepts include a WAS pretreatment step, biologically redissolving a part of phosphorus contained in the biomass already prior to anaerobic digestion. The redissolved phosphorus can be recovered in a separate system in the form of Calciumphosphates (2c), for example, or being combined with the nitrogen and phosphorus rich liquor of the dewatering (2b). If sludge is exclusively incinerated in sludge mono-incinerators, the resulting ash contains the highest available concentrate of P within the wastewater stream (3 in Figure 5). Due to the very limited plant-availability of the nutrient within most of the ashes, further treatment is required.



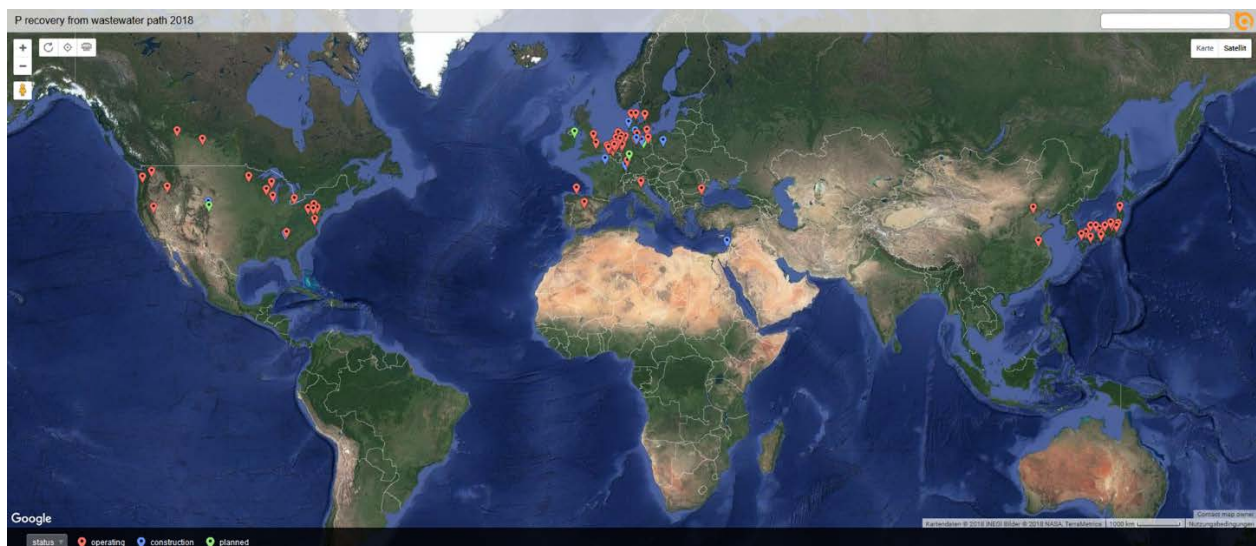
**Figure 5:** Hotspots for P recovery from the wastewater stream (simplified for centralised sanitation systems) (updated from Kabbe, 2013).

*Legend: 1 = direct sludge (biosolids) application in agriculture; 2a = P recovery within digested sludge prior to dewatering; 2b = P recovery from sludge liquor after dewatering; 2c = P recovery from liquor of pre-treated WAS; 3 = P recovery from mono-incineration ash*

For market deployment, new technologies must be proven to be capable and feasible. Otherwise, ideas and developments end up as fancy high-tech, but fail to mature into innovation. Table 1 inventories the current state of implementation. It clearly reflects the prominence of the so-called struvite technologies of first and second generation with more than 80 installations on three continents. But, why is struvite recovery so prominent? The answer is: struvite recovery technology has been implemented due to operational

needs at WWTP with the combination of EBPR and anaerobic digestion (AD). During anaerobic digestion, biomass is degraded. The P is removed from the wastewater applying phosphorus accumulating organisms (PAOs), most of the removed P is accumulated in the biomass in form of polyphosphates. After degradation of the biomass in the digester, these polyphosphates are redissolved into the sludge water as ortho-phosphate ( $\text{PO}_4\text{-P}$ ). In presence of sufficient ammonia ( $\text{NH}_3/\text{NH}_4^+$ ) and Magnesium ions ( $\text{Mg}^{2+}$ ) struvite starts crystallizing and can precipitate in the digester itself as well as in the downstream piping system and dewatering devices. The mitigation or even prevention of the potential scaling and related increased demand for maintenance was the initial driver to develop and implement struvite recovery units beginning in the late 1990-ies. The phosphorus recovery itself was and still is a nice to have side effect, unless additional measures are taken to enhance the P-redissolution to achieve substantially higher recovery rates.

A closer look at the global distribution of P recovery installations reveals three hotspot regions: (Central) Europe, Japan and North America. The following map (Figure 6 ) provides a global view accordingly.



**Figure 6:** Global distribution of P recovery from sewage installations (Kabbe 2018).

<https://de.batchgeo.com/map/0f9d56a3aa57a51379a3cb23af27d202>

**Table 1:** Overview of phosphorus recovery from the wastewater stream facilities operating or under construction. (Schoumans et al., 2015; Kabbe et al., 2015; Ohtake and Okano, 2015; Walker, 2017; Kabbe, et al. 2017; Hitachi Zosen 2018)

Technology	Location and operator	Operational since	Recovered material or product	Qty/a in tons
<b>Onsite wastewater treatment plants</b>				
AD-HAP (since 2014 by Hitachi Zosen)	Senboku Blackwater TP (JP), Senboku City	2007	HAP (from Night Soil)	15
	Totsugawa Village (JP)	2008		2
	Seihokugo Environment Improvement Assoc. (JP)	2009		40
	Kushimoto Town (JP)	2011		11
	Shimanto Town (JP)	2011		11
	Kofu Town (JP)	2015		4
AirPrex®	MG-Neuwerk (DE), Niersverband	2009	Struvite	100
	Wassmannsdorf (DE), Berliner Wasserbetriebe	2010		350

Technology	Location and operator	Operational since	Recovered material or product	Qty/a in tons
	Echten (NL), Drents Overijsselse Delta	2013		n.i.
	Amsterdam-West (NL), Waternet	2014		500
	Salzgitter Nord (DE), ASG	2015		50
	Uelzen (DE), SE Uelzen	2017		n.i.
	Wolfsburg (DE), SE Wolfsburg	2017		50
	Tianjin (CN), Tianjin CEPG	2016		offline
	Liverpool, OH (USA), Medina County	2018		--
	Savage, MD (USA), Howard County	2018		--
	Denver, CO (USA), Denver Metro	2019		--
	Ft. Collins, CO (USA)	2019		--
	Göppingen (DE), SE Göppingen	2020		--
ANPHOS®	Well (NL), EcoFuels, (biomass digestion)	2005		n.i.
	Odiliapeel (NL), Peka Kroef	2006		400
	Kruiningen (NL), Lamb Weston Meijer	2003		650
	Bergen op Zoom (NL), Lamb Weston Meijer	2007/16		290
	Budrio (IT), Pizzoli	2010	Struvite	150
	Haps (NL), Waterschap Aa en Maas	2011		n.i.
	Oosterbierum (NL), Lamb Weston Meijer	2016		580
	Den Bosch (NL), Waterschap Aa en Maas	2018		n.i.
	Asturias (ES), Longas	2018		n.i.
	Tiel (NL), Waterschap Rivierenland	2019		n.i.
Crystalactor®	Nanjing (CN), Royal Haskoning DHV	2010	Struvite	n.i.
EloPhos®	Lingen (DE), SE Lingen	2016	Struvite	n.i.
EXTRAPHOS® (Budenheim)	Itzehoe (DE), Kommunalservice Itzehoe	2018 (demo)	DCP	n.i.
Gifhorn	Gifhorn (DE), ASG	2007	Struvite/CaP	70
J-Oil	Yokohama (JP), J-Oil Mills Co.		HAP	260
JSA	Kawasaki (JP), Japan Synthetic Alcohol Co.	1998	HAP	n.i.
KURITA	Fukuoka North, South and Wasui (JP), Fukuoka C.	1997	Struvite	120
Kyowa Hakko	Hofu (JP), Kyowa Hakko Bio Corp.	2006	HAP	90
Multiform™	Yakima, WA (USA)	n.i.		n.i.
	Boise, ID (USA)	n.i.		n.i.
	Massey, MD (USA), Jones Family Farms (dairy)	n.i.	Struvite	n.i.
	Green Bay, WI (USA)	n.i.		n.i.
NASKEO	Castres (FR)	2015	Struvite	25
NuReSys®	Harelbeke (BE), Agristo	2008		250
	2x Niewkuerke (BE), Clarebout Potatoes	2009/12		650
	Waasten (BE), Clarebout Potatoes	2012		n.i.
	Geel (BE), Genzyme	2014		80
	Leuven (BE), Aquafin	2013	Struvite	50
	Land van Cuijk (NL), Logisticon	2015		150
	Apeldoorn (NL), Vallei & Veluwe	2016		550
	Braunschweig Steinhof (DE), SE BS / AVB	2018/19		--
NutriTec® (Sustec, DMT)	Zutphen (NL), SaNiPhos® GMB	2010	Struvite & DAS	offline
PEARL®	Tigard, OR (USA), Clean Water Services	2009		760
	Suffolk, VA (USA), Hampton Roads Sanit. District	2010	Struvite	400

Technology	Location and operator	Operational since	Recovered material or product	Qty/a in tons
(OSTARA)	York, PA (USA), City of York	2010	(Crystal Green®)	270
	Hillsboro, OR (USA), Clean Water Services	2012		1000
	Slough (UK), Thames Water	2012		130
	Saskatoon, SK (CDN), City of Saskatoon	2013		500
	Madison, WI (USA), Madison Metro. Sew. Distr.	2014		1000
	Burford, GA (USA), Gwinnett County	2015		1000
	Amersfoort (NL), Vallei & Veluwe	2015		500
	Edmonton, AB (CDN), EPCOR Water Services	2015		2500
	Stickney, IL (USA), Metro. Water Recl. Chicago	2016		7700
	Reno, NV (USA), Cities of Reno and Sparks	2016		500
	Madrid (ES), Canal de Isabel II	2016		500
	Winchester, VA (USA), F. Winchester Service A.	2016		500
	St. Cloud, MN (USA), City of St. Cloud	2018		500
	Atlanta, GA (USA), City of Atlanta	2018		(1000)
	Jarocin (PL), City of Jarocin	2019		(130)
	Tel Aviv, (IL), Mey Ezor Dan	2020		(5000)
Phosforce (Veolia)	Schönebeck (DE), OEWA Wasser & Abwasser GmbH	2019	Struvite or Brushite (DCP)	n.i.
PHOSNIX® (Hitachi Zosen)	7 plants installed in Japan between 1989 and 2011 with capacities between 80-500 m³/d	1989	Struvite	n.i.
	--	1992		n.i.
	--	1995		n.i.
	Lake Shinji-East (JP), Matsue City (1998)	1998		125
	--	2000		n.i.
	--	2009		n.i.
	--	2011		n.i.
	Kinan Environment Improvement Association (JP)	2014		n.i.
PHORWater	Calahorra (ES), El Cidacos	2015 (demo)	Struvite	n.i.
PHOSPAQ™	Olburgen (NL), Waterstromen (municipal & food)	2006	Struvite	400
	Lomm (NL), Waterstromen (food)	2007		260
	China (brewery)	2011		(1100)
	Poland (bio-ethanol)	2011		(500)
	Nottingham (UK), Severn Trent Water	2012		730
	USA (confidential)	2013		(800)
	Hünfeld (DE), BFG-IAR Hünfeld GmbH (dairy)	2014		730
	China (food processing)	2015		(1400)
	China (ethanol)	2016		(90)
	Tilburg (NL), Waterchap de Dommel	2016		340
	UK (municipal)	2017		(600)
PhosphoGREEN (SUEZ)	Aaby (DK), Aarhus Water	2013	Struvite	110
	Herning (DK), Herning Water	2016		106
	Marselisborg (DK), Aarhus Water	2018		302
	Villiers Saint Frederic (FR), SIARNC	2019		43
	Sausheim (FR), Mulhouse	2019		88
REPHOS® (delivered by NuReSys)	Altentreptow (DE), Remondis Aqua (dairy)	2006	Struvite	200
Rintoru®	Mobile unit applying A-CSH to recover P	--	CaP at CSH	--
STRUVIA™	Helsingør Southcoast (DK)	2015	Struvite	40
Stuttgart	Offenburg (DE), AZV	2011 (demo)	Struvite (after acid leaching)	20



Technology	Location and operator	Operational since	Recovered material or product	Qty/a in tons
	Mobile Pilot – MSE Mobile Schlammentwässerungs GmbH	2015 (mobile)		--
Swing	Higashi-Nada, Kobe City (JP), Swing Corp.	2012	Struvite	130
<b>Downstream wastewater treatment plants and ashes</b>				
Ash2®Phos	Helsingborg (SE), EasyMining Sweden AB	2022	MAP/DCP	--
	Bitterfeld (DE), EasyMining & Gelsenwasser	2022		--
EcoPhos®	Varna (BG), DecaPhos (for testing ashes)	2016	H <sub>3</sub> PO <sub>4</sub> /DCP/ MCP	--
	Dunkerque (FR), EcoPhos	2020		--
Fertiliser industry	Various companies already apply or consider use of secondary P sources	tested and intended	Commercial fertiliser	Mixed in
METAWATER	Gifu North (JP), Gifu City	2010	HAP	300
	Akisato (JP), Tottori City	2013		150
Nippon PA	Chiba (JP), Nippon Phosphoric Acid	2009	H <sub>3</sub> PO <sub>4</sub>	n.i.
TetraPhos®	Hamburg (DE), Remondis Aqua	2020	H <sub>3</sub> PO <sub>4</sub>	--

## 2.1 Phosphorus recovery integrated on-site WWTP

As indicated in Figures 4 and 5, there are several concepts to recover phosphorus within the wastewater treatment schemes.

Struvite (magnesium ammonium phosphate, NH<sub>4</sub>MgPO<sub>4</sub>·6H<sub>2</sub>O) recovery tends to be a favoured approach and is the final step of many P recovery technologies, providing a proven slow-release fertiliser with excellent plant-availability of the nutrients phosphorus, nitrogen and magnesium (Römer, 2013). It is even considered a suitable mineral fertiliser for organic farming (EGTOP, 2016).

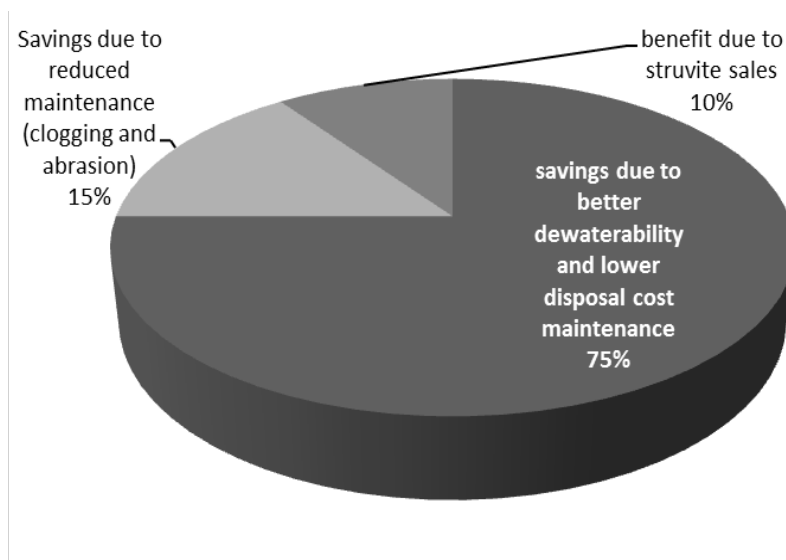


When crystallising and harvesting struvite directly after digestion within the sludge prior to mechanical dewatering, the efficiency of the sludge dewatering can be increased dramatically. In large WWTP in Germany like Wassmannsdorf (Berliner Wasserbetriebe) or Neuwerk (Niersverband) this kind of optimisation after installation of an AirPrex® unit, as shown in Figures 7 and 8 led to substantial reduction of operational costs. These add to several hundred thousand Euros per year, even before selling the struvite (Heinzmann and Lengemann, 2013; Ewert and Wagenbach, 2013). The market value of struvite strongly depends on a local or regional demand. In many cases, struvite is given away for free. In some cases, it is valorized as premium, slow-release fertiliser.





**Figure 7:** AirPrex® struvite recovery installation at WWTP Wassmannsdorf near Berlin, ©Kabbe.



**Figure 8:** Distribution of the specific monetary benefits at WWTP Neuwerk (Niersverband, Germany) after installation of AirPrex® struvite recovery (Ewert and Wagenbach, 2013).

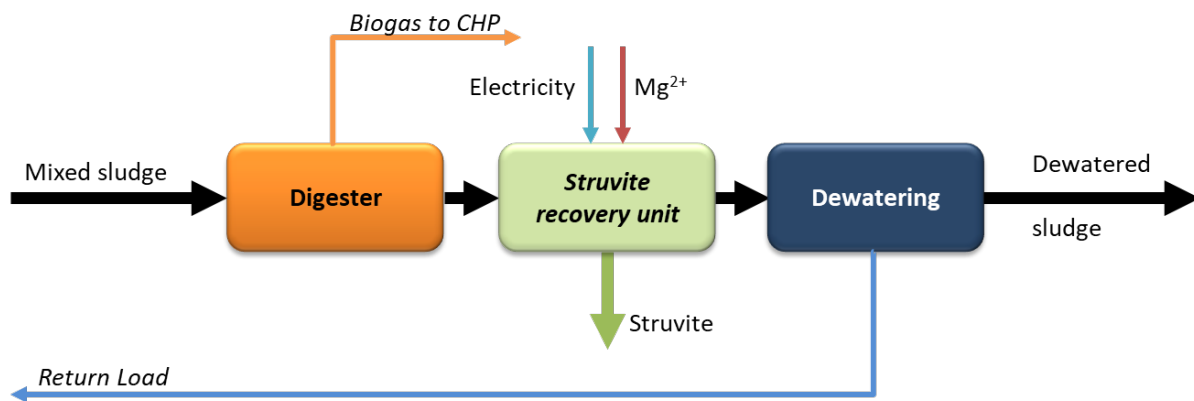
The economic benefits are mainly achieved by reduced sludge disposal costs due to improved dewatering of sludge, lower polymer (flocculation aid) demand, lower maintenance costs (scaling in pipes and abrasion in centrifuges) and a reduced return load in the sludge liquor. Every process optimisation also has the potential to increase the overall energy efficiency. Options to enhance the yield of recovered phosphates are re-dissolution steps mainly installed to treat the WAS prior to digestion or within digester cascades. These options can be biological acidulation (WASSTRIP, MultiWAS, CalPrex, PhosForce) and/or thermal (i.e. CAMBI) or chemical (i.e. PONDUS) hydrolysis for disintegration of waste activated sludge (WAS) or chemical

acidulation of digested sludge with mineral acids (Stuttgart, Gifhorn, ExtraPhos®). Table 2 provides an overview of available on-site WWTP technologies and their field of application.

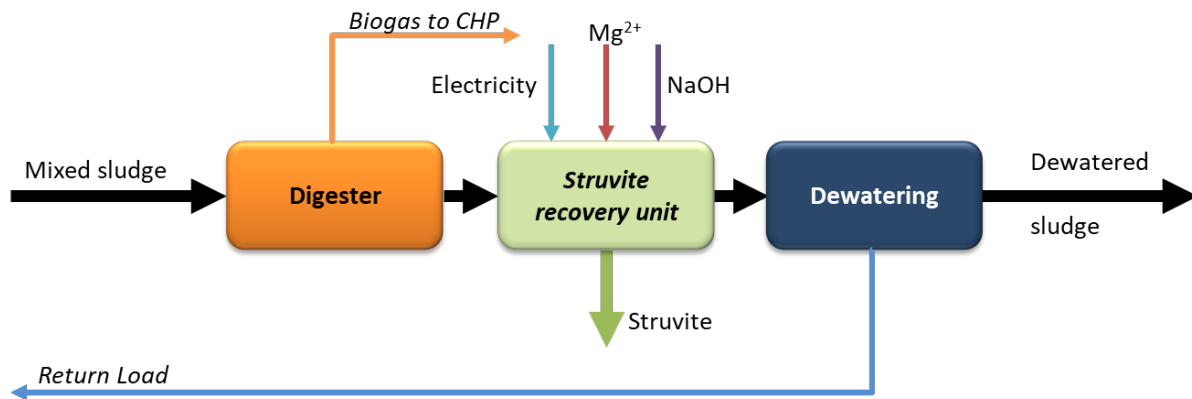
Besides precipitation/crystallization processes for recovery, adsorption (i.e. Calcium silicate hydrate (CSH)) found its way towards implementation. The final recovered material can be used as fertiliser or fertiliser ingredient as well, without the expensive need to chemically re-dissolve the phosphates from the adsorbent. In cases where the sludge is about to be combusted in sludge mono-incinerators and the P to be recovered from the resulting ash, crystallized phosphates can be left in the sludge matrix and do not have to be recovered separately.

The phosphates recovered within the sludge matrix might include more impurities than the material crystallised from the liquor after dewatering. However, in the end for the case of struvite, both qualities are officially certified as fertilisers (Berliner Pflanze, Crystal Green®, BioStru® or PhosphoCare®) and every plant operator needs to choose the option that fits best for their expectations, needs, and infrastructure. Operational benefits are of course a strong argument, especially when the feasibility of a technology is independent from the sale price for the obtained recycling product. Unfortunately, most of these technologies are limited to WWTP with enhanced biological phosphorus removal (EBPR) followed by anaerobic digestion. Figures 9-13 provide an overview of the general principles applied for phosphorus recovery from digested sludge or sludge liquors.

#### *Digestate (Hotspot 2a in Figure 5)*



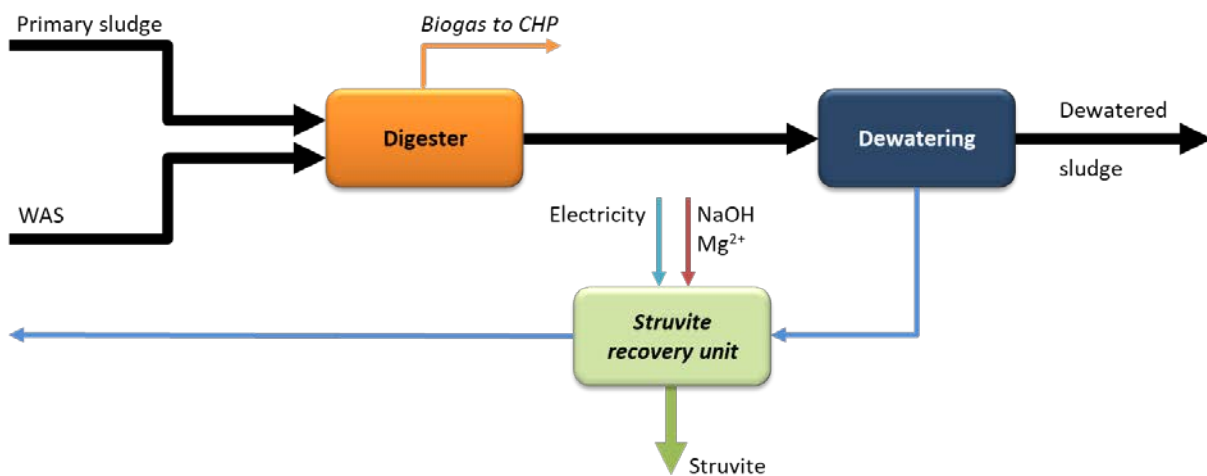
**Figure 9:** Struvite recovery from digestate with a fluidized bed, aerated reactor like AirPrex using CO<sub>2</sub> stripping for pH adjustment (adapted from Kraus et al., 2018).



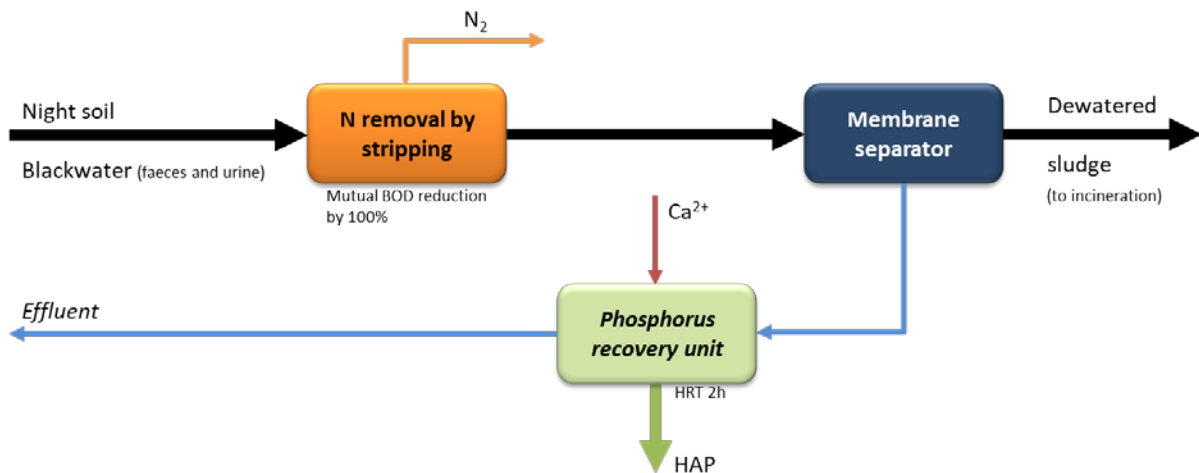
**Figure 10:** Struvite recovery from digestate with a mixed tank reactor using caustic (i.e. Rephosmaster, Nuresys) or the mixing itself for pH adjustment (Swing Corp.) (adapted from Kraus et al., 2018).

Several projects had to cope with the suspended solids (SS) in the beginning. As a resulting conclusion SS should be below 200 mg/l.

#### *Sludge liquors, filtrates*

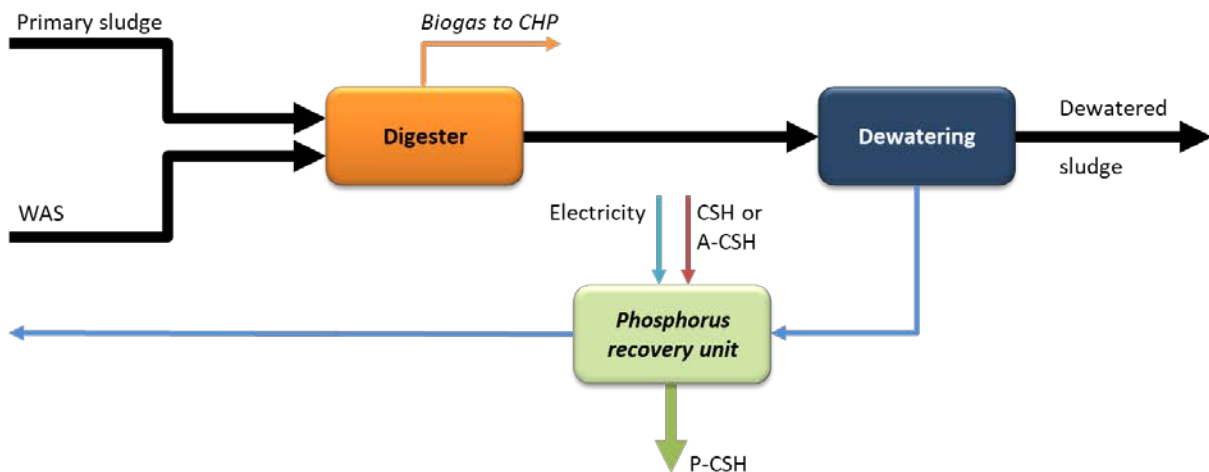


**Figure 11:** Struvite recovery from sludge liquor/filtrate using caustic soda for pH adjustment i.e. Pearl, Phosnix, Phos-paq, Phosphogreen, Nuresys (adapted from Kraus et al., 2018).



**Figure 12:** Phosphorus recovery as Calcium hydroxyapatite (HAP) from night soil/blackwater in a continuously stirred tank at blackwater treatment plants in Japan. In Senboku,  $\text{CaCl}_2$  is dosed as precipitant. Example Technology: AD-HAP

HAP is the resulting Calcium Hydroxyapatite formed by the reaction of dissolved phosphate and calcium ions. In regions sensible for salinity, lime can be used instead of the calcium chloride.



**Figure 13:** Phosphorus recovery from process waters or sludge liquor by adding Calcium silicate hydrate (CSH) as absorbent.

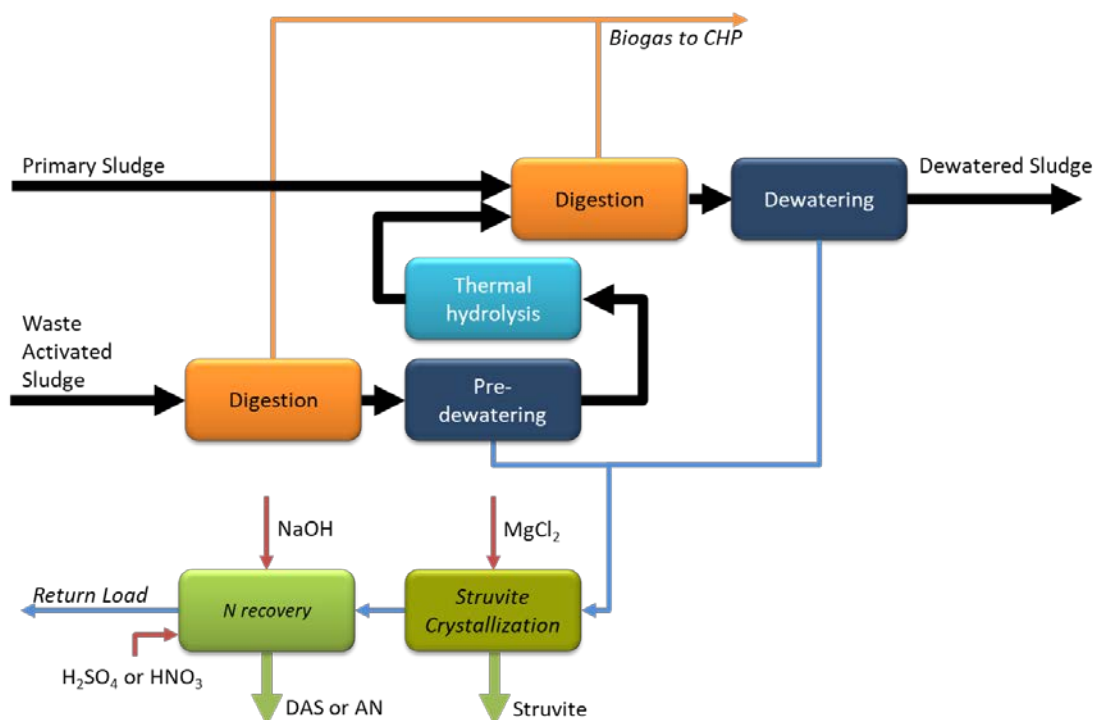
In Germany the P-RoC process uses CSH, in Japan the amorphous CSH (A-CSH) is preferred and even registered as brand Rintoru®. CSH is normally cheaply available and is said to settle together with absorbed P without coagulants at pH between 7-9.

### *Second or next generation, multi-modular nutrient recovery (cascades)*

Next generation recovery concepts are not just focusing on energy or phosphorus recovery, they make use of synergies between them both and can optionally include nitrogen recovery as well. Figure 14 reflects such a multi-modular concept, as it is currently under construction at WWTP Steinhof, near Brunswick in Germany.

The lysis of the waste activated sludge for disintegration not only increases the biogas yield due to improved bio-degradation of the biomass, but it also increases the re-dissolution of polyphosphates accumulated in the biomass as consequence of the biodegradation. Since the phosphorus can only be transformed into another phosphate, it dissolves in the aqueous phase of the digested sludge and can be recovered by precipitation/crystallization, prior or after dewatering. This combination allows higher biogas yields (energy recovery) and higher phosphorus recovery rates. If the recovery rate of first generation phosphorus recovery facilities are limited to 10-25% at maximum, this type of enhancement may allow potential recovery rates between 30-45%.

Depending on the plant size, thermal pressure hydrolysis like CAMBI, Haarslev, etc. are recommended for the bigger ones, whereas Lysotherm (heat exchange) or PONDUS can be found at the smaller ones.

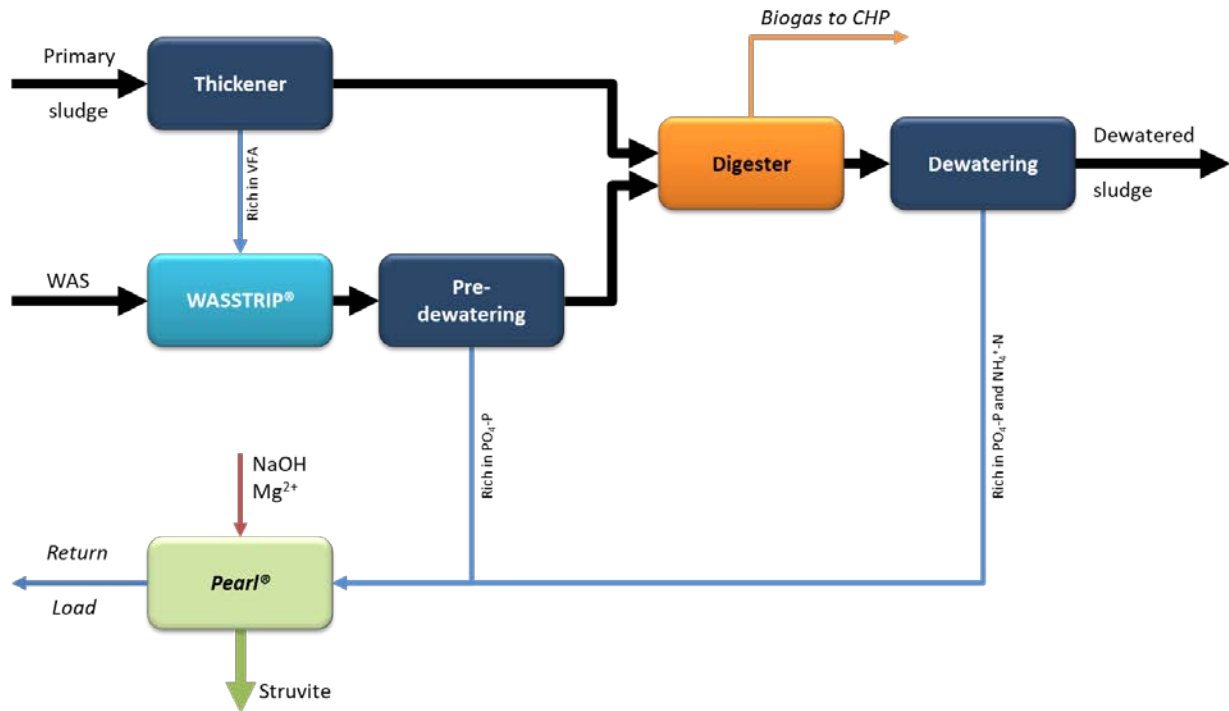


**Figure 14:** So-called next generation energy and nutrient recovery cascade concept as it is currently under construction at WWTP Steinhof (Brunswick, Germany).

One limiting parameter for the implementation of thermal lyses is the generation of hard COD at lifted temperatures. Thus, WWTP right at the limit of COD in their discharges need to be aware of that and should quantify the potential increase of hard COD at their sites. Current investigations in Berlin are taking a closer look and compare a CAMBI system operating at temperatures around 160 °C and a PONDUS system operating at 90° to quantify the specific hard COD generation.

Besides the above mentioned lysates, bio-acidolysis (acidogenesis) of WAS has been implemented and replicated in several locations providing similar advantages including lifted phosphorus recovery rates.

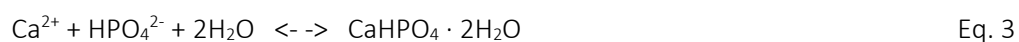
The most widely implemented system is Ostara's WASSTRIP/PEARL combination, recovering struvite from the two liquors obtained from thickening and dewatering.



**Figure 15:** Combination of WAS bio-acidolysis (WASSTRIP®) prior digestion and struvite recovery from both P-enriched liquors in a PEARL® reactor (currently installed at eight WWTP and planned for another five sites at two continents (scheme adapted from Kraus et al., 2018).

Alternative to the recovery of struvite from both liquors, dicalcium phosphate (DCP, brushite) precipitation provides a prominent option for the pre-digestion recovery step of the phosphate enriched, but ammonia lacking pre-digestion liquor.

Figures 16 and 17 show the two brushite / struvite systems entering the market, CalPrex™ (by CNP) and Phosforce (by Veolia), respectively. In both cases, the acidic digestion happens under mesophilic conditions and slightly lowered pH achieving solubilization of crystallized and biologically bound phosphates. For Bio-P sludge a P solubilization of up to 60% has been observed, for non-bio-P sludge up to 40%. In both concepts, the P enriched liquor of the pre-dewatering is fed into the brushite reactor, where at a pH of around 6.5 and addition of lime (Ca(OH)<sub>2</sub>) the intended brushite is formed.





**Table 2:** Prominent on-site WWTP P recovery technologies or approaches and their localisation within the sludge train.

Technology	Supplier	Input for recovery step			Recovered Material	TRL
		2a Diges- tate	2b De- watering Liquor	2c WAS Thickening Liquor		
AD-HAP	Hitachi Zosen		X		HAP	9
AirPrex	CNP	X			Struvite	9
Anphos	Colsen		X		Struvite	9
CalPrex	CNP			X	Brushite (DCP)	7
Crystalactor	RoyalhaskoningDHV		X		Struvite	9
EloPhos	Eliquo Stulz	X			Struvite	7
ePhos	Fraunhofer IGB		X		Struvite	7
ExtraPhos*	Budenheim	X			Brushite (DCP)	7
MultiForm + MultiWas	MultiForm		X		Struvite	9
	Harvest			X		n.i.
Naskeo	Naskeo		X		Struvite	8
NureSys	NuReSys	X	X	X	Struvite	9
NutriTec	Sustec DMT		X		Struvite	9
Pearl + WASSTRIP	Ostara		X		Struvite	9
				X		9
Phosnix	Hitachi Zosen		X		Struvite	9
PhosForce	Veolia			X	Brushite (DCP)	7
PhosphoGreen	Suez		X	X	Struvite	9
Phospaq	Paques		X		Struvite	9
P-RoC	CMM		X		Struvite at CSH	7
Rephos	Remondis		X		Struvite	9
Rephosmaster	Swing	X			Struvite	9
Struvia	Veolia		X		Struvite	9
Stuttgart*		X			Struvite	7



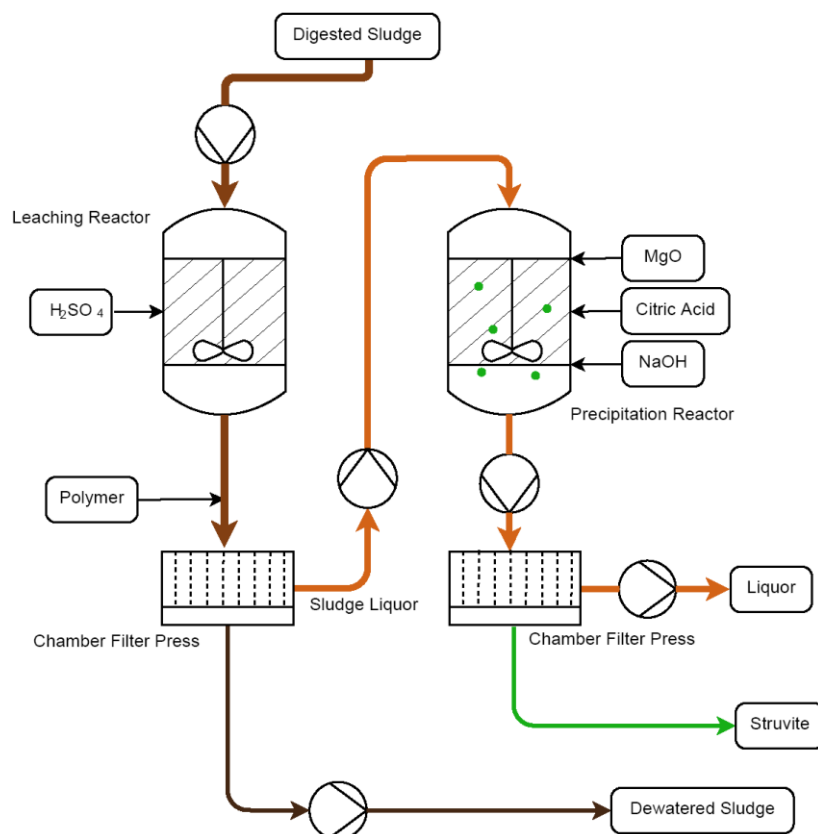
*\*The lines marked in light blue indicate technologies based on chemical P solubilisation by dosing mineral acids or CO<sub>2</sub>.*

Considerable factors to generate monetary benefits for the WWTP operator are:

- Reduced return load to achieve stricter P discharge consents
- Reduced maintenance due to mitigation of unintended struvite scaling in the sludge train
- Improved sludge dewaterability and reduced flocculation aid consumption
- Reduced sludge volume to be disposed off
- Potential to generate an income from struvite or brushite sales (strongly dependent on quality, physical shape, regional demand and legislation)

As in the case of Germany, where P recovery will be obligatory after 2029 for the bigger WWTP and in case co-incineration capacities are available and less costly compared to mono-incineration routes, the P depletion of the sludge can reduce disposal costs as well.

It must be mentioned that the described technologies without pre-digestive solubilisation are limited to sewage sludge mainly derived from EBPR. In some cases, the phosphorus has been precipitated with Fe or Al salts in the P removal step, biological redissolution is far less effective and chemical enforcement is required.



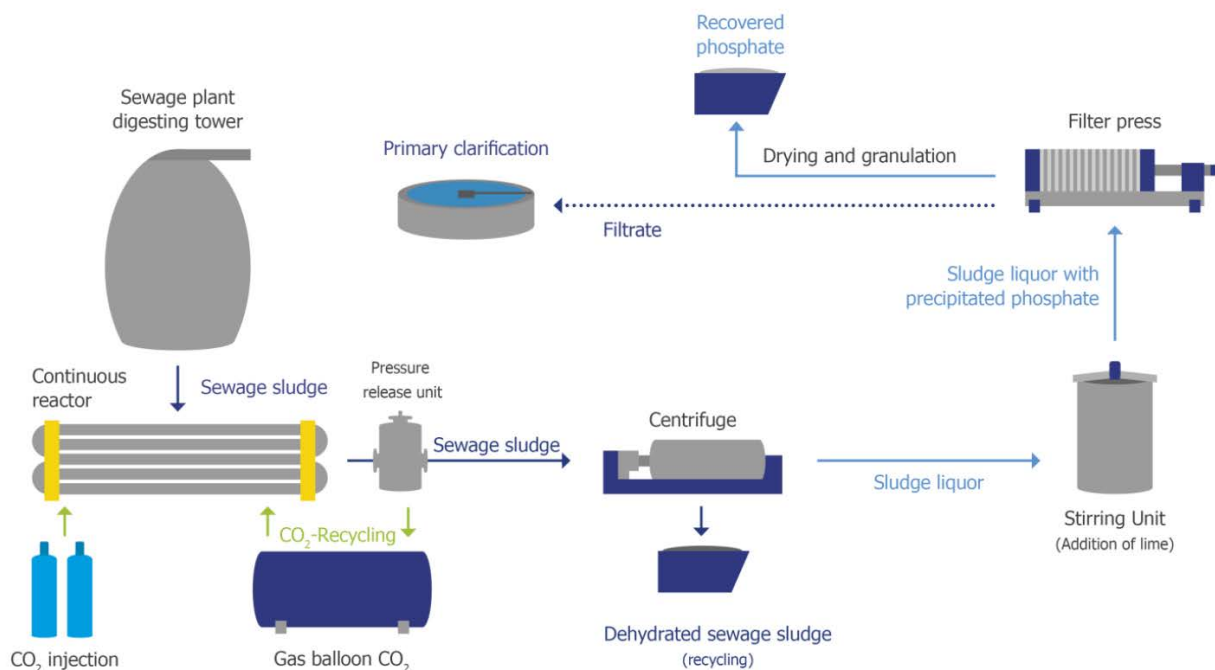
**Figure 18:** Process scheme of the mineral acid leaching Stuttgart process (P-REX factsheet 2015).

In that case, mineral acids like sulfuric acid or hydrochloric acid have been tested in various approaches. Given the corrosive property of the latter, sulfuric acid turned out to be the more common. But having in

mind that P solubilisation correlates with decreasing pH and therefore acid consumption, higher recovery rates are always linked with higher recovery costs. It is unlikely, that approaches like the Stuttgart process, consuming sulfuric acid for the sludge leaching, citric acid to mask the heavy metals and keep them separate from the P, as well as the caustic soda consumption to re-increase the pH struvite precipitation will ever become economically viable. Besides that, another question out of reasonable thinking needs to be asked: *Isn't acid leaching more reasonable to treat sewage sludge ash instead of digested sludge?* Digested sludge mainly consists of water and shifting the pH of the water consumes a lot of acid or caustic. In the case of ash leaching, the acid will much more effectively attack the solids and not be spoiled to adjust the pH of the water content.

The EXTRAPHOS process developed by the chemical company Budenheim intended to overcome the burden of high chemicals consumption. It can be roughly divided into three process steps.

- Step 1 is the carbon dioxide extraction, where digested sewage sludge and process water suspension is sealed in a reactor, heated up to 50–60°C, and CO<sub>2</sub> is added under a pressure of 10 bars. This increases the acidity of the water to pH levels down to 4.5-5.5, causing a fraction of the phosphate in the sludge matrix to dissolve (Schnee and Opitz, 2018).
- Step 2 is the solid/liquid separation with state-of-the-art dewatering. During dewatering and pressure release, the CO<sub>2</sub> used for P release is stripped off, captured, condensed and can be recycled within the process. The dewatered and P depleted sludge is then destined for co-incineration in cement kilns, whereas the P enriched liquor enters step three – the phosphate precipitation.
- Step 3 Lime (Ca(OH)<sub>2</sub>) is added to trigger the precipitation of dicalcium phosphate (Brushite). After separation, drying and granulation, the obtained Brushite can be used as fertiliser or fertiliser component.



**Figure 19:** Process scheme of Budenheim's Extraphos® CO<sub>2</sub> P recovery process (courtesy of Budenheim).

The process intended to be used for sewage sludge, independent from the type of P removal applied at WWTP, providing high versatility. First pilot trials at WWTP Mombach in Mainz (Germany) in 2017 indicate a limited P solubilisation for iron precipitated phosphates. The pilot moved to Itzehoe, where the share of biologically removed P is higher. Therefore, expectations for the P recovery rate are higher. The results

from Mainz indicate that there will be a need for a sequence of CO<sub>2</sub> extraction steps to meet the 50% P depletion requirement set by the new sewage sludge regulation to allow down-stream co-incineration of the sludge. Together with technology concepts such as CalPrex™ and Phosforce they may provide considerable options for WWTP operators, having the opportunity to dispose the P depleted sludge in a nearby co-incinerator, like cement kilns or municipal waste incinerators. Using sludge as co-fuel in coal power plants is no longer considered a disposal route with long-term security, since Germany is about to phase out coal firing. The replication in other countries, still providing a broader variety of co-incineration might be higher.

The piloting in Mainz also indicated some beneficial side-effects, as can be seen with other P recovery technologies treating digested sludge. Also, a positive impact on sludge dewatering in the form of higher dry solids can be expected, but dependencies regarding type of sludge still wait to be verified.

For all on-site P recovery approaches, one thing is still to be achieved to be suitable for the German market: P content in the sludge to be disposed off in co-incineration needs to be below 2 kg P/kg dry solids or a P recovery rate of at least 50% under economically viable conditions and without causing harm to human health and the environment. Besides that, if an operator or utility produces sludge at several plants, the following questions need to be answered:

1. Which sludge disposal route is available in my region and are the capacities secured for long-term as well as for the whole volume of sludge produced?
2. Where to dispose the P depleted sludge, if the nearby cement kiln stops rotating?
3. How can the sludge producer keep cost control? Is there competing sludge supply?
4. Does the sludge producer want to go to diverse sludge disposal routes or just focus on one single route?
5. What is the P recovery at one of the several plants good for, if the others are not suitable for the same option? A single disposal route for the total sludge volume is more favourable than diverse disposal routes within one WWTP operating organisation.

Under current conditions, as stated in the new German sewage sludge regulation, there is a clear favouring of mono-incineration by providing the only route for sludge disposal without quality requirements and allowing the separate and recoverable storage of sludge ash. All other routes are limited in terms of P content, pollutant limits etc. Still one question remains and needs to be answered: Which route for sludge disposal and nutrient recovery is sustainable or not?

Technology development will continue and provide better options. Today, there are quite a number of technologies on the market for P recovery on-site WWTP, more or less following the concepts having proven successful in the past. Struvite recovery provides a good example how useful and successful concepts are copied or adapted by other technology providers, leading to a variety of options to be chosen by potential customers. In that case, competition and diversification will accelerate the market uptake of the leading concepts.

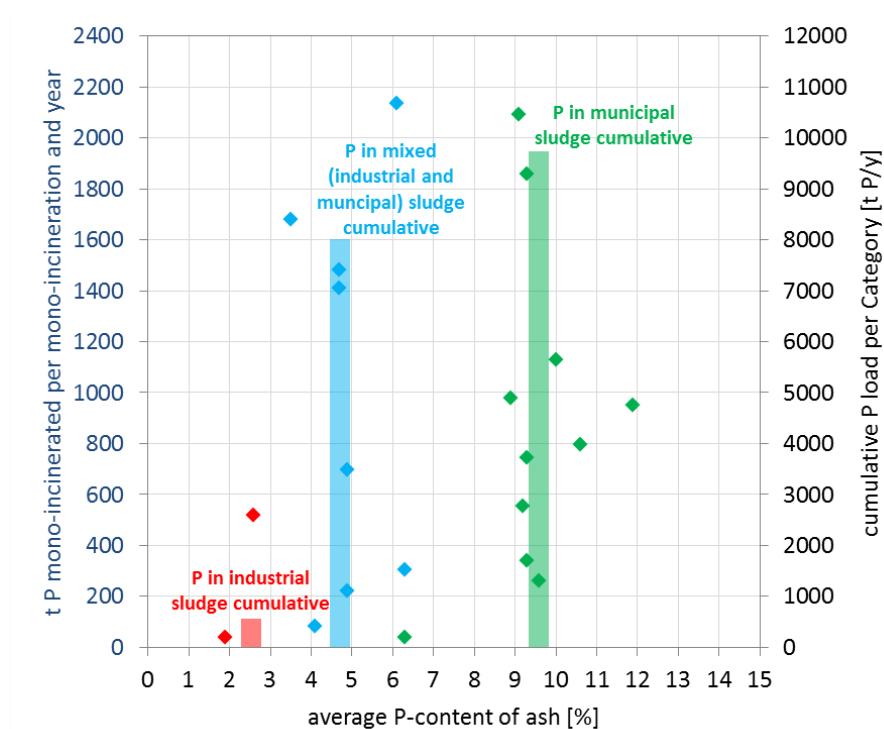
But what happens if nutrient recovery on-site of WWTP and sludge disposal on arable land are hampered or even banned, or competing farm residues are reducing land area available for sludge disposal? Then, the sludge has to be thermally treated or incinerated.

## **2.2 Phosphorus recovery downstream of wastewater treatment**

If sludge is to be thermally treated, be it as fuel for energy recovery or just as volume reduction for disposal, it is usually incinerated in co-incinerators, like coal power plants, municipal waste incinerators or cement kilns, or in dedicated sludge incinerators or gasifiers. Co-incineration means, the phosphorus content of the sludge is dramatically diluted due to the small proportion of the sludge being mixed into the total fuel volume of these incinerators. It means, the phosphorus in these resulting co-incineration ashes is lost for nutrient recycling. Thus, intending phosphorus recovery from incineration residues calls for an exclusive

incineration without dilution of the contained phosphorus. Besides mono-incineration, sludge gasification or even pyrolysis are considered. But on global scale, fluidized bed incinerators are the most established types for sludge incineration, yielding very fine ashes with less than 1% organic carbon left. The organic remains play an important role for further options to use these ashes/residues. Higher TOC levels pose rather obstacles and limitations than opportunities.

When the sludge is about to be incinerated in mono-incinerators, several options for phosphorus recovery can be applied. At present, only a part of the sewage sludge is incinerated without dilution, concentrated in highly industrialised countries with high population densities compared to available land area.



**Figure 20:** Distribution of P content in mono-incineration ashes in Germany (Kraus, 2015 based on Krüger and Adam, 2014).

*Legend: left (red) – purely industrial sludge ash; centre (blue) – mixed mono-incineration of industrial and municipal sludge; right (green) – purely municipal sludge ash*

If legal requirements enter into force, as discussed in Germany, the quantities of sewage sludge being incinerated in mono-incinerators will raise from about 26% up to 75-80%, leaving 10% for direct land application for the smaller WWTP and 10-15% for co-incineration where capacities are available.

When sludge is incinerated in a mono-incinerator, a high P concentrate can be produced from waste streams. The phosphorus content in sewage sludge ashes (SSA) varies between 2% and 12% P in Germany (Krüger and Adam, 2014), clearly indicating the highest P contents for municipal sewage sludge ashes, not mixed with industrial ones. For Europe, an average P content of about 9% can be observed, which compares to above 20%  $P_2O_5$ . However, due to very limited plant availability of the nutrient within the ash, further treatment is needed before it can be fully utilised as a secondary P resource, especially if it comes to its essential functionality as irreplaceable nutrient.

Looking at existing infrastructure, partial substitution of phosphate rock in commercial fertiliser production looks promising. European fertiliser companies have already been starting to test, even at full-scale, the substitution potential of sewage sludge ash and other secondary sources (Langeveld and ten Wolde, 2013; Hermann, 2013; Langeveld, 2014). Table 3 shows a range of potential P-materials and their suitability as a raw material for conventional fertiliser production.

In addition to legal barriers for the integration of waste material, specific requirements from the operator's perspective limits this application. Not only is it desirable to have a high phosphorus content in the ashes, but also the presence of iron and chlorine, the availability of sufficient material, and organic contamination etc. turn out to be limiting. Attractive aspects of this particular phosphorus recycling route are the facts that processing units already exist, as well as the established high-volume markets for fertilisers, including existing distribution networks. Thus, once this kind of recycling route works, the extra costs of implementing substantial phosphorus recovery and recycling will be kept at moderate levels, as the existing infrastructure just needs to be adapted. Here, the limiting factor is the availability and existing capacity of phosphate rock digesting plants in the region, country or at the continent. This already indicates, that this route can only be one option amongst others, thus will not be an exclusive one.

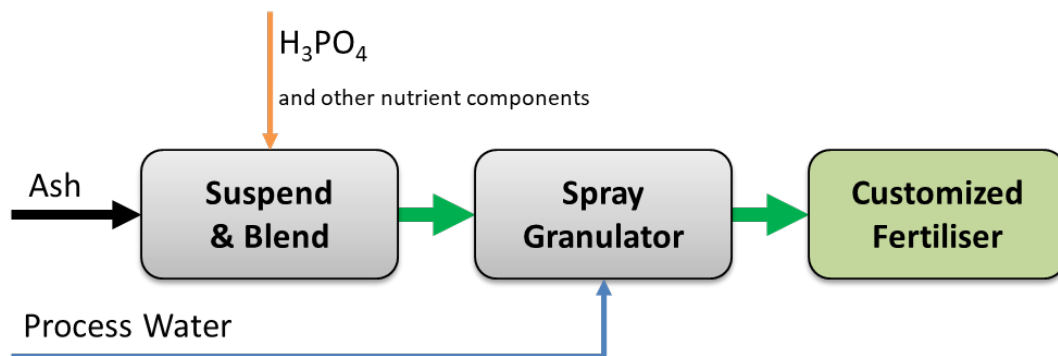
**Table 3:** General characteristics of and criteria for phosphorus (P) sources used and considered for commercial fertiliser production (Langeveld, 2014).

Ash type	P content	Consistency	Low heavy metals	Low cadmium	Low iron and aluminium
Sewage sludge ash (municipal)	+/-	--	--	+	--
Meat & bone meal ash	+	+	++	++	++
Wood ash	--	-	+	++	-
Phosphate rock	++	++	+/-	-	++

Looking at the phosphorus recovery from ash technologies, an obvious trend can already be seen. The most promising ones are wet chemical processes dissolving ash in mineral acids and extracting the phosphorus and separating it from undesired heavy metals with varying efficiencies. Only a few of these technologies are aiming to yield ready to use fertilisers (SeraPlant, EuPhoRe). The most promising tend to yield known phosphates like calcium phosphates (i.e. DCP), ammonium phosphates (i.e. MAP, DAP) or phosphoric acid (i.e. MGP). Even the production of white phosphorus ( $P_4$ ) from suitable ashes has been targeted in the past but has been paused due to economic reasons.

The following sections provide some examples of technical approaches and concepts currently at the market or with good prospect to enter the market in the near future, especially in countries, where phosphorus recovery from ashes has been made, or will be made obligatory. The frontrunners in setting the legal frame are Switzerland and Germany, with the latter providing the biggest market potential.

Very close to the common fertiliser manufacturing process chain is the Glatt SeraPlant concept, consisting mainly of the three steps: ash suspension in phosphoric acid, blending and granulation, finally yielding a customized fertiliser. The quality of the product depends on the quality of the input materials used, since no actual heavy metal depletion or separation is provided. This limits the applicability of the process to input material of good (enough) quality. Since most of the sewage sludge ashes show exceeding heavy metal contents compared to the requirements of sludge or fertiliser regulations, it can be assumed that the Glatt® SeraPlant process will remain a very scarcely applied process, as long as dilution as an option to meet heavy metal contents as required by regulations is excluded, i.e. in Europe by the Waste Framework Directive (2008/98/EC).



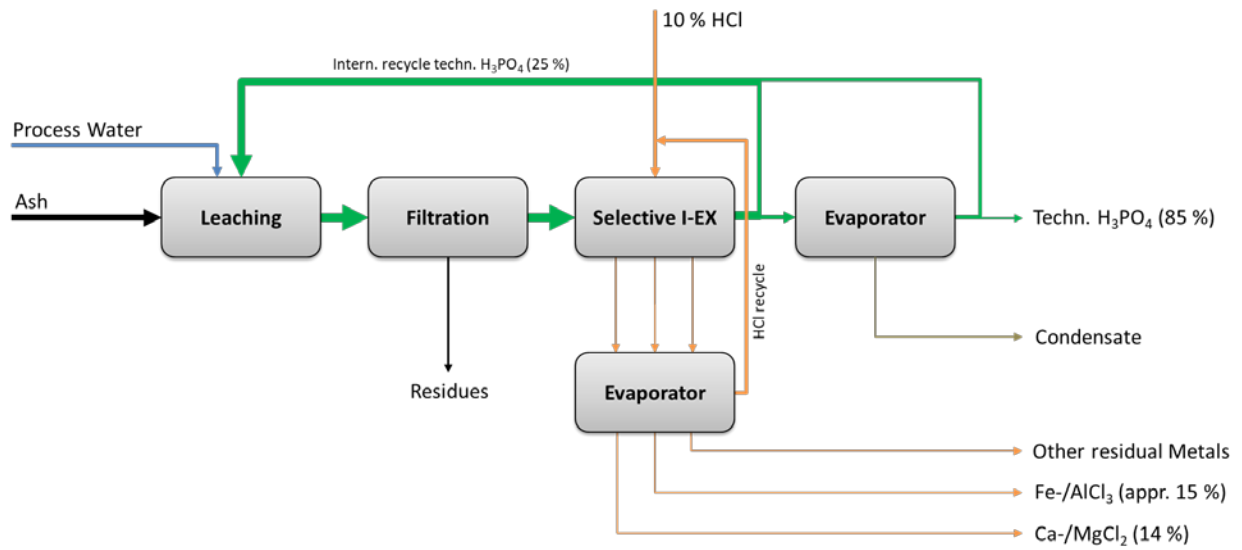
**Figure 21:** Schematic flow of the Glatt® SeraPlant process.

The molar ratio typically applied between the P from the added acid and the P contained in the ash is 2:1. Thus, the economic feasibility mainly depends on the price of the consumed phosphoric acid. The green acid is relatively cheap, but rather contaminated with i.e. Cadmium as worst representative of heavy metals. It is unlikely that merchant grade phosphoric acid (MGP) will be used due to higher price levels, but also due to sustainability aspects. Why would you be contaminating MGP of good quality with contaminated ash? That is a question to be asked when it comes to sustainability aspects.

The following technologies appear to be similar at first glance but have some specific tricks to justify separate announcements.

### *ECOPHOS*

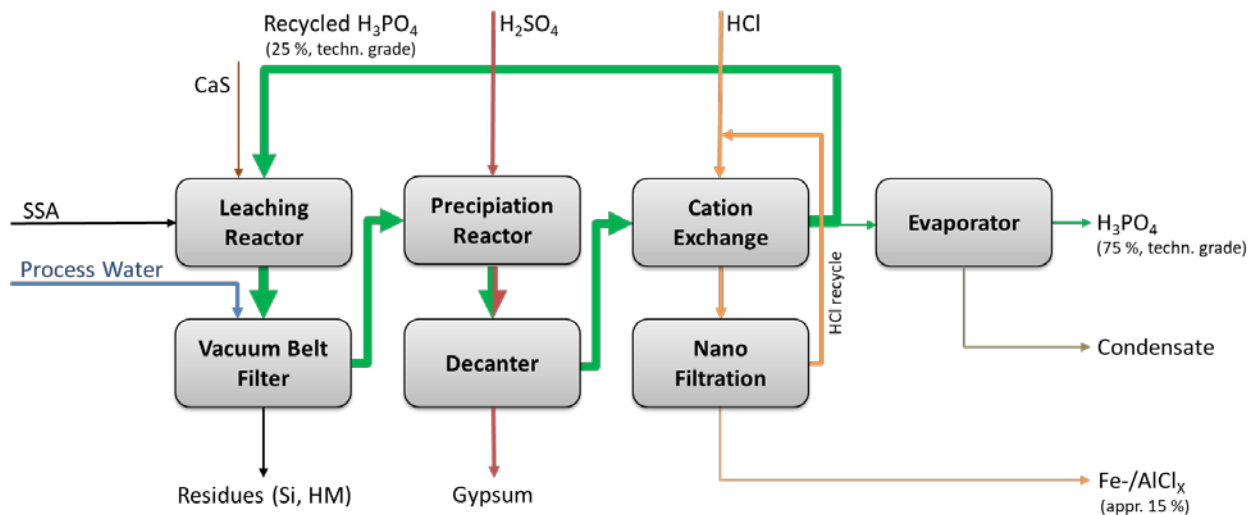
Another approach is the wet chemical extraction and ion-exchange purification of low-grade phosphate rock and other raw materials developed by EcoPhos, Belgium. It enables the production of high-grade phosphates (i.e. DCP,  $\text{H}_3\text{PO}_4$ ) from low-grade raw material. Various full-scale plants have been installed worldwide to produce high-grade phosphates from low-grade phosphate rock (less than 30%  $\text{P}_2\text{O}_5$ ). One full-scale facility in Dunkerque, France has been commissioned recently on low-grade rock base and is about to start using sewage sludge ashes by 2020/21 in one line. EcoPhos were signing a contract in February 2015 with SNB and HVC, both Dutch mono-incinerators, to recycle phosphorus from 60,000 tonnes of sewage sludge ash per year.



**Figure 22:** Schematic flow of the ECOPHOS H<sub>3</sub>PO<sub>4</sub> process (adapted from Kraus 2018 and Takhim et al., 2018).

### TETRAPHOS

A similar approach is proposed by the German company Remondis Aqua with their TetraPhos® technology yielding high-grade phosphoric acid (Rak and Lebek, 2016) from sewage sludge ashes and meat and bone meal ashes.



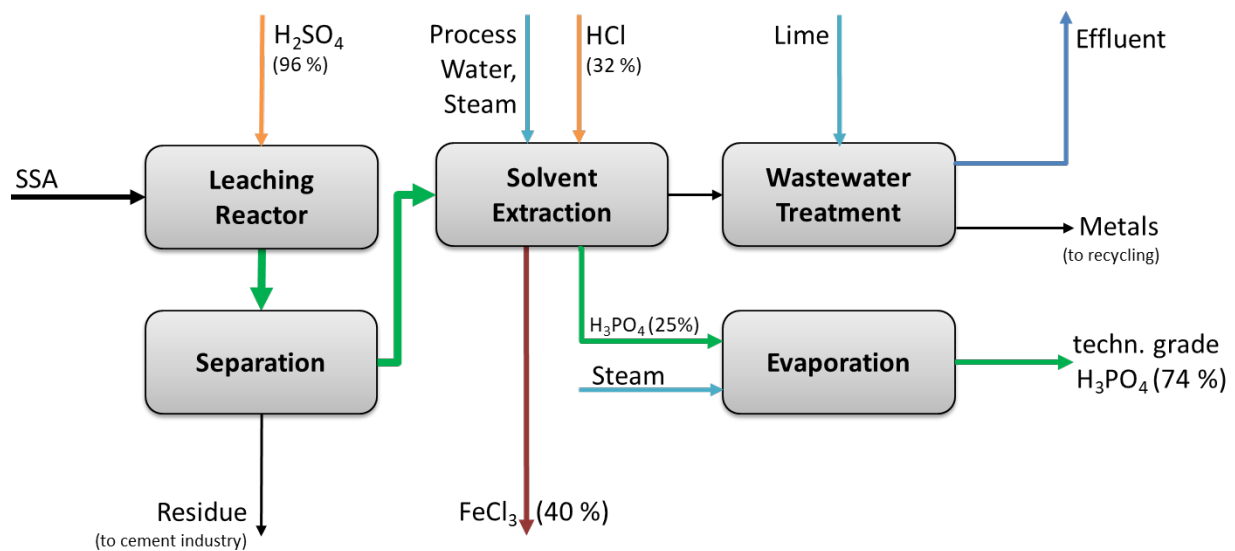
**Figure 23:** Schematic flow of the TetraPhos® process (adapted from Kraus 2018).

A first pilot unit was operated in Hamburg and is now to be up-scaled by a full-scale plant next to the local sludge incinerator VERA at WWTP Köhlbrandhöft. The plant's capacity will be sufficient to up-cycle all the ash of appr. 20,000 Mg/a generated by the local incinerator, yielding approximately 7,000 Mg/a techn. grade H<sub>3</sub>PO<sub>4</sub> and applying an evaporator for concentration. The pilot was moved to another site to prepare the potential installation of a second TetraPhos® plant in Germany.

### Phos4Life

The Phos4Life process, currently in the stage of piloting, is being jointly developed by Tecnicas Reunidas (Madrid, Spain) and the Foundation ZAR (Canton Zurich, Switzerland). It is expected to allow the production of technical grade phosphoric acid from sewage sludge ash by acidic leaching with sulfuric acid and subsequent separation and extraction steps. In a second step, iron chloride, reusable as coagulant in WWTP is separated. In the following stage, phosphoric acid (approximately 25 % conc.) is released from the co-extracted heavy metals by solvent extraction. To obtain technical grade concentration of the phosphoric acid, evaporation serves as concentration step. The main product of the process is a 74% conc.  $\text{H}_3\text{PO}_4$ .

The ongoing pilot tests are intended to provide all relevant data for a decision to go towards a full-scale plant in Zurich or not. The capacity will then be 30,000 Mg/a SSA transformed into 11,000 Mg/a MGP (74%), 34,000 Mg/a iron chloride solution (40%) and solid residues for disposal in cement works of about 42,000 Mg/a (Morf et al., 2018).



**Figure 24:** Phos4Life process to produce phosphoric acid from sewage sludge ash.

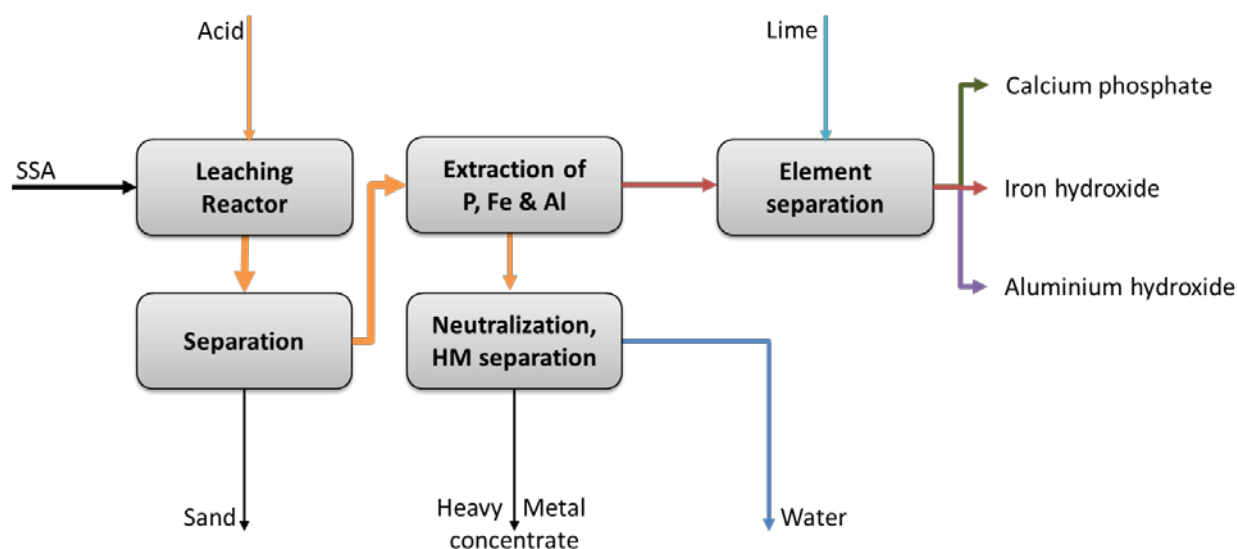
[https://zar-ch.ch/fileadmin/user\\_upload/Contentdokumente/Veranstaltungen/P-Tagung\\_2017/ZAR-P-Tagung2017-TecnicasReunidas\\_Presentation\\_Zurich\\_P4L.pdf](https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Veranstaltungen/P-Tagung_2017/ZAR-P-Tagung2017-TecnicasReunidas_Presentation_Zurich_P4L.pdf)

The above mentioned three technologies provide efficient heavy metal (HM) depletion and therefore show good versatility in terms of chemical ash input quality. However, the three of them are vulnerable in terms of product concentration and therefore water balance within the system. The used evaporation to allow the concentration steps are highly energy consumptive, which has a substantial impact on the cost side. A less vulnerable approach and concept has been developed by EasyMining Sweden AB.



### *Ash2®Phos and CleanMAP®*

The Swedish company EasyMining Sweden AB, since 2014 daughter of the Ragn-Sells Group, has developed two processes for P recovery from ashes which can be linked to an up-cycling process chain, depending on local/regional structures and markets. The first process named Ash2®Phos as shown in Figure 25 starts with the ash as input material and yields common intermediates of high quality.



**Figure 25:** Schematic flow of the Ash2®Phos process (adapted from Kraus et al., 2018).

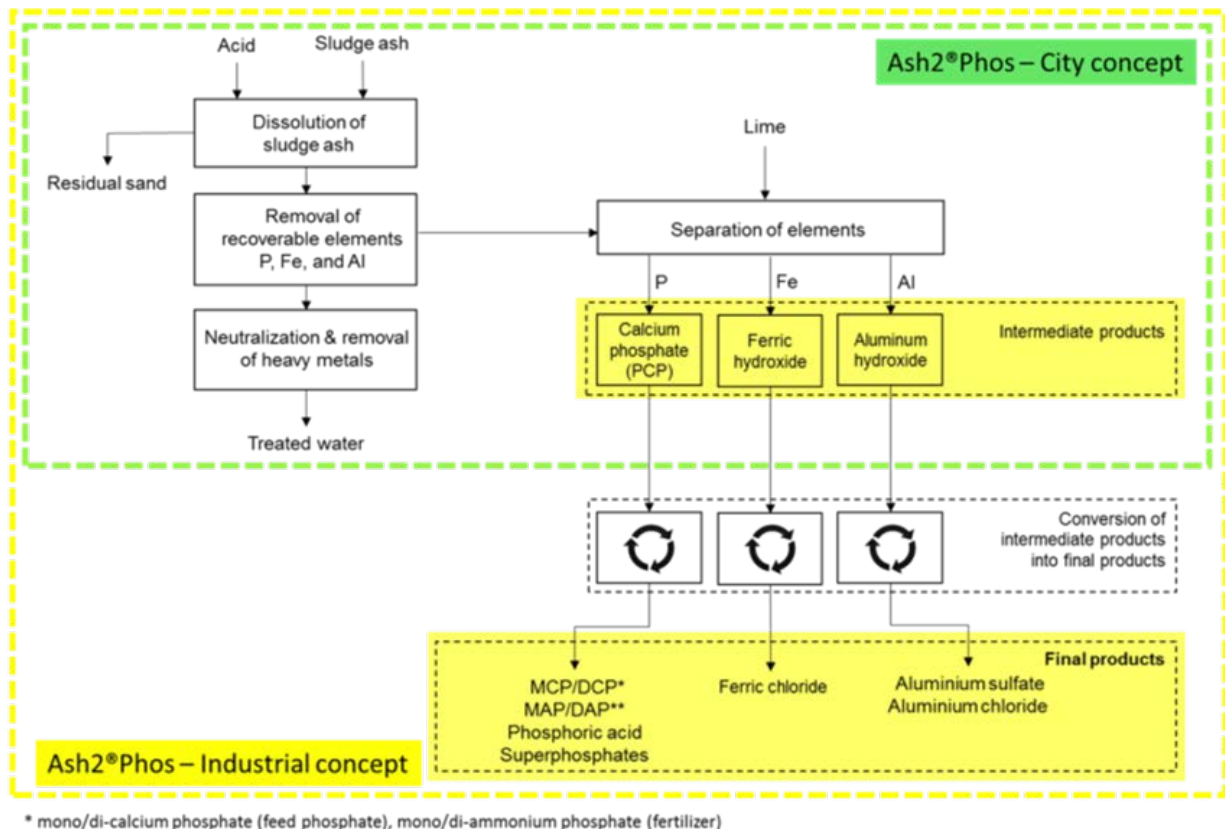
The process starts by dissolving the sludge ash in acid. Commercial hydrochloric acid or sulfuric acid can be used. The process is also adapted to enable the use of waste acid from waste incineration plants such as scrubber acid from flue gas treatment. Dissolution of phosphorus and calcium from sludge ash is generally high (Cohen, 2009), exceeding ninety percent. Dissolution of aluminium is up to eighty-five percent and that of iron is up to twenty five percent.

In the next process step recoverable elements are removed from the obtained solution. Phosphorus, iron and aluminium are separated from the solution by precipitation steps in a unique combination. Thereafter, the solution is neutralized and treated for removal of heavy metals. The non-dissolved residue which mainly consists of inorganic silicates can be used after separation and washing, e.g. in the cement industry or in sand filters. The recoverable elements are thereafter separated from each other by dissolution and precipitation reactions in a process which is characterized by internal recirculation of chemicals. The main chemical consumed in this process is lime. The recoverable elements are separated into three intermediate products: calcium phosphate, ferric hydroxide and aluminium hydroxide.

The final step is conversion of intermediate products into final products. Several options exist depending on the form of the desired end-products. The intermediate calcium phosphate can be converted into calcium chloride and ammonium phosphate (monoammonium phosphate, MAP, or diammonium phosphate, DAP) by addition of hydrochloric acid and ammonia using the CleanMAP® process. The CleanMAP® process enables energy effective production of pure and well-defined ammonium phosphates of technical grade. The technical grade of ammonium phosphate has lower metal contents and is fully water soluble compared to the fertilizer grade which is the large volume commodity for phosphorus fertilizers.

Other options include conversion of the intermediate calcium phosphate into monocalcium phosphate (MCP) or dicalcium phosphate (DCP) by reaction with an acid (phosphoric acid, hydrochloric acid or sulfuric acid) according to a suitable process. The intermediate calcium phosphate can also be used as a raw mate-

rial for production of other phosphorus products such as phosphoric acid or superphosphates. Intermediate ferric hydroxide is converted into ferric chloride by reaction with hydrochloric acid. The final ferric chloride product can be used as a coagulant for phosphorus removal in wastewater treatment plants. Intermediate aluminium hydroxide can be converted into aluminium sulfate or aluminium chloride by reaction with sulfuric acid or hydrochloric acid respectively.



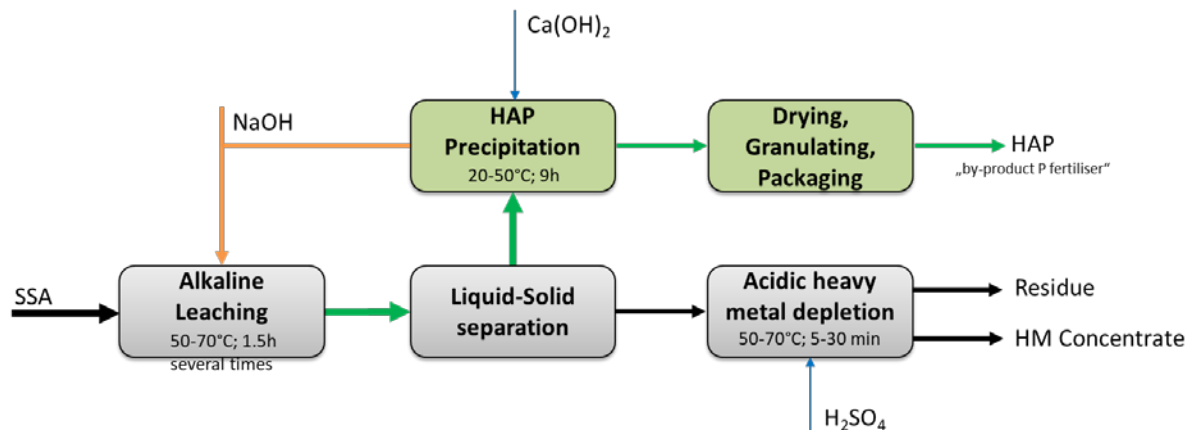
**Figure 26:** EasyMining’s two concepts for phosphorus recovery from ash and up-cycling.

<http://www.easymining.se/our-technologies/ash2phos/ash2phos-information/>

### **METAWATER** (Alkaline Ash Leaching Process)

Driven by the goal to reduce sludge and sludge ash disposal cost and the price spike for phosphates in 2008, another approach has been developed and implemented in Japan in 2010. The municipality of Gifu and the company METAWATER Corp. developed, tested and implemented an alkaline ash leaching plant at WWTP Gifu-North, where about 1,000 Mg SSA/a are treated to yield appr. 300 Mg/a of a “by-product P fertiliser” with the local brand Gifu-no-daichi® being sold by the JA-Zen-Noh (National Federation of Agricultural Co-operative Associations) to local farmers.

In the process, ash is repeatedly leached with NaOH at 50-70°C for 1.5 h. The P is mainly extracted from  $\text{AlPO}_4$ . After a membrane-type liquid-solid separation, dissolved P is then precipitated with  $\text{Ca}(\text{OH})_2$  at 20-50°C for 9 h to form HAP. The NaOH is recycled back into the leaching reactor to save cost. The recovered HAP is then being washed, dried, granulated and packed in flexible container bags. The product contains 25-30% citrate soluble  $\text{P}_2\text{O}_5$  and meets the requirements for “by-product P fertiliser” specified by the Fertiliser Regulation Act.



**Figure 27:** The alkaline ash leaching process as implemented in Gifu and Tottori in Japan (Nakagawa and Ohta, 2018).

The solid residue is subject to weak acid leaching with dilute  $\text{H}_2\text{SO}_4$  for 5-30 mins at 50-70°C for heavy metal depletion. The dried remains are then used as roadbed materials or filler in asphalt.

The city of Tottori implemented essentially the same technology at Akisato WWTP in 2013 and recovers appr. 150 Mg HAP/a from about 500 Mg SSA/a.

The biggest barrier for further technology roll-out seems to be the fact that the about 300 sludge incinerators in Japan are smaller units, therefore making it hard to meet the economy of scale. Clustering and cooperation of various ash producers may help to improve the operational cost for the ash treatment.

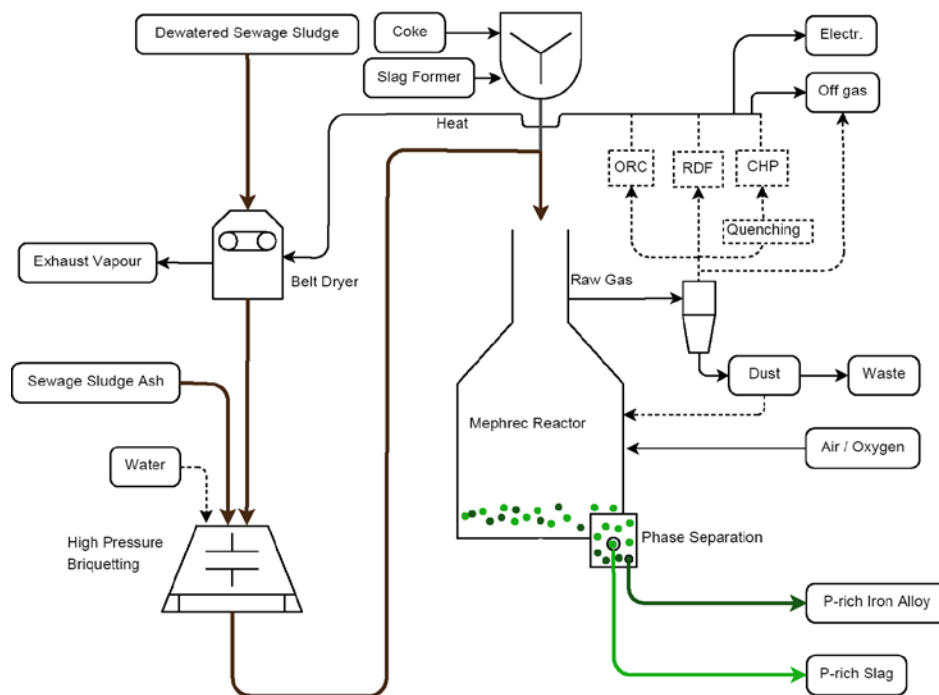
Various other wet chemical processes to recover phosphates from sewage sludge ash or other relevant mineral solids are under development, but still too immature or in many stages quite similar to the ones described before. Some include electro dialysis (EDASK, DK; Parforce, DE;) or apply bacteria for bio-leaching (P-bac, DE). Future will show, if they manage to enter the market or not.

Besides wet chemical processing, also thermal treatment or thermo-chemical treatment can be applied to transform sewage sludge ashes into minerals containing phosphates with better plant availability and lower heavy metal contamination.

The following two technologies can be considered metallurgic sludge or ash treatment options. One has been developed in Germany and still is at pilot stage, whereas the other has already been implemented in Japan.

### **MEPHREC**

The Mephrec process has been developed by the German company Ingitec for recovery of phosphorus from sewage sludge and/or ash. Dewatered sludge (>25% dry solids (DS)) is dried to 80% DS and briquetted. The briquettes are then thermally gasified in a shaft furnace at temperatures above 1,450°C. Heavy metals are reduced under these conditions into their elemental form. Volatile metals (Cd, Hg, Pb, Zn) are evaporated and separated, whereas non-volatile heavy metals are separated from the slag in form of a molten metal phase. The phosphorus present in the sewage sludge is transformed into silico-phosphates (said to be comparable to 'Thomas phosphate').



**Figure 28:** Process scheme of the Mephrec metallurgical sludge or ash treatment (P-REX Technical Factsheet 2015).

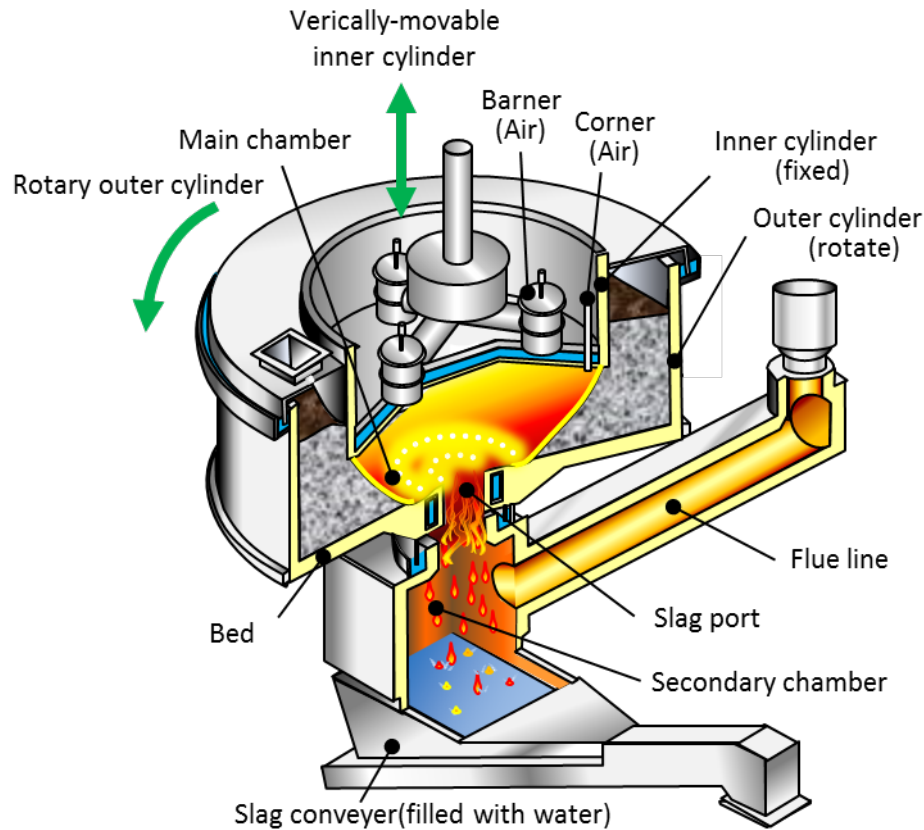
When sewage sludge is used as reactor feed, electricity and heat with high caloric raw gas can be produced. The raw gas can then be directly injected into an Organic Rankine Cycle (ORC) process or municipal waste incineration plant. If there is an opportunity to refine the gas, it can be valorised in a combined heat and power plant (CHP). A large pilot has been operated 2016/2017 at a WWTP in Nuremberg (Germany). It turned out to be hard to reproduce representative batches during the pilot campaigns. Besides that, potential operators need to be aware, that they need to employ very skilled smelters, which can only be found in the remaining steel making industry. The resulting P rich slag cannot be considered a ready to use product and needs further treatment. The local WWTP operator indicated to further elaborate the overall concept of sludge management and P recovery in the region. The new approach called P.KON is now aiming at the production of phosphoric acid after melt-conversion of the sludge. More details can be expected to be available in the near future.

### ***KUBOTA Surface Melting Furnace***

The Japanese company KUBOTA has a lot of experience in waste and sewage sludge incineration. In Japan alone, eleven KUBOTA melting furnaces have been deployed for sewage sludge incineration between 1979 and 2017 (KUBOTA brochure).

The KSMF can treat various materials, combustible, incombustible, or moist. The furnace has a double cylinder structure. The outer cylinder rotates to allow the feed material to be equally layered and continuously fed into the inner main chamber. The furnace is operated at temperatures between 1,250 to 1,350 °C. The material is pushed towards the centre of the main chamber, where it burns at the surface and melts, before flowing down into the granulation unit with cold water. There, the P containing mineral phase can be easily separated from the metal phase by magnetic separation. Although phosphorus tends to volatilize at temperatures above 1,000 °C, the unique design of the KSMF ensures more than 90% of the phosphorus remaining in the slag. The heavy metals are depleted by transformation into the gaseous phase with up to

90% efficiency (depending on the element). No additional fuel is needed to operate the furnace, if the calorific value of the waste fed into is sufficiently high. This is the case for dried sewage sludge. Excess heat can be used to pre-dry the incoming sludge.



**Figure 29:** Schematic view of the KUBOTA Surface Melting Furnace (KSMF), (courtesy of KUBOTA Corp. / Hosho, 2018).

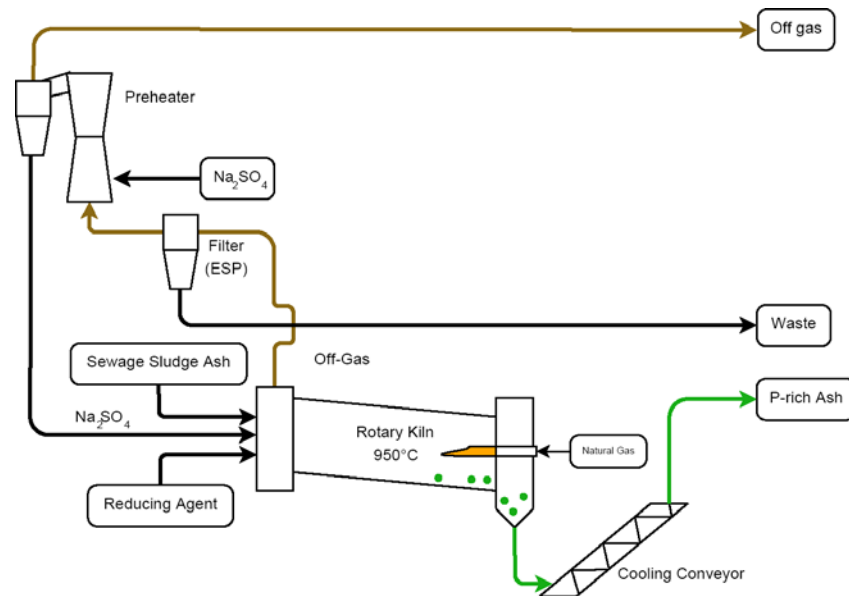
Although the slag is allowed to be used as fertiliser in Japan, the same needs to be approved in other countries.

Other thermo-chemical concepts treat sludge or sludge ash in rotary kilns and dose salts to provide anions like chlorides as metal donors for heavy metal depletion; i.e. the metal chlorides have higher volatilities and can therefore be transferred more easily from the mineral phase into the gaseous phase, where they get trapped in the subsequent gas cleaning steps.

### *AshDec*

The Ashdec process thermo-chemically treats sewage sludge ash (SSA) in a rotary kiln and has been jointly developed and optimised by Outotec and the German Federal Institute for Material Research and Testing (BAM). The phosphates present in the SSA are transformed into bio-available  $\text{NaCaPO}_4$  by reaction with  $\text{Na}_2\text{SO}_4$  at 900-1,000°C, with a minimum retention time of 20 minutes. Dry sewage sludge is used as a reducing agent. Volatile heavy metals (As, Cd, Hg, Pb, Zn) evaporate and are removed via the gas phase. The hot kiln off-gas can be used for pre-heating the ash, the sodium sulphate and kiln air for energetic process optimisation.

An alternative Ashdec process, or better the initial one applied magnesium chloride ( $\text{MgCl}_2$ ), providing better heavy metal removal in the form of volatile chlorides and oxichlorides. The phosphorus is transformed into calcium-magnesium phosphates. Heavy metal removal is more efficient with the chloride path, but the bioavailability of the recovered phosphate-containing material is limited to acidic soils (tropical), whereas the process under reducing conditions yields a material with good bioavailability of the P, independent of soil pH.



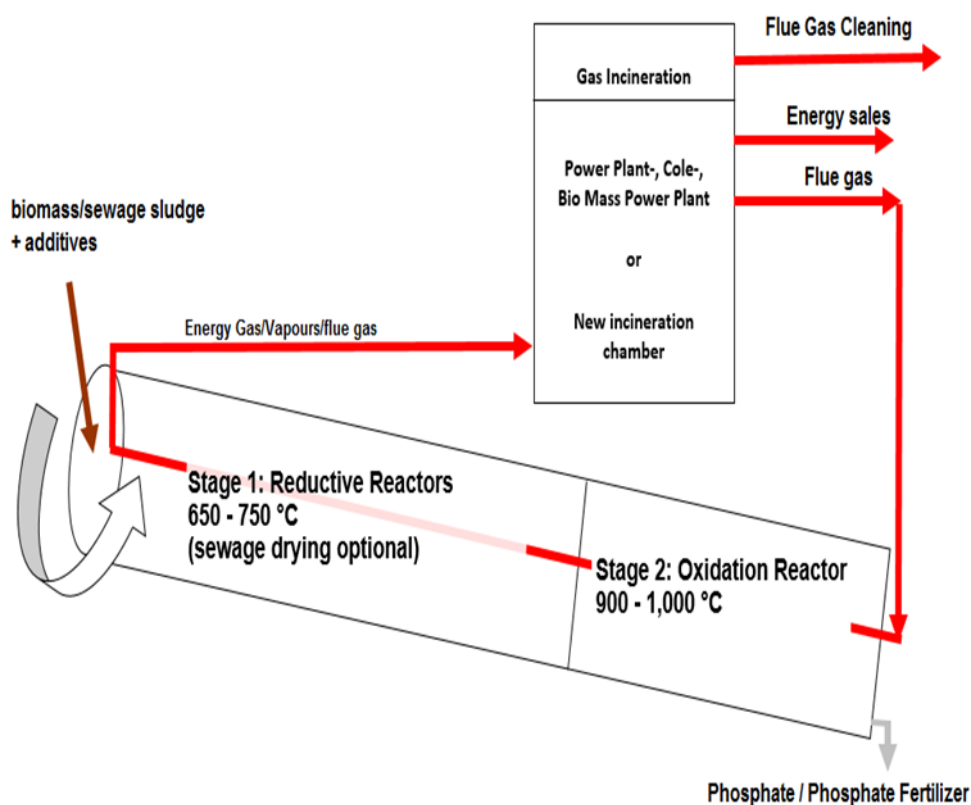
**Figure 30:** Process scheme of the Ashdec thermo-chemical ash treatment (P-REX Technical Factsheet 2015).

A larger pilot scale plant has been operated in Leoben (Austria) back in 2008/2009 with the  $\text{MgCl}_2$  option, whereas the  $\text{Na}_2\text{SO}_4$  option was demonstrated within the EU FP7 project P-REX back in 2014 with an existing rotary kiln of IbuTec® in Weimar (Germany). All further process optimizations have then been conducted at the technical facilities of BAM in Berlin. A full-scale plant is now intended for implementation in Southern Germany for the years to come.

## EUPHORE

Similar to the AshDec process, the EUPHORE process is operated with a rotary kiln. The first step is the dosage of additives like alkaline (KCl) or alkaline earth chlorides ( $\text{MgCl}_2$ ) or sulfates to trigger heavy metal depletion and phase transformation of the phosphates towards better solubility. The first thermal treatment step is drying of the dewatered sludge before entering the reductive zone of the rotary kiln - the pyrolysis step. Here, the metals are reduced and volatilized as chlorides into the gas phase at temperatures above  $650^\circ\text{C}$ . When the material enters the combustion stage with more than  $900^\circ\text{C}$ , it sublimates into phosphates with improved plant availability.

Various test and pilot campaigns have been conducted in Switzerland and Germany so far. At current state, facilities in Oftringen and Urvier (both Switzerland) are intended, as well as in Mannheim (MVV, Germany) where two rotary kilns are about to be integrated into the existing municipal waste incineration plant (November 2018). The capacity there will be around 37,500 Mg DS/a sewage sludge, yielding about 15,000 Mg phosphate containing material, depending on the additives applied.



**Figure 31:** Process scheme of the EUPHORE® RedOx ash treatment (Courtesy of EUPHORE).

**Table 4:** Prominent down-stream of wastewater treatment P recovery technologies or approaches.

Technology	Supplier/User	Input for recovery/recycling step			Recovered Material	TRL
		Sludge	Sludge ash	Intermediates*		
Ash2Phos	EasyMining		X		DCP, Fe/Al hydroxides	6
AshDec	Outotec	X	X		Calcined Intermediates	6
EcoPhos	Ecophos		X		DCP, H <sub>3</sub> PO <sub>4</sub> , FeCl <sub>3</sub>	9 (8)
EuPhoRe	EuPhoRe	X			Intermediates Min. Fertiliser	6
CleanMAP	EasyMining			X	MAP, DAP, SSP FeCl <sub>3</sub> , Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>	5
Conventional Fertiliser Manufacturing	Various companies		X	X	Customized fertilisers	9

Technology	Supplier/User	Input for recovery/recycling step			Recovered Material	TRL
		Sludge	Sludge ash	Intermediates*		
					(SSP, NP, NPK)	
Glatt SeraPlant	Glatt Seraplant		X		MCP, customised Fertiliser	6
HTC**	Various	X			Carbonisates	7
KUBOTA SMF	Kubota	X			P-slag	9
P.KON	KRN Nuremberg	X	X		H <sub>3</sub> PO <sub>4</sub>	2
METAWATER	METAWATER		X		HAP	9
Parforce	Parforce		(X)	X	H <sub>3</sub> PO <sub>4</sub>	6
Phos4Life	Tecnica Re-unidas		X		H <sub>3</sub> PO <sub>4</sub> FeCl <sub>3</sub>	6
Pyrolysis**	Various	X			Pyrochar	7
TetraPhos	Remondis Aqua		X		H <sub>3</sub> PO <sub>4</sub> FeCl <sub>3</sub>	6

\*Intermediates are materials recovered from the ash with improved quality making them marketable as raw materials for further up-cycling processes

\*\*Both, HTC and Pyrolysis are yielding material neither applicable as fertilisers nor soil improvers in various countries. Pyrolysis can be seen as thermal sludge pre-treatment only partly depleting contaminants. HTC generates carbonisates with barely reduced heavy metal concentrations. Also here, further treatment is necessary. Both technologies have been proven useful for treatment of biomass, whereas sewage sludge seems to be a very challenging field of application with its rather high sand content as just one of the various issues to cope with.

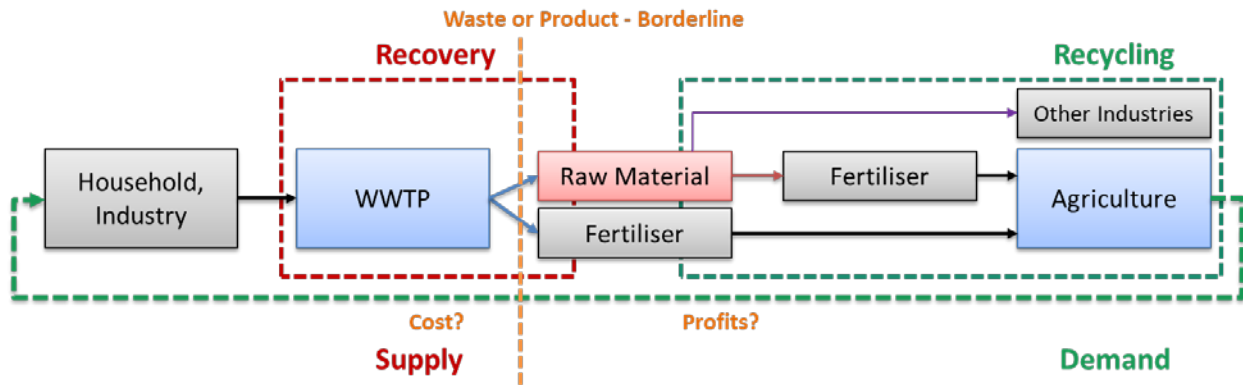
## 2.3 Phosphorus recycling – not without value chains

Proven by the previous sections of this compendium, technologies to recover phosphorus from P-rich wastes like sewage sludge, ashes, manures, and bio-wastes are already there (Schoumans et al., 2015; Kabbe et al., 2015; Ohtake et al., 2015). Some of them well advanced and already considerable as state-of-the-art, others still needing optimization in technical, but also in economic terms. The major challenge will be bridging of the gap between recovery and actual recycling (Figure 32).

Closing the loop will only work with value chains. Otherwise, stockpiles of recovered nutrients will grow without being valorized. It also means that there need to be customers for the materials recovered, be it for direct use as a product (fertilizer) or as raw material for further treatment and processing. Every processing step is linked with additional efforts (labour, energy, chemicals), finally meaning costs. The challenge will be, once the value chain is legally allowed to find customers seeing the positive value in these materials and being able and willing to pay an adequate price. If the process chain fails to generate a positive value, only law enforcement can foster a rather artificial market for these recovered materials.



Technologies cannot be more than just one pillar to switch towards sustainable nutrient management and circular economy. Preventing waste is at least as important, if not the most important approach. In the end, it is a societal challenge to define if, how and how fast we move forward and become circular.



**Figure 32:** Bridging the gap between nutrient recovery from sewage/sludge/ash and nutrient recycling – value chains.

The need to create value from recovered materials underlines the importance to generate recyclates that are known on the market with a real demand. Per definition, a material is only a product, if someone pays a positive price for it.

Besides value and price, volume plays an important role. So far, the available volumes for recovered phosphates are rather modest and often considered suitable to address niche markets. But, what happens in Germany as an example, if suddenly, recovered phosphates containing approximately 45,000 Mg P are flushed to the market in 2029. The P content compares to roughly a third of the German mineral phosphate import for fertiliser application. A third is neither to be considered a niche nor will all the material find their own special application or fit into the same niche.

In common saying: Everyone can try to find a niche for the material, but not all of them will fit into it.

Finally, the conclusion can only be to recover phosphates in known, already established forms which are traded in large volumes and considered commodities. Under this light, technologies delivering commodities like phosphoric acid, calcium phosphates or ammonium phosphates are the most promising candidates. Struvite, given its unique and beneficial properties and purity is a prime candidate to replace soft-ground phosphate rock as mineral P source in organic farming, thus being one of the few materials actually having a chance as premium niche product.

Materials intended to be sold as fertiliser but being something new, different, and unknown to potential end-users will have to compete with an existing bulk market. Even if they could be sold for lower prices to consumers, a real demand is not guaranteed. It is more likely, that such materials end up as raw materials to be fed into existing production process chains as rather low (or even zero) priced materials.

Besides economic aspects, legal aspects turn out to be even more important and lead to the same conclusion: To avoid additional burden for bringing a certain material to the market, also existing materials and infrastructures are the route of choice. From the legal side, we observe enabling frameworks, but also a disabling framework, depending on targeted application of the material or country.

### 3 Implementation – challenges and opportunities

There is no doubt, 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 solely installed to recover phosphorus. The key drivers were and still are operational issues like process stability and monetary benefits (mainly cost reduction). But there is a wind of change from the policy side. Circular economy is gearing up not only in speaking. Slowly, first regulatory steps have been taken in some countries to facilitate nutrient recovery and recycling.

#### 3.1 Legal aspects

Before diving into details, it can be stated, that any environmental protection measure would not have been implemented without law enforcement, especially when it leads to additional costs. In general it can be claimed, the legal framework, especially the environmental regulations, are key innovation drivers of our society.

Looking at Switzerland (2016) and Germany (2017), being the first countries to really set and not just announce legal requirements for phosphorus recovery, an acceleration for P recovery technology development and implementation can be expected. Other countries already announced that they will follow the given examples of the both frontrunners with some flexibility. But, recovery alone is not yet recycling! Sure, there will be transition phases for implementation, but the clock is already ticking for the legislators to enable actual recycling.

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 also a prerequisite to enable value chains to bridge the gap between recovery and recycling, and making a circular economy really happen. Therefore, in the case of Europe, the revision of the EU fertiliser regulation (EC 2003/2003) needs to be progressed to provide a level playing field for fertilisers, irrespective of whether they are produced from fossil or secondary sources. (Hukari et al., 2015 and 2016). Another issue that needs to be considered is the application of appropriate products for use in organic farming, for instance by adding recovered struvite to the list of approved fertilisers in regulation EC 889/2008.

Struvite recovery can be considered the 'lowest hanging fruit', combining operational benefits with phosphorus recovery as a nice to have by-product. It should be implemented where ever suitable and applicable.

But will utilities adopt and implement biological P removal instead of chemical P removal? It is easy and also a prerequisite to set discharge limits from the authority side. The real challenge is how these limitations are monitored or enforced. There seems to be a tendency for higher bio-P rates in countries, where the TP limit is monitored on an annual average value base. In countries like Germany, where absolutely no flexibility is given to the utilities as a result of the 4 out of 5 rule for effluent monitoring, the bio-P rate is rather low and utilities tend to dose more  $\text{Fe}/\text{Al}$  salts then necessary. This has a huge impact on the sludge, but also the ash quality after incineration. Bio-P sludge in the end contains higher P concentrations compared to the dry solids, whereas Chem-P sludge contains more minerals and P is more diluted. Thus, the P recovery from Bio-P sludge would be easier and economically better, compared to the Chem-P sludge/ash.

It would be interesting how the holistic environmental footprint or impact would look like if more Bio-P could be enabled.

The existing heterogeneity of legislation between the different “domains” and between countries still uses to appear as barriers if it comes to i.e. EU wide marketing of recovered nutrients. Even the recovery, when it comes to large scale operations, as in the case of sewage sludge ashes is hampered, since the border crossing transport of waste is very challenging from the operator’s point of view. Here, initiatives or green deals like the North Sea Resources Roundabout (<http://www.greendeals.nl/north-sea-resources-roundabout/>) can provide a good template how these obstacles can be resolved on regional, multi-national level. Recycling and Recovery are explicitly addressed in the 5-stage waste hierarchy of the European Waste Framework Directive (2008/98/EC) setting the frame for all EU Member States.

The waste hierarchy is defined as following, also setting the border line between waste and non-waste status:

Prevention of waste	non-waste
<hr/>	
Preparing for re-use	waste
Recycling	
Recovery	
Disposal	

Stage 1 represents the non-waste domain, whereas all other stages 2-5 represent the waste domain. Re-gaining product or end-of-waste status is the prerequisite for all materials to be allowed to be marketed in Europe as a product. The specific product or end-of-waste criteria for materials destined for a certain use are defined in the related regulations or ordinances. In the case of fertilisers, the European fertiliser regulation (2003/2003/EC), currently under revision, has to define the criteria for substances or materials to be used as fertilisers (PFC; Product Function Category) or raw materials for fertiliser production (CMC; Component Material Category). The European Commission follows the ambition to create a level playing field for both primary/virgin materials and secondary/renewable materials recovered from wastes. Although there are already various value-chains established to enable the recycling of recovered nutrients, the implementation and interpretation of EU legislation can vary from member state to member state. Depending on the pragmatism of authorities, it can be observed that recovered materials allowed to be used as fertiliser or fertiliser raw materials in one member state can face a ban from this application route in another member state. Hopefully, this heterogeneity will be phased out after the revised EU fertiliser regulation entered into force. However, this is not to be expected before 2019/20.

The national implementation of the Waste Framework Directive for example in Germany is the Circular Economy Act (Kreislaufwirtschaftsgesetz, KrWG), implemented in 2012. End-of-Waste status in general is defined under §5:

1. The waste status of a material ends, once having been processed/valorised and fulfilling the following basic requirements:
  - a. Being used for specific purposes,
  - b. Has a market or demand,

- c. Meets all technical requirements for the intended application and complies with all legal requirements and standards for products (also implicating that it is registered under REACH → product status), and
  - d. Its use does not lead to harm for human health and environment.
2. The federal government is mandated to define specific EoW criteria and implement regulations after approval by the federal council including limit values for contaminants etc.

Both, the sewage sludge regulation and the fertiliser regulation are such references.



**Figure 33:** Most relevant regulations for the valorization of recovered nutrients as (mineral) fertilizer in Europe and Germany.

Table 5 provides an overview on contaminant limits set in different regulations or being currently under discussion for implementation in the hotspot regions for nutrient recovery. These are to be considered as part of the end-of-waste criteria.

**Table 5:** Quality criteria for land application of biosolids/recyclates in selected countries/regions.

Parameters in mg/kg DS	EU municipal sludge framework dir.	EU mineral fertilizer reg. draft 2016 PFC 1	STRUBIAS proposed PFC levels for inorg. macronut. fertiliser	Germany Fertiliser Ordinance	Germany Sludge Ordinance	US CFR 40 § 503/13	Japan
	1986	2016	2017	2017	2017		
Heavy Metals							
As - Arsenic	--	60	60	40	--	41	50
Tl - Thallium	--	--	--	1	--		
Cd - Cadmium	20 - 40	3	--	1.5	Fert. Ord.	39	5
Cd for P <sub>2</sub> O <sub>5</sub> >5%	--	60-40 mg/kg P <sub>2</sub> O <sub>5</sub>	60-40-20 mg/kg P <sub>2</sub> O <sub>5</sub>	50 mg/kg P <sub>2</sub> O <sub>5</sub>	--	--	--
Cu - Copper	1000 - 1750	--	--	900	Fert. Ord.	1500	--
Hg - Mercury	16 - 25	2	--	1	Fert. Ord.	17	2
Ni - Nickel	300 - 400	120	120	80	Fert. Ord.	420	300
Pb - Lead	750 - 1200	150	150	150	Fert. Ord.	300	100
Se - Selenium	--	--	--	--	--	100	
Zn - Zinc	2500 - 4000	--	--	--	4000	2800	
Cr - Chromium (total)	--	--	--	--	Fert. Ord.	--	500
Cr - Chromium (VI)	--	2	2			--	--
Organic Contaminants							
PCB 28, 52, 101, 138, 153, 180 each	--	--	--	--	0.1	--	--
AOX	--	--	--	--	400	--	--
Benzo[a]pyrene	--	--	--	--	1	--	--
PAH <sub>16</sub>	--	--	6?				--
PFC (PFOA + PFOS)	--	--	tbc	0.1	Fert. Ord.	0.1	--
I-TE Dioxines and dI PCB (WHO-TEQ 2005)	--	--	--	0.03	Fert. Ord.	0.03	--
Biuret (C <sub>2</sub> H <sub>5</sub> N <sub>3</sub> O <sub>2</sub> )	--	1200	--	--	--	--	--
Perchlorate (ClO <sub>4</sub> <sup>-</sup> )	--	1	--	--	--	--	--

\*A more exhaustive global overview is provided in the annex of the ISO draft standard ISO/DIS 19698:2018 – Sludge recovery, recycling, treatment and disposal – Beneficial use of biosolids – Land application, prepared by ISO/TC 275 WG4

A big impact of pro recycles, since most of them contain far less Cadmium (Cd) compared to some fossil based mineral phosphate derivatives, can be expected from implementation of Cadmium limits under the revised EU fertilizer regulation. The European Commission's ambition is not only to introduce a Cd limitation, but also to tighten the limit over the coming years. The starting point is intended to be set at 60 mg Cd per kg  $P_2O_5$ . It is still uncertain, if and where the tighter limit will be set in the regulation after passing all political and juridical stages in the coming years. Without any doubt, Cd must be limited for the sake of our health and a healthy environment, esp. soils.

Thus, there still is a long way to go to adapt the legal framework from an inconsistent, partly fostering, often disabling setting.

### 3.2 Technical and operational aspects

As already explained in chapter two, so far phosphorus recovery has only been implemented when there was an operational need or the prospect to save or reduced operational cost within the wastewater/sludge treatment train or downstream along the disposal route.

Besides existing infrastructures of the utilities themselves, the availability of sludge disposal routes plays one, if not the most important role.

It is obvious, that sludge incineration is preferred in regions, where the amount of sludge is exceeding the land area having been traditionally used for disposal – meaning the nutrients are succeeding the capacity or demand of the domestic agriculture. This is especially the case in urban areas and rural areas with excessive livestock farming. The obvious option to reduce the volume of material and to concentrate the nutrients is incineration or thermal mineralization.

The resulting ashes or mineral concentrates have been disposed in the past, but, if P recovery becomes obligatory, they will have to be stored separately and recoverable or directly fed into an ash treatment plant for P recovery. Thus, in case of the ash route, technical needs for the wastewater utility are not the driver, it is the compliance with regulation and/or cost reduction for disposal.

Installations implemented on-site WWTP are characterised by the following general aspects:

- Prevention or mitigation of unintended scaling along the sludge train
- Improved sludge dewaterability
- Reduced polymer consumption for dewatering
- Reduced sludge volume for disposal (reduced cost)
- Partly better energy recovery (depending on additional modules)
- Improved effluent quality (reduced return load); better compliance with regulation

Once a utility intends to valorize recovered nutrients, additional tasks for them appear. A new material or waste flow additional to the sludge/residues to be disposed of turns up and needs to be managed. New regulatory issues appear to be met and complied with. Here, technology suppliers providing a complete or all-inclusive package from recovery to sales are critical.

The following issues can be seen as a challenge for, or even barrier to, the widespread 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.
- Many technologies, mainly developed without the direct involvement of potential users, are more complicated than necessary, failing to match operational needs and viability. Current market deployment reflects this, in that only technologies providing operational benefits for their users are being implemented.
- Technologies and recovered materials which cannot be integrated into existing infrastructure and markets have to cope with strong competition within established structures. Thus, the more versatile the recovered product can be used, the better. In the case of phosphorus, widely used commodities or chemicals like white phosphorus  $P_4$  as the highest premium product or phosphoric acid ( $H_3PO_4$ ), ammonium phosphates (MAP, DAP) or calcium phosphates (MCP, DCP) are the most promising materials. 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 crucial as well. 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. Limitations are getting even worse, if the technology is not sufficiently decontaminating or detoxifying the input material.

### 3.3 Financial aspects

Determining whether to invest in P- recovery has to be distinguished between cost and price. Of course, though reducing cost is a definite driver to innovate, prices are a more complicated figure with much more diverse dependencies. In the end, a wastewater utility will only invest if a P recovery technology comes along with operational (technical) and financial benefits. It is unlikely, that there will be investments to just recover P as such and at any cost.

The global implementation inventory clearly shows P recovery has only been implemented as a result of operational needs or when costs had to be reduced. However, these technologies only recovered a minor fraction of the P contained in the sewage.

A game changer towards higher recovery rates can only be law enforced P recovery. But making P recovery mandatory is only one thing; the package should also include an easing of the valorization for recovered materials.

In countries like Germany, the gap between cost for recovery and the price for them on the real market will be compensated by German households (in the end by tax payers). This actually means that consumers pay for the recovery via wastewater treatment fees, whereas potential users for the recovered materials can make profits by their own with these heavily subsidized materials. So, the question is *how to match with sustainability always consisting of the three components economy, ecology, and society?*

So far, the recovered materials are only exceptionally sold as real products like Crystal Green at premium prices. Most of them are given away for free or at more or less just symbolic prices. This accounts for the most installations on the three continents.

### 3.4 Scale

Scaling for P- recovery is an easy formula. If the cost for certain investments are high, bigger volumes or scales can help to reduce the specific cost per unit P recovered. The Return on investment (ROI) is a good indicator. Whereas most recovery technologies already implemented at WWTP have rather short ROIs, the downstream options tend to be more costly and have longer ROIs respectively.

For instance, in Japan with more than 300 sludge incinerators, so far only two P recovery from municipal sludge ash have been materialized in the cities of Gifu and Tottori. The costs are still high. Why haven't these applications been replicated elsewhere? One of the main reasons could simply be the circumstance, that most of the sludge incinerators are rather small and therefore local ash treatment too expensive or not competitive compared to other disposal routes for the ashes.

In the European setting, with rather large sludge incinerators, the setting looks different. Feasibility studies of the past mainly concluded a minimum ash volume of 20,000 Mg/a to match economic feasibility for P recovery from ash. Of course, this is a very general conclusion and local/regional conditions should always be included into consideration. The years to come will show, especially in Germany and Switzerland, that P recovery from ash will be implemented most likely in form of regional clusters to improve the economy of scale.

Overall, the clustering of ash treatment in ChemParks appear to be the most promising and reasonable approach. In most cases also chemicals are "on tap" and looking at HCl cheaply available. Besides that, all ChemParks are extremely well connected to any kind of transportation system and additionally, often include potential users for the recovered materials.

Looking at Germany again, 4-5 P recovery from sludge ash facilities strategically spread across the country would be enough to treat the future quantities of more than 500,000 Mg/a sludge ash (containing appr. 45,000 Mg/a P). A similar approach could work for Japan as well, even if the ash comes from much smaller incinerators.



## 4 Conclusions

There is no doubt that phosphorus is a limited essential resource. Efforts should be taken to increase the resource efficiency of phosphorus while we have a choice. In the light of existing technologies, attention should be focused on bringing these to the market, rather than increasing the range of technologies. There is no need to reinvent the wheel.

Additionally, the existing infrastructure already provides the opportunity to recover and recycle substantial quantities of P, including from ash. Smart sludge management will help to make the most out of the existing infrastructure without the need for huge investments. Of course, recovery alone will not work. Feasible value chains are needed to bridge the gap between recovery and recycling.

The current legal framework and the low prices for raw materials have to be considered as market barriers. At current price levels for phosphate rock and other raw materials, only legal requirements are likely to boost a wide-spread implementation of phosphorus recovery and recycling from the wastewater stream. A 'level playing field' is needed for fertilisers, so that it does not matter if they are made from fossil or from renewable secondary sources. The definition of End-of-Waste criteria for recovered nutrients needs to be addressed, and binding recycling targets (comparable to the CO<sub>2</sub> emission reductions goals) have to be developed. Otherwise, no recovery and recycling technology will be widely implemented if it is not providing benefits to its operators under current conditions.

Recently, the need for a globally streamlined P recovery knowledge base has been proven.

More and more countries world-wide are starting to consider alternative P recovery options to the traditional recycling route – sludge spreading on arable land.

Whereas P recovery on-site will be limited to WWTP where they really meet operational needs and reduce cost, the “big P fish” will be caught down-stream of the wastewater treatment itself. Since sludge incineration is a well established and easy to manage operation, undiluted sludge incineration can be seen as the biggest source of the still untapped P potential from sludge in the future, in regions, where direct application of sludge/biosolids is banned or no longer possible.

Although P scarcity is often linked as told to be the motivator for recovery and recycling, the reality shows the opposite. Most P recovery installations are operated in countries or regions with nutrient surplus, often linked to excessive livestock farming, limited land area, and high population density.

## 5 Outlook

A few countries are ahead of the game and seen as frontrunners. But already today, a trend for more and more countries towards technical P recovery becomes visible, also revealing, a demand for a streamlined global knowledge and know-how base covering phosphorus recovery not only from wastewater, but also from other relevant nutrient containing wastes like manure, biowaste, etc. Besides the traditional biosolids application to land, the technical nutrient recovery and recycling alternatives need to be incorporated under the GlobalG.A.P. umbrella as well.

Here, all relevant stakeholders from industry, policy, and science need to be better linked. The already existing phosphorus or nutrient platforms can and should be used as facilitators and regional hubs.

Although some countries have already implemented or are about to implement legal requirements for P recovery, the bridging of the gap towards actual recycling remains the biggest challenge. Europe may play a leading role if the new fertiliser regulation actually manages to create a level playing field for recovered materials (secondary sources) and virgin materials (primary sources).

Many countries are currently observing, what is happening in Germany. There is a global interest in the recent developments. Depending on the shape of the sanitation infrastructure, Germany may serve as an example to follow more or less the same route.

In the end, it will be the question of available land area and population/livestock density, that gives the answer, if the traditional route for direct land application of sludge/biosolids can be considered sustainable or not. Where the pressure of sludge and/or manure is high, alternative routes provide the better solutions. Both routes will be common practice, depending on the regional/national conditions.

Unlike sludge application on land, the alternative recovery of mineral nutrient concentrates provide new opportunities, towards better balanced nutrient budgets due to the following properties:

- Definable composition
- Defined fertilising efficiency (less nutrient losses to the environment)
- Enable better handling, storage and longer transport distances up to even exports, esp. relevant for countries with high food and feed imports, but limited agriculture
- Other fields of industrial application and therefore value creation

The time is now to implement and exploit the results of numerous projects conducted in the past.

*Wisdom just written on paper will be dust (or ash) one day; only the wisdom applied will shape our future!*

*Think forward, act circular!!!*

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## 7 Annex

### 7.1 Supply - Technologies for P recovery on-site WWTP

AirPrex® and CalPrex™	
Europe	North America
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ANPHOS®	
Europe	North America
<b>Colsen BV</b> Kreekzoom 3   4561 GX Hulst   Netherlands Phone: +31 (0)11431 1548 Email: info@colsen.nl URL: www.colsen.nl	

CRYSTALACTOR®	
Europe	North America
<b>Royal HaskoningDHV</b> Postbus 1132   3800 BC Amersfoort The Netherlands Phone: +31 88 348 91 81 Email: Aad.van.Duyvenvoorde@rhdhv.com URL: www.royalhaskoningdhv.com	

EKOBALANS	
Europe	North America
<b>EkoBalans Fenix AB</b> Scheelevägen 22   223 63 Lund   Sweden Phone: +46 (0)70 515 3789 Email: gunnar.thelin@ekobalans.se URL: www.ekobalans.se	

ELOPHOS	
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<b>Eliquo Water Group GmbH</b> Seedammweg 55   61352 Bad Homburg v.d. Höhe Germany Phone: +49 6172 404-0 Email: info@eliquowater.com URL: www.eliquowater.com	

ePhos	
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EXTRAPHOS	
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Hitachi Zosen (AD-HAP and Phosnix®)	
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KURITA	
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Multiform™ and MultiWAS™	
	<b>North America</b>
	<b>Multiform Harvest Inc.</b> Has been acquired by Ostara Nutrient Recovery Technologies Inc. in January 2019

NASKEO	
<b>Europe</b>	
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NuReSys	
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Europe	
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PEARL and WASSTRIP	
Worldwide	
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Phospaq®	
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<b>Paques BV</b> T. de Boerstraat 24   8561 El Balk The Netherlands Phone: +31 514 60 85 00 Email: info@paques.nl URL: www.paques.nl	<b>Paques Environmental Technologies Inc.</b> 2400 District Avenue, Suite 330   Burlington, MA 01803   USA Phone: +1 781 362 4636 Email: c.rinaldi@paques-inc.com URL: www.paques-inc.com

PhosphoGreen®	
Worldwide	
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STRUVEX®	
Europe	South Africa
<b>P.C.S. Pollution Control Service GmbH</b> Merkurring 100   22143 Hamburg   Germany Phone: +49 40 6391 705-0 Email: info@pcs-consult.de URL: www.pcs-consult.de	<b>WEC Projects Johannesburg – Head Office</b> Plot 15 William Nicol Drive (R511)   Diepsloot A/H 2021 South Africa Phone: +27 11 754 5500 Email: info@pcs-consult.de URL: www.pcs-consult.de

STRUVIA™ and PhosForce (Veolia)	
Europe	Europe
<b>KRUGER A/S</b> Gladsaxevej 363   2860 Søborg Denmark Phone: Email: mikkel.poulsen@kruger.dk URL: www.kruger.dk	<b>Veolia Watersystems Iberica</b> C/ Electrodo 52   P.I. Santa Ana   28522 Madrid Spain Phone: +34 91 660 4023 Email: angela.manas-llamas@veolia.com URL: www.veoliawatertechnologies.es

## 7.2 Supply - Technologies for P recovery – Thermal route

Ash2®Phos and CleanMAP®	
Europe	
<b>EasyMining Sweden AB</b> Travvågen 8   75651 Uppsala Sweden Phone: +46 70 978 64 74 Email: Jan.Svard@easymining.se URL: www.easymining.se	

AshDec®	
Europe	
<b>Outotec GmbH &amp; Co. KG</b> Ludwig-Erhard-Str. 21   61440 Oberursel Germany Phone: +49 6171 9693 0 Email: Andreas.Orth@outotec.com Email: Tanja.Schaaf@outotec.com URL: www.outotec.com	

EcoPhos®	
Europe	
<b>ECOPHOS®</b> Avenue Jean Monnet 1   1348 Louvain-La-Neuve Belgium Phone: +32 10 47 73 70 Email: info@ecophos.com URL: www.ecophos.com	

EUPHORE®	
Europe	
<b>EuPhoRe GmbH</b> Raestrup 7   48291 Telgte   Germany Phone: +49 2504 98592 81 Email: frank.zepke@euphore.de URL: www.euphore.de	

## Glatt® SERAPLANT

### Europe

#### Glatt Ingenieurtechnik GmbH

Nordstrasse 12 | 99427 Weimar | Germany

Phone: +49 3643 47-0

Email: info.we@glatt.com

URL: www.glatt.com

## KUBOTA Surface Melting Furnace

### Japan

#### KUBOTA Corporation

2-47, Shikitsuhigashi 1-chome, Naniwa-ku | Osaka  
556-8601 | Japan

Phone: +81 6 6470 5370

Email: Hiroyuki.Hara@kubota.com

URL: www.kubota.com

## METAWATER

### Japan

#### Metawater Corp. Ltd.

Japan

Phone:

Email:

URL: www.metawater.co.jp

### North America

#### METAWATER USA

301 Route 17 North, Suite #504 | Rutherford, NJ  
07070 | USA

Phone: +1 201 935 3436

Email:

URL: www.usa.metawater.com

## Phos4Life

### Europe

#### Tecnicas Reunidas

C/Arapiles 13 | 28015 Madrid | Spain

Phone: +34 91 409 8950

Email: gdiaz@tecnicasreunidas.es

URL: www.tecnicasreunidas.es

TetraPhos®	
Europe	Asia
<b>REMONDIS AQUA GmbH &amp; Co. KG</b> Brunnenstrasse 138   44536 Lünen Germany Phone: +49 2306 1068900 Email: info@remondis-aqua.de URL: www.remondis-aqua.de	<b>REMONDIS China Ltd.</b> 19 Lam Lok Stree Room 1516-1520 , 15 <sup>th</sup> Floor Nan Fung   Kowloon Bay   Kowloon   Hong Kong Phone: +852 657 46302 Email: info@remondis.com URL: www.remondis.com

## 7.3 Phosphorus Platforms

Europe	
EU	Baltic Sea Region
<b>European Sustainable Phosphorus Platform, ESPP</b> 8 Avenue du Dirgeable   1170 Brussels   Belgium Phone: +33 474 93 07 93 Email: info@phosphorusplatform.eu URL: www.phosphorusplatform.eu Twitter: @phosphorusfacts	<b>Baltic Sea Action Group</b> Ratakatu 1 b A 5   00120 Helsinki   Finland Phone: +358 40 775 0686 Email: office@bsag.fi URL: www.bsag.fi Twitter: @bsag_
Germany	Ireland (Island)
<b>Deutsche Phosphor-Plattform DPP e.V.</b> Bornheimer Landwehr 46HH   60385 Frankfurt am Main   Germany Phone: +49 (0)69 3487 6068 Email: info@deutsche-phosphor-plattform.de URL: www.deutsche-phosphor-plattform.de Twitter: @dpp_ev	<b>All Ireland Phosphorus Platform (Project)</b> Queen's University Belfast Phone: +44 (0)28 9097 2602 Email: k.macintosh@qub.ac.uk URL: www.phosphorus.ie Twitter: @Phosphorus_ie
Netherlands	CH, CZ, ES, IT, UK
<b>Nutrient Platform</b> P/a Netherlands Water Partnership   Bezuidenhoutsweg 2   2594 AV Den Haag   Netherlands Phone: +31 (0)70 304 3700 Email: info@nutrientplatform.org URL: nutrientplatform.org Twitter: @NutrientP	Various networks in establishment

Asia	
Japan	
<b>P Recycling Promotion Council of Japan (PRPCJ)</b> Will be reorganised in 2018 into: <b>P Industry Development Organization (PIDO)</b> Phone: Email: info@pido.or.jp URL: Twitter:	

North America	
USA	Canada
<b>Sustainable Phosphorus Alliance (SPA)</b> Arizona State University   1001 South McAllister Ave   Tempe, AZ 85287-5701 Phone: +1 (480) 727 4271 Email: <a href="mailto:scholz@phosphorusalliance.org">scholz@phosphorusalliance.org</a> URL: <a href="http://www.phosphorusalliance.org">www.phosphorusalliance.org</a> Twitter: @SustainP	See USA